JOINT TRANSPORTATION RESEARCH PROGRAM

INDIANA DEPARTMENT OF TRANSPORTATION
AND PURDUE UNIVERSITY

Costs and Revenues Associated With Overweight Trucks in Indiana

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SPR-3502 • Report Number: FHWA/IN/JTRP-2013/01 • DOI: 10.5703/1288284314987

RECOMMENDED CITATION

Ahmed, A., B. R. D. K. Agbelie, S. Lavrenz, M. Keefer, S. Labi, and K. C. Sinha. *Costs and Revenues Associated With Overweight Trucks in Indiana*. Publication FHWA/IN/JTRP-2013/01. Joint Transportation Research Program, Indiana Department of Transportation and Purdue University, West Lafayette, Indiana, 2013. doi: 10.5703/1288284314987.

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ACKNOWLEDGMENTS

The valuable support and guidance provided by the following Study Advisory Committee members are gratefully acknowledged: Guy Boruff, Clark Snyder, Dennis Belter, Edward Pollack, Keith Bucklew, and Abby Weingardt of INDOT Central Office; Samy Noureldin and Victor Hong of INDOT Research Division; Karen Stippich, Mohammad Hajeer, and Thomas Duncan of FHWA Indiana Division; and Dick Hayworth of Indiana Department of Revenue. The authors, however, are solely responsible for the contents of the report.

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The Joint Transportation Research Program serves as a vehicle for INDOT collaboration with higher education institutions and industry in Indiana to facilitate innovation that results in continuous improvement in the planning, design, construction, operation, management and economic efficiency of the Indiana transportation infrastructure. https://engineering.purdue.edu/JTRP/index_html

Published reports of the Joint Transportation Research Program are available at: http://docs.lib.purdue.edu/jtrp/

NOTICE

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/IN/JTRP-2013/01		

4. Title and Subtitle	5. Report Date
Costs and Revenues Associated With Overweight Trucks in Indiana	November 2012
	6. Performing Organization Code
7. Author(s)	**8. Performing Organization Report No.**
Anwaar Ahmed, Bismark R. D. K. Agbelie, Steven Lavrenz, Michael Keefer, Samuel Labi, and Kumares C. Sinha	FHWA/IN/JTRP-2013/01
9. Performing Organization Name and Address	**10. Work Unit No.**
Joint Transportation Research Program Purdue University 550 Stadium Mall Drive West Lafayette, IN 47907-2051	**11. Contract or Grant No.** SPR-3502
12. Sponsoring Agency Name and Address	**13. Type of Report and Period Covered**
Indiana Department of Transportation State Office Building, 100 North Senate Avenue Indianapolis, IN 46204	Final Report
	14. Sponsoring Agency Code

15. Supplementary Notes

Prepared in cooperation with the Indiana Department of Transportation and Federal Highway Administration.

16. Abstract

This study estimated highway pavement and bridge damage costs, and analyzed the adequacy of permit revenues to cover these costs. The study began with an extensive review of the literature on the subject, thus facilitating identification of the gaps in the existing practice and research. The developed framework includes the establishment of asset families, realistic types and timings of reconstruction, rehabilitation, and maintenance, traffic volumes and growth projections. The cost of damage was estimated for each asset family and age group, and the sensitivity of asset damage cost with respect to key policy and analysis variables was explored. Finally, the study examined cost and operational issues associated with the enforcement of overweight truck policies. In addressing the gaps in existing research, this study showed that the damage cost of highway assets due to overweight trucks is influenced significantly by the asset type and age. For pavement assets, the pavement damage cost estimates were found to range from $0.006 per ESAL-mile on Interstates to $0.218 per ESAL-mile on non-national highways. The study also showed that non-consideration of reconstruction or maintenance cost can result in underestimation of the actual pavement damage cost by 79% and 83%, respectively. The analysis also showed that the unrealistic approach of considering only rehabilitation treatments applied at fixed intervals can lead to as much as 86% underestimation of the actual pavement damage cost. The results also suggest that pavement damage cost is highly sensitive to the pavement life-cycle length, interest rate, rest period, and the costs and service lives of rehabilitation treatments. For the bridge assets (classified on the basis of their superstructure material type), the incremental methodology was found to be suitable to estimate the cost of bridge damage due to overweight vehicles. This methodology determines and assigns bridge damage cost to all vehicle classes on the basis of vehicle axle configurations and usage frequency (vehicle-miles travelled). Incremental designs were carried out and cost functions were developed using AASHTO's design vehicles. Each FHWA vehicle weight group was classified into an equivalent AASHTO loading regime using the modified equivalent vehicle (MEV) model which is based on gross vehicle weight, axle loading and axle spacing. The results were used to incrementally assign bridge cost to each vehicle class. For each class of overweight vehicles, the bridge damage cost was computed as the ratio of the cost responsibility and the volume of these vehicles. The bridge damage cost was estimated under two permit fee options and three user charging scenarios. The results suggest that approximately 22% of total bridge cost can be considered attributable to overweight vehicles. Also, it was observed that the bridge damage cost is not just a factor of gross vehicle weight but a function of all the three vehicle-related variables: gross vehicle weight, axle spacing and axle loads. It was concluded that the adoption of a permit structure on the basis of gross vehicle weight only, will result in certain vehicle classes underpaying by as much as 92% of their actual contribution to bridge damage. Finally, the study examined cost and operational issues associated with the enforcement of overweight truck policies and identified a number of locations that could be considered for establishing new weigh stations and other enforcement facilities.

17. Key Words	18. Distribution Statement
overweight trucks, overweight permits, pavement damage cost, bridge damage cost, truck weight enforcement	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	248	

Form DOT F 1700.7 (8-69)

EXECUTIVE SUMMARY

COSTS AND REVENUES ASSOCIATED WITH OVERWEIGHT TRUCKS IN INDIANA

Introduction

In order to protect the investments made in highway pavements and bridge infrastructure, the Indiana Department of Transportation regulates trucking operations using legislation and federal-recommended policies. Under certain circumstances, special permits are granted to truck operators to allow excess over the specified operational weight restrictions. As the steward of the public highway infrastructure in Indiana, INDOT has a special duty to ensure that operating policies are not unduly restrictive as to discourage economic development but also realistic enough to prevent premature and accelerated highway deterioration. With the changing patterns of commercial vehicle movements over the years, there is a need to continually review the costs and revenues associated with overweight trucks, in terms of their pavement and bridge damage costs and permit fees.

This study addressed the vital issue of pavement and bridge damage cost estimation and analyzed these costs in terms of the adequacy of permit revenues for highway pavements and bridges. Analytical frameworks were developed for estimating the marginal damage cost on the basis of practical and realistic strategies for pavement and bridge maintenance over their life cycles or remaining lives. The study began with an extensive review of the literature on the subject, thus facilitating identification of the gaps in the existing practice and research. The framework, involves development of asset families, establishment of realistic schedules for reconstruction, rehabilitation, and maintenance, and projections of traffic volumes. Using the developed framework, the marginal cost of damage was estimated for each asset family and age group. Furthermore, the sensitivity of marginal asset damage cost with respect to key policy and analysis variables was explored. Finally, the study examined cost and operational issues associated with the enforcement of overweight truck policies.

Findings

The literature review showed that very few studies in the past, had adopted a truly comprehensive approach for asset damage cost estimation on the basis of practical and realistic maintenance, rehabilitation and reconstruction practices. Key gaps in existing research include the use of data from limited sources that do not adequately capture loading patterns across the different functional classes, the impractical assumption of perpetual application of only a single type of overlay applied at fixed intervals, inadequate use of actual data on asset treatment cost and performance and traffic volumes, failure to distinguish between strength-driven and capacity-driven expenditure, lack of an analysis time frame of sufficient length to accommodate realistic long-term expenditures, traffic, and performance trends, and use of inappropriate road-use measures. In developing a framework that addresses these gaps, this study showed that the damage cost of highway assets due to overweight trucks is influenced significantly by the asset type and age, among other factors.

For pavement assets, the overall pavement damage cost estimates were found to range from $0.006 per ESAL-mile on Interstate highways to $0.218 per ESAL-mile on non-national highways. The study also showed that non-consideration of reconstruction or maintenance cost can result in underestimation of the actual pavement damage cost by as much as 79% and 83%, respectively. The analysis also showed that the unrealistic approach of considering only rehabilitation treatments applied at fixed intervals in asset life cycle, can lead to as much as 86% underestimation of the actual pavement damage cost. The results suggest that the pavement damage cost estimates are highly sensitive to the pavement life cycle length, interest rate, rest period, and the costs and service lives of rehabilitation treatments.

For bridge assets (classified by their superstructure material types), the incremental methodology was found to be suitable for the damage cost estimation. This methodology yields a damage cost to each vehicle class on the basis of the axle configurations and usage frequency (vehicle-miles travelled) in that vehicle class. The bridge damage cost was estimated for two permit fee options and three user-charging scenarios. An important result of the study was the confirmation of the fact that bridge damage cost is a function not only of gross vehicle weight but also of axle spacing and axle loads. Also, it was shown that adopting a permit structure on the basis of gross vehicle weight only will result in the situation where certain vehicle classes underpay by as much as 92% of their actual damage contribution.

Finally, the study identified a number of locations that could be considered for establishing new weigh stations and improving the staffing. The study also made recommendations for enhancing the efficiency of monitoring and inspecting the operating weights of commercial vehicles in the state.

Implementation

This study can be used by a number of offices, program areas, and units at INDOT to assess the consequences of truck weight policies on the longevity of assets within their jurisdiction. These include the Indiana Toll Road, Offices of Freight Mobility, Economic Opportunity, and the Indiana Department of Revenue. These offices have a stake in knowing the potential impact of any changes on vehicle license fees and overweight truck permits on the revenue generated from each of these fee structures, and the impact of pavement damage in response to overweight policy changes.

In summary, implementing the study product can assist the state of Indiana in updating and streamlining its overweight vehicle permitting process. The state will be in a better position to monitor the impacts of the use of its highways by overweight vehicles, make its permit fee structures more equitable, and ultimately, strike a balance between the need to preserve its investments in highway infrastructure and the need to help make the state more competitive economically.

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GLOSSARY OF ACRONYMS AND TERMS

AADT: Average Annual Daily Traffic.

ESAL: Equivalent Single Axle Load.

Highway Costs Allocation (HCA): The assignment of the amounts expended on highway construction, reconstruction, rehabilitation, and maintenance, including capacity-driven and strength-driven expenditure to highway users.

ISP: Indiana State Police

Marginal Pavement Damage Cost (MPDC) Estimation: The incremental cost of pavement damage repair due to the addition of one extra unit of usage (such as 1 ESAL-mile or VMT).

MCSD: Motor Carrier Services Division.

MR&R: Maintenance, rehabilitation, and reconstruction.

MR&R Strategy/Schedule/Activity Profile: The set of pavement or bridge treatments from construction to infinity. This involves a partial cycle and a number of full cycles to perpetuity. This definition is specific to this report.

Life-cycle Activity Profile: The set of pavement or bridge treatments between periods of reconstruction.

Load Equivalency Factor (LEF) or ESAL Factor: Is the ratio of the damaging effect of a non-standard axle to that of a standard axle load, in other words, LEF is the equivalent number of ESALs for a certain combination of weight and axle.

Pavement Damage Cost (PDC) Estimation: The development of the unit cost of highway facility damage repair due to usage. This is based on the equating the frequency and intensity of usage of the facility cost on one hand, to the costs of repairing the damage inflicted on the facility due to the usage on the other hand. The repair costs include the rehabilitation and maintenance costs as well as the cost of reconstruction due to the damage.

NAPCOM: National Pavement Cost Model

OW: Overweight (vehicle)

Road-use Measure: A parameter that shows the extent to which a facility is used. This serves as the basis for reporting the cost of pavement damage repair, for example, $/vehicle-mile and $/load-mile.

SRI: Smart Roadside Initiative.

VMT: Vehicle miles of travel.

PART I. INTRODUCTORY INFORMATION

1. INTRODUCTION

1.1 Background Information

The Indiana Department of Transportation (INDOT), tasked with the stewardship of billions of dollars' worth of publicly invested highway infrastructure in the state of Indiana, continually seeks policies that prevent accelerated deterioration of its assets through excess loading and other factors. Consistent with this objective, INDOT desires to have knowledge of the infrastructure damage caused by overweight vehicles to (i) ascertain the true costs of overweight vehicle operations in terms of pavement and bridge damage repair and (ii) serve as a basis for updating the existing overweight permit fees. Specifically, such knowledge would enable the agency to design the most efficient and effective permitting structure from various perspectives including axle- or gross weight-based permitting and permit coverage types (annual vs. single trip).

It is important for INDOT to continue to monitor overweight vehicles because such vehicles not only inflict great damage to highway pavement and bridge infrastructure (thus reducing their longevity) but also often constitute a safety hazard to other motor operators, pedestrians, and the general public. Overweight vehicles cause undue stress on critical components of the vehicle drivetrain including brakes, transmission, steering, and suspension, often leading to early failure of components; sudden failure of these components could cause a serious crash. This study focuses on the pavement and bridge damage costs only and excludes the safety and congestion consequences of overweight vehicle operations.

In the past few decades, INDOT and the USDOT have carried out or sponsored research that examined, directly or indirectly, the issue of overweight vehicle operations, their impacts on highway infrastructure condition or longevity, and the user permit fees to cover such damage. In 1984, INDOT commissioned a cost allocation study (*1*) to restructure the user charges that existed at the time. In 1988, the 1984 study was updated to provide information for a fuel tax rate change (*2*). Also, a 2000 US DOT study (*3*) presented data that could be used by the states to assess the increase in pavement costs for every ton increase in payload or the decrease in pavement costs for every increase in the number of axles, for any given truck class. A recent SPR study (*4*) in Indiana that synthesized overweight vehicle permitting practices, including permit fee schedules and amounts, across the Midwest states in relation to the practice in Indiana, further accentuated the need for a study in Indiana to investigate the costs of pavement and bridge damage for purposes of updating the state's heavy truck permitting free structures. From that study, a research need was identified to (i) investigate how to relate permit fees to infrastructure damage in terms of axle weight and gross vehicle weight; (ii) identify all costs related to the use of overweight trucks in Indiana; (iii) estimate all revenues from the overweight truck permitting process; (iv) establish an equitable permit fee structure by each heavy vehicle class on the basis of axle weights instead of, or at least in addition to gross vehicle weight.

1.2 The State of Truck Permitting Practice in Indiana

Indiana's roads and highways were constructed to accommodate vehicles of certain attributes (dimensions and weights). For any vehicle whose attributes exceed those established by law, a permit is required. The permitting process in Indiana DOR's overweight permitting handbook also helps ensure that appropriate routes and bridges are used, and enforces the required safety procedures. Also, the permit fee is a way to hold the extra-legal vehicle operators responsible, in a mostly aggregate fashion, for the damage caused by overweight vehicles to the highway bridges and pavements and also for the safety risks posed by oversize vehicles. By imposing such fees, not only is excessive use of overweight/oversize vehicles regulated but also revenue is generated to repair any damage caused by these vehicles and also to upgrade these infrastructure to standards that can better withstand and support such extra-legal operations. In this manner, the investments made in the highway infrastructure and the safety of Indiana motorists, are better safeguarded. Fees collected for the permits are distributed to the State Highway Fund which enables financing of state and local road improvements, maintenance and policing.

An overweight vehicle is generally any vehicle whose overall weight exceeds 80,000 pounds. However, road and bridge stress levels are determined by the distribution of the weight, so it is also important that the weight per axle or sets of tandem axles (or in some cases, weight per tire) is also monitored. The total gross weight for a permit applicant is calculated using federal bridge formula and then compared with the established weight limits. See Oversize-Overweight Vehicle Permitting Handbook, Motor Carrier Services Division (MCSD), Indiana Department of Revenue, Indianapolis (*5*), for details of the federal formula and federal tables. The acronym OSW or OS/OW represents oversize and/or overweight vehicles. In extreme cases, permits may be sought for a "superload" (a load that exceeds certain threshold dimensions and/or threshold weight (in Indiana, the thresholds are 15 ft height, 16 ft width, and 110 ft length; and 120,000 lbs, respectively), or a load that fails the overload analysis.

In seeking a permit for a vehicle that violates legal load levels, the applicant first confirms that their load is not divisible. Definition of nondivisible loads are stated in 23 Code of Federal Regulations 658.5 (*5*). There is one exception to the rule of nondivisible loads: for the Indiana-designated "extra heavy-duty highways" in northern Indiana, applicants may haul divisible loads with a total gross weight of up to 134,000 pounds, subject to legal axle weights with a special permit commonly known as a "Michigan Train Permit". In Indiana, weights between 80,000 lbs and 120, 000 lbs are simply described as "overweight"; those over 120,000 lbs are considered as superloads (*6*).

Permits for overweight vehicles are provided through the consolidated efforts of the Indiana Department of Transportation and the Indiana Department of Revenue. The Department of Transportation maintains and safeguards Indiana highways and evaluates particular road conditions and passability. Permits are issued after it has been ascertained that road traffic will not be severely affected and the highway and bridges will not be seriously damaged. The Department of Revenue ensures that the proper permits are issued and the fees paid. In Indiana, there are a number of exemptions from overweight permits (see Part V of this report). The lists of permit types and fees are provided in Part V.

In Indiana, options for obtaining a permit are the Internet, permitting service, fax, mail, and walk in. Details for each option are provided in Part V. For trucking organizations new to Indiana, the permit applicant visits the Motor Carrier Services page of the Indiana Department of Revenue website to set up an OSW account by clicking the link: "New to Indiana? Apply for an OSW Account." The applicant enters basic information, account information, USDOT numbers, and address and contact information. For pre-approval, INDOR has in place a process that facilitates the process of superload permit approvals for the benefit of applicants who face time constraints. Indiana's current permitting system allows the applicant to have the INDOT engineering analysis done ahead of time, well before the time that the permit is needed, and the applicant receives a superload pre-approval number. With this pre-approval number, the applicant (for the next 30 days) can obtain the trip permits using the same vehicle configuration and route without any additional INDOT analysis or delays. "Superload" permits are issued if the load exceeds the threshold dimensions (15 ft height, 16 ft width, and 110 ft length) and/or weight threshold (120,000 lbs).

Any load that fails the overload analysis or is over 200,000 lbs is reviewed by an INDOT engineer, and this typically requires additional processing time. INDOR's form M-233ST, which lists the allowable weights and axle characteristics for a special-weight single-trip application, is presented in Part V of this report. Also, INDOR has established a list of the 22 extra heavy duty highway routes in Indiana.

1.3 Overview of Past Studies Related to Highway Damage Cost Estimation

To ensure the equity of existing or proposed structures for highway user fees, studies on pavement or bridge damage cost estimation and also on highway cost allocation compare the cost responsibility and the revenue contributed by each vehicle class. The common objective across these studies is to narrow the gap between costs occasioned and actual revenues paid by each vehicle class. The last major cost allocation study at the federal level was carried out in 1997 (*7*) which was subsequently updated by an addendum in 2000 (*8*). The concept of equity, which is the fair sharing of costs in proportion to the revenues (*9*), is consistent with the decomposition of damage repair costs into attributable costs (these are caused by traffic loading and thus are allocated to the different vehicle classes) and non-attributable costs (these are the so-called "common costs", which are caused by climate, aging and other non-load factors.

Most highway cost allocation studies (HCAS) use an incremental method. In this methodology, the cost of facility construction and maintenance for the lightest vehicle class, termed the "base cost", is determined as the first step. All vehicle classes are responsible for their appropriate share of this base cost. Next, the facility is enhanced (stronger bridges and thicker pavements) to accommodate heavier vehicles and the cost of the design increment (facility enhancement) is shared among the heavier vehicle classes only. Such an incremental approach could have limitations because it gives undue advantage to heavy vehicles (that is, it assigns to heavy vehicles, relatively lower costs than their actual cost responsibilities) due to economies of scale; in other words, this approach inherently suggests that for heavy vehicles (higher loads), a unit increase in load is less deleterious compared to the effect of a unit increase in load for smaller vehicles (lower loads) (*10*). In the nineties, enhanced highway cost-allocation techniques were developed to take cognizance of new research findings in pavement deterioration and investment evaluation (*10,11*). The national pavement cost model (NAPCOM), which was adopted for the federal HCAS of 1997, used a "cost occasioned approach" where each user class pays for road use according to the extent of system use. However, unlike previous studies, the NAPCOM study also considered marginal social costs such as air pollution, noise, congestion, and crash costs (*7,11*).

With continuing advancements in pavement and bridge deterioration research, greater opportunities exist for a clearer understanding of the relative share of damage by different vehicle classes and the equitable restructuring of permit fees (vis-à-vis existing fees). These advancements include those in the areas of pavement and bridge deterioration modeling, the evaluation of the life-cycle costing and longevity benefits of pavement and bridge rehabilitation and maintenance treatments, and mechanistic analysis of the behavioral response of bridge and pavement components to load and non-load stresses. Specifically, in Indiana, the development of the state's bridge and pavement management systems as well as the traffic monitoring program, have made available rich data on the initial and life-cycle costs and effectiveness of various standard treatments, the performance of the highway facilities by functional class, and the facility demand (usage) and loading intensities by vehicle class and weight groups. The present study takes advantage of the current availability of such data in Indiana to carry out a comprehensive damage cost estimation analysis that is based on realistic and practical rehabilitation and maintenance practices at INDOT.

1.4 Study Objectives and Scope

The primary objective of this research is to investigate how to relate highway use fees to infrastructure damage and other costs related to overweight truck operations in Indiana. The investigation is expected to yield an updated and more detailed methodology for attributing the costs of pavement and bridge repair as well as enforcement and other costs occasioned by each vehicle class. Other objectives are to provide guidelines for INDOT to establish a balanced fee structure that would not discourage economic development and yet ensure that all heavy vehicles pay their fair share of costs; and to investigate the pros and cons of INDOT establishing permit fees on the basis of axle weights as opposed to gross vehicle weights.

Consistent with the above study objectives, the scope of the study was to identify all costs and revenues related to overweight vehicle operations in Indiana. From the cost source perspective, the study scope includes infrastructure type preservation activity costs, and enforcements costs. From the activity type perspective, the scope includes reconstruction, rehabilitation, and maintenance. From the highway facility type perspective, the scope includes pavements and bridges only. The study scope also includes a comparison of the costs and revenues by vehicle weight class.

1.5 Overview of the Study Methodology

In order to establish the unit costs of pavement or pavement damage, there were two key aspects of the study: one addressed the **cost of providing the facility** and the other addressed the **extent of usage** over the facility life cycle. A synthesis of these two aspects yielded the cost per usage in other words, the unit costs of facility use. To do this, data on pavement reconstruction, rehabilitation, and maintenance costs were collected and analyzed, and cost vs. usage models were developed. For enforcement and other costs, the report includes personnel costs and other costs incurred by the Indiana State Police (ISP) associated with enforcement of the overweight permitting process involving weighing and escorting tasks. The adequacy of revenue collected under the current permitting structure was carried out not for the entire highway system but for individual vehicle classes and weight groups: to do this, the existing permit fee (unit revenue) on one hand was compared to the actual cost of pavement or bridge damage estimated by the study on the other hand. The report also provided a conceptual discussion of the pros and cons of basing fees on axle weights and gross vehicle weights and also of the consequences of annual (blanket) vis-à-vis single-trip permitting structures.

1.6 Contents of this Report

Part I of this report discusses the study background, objectives and scope. Parts II, III, and IV address the costs and revenues associated with pavement and bridges, and the costs of enforcement that are associated with overweight vehicle uses in Indiana. Part V briefly addresses overall revenue analysis and permitting issues for purposes of revenue generation. Part VI summarizes the study methodology and findings, and highlights the study contribution to the research literature on the subject.

PART II. PAVEMENT DAMAGE COSTS

2. INTRODUCTION

2.1 Background

Hundreds of billions of dollars are needed annually for preserving U.S. highway pavements (*12*). As such, highway agencies in the U.S. continually seek policies that yield adequate revenue and prevent undue deterioration of the highway pavements. Pavement damage is accelerated mostly due to factors related to the pavement material type, age, climatic severity, and traffic loading. For pavements, traffic loading (particularly by heavy vehicles such as trucks with at least five axles) contributes the most damage and therefore is the key factor in design procedures for that asset (*13–15*). In recognition of this fact, highway agencies seek reliable knowledge about the portion of the damage caused to the pavement by heavy vehicles, which can serve as a basis for establishing an efficient and equitable road user charging system. The results of past studies suggest that the current road user charging systems do not recover the full cost occasioned by different vehicles and/or that most heavy vehicles are paying less than their equitable share on many highways, and thus are being subsidized by light vehicles (*16–20*).

2.2 Problem Statement

For pavement damage cost (PDC) estimation, two approaches have been used in the past studies: the so-called empirical and engineering approaches. The empirical approach hinges on the establishment of a statistical relationship between the usage (or road-use) of the pavement (in terms of vehicle miles traveled or load-miles, for example) on one hand, and the costs of pavement maintenance, rehabilitation and reconstruction (MR&R) on the other hand. This is then followed by finding the derivative of the estimated cost function with respect to the road-use variable to yield the marginal pavement damage cost (MPDC). The "engineering" approach is based on the derivation of theoretical relationships between road-use (for example, traffic loading) on one hand and pavement damage on the other hand, and then translating such damage to cost using damage-cost relationships.

In past studies that used these approaches, the pavement reconstruction costs were not considered as a cost item as only maintenance and rehabilitation costs were analyzed. Also, in studies that used the empirical approach, the temporal inconsistencies between the time-span of the traffic data and that of the MR&R cost data appear not to have been adequately addressed. Also, in most studies that used the engineering approach, only rehabilitation activities were considered while reconstruction, periodic, and routine maintenance activities were generally not included in the analysis. Other problems associated with the methodologies used in several existing studies include the collection of traffic data from only one or few weigh-in-motion sites thus precluding the acquisition of truly representative distribution of traffic classification and loads. Further, most studies have utilized MR&R schedules that do not adequately reflect the true practices of highway agencies, for example, some studies have used only a single rehabilitation type applied at regular intervals of about 10–15 years.

To improve the methods used in pavement damage cost estimation, it is important to overcome these limitations. First, in studies of this nature, it is critical that the traffic and MR&R data span same time period. Also, the time period should be adequate, for example, 15–20 years span of data, rather than just a couple of years. In other words, an appropriate time span for the analysis must be established so that long-term expenditure, traffic, and performance trends can be established with minimal bias.

Secondly, the methodology should accommodate not a single pavement segment or a single type (surface type and functional class) of pavements but rather for each distinct family of an entire network in a region of interest.

Thirdly, for the purposes of damage cost estimation, it is important to establish a pragmatic schedule of MR&R activities (and hence obtain a reliable representation of amounts expended on such preservation actions), so that realistic costs can be attributed to the users. At most agencies, actual MR&R practice is characterized by the application of different treatments and this is done not for a single pavement type but for each family of pavements (grouped on the basis of functional class, pavement surface type, among other attributes). In this respect, there is a need to incorporate all the appropriate treatment categories of pavement damage repair, not just one or a select few. In other words, the entire gamut of treatments spanning routine and periodic maintenance, rehabilitation, and reconstruction must be considered as appropriate and as reflective of the actual agency practices.

Related to the above consideration is the issue of strength- and capacity-driven expenditure. The analysis should necessarily exclude capacity-driven expenditure such as lane-widening projects and must not include the costs of such work in the cost aspect of the equation. Only strength-driven expenditures must be considered because the problem statement is related to the cost of pavement damage. Also, for strength driven expenditures, the shares of load and non-load damage (and therefore, expenditure) must be established, so that load-related costs may be fairly assigned to the facility users.

Fifth, an appropriate road-use measure should be selected that is consistent with the objective of analysis (in this case, pavement damage). For stated or ostensible reasons that often include lack of data, several studies have used road-use measures that make it difficult to establish a fair and equitable cost of pavement damage and consequently, fee. For example, a pavement damage cost in dollars per vehicle per mile does not account for vehicle load. Nor does one expressed as dollar per vehicle weight per mile as it does not account for the damaging effect of axles. Related to this is the issue that an appropriate exponent for the load equivalency factor (LEF) must be determined on the basis of the agency-specified performance indicator and threshold values for each family of pavements under consideration: to avoid the unduly restrictive assumption of past studies that the fourth-power law is valid, there is a need examine the sensitivity of pavement damage costs estimates with respect to differences in the LEF ratio.

2.3 Study Objective

On the basis of the problem statement discussed in the previous section, there is a need for highway agencies such as INDOT to establish appropriate unit costs of pavement damage and thus to establish a foundation upon which existing permit fees for overweight vehicles could be reviewed. As such, the primary objective of the study this study developed and implemented a methodology to address the following objectives:

- To provide a comprehensive overview of the various approaches used in the past for highway PDC estimation.
- To develop and demonstrate a practical framework for damage cost estimation by incorporating realistic highway agency maintenance, rehabilitation and reconstruction practices.
- To quantify the influence of pavement age on the amount and cost of pavement damage per unit load.

The entire framework is based on the concept of marginal pavement damage cost (MPDC), defined as the increase in agency MR&R expenditure due to addition of one more road-use variable.

2.4 Overview of Study Approach

A general outline of the pavement part of the study is presented as Figure 2.1. First, a comprehensive literature review was conducted on PDC estimation, MR&R strategy formulation, and highway agencies MR&R practices. Next, pavement families, pavement rest period and treatment service life, formulation of MR&R strategies (using pavement life-cycle M&R

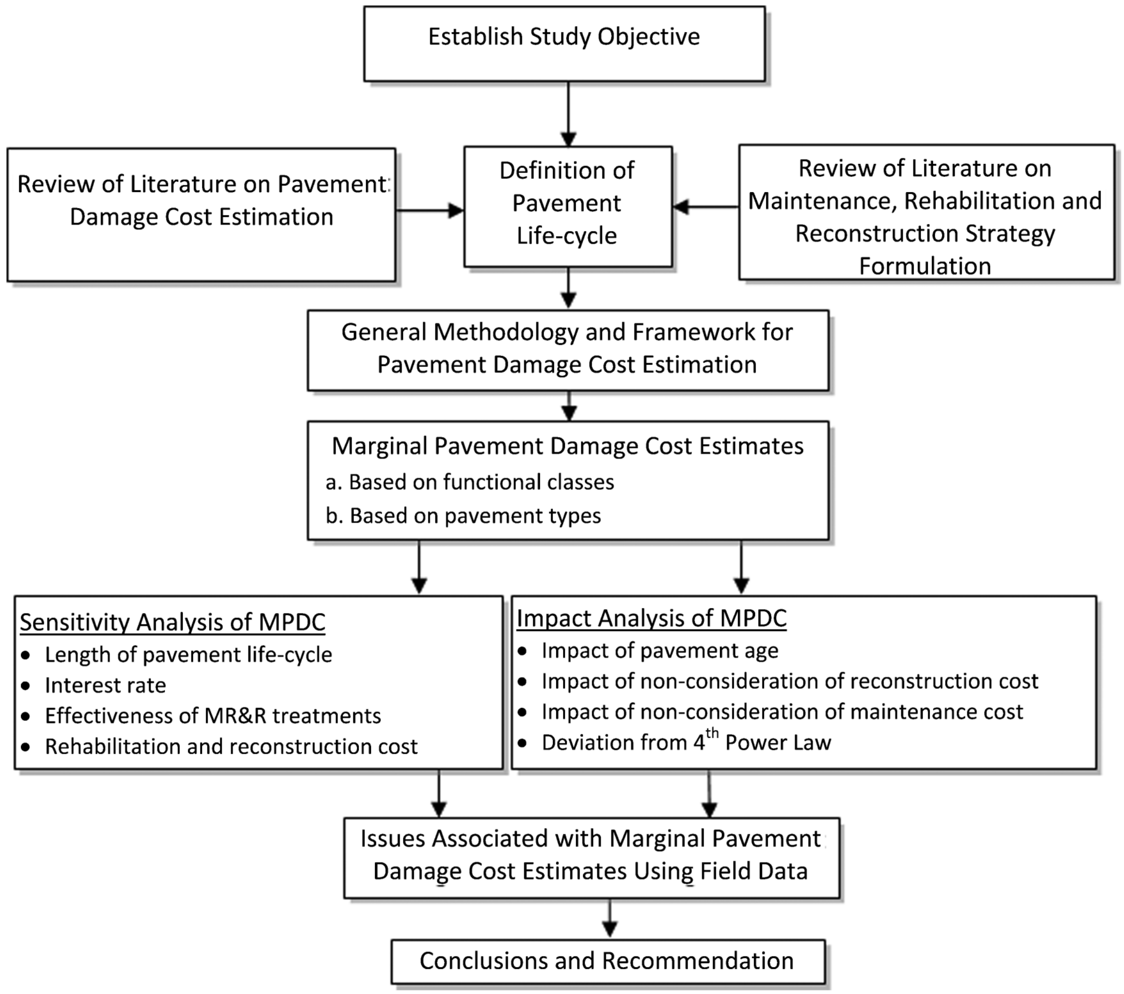


Figure 2.1 An overview of the study approach for pavement damage cost estimation.

profile) were carried out, followed by the development of cost functions and MPDC estimates. This was done for each highway functional class. The impact of non-consideration of certain cost categories on PDC estimates was investigated. In addition, the study investigated the consequences of non-consideration of non-truck traffic in the analysis, and examined the impacts of deviations from the established relationship between pavement loading and deterioration (i.e., the fourth-power law). Variations of the MPDC with respect to key policy and analysis variables (i.e., the length of the pavement life cycle, the interest rate, the effectiveness of the MR&R treatments, and the reconstruction and rehabilitation costs) were explained. A number of issues and problems areas associated with direct use of field data for MPDC estimation were discussed. This study also quantifies the variation of MPDC estimation across roadway segments.

2.5 Organization of Part II of This Report

This part (Part I) of the report is organized into six chapters. Chapter 2 discusses need for reliable estimation of MPDC, the study objectives, and the study approach. Chapter 3 presents a summary of the literature review on MPDC estimation and the impacts of the evolution of pavement designs on MPDC estimation reliability. Chapter 4 presents the highway pavement MR&R strategies that were formulated for the study and the research methodology. Chapter 5 describes the estimation of MPDC using the developed methodology. Also, this chapter discusses the impact of pavement age, the impact of not including the reconstruction/maintenance cost, and the variation in MPDC when the fourth-power law is invalid. Chapter 6 describes the sensitivity analysis of MPDC with respect to the length of the pavement life cycle, the interest rate, the effectiveness of MR&R treatments, and the reconstruction and rehabilitation costs. Lastly, the research summary, conclusions, and recommendations for future work are presented in Chapter 7.

3. LITERATURE REVIEW

3.1 Introduction

To assess the adequacy and/or inequity of highway permit and license fees to cover pavement damage, a number of studies have been carried out in the U.S. and abroad. The goal of these studies was to design suitable fee structures so that vehicles pay their fair share of highway use. Often, this has been done as part of broader studies on cost allocation. A major, common component of these past studies was the estimation of the costs of highway upkeep (maintenance, rehabilitation, and reconstruction) and the allocation of these costs to users through different vehicle classes in a manner that is commensurate with their respective pavement damage contributions. This procedure was followed by a comparison of the resulting cost responsibility estimates to the existing user fees, for each vehicle class. The calculated difference (or gap) between the estimated and actual costs represents the equity (or lack thereof) of the existing user fee. Some of the past studies went further to make recommendations geared towards narrowing the gap. In the U.S., the most recent major study at the national level was conducted in 1997 (*17*) which was subsequently updated in a 2000 addendum (*18*).

As will be seen in subsequent sections of this chapter, the estimation of a consistent unit cost of pavement damage has remained largely unresolved (and even controversial) in spite of significant and earnest past research efforts spanning several decades. Fortunately, with the continuing maturity of pavement management systems at several state highway agencies and with ongoing advancements in pavement deterioration research, there is a new dawn of unprecedented opportunities for a more lucid understanding and reliable quantification of the actual damage inflicted by different vehicle classes on pavements. This will help pave the way for a resolution to the larger user charging challenge by facilitating the development of more efficient and more equitable fee structure. Resolving the problem could also help agencies to establish policies that encourage the use of more appropriate axle load distribution that inflicts lower damage to the pavement.

3.2 Major Research Directions for PDC Estimation

There exist at least two categories of studies that have addressed the issue of pavement damage cost. The first category, highway cost allocation (HCA) studies, were not aimed at pavement damage cost estimation but needed to carry out such analysis in order to allocate all costs of pavement provision and upkeep. As such highway cost allocation studies included projects geared towards highway capacity expansion as well as pavement strengthening. The second category of studies specifically addressed the cost of pavement damage as their final end product. For purposes of this report, we herein refer to such studies as pavement damage cost (PDC) studies.

For HCA and PDC estimation studies, a number of methods/approaches have been used in past studies. The prominent methods/approaches used for HCA and PDC estimation are shown in Figure 3.1, and a discussion of these methods/approaches follows in the ensuing paragraphs.

3.3 Highway Cost Allocation (HCA) Studies and Methodologies

Simply put, HCA is the assignment of specific fees to each user class of a highway system. Traditionally, HCA studies are based on the principle of equity. In the literature, the terms "Cost Allocation Approach" (*17,18,21*) and "Club and Equity Approach" (*22*) have been used to describe such studies. The primary objective of HCA studies is to evaluate the equity and efficiency of federal highway user charges based on the

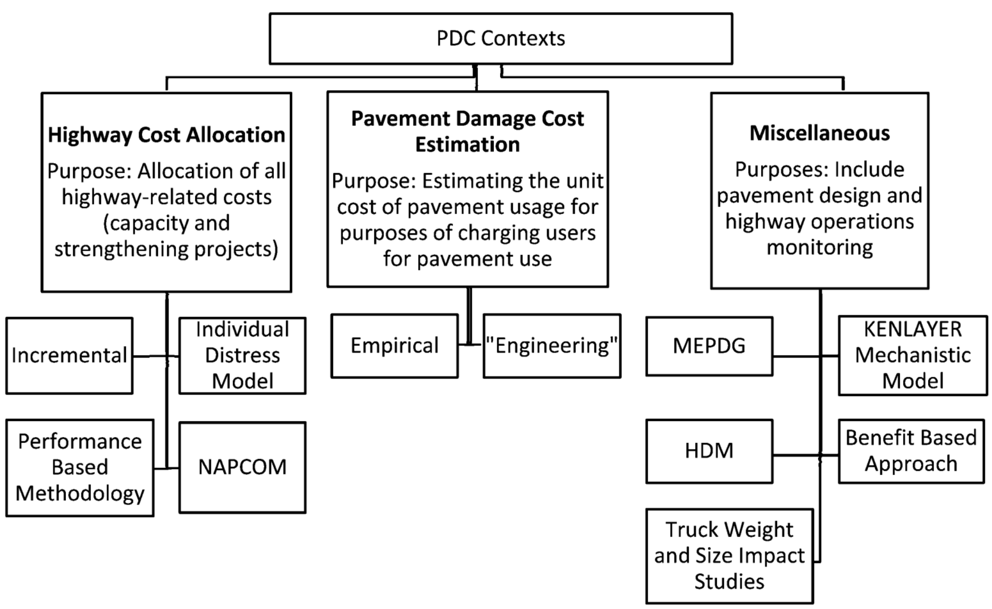


Figure 3.1 Contexts for PDC estimation.

costs assigned to different vehicle classes (*17*). Equity can be defined as the fair sharing of cost in proportion to either the benefits accrued or to the cost occasioned by each vehicle class. A key aspect of equity is the consideration of attributable pavement repair costs (which vary across vehicle classes due to their weight) and non-attributable costs (common costs that are due to climate, weather, aging, application of deicing salt, and other factors not related to vehicle loading) (*23*). HCA involves a detailed comparison of the actual user fees paid and the equity-based cost responsibility (*17,24,25*).

For most studies that estimated the cost of pavement damage, the study context was to allocate cost, in other words, to assign highway repair costs to various classes of highway users. A brief introduction to the cost allocation approach is herein presented to highlight the major contextual differences between HCA and PDC studies.

From the asset type perspective, highways consist of more than pavement: they include bridges, safety assets, mobility assets, etc. Thus, highway cost transcends pavements costs alone; even for pavements, not all investments are meant to solely address damage: some investments are to increase highway capacity by adding more lanes of pavement. As such, HCA studies consider the cost of capacity addition ((re)construction, major widening, etc.), system enhancement (safety, management, ITS projects etc.), and system preservation. For pavements, the cost categories include: new construction, major widening, reconstruction with lane addition, minor widening and maintenance, and rehabilitation (*17*). Within these cost categories are sub-categories; for example, in a 1984 Indiana HCA study, the rehabilitation cost subcategories included: pavement and shoulder, right-of-way, grading and earthwork, and drainage and erosion control. Similarly, different cost allocators are used to allocate the estimated cost within individual cost categories.

The methods used in past HCA studies can be categorized as follows: traditional incremental (*21*), thickness incremental (*23,26*), performance-based methodology (*28*), facility consumption (*21*), individual distress models (*18,21,29*), and game theory (*30*). The major HCA studies are summarized in Part II Appendix A, and the underlying methods used in these studies are discussed in the ensuing paragraphs.

3.3.1 Incremental Method

Until 1982, most of the HCA studies in the U.S. (including the first federal HCA study of 1962) used the "incremental method" (*31*). Pavement construction cost was the major cost element for HCA studies carried out in the 1960s and 1970s because at that time the pavement maintenance cost constituted only a small part of overall highway expenditures. In early HCA studies, costs were allocated either on the basis of vehicle-miles travelled (VMT) or the traditional incremental method (*28,31*). In the traditional incremental method, the first step is to determine the cost of facility construction and maintenance for the lightest vehicle class, referred to as the "base cost," The base cost is shared by all vehicles in proportion to their facility use (i.e., number of miles travelled). The next step is to increase the pavement thickness one inch at a time to accommodate heavier vehicles (trucks) and hence the cost of these subsequent thickness increments is assigned to the heavier vehicle classes. These are termed as the "incremental cost" (*26,29*).

Therefore, the traditional incremental approach, instead of applying random loadings to the pavement structure, adds vehicle classes sequentially from the lightest to the heaviest. Thus, those vehicle classes that are added at the last increment seem to pay the least share of pavement cost. This approach has been widely criticized as heavy vehicles enjoy the benefits of the economies of scale and results in unfair cost allocation. Generally, a greater thickness of pavement is designed to accommodate higher traffic loads; however, the relationship between traffic load and pavement thickness is non-linear (*26*); in other words, a 100% increase in traffic load requires less than a 100% increase in pavement thickness. Such scale economy in pavement design is illustrated in Figure 3.2 where a plot of the pavement thickness vs. the traffic load shows the curve flattening out at the higher loads. As shown in the figure, the first unit thickness ΔT accommodates a small increase in load $(\Delta L)_1$ while the last unit thickness which is the top most unit thickness of pavement, accommodates a much higher load $(\Delta L)_2$. This clearly shows a wide gap between the added ability of pavements to withstand loads for the initial and final thickness increments. These two increments have almost the same cost but differ on the extent to which they enhance the load-carrying capacity. Therefore, the incremental method of cost allocation and similar other methods that distribute the cost of additional pavement thickness to accommodate additional loads, are not equitable as they yield fee structures that make lighter vehicles bear an unfair burden of the cost.

3.3.2 The Facility Consumption Method

Realizing the limitations of the incremental method, efforts were made in the late 1970s to improve the allocation of pavement costs. The facility consumption method is a set of cost allocation procedures developed during the 1982 federal HCA study. In this method, the cost of new pavement construction is allocated on the basis of a uniform removal technique instead of the incremental method, whereby a base facility cost is established and allocated to all vehicle classes on the basis of VMT. The enhanced facility cost was allocated by using a reverse incremental approach or uniform traffic removal technique. The traffic loading is reduced gradually by removing vehicle classes systematically until any further reduction would result in a pavement structure thinner than the minimum pavement thickness or base facility. For each vehicle class removed, the

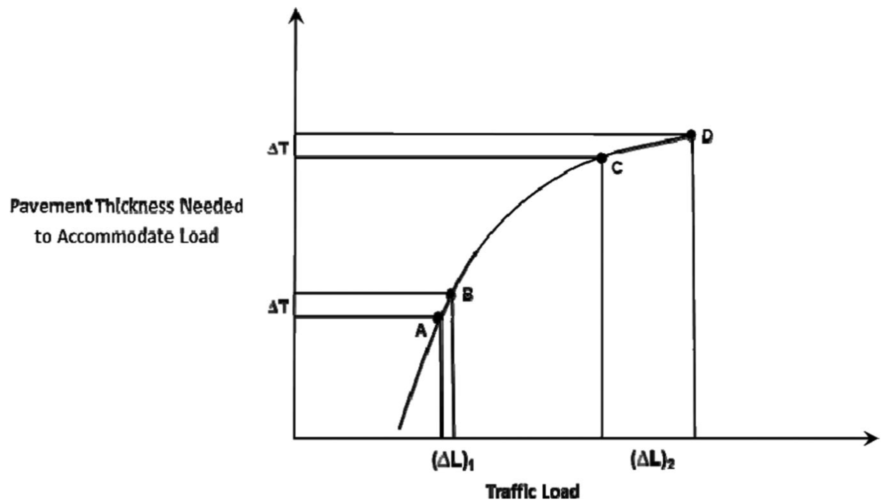


Figure 3.2 Illustration of scale economies of pavement thickness w.r.t loading.

resulting cost saving was assigned to the vehicle class under consideration on the basis of its Equivalent Single Axle Load (ESAL) contribution.

3.3.3 Individual Distress Models

In this method, mathematical models are developed for the individual distresses that are considered to reflect of pavement deterioration and thus lead to highway rehabilitation decisions. The cost responsibility is then established by identifying the individual vehicle class responsible for a particular distress and the relative importance of that distress in the decision to rehabilitate a given pavement segment. This method was used in the 1982 federal HCA study for allocating the cost of pavement rehabilitation treatments.

Improvements to the facility consumption and individual distress models for PDC estimation continued during the 1980s and 1990s. The mechanistic pavement distress models developed for the 1982 federal HCA study were based on a small number of hypothetical pavement sections (*17*). The original models were improved using data on actual pavement sections in the Highway Performance Monitoring System (HPMS) database. Also, in addition to the models used in the 1982 federal HCA study, some new models for both flexible and rigid pavements were developed which resulted in the National Pavement Cost Model (NAPCOM). NAPCOM uses individual distress model for flexible and rigid pavement. For flexible pavements, NAPCOM has individual distress models for traffic-related Present Serviceability Rating (PSR) loss, expansive-clay-related PSR loss, fatigue cracking, thermal cracking, rutting, and loss of skid resistance; for rigid pavements, the distress models includes traffic-related PSR loss, faulting, loss of skid resistance, fatigue cracking, spalling, and soil-induced swelling and depression. The details of the NAPCOM model are presented in Part II Appendix A.

3.3.4 Performance-based Methodology

In 1984, the Indiana Department of Transportation (INDOT) conducted a cost allocation study to determine the cost responsibility of different vehicle classes for highway use (*28*). Recognizing that the 1982 federal HCA study did not explicitly consider the effect of maintenance or the interaction of different distresses, the authors of the INDOT study (*28*) proposed an aggregate damage model that related pavement performance to maintenance, thus facilitating the allocation of rehabilitation and routine maintenance costs. The concept of PSI-ESAL loss represented the aggregate pavement damage due to loading under given levels of maintenance, including zero maintenance. Further details of this methodology are discussed in Part II Appendix A.

3.4 PDC Estimation Studies

Besides HCA, the most common purpose for estimating the damage attributable to each vehicle class in past studies, was to estimate the unit cost of pavement damage by highway users, and thus establish a suitable fee to recoup these costs. Unlike HCA studies that typically cover a wide scope of costs including vehicle operating cost (VOC), pavement MR&R cost, congestion cost, accident cost, and environmental cost, PDC estimation studies only consider pavement MR&R cost; this is the focus of the present study. Specifically, PDC estimation studies, only consider those costs that are associated directly with the pavement structure, such as M&R costs (both periodic and routine), and excludes (i) cost incurred outside the pavement structure such as right-of-way cost, grading and earthwork cost, and drainage and erosion control costs, (ii) work on non-pavement assets, and (iii) non-strength pavement work such as lane addition.

PDC estimation studies seek to (i) estimate the average PDC for full cost recovery of the pavement "consumed" by different vehicle classes or (ii) the marginal PDC so that vehicles can be charged on the basis of the incremental cost they incur to the pavement. The average cost is the total MR&R cost divided by the total usage (e.g., number of vehicles) while marginal PDC is the MR&R cost of an additional vehicle on a given highway. To determine the MPDC, two main approaches have been used in past studies: the so-called "empirical" approach, which establishes the relationship between the observed field values of cost and usage, and the so-called "engineering" approach which is based on theoretical relationships between damage cost or damage, and usage (load). The empirical approach is top-down, starting with actual knowledge of the cost incurred in each category (MR&R expenditure incurred at each individual pavement segment) and then establishes a relationship between the total cost and the usage. After this relationship is established, a simple first derivative of the total cost function with respect to the usage (i.e., road use measure, such as VMT or ESAL), gives the MPDC. The engineering approach, on the other hand, is bottom-up and involves analysis of a unit length of road segment to establish a theoretical relationship between the total cost and pavement durability and traffic loading. After the relationship is established for the unit road segment, the results are generalized for the entire network or road system (*32*). The marginal PDC estimation on the basis of these and other miscellaneous approaches is discussed in ensuing paragraphs.

3.4.1 MPDC Estimation using the Empirical Approach

An empirical approach for MPDC estimation using field data, which has in the recent past been referred to as the "econometric" approach by some researchers (*22*), is a two-step process: (1) models are estimated to explain the MR&R cost as a function of independent variables such as usage, climate, pavement condition, and pavement structure characteristics; and (2) the estimated models are differentiated with respect to the usage (i.e., the road-use variable (traffic)) to yield the desired marginal cost. A number of past studies that used this approach are discussed herein.

Gibby et al. (*33*) studied the factors affecting pavement maintenance cost and also evaluated the impact of heavy traffic on maintenance cost. Using a Cobb-Douglas model for pavement maintenance cost, the authors established that the impact of one heavy truck (defined as a truck with at least five axles) on a pavement is about 70 times that of a light truck. The details of the model developed by Gibby et al. (*33*) are presented in Part II Appendix B.

The authors estimated that the average annual maintenance cost per heavy truck and passenger car was approximately \$7.60 and \$0.08 per mile, respectively. The study results suggested that the climate has a small impact on pavement maintenance cost, and that trucks inflict much more damage to road infrastructure compared to autos. The authors used over 1,000 one-mile segments for which traffic data were available, and with a dependent variable of total pavement maintenance cost for each one-mile section during the three fiscal years 1984–1987. Because the analysis period considered by the authors was rather short, it is likely that the data may not have contained those pavement activities typically performed at longer time intervals such as minor or major rehabilitation. Also, the estimated model does not have an explanatory variable representing the pavement condition or age. Since pavement maintenance activities are condition-responsive, it may have been useful to include a pavement condition explanatory variable in the cost model.

Martin (*34*) conducted a study for the Australian Road Research Board (ARRB) that estimated load-related pavement maintenance and construction costs. Separate models were developed for annual average total maintenance expenditure, annual average routine maintenance expenditures, and annual average periodic maintenance expenditure. The author used pavement age, cumulative traffic loading ESAL, Gross vehicle mass, passenger car units, and AADT as independent variables. The model details are presented in Part II Appendix B. The models took weathering into account because a variable representing age was included in the models. The study estimated that, on average, 50% of pavement maintenance expenditures were load-related and can be attributed to heavy vehicles on the basis of the gross weight. Also, approximately 45% of pavement construction/replacement costs were found to be load-related and could be allocated among heavy vehicle on the basis of ESAL-Km (*34*).

Hajek et al. (*35*) used simulated data on pavement maintenance and rehabilitation cost to study the impact of truck weight regulations on pavement maintenance costs in Ontario. That study investigated the impact of four proposed truck regulatory scenarios which addressed truck size and weight changes. The cost impact was evaluated on the basis of the difference between the truck traffic resulting from existing and proposed truck regulation scenarios. The assessment was done for a 20-year analysis period. The entire Ontario road network was divided into 20 representative categories, and the truck fleets which needed regulatory changes were divided into 25 vehicle classes. Using projections, the anticipated traffic stream for each regulatory scenario and each road type was estimated in terms of ESAL-Km. The total change in ESAL-km for each road segment for 20-year analysis period was then estimated, and the anticipated traffic stream was allocated to the 20 representative road categories. In the last phase of the study, the total change in pavement cost resulting from different regulatory scenarios was estimated. For each road type, the maintenance and rehabilitation activities were simulated for 60 years, and their corresponding cost was estimated over the 60-year period and annualized. The annualized cost was modeled as a function of the annual ESALs and different geographic regions (southern and northern Ontario). The estimated model was differentiated with respect to ESALs to estimate the PDC per ESAL-km. On the basis of the PDC estimate and expected total change in ESAL-kms associated with each regulatory scenario, the total cost impact was calculated for each of the four regulatory scenarios, each representative road category, and each year of analysis period. Part II Appendix B of the present report presents the pavement maintenance and rehabilitation cost models and PDC for different road classes. The adopted methodology and results of the study clearly demonstrated that it is quite feasible to use simulated data and a highway agency's MR&R strategies can be used to quantify the pavement damage caused by heavy vehicles under different load scenarios.

In 2000, Li and Sinha estimated the load and non-load shares of pavement maintenance and rehabilitation expenditures using Indiana data (*36*). In that study, the pavement maintenance and rehabilitation expenditure were estimated separately for flexible, rigid, and composite pavements. Ordinary least square (OLS) regression models were developed to establish the relationship between pavement rehabilitation expenditures and pavement deterioration factors. The general form of the developed models is as follows:

$$\text{EXPEND} = \alpha_o + \sum_{i=1}^{k} (\alpha_i * X_i) + \varepsilon_i \qquad (3.1)$$

Where: EXPEND= expenditure on maintenance and rehabilitation or rehabilitation only; α_o, α_i = model parameters; X_i= A set of parameters representing the change in international roughness index (IRI) in one life cycle (climate, pavement age, annual ESALs, pavement structure, and construction features); ε_i = error term.

The specific models developed for the different pavement types are presented in Part II Appendix B of the present report.

After estimating the expenditure models, the expenditure per ESAL-mile was calculated by differentiating the expenditure models with respect to the cumulative ESALs for each pavement type, as follows:

$$\text{MEXPEND} = \frac{\partial\,\text{EXPEND}}{\partial\,\text{CESALs}} \qquad (3.2)$$

Where, MEXPEND is the marginal periodic maintenance and rehabilitation or rehabilitation only expenditure per ESAL-mile (*36,37*). The study estimated the marginal pavement rehabilitation expenditure using the average thickness for different types of pavements. The marginal pavement rehabilitation expenditure was estimated as \$0.023 and \$0.038 per ESAL-mile (2000 constant \$) for flexible and rigid pavements, respectively (details are provided in Part II Appendix B of the present report).

For routine maintenance expenditures, the concept of a modified damage index was used. A system of simultaneous equations was established to estimate the routine maintenance expenditure, thus taking care of endogeneity bias. Pavement performance was represented by the modified damage index as follows:

$$\text{MDI}_{(t)} = 100\left[\frac{IRI_t - IRI_{t-1}}{IRI_{t-1}}\right] \qquad (3.3)$$

Where: MDI_t= Modified damage index at year t; IRI_t = IRI at year t; IRI_{t-1}= IRI at year t−1.

The Li and Sinha study (*36*) assumed that the relative change in pavement condition at the end of a given year (year t) is a function of pavement traffic and climatic loading for the same year and that the funds needed to maintain in the following year (year t+1) will depend upon the given year's (year t) pavement deterioration (*37,38*). The general form of the model developed for flexible, rigid and composite pavement for annual routine maintenance expenditure is as follows:

$$\text{ARME}_{(t+1)} = \alpha_o + \sum_{i=1}^{k} (\alpha_j X_{it}) + \varepsilon_1 \qquad (3.4)$$

$$\text{MDI}_{(t)} = \beta_o + \sum_{j=1}^{l} (\beta_j X_{it}) + \varepsilon_2 \qquad (3.5)$$

Where: ARME_{t+1}= Annual routine maintenance expenditure for year t+1; MDI_t= Modified damage index at year t; X_{it}= A set of parameters representing climate, pavement age, annual ESALs, pavement structure and construction features; α_o, β_o, α_i, β_i = model parameters; ε_1, ε_2 = error terms.

Ghaeli et al. (*39*), on the basis of the maintenance strategy used by the Ontario Ministry of Transportation, studied the cost implications of road characteristics and different vehicle configurations using a 30-year life-cycle pavement cost for Ontario roads. That study used the Ontario Pavement Analysis of Costs (OPAC) model to estimate the pavement maintenance and rehabilitation costs per ESAL-Km. OPAC has separate equations calibrated for northern and southern Ontario and estimated the load- and non-load-related PDCs separately. The analysis cost elements included: construction, reconstruction, and maintenance costs as well as salvage value. Using the OPAC model the authors predicted the maintenance and reconstruction activities for different pavement sections depending on the traffic loading and geographical location. For pavement life-cycle cost estimation, the average costs for different maintenance and rehabilitation activities were obtained from Ontario's Ministry of Transportation. A relationship was established between the pavement life-cycle costs and the traffic loading and was used for PDC estimation. The researchers found that construction specifications, vehicle class, and road class can have significant influence on the cost responsibility. The study speculated that if trucks were the only users of the road system (e.g., truck-only lanes), then the actual life-cycle cost would be about 80% of the total life-cycle cost of a system which has both passenger cars and trucks although fewer lanes would be required. The study concluded by arguing that trucks derive a significant benefit from the road system and therefore need to share a greater proportion of the cost for road damage (*39*).

Herry and Sedlacek (*40*) estimated marginal maintenance and renewal (rehabilitation) costs using data from Austria. Cost and traffic data (volume, gross tons, and axle loads) for 46 motorways sections from 1987 to 2004 were used to estimate OLS regression models. The model developed for marginal maintenance and renewal cost has the following form:

$$C = \alpha_o + \alpha_1 AADT_{car} + \alpha_2 AADT_{trucks\&buses} \quad (3.6)$$

Where: C is the maintenance and rehabilitation cost for one year; $AADT_{car}$ is the car AADT; $AADT_{trucks\&buses}$ is the truck and bus AADT; α_0, α_1 and α_2 are the model parameters.

Based on the developed model, the estimated marginal PDC (in 2002 constant dollars) was found to be \$0.0007 per vehicle-kilometers (VKm) for vehicles up to 3.5 tons (gross vehicle weight (GVW)) and \$0.023 (2002 Constant \$) per VKm for vehicles weighing more than 3.5 tons. The average MPDC was found to be \$0.0017 per VKm. A major issue with the Herry and Sedlacek study (*40*) was that both of the independent variables in the estimated model were found to be statistically insignificant at a 95% significance level, which raised serious concerns about the statistical validity of the results reported by the study.

Schreyer et al. (*41*), using 1985–1998 data from 127 sections on the Swiss road network, estimated marginal maintenance and rehabilitation costs for different vehicle classes. The costs were estimated on the basis of total VKm (all vehicles), total gross ton-Km, and total axle load equivalent kilometers. The axle weights of all vehicles were converted to the standard axle of 18,000 lbs. Thus, cars, light trucks, and heavy trucks were considered to have 0.0001, 1.21, and 1.32 standard axles, respectively. The three types of models developed by that study have the following general form:

$$\mathrm{Ln}\left(\mathrm{Cost}_{operational\&maintenance}\right) = c + b.\ \ln(X) \quad (3.7)$$

$$\mathrm{Ln}\left(\mathrm{Cost}_{construction\&maintenance}\right) = c + b.\ \ln(X) \quad (3.8)$$

$$\mathrm{Ln}\left(\mathrm{Cost}_{upgrade\&rehabilitation}\right) = c + b.\ \ln(X) \quad (3.9)$$

Where: X is the total kilometer travelled, total weight-distance, or total ESALs by vehicles, for each class; c and b are the model parameters.

Of the various models that used different units of facility usage, the weight-distance provided the best-fitting model. The marginal cost for one additional weight-distance unit for the three vehicle categories was obtained by differentiating the cost functions with respect to weight-distance. Based on the developed model, the estimated marginal PDC (in 2002 constant dollars) was found to be \$0.0005per VKm for passenger cars and \$0.0472 (2002 constant \$) per VKm for trucks using the average weight of a car and a truck (*41,42*).

In 2002, Link used cross-sectional data from Germany's road network for estimating the renewal cost (rehabilitation cost) (*43*). The author calculated the MPDC for one additional truck by fixing the annual average daily traffic (AADT) of passenger cars. The MPDC was calculated on the assumption that all cost is attributed to heavy vehicles. The MPDC for trucks ranged from \$0.009 to \$2.000 per VKm (*43*). The average value of MPDC was found to be \$1.486 per VKm. Details of the Link model are presented in Part II Appendix B of the present report.

Ozbay et al. (*44*) estimated MPDC using data from rehabilitation and periodic maintenance projects in 2004–2006 in New Jersey. The estimated cost model is presented as follows:

$$Cost = \frac{796.32 * (L)^{0.40} (NL)^{0.89}}{P} \quad (3.10)$$

Where: Cost = cost of maintenance per lane (\$1000s/year); L = roadway length in miles; NL = number of lanes; P = time in years between two resurfacing activities.

Using the procedure developed by Huang (*45*), the authors estimated the time between two resurfacing activities as the ratio of allowable and actual traffic loading, based on the annual number of trucks. The time between two resurfacing activities (P) was calculated as follows:

$$P = \frac{1{,}50{,}000}{Q * T_p * T_f * 365} \quad (3.11)$$

Where: Q= traffic volume (vehicles/day); T_p = truck percentage in traffic volume; T_f = truck factors for different road functional classes.

The marginal cost based on the resurfacing cost and the design period was estimated as follows:

$$Cost(M) = \frac{796.32 * (L)^{0.40} (NL)^{0.39} * t}{P * Q * 365 * 24} \quad (3.12)$$

Where: t = trip duration in hours; Cost (M) = marginal maintenance cost \$ per vehicle (\$2005); Q = traffic volume (vehicles/hour); L, NL and P are as defined earlier.

Haraldsson (*46*) estimated the MPDC for the Swedish national road network using data from 1998–2002. The dataset comprised the maintenance and operational cost, VMT by passenger car and heavy vehicles, pavement type, and road functional class. The dataset was available for 145 geographic regions but not for individual pavement sections. Consistent with practices of the Swedish Road Administration at the time, 0 and 1.3 ESALs were used for passenger cars and heavy vehicles, respectively. Thus, the model results estimated MPDC per VKm for heavy vehicles only.

The generalized model estimated by Haraldsson (*46*) is presented as follows:

$$LnC_{it} = \alpha + \beta_1(R) + \beta_2(Y) + \beta_3(lnC_{it-1}) + \beta_4(lnQ_{it}) + \beta_4(lnQ_{it})^2 + \beta_5(lnZ_{it}) + \varepsilon_{it} \tag{3.13}$$

Where: C_{it} = total pavement maintenance cost for each geographic region *i* in year *t*; *R* = region-specific dummy variable (for example, North); *Y* = year dummy variable; Q_{it} = total heavy-vehicle Km travelled in geographic region *i* in year *t*; *Z* = vector describing the road network (length of road network and pavement types); ε_{it} = random error term.

From the model results, Haraldsson (*46*) estimated that the overall MPDC (2007 constant dollars) for heavy vehicles ranged from \$0.0957–\$0.1860 per VKm. For paved and gravel roads, MPDC ranged from \$0.0222–\$0.0236 and \$0.0819–\$0.0847 per VKm, respectively. The author used the aggregate cost data for each geographic region as the dependent variable; this is the first serious limitation of the study. A more appropriate approach might have been to use the disaggregate traffic and maintenance expenditure data for each of several individual roadway sections. There are a number of other problems with the methodology used in that study: The cost data spanned a very short period of time, and it is likely that the cost of maintenance activities that are carried out at longer time intervals, such as minor and major rehabilitation, were inadequately accounted for in the analysis. Finally, because a single ESAL value of 1.3 for each truck was considered, this yielded a single MPDC value for all truck types, irrespective of their GVW and number of axles.

Liu et al. (*47*) used field data to estimate the PDC due to heavy vehicle loading resulting from the shipment of processed beef in southern Kansas on a 41-mile highway section (US 50/400 from Dodge City to Garden City, Kansas). This section was divided into four segments depending upon the type of pavement structure. The pavement maintenance data were collected from the Kansas Pavement Management Information System (PMIS). The PMIS provided information on all major and minor rehabilitation activities, but no information was available on routine maintenance. Synthesized traffic data were used as no traffic estimates were available from the Kansas Department of Transportation for the highway segments selected for the study. Approximate values of the total shipments were obtained from nearby industries and counties. The numbers of vehicles using US50/400 were estimated on the basis of shortest-path routes. The load-related pavement damage (PSR loss) was estimated using the standard AASHTO equation, and the pavement structure deterioration due to environmental factors was estimated using the Tolliver decay function, which is embedded in the pavement deterioration model of the Highway Economic Requirement System (HERS). The pavement decay rate due to environmental factors is given by the following equation:

$$P_{Env} = P_{ini} * e^{(-t\theta)} \tag{3.14}$$

Where: θ = decay rate due to environmental loss; P_{Env} = pavement decay rate due to environmental factors; P_{ini} = Initial PSR; L = design life of pavement.

The entire procedure used to estimate the PDC is summarized as follows:

- Annual ESALs for each pavement segment was determined on the basis of data including truck miles traveled and the number of ESALs per truck.
- The ESAL life of the pavement segments (loss in PSR from an initial PSR of 2.5 to a terminal PSR of 4.2) was determined using the AASHTO equation.
- The PSR loss due to environmental loading was estimated using the Tolliver procedure.
- The average annual maintenance cost per mile was computed using the data provided by the Kansas PMIS.
- The portion of the load-related PDC was estimated by dividing the PSR loss due to environmental loading by the total allowable PSR loss (1.7 units).
- The adjusted average annual maintenance cost was estimated by multiplying the average annual maintenance cost with the load-related PDC factor estimated in the previous step.
- The maintenance cost per ESAL-mile was estimated by dividing the adjusted average annual maintenance cost per mile by the ESAL life of the pavement.
- The PDC occasioned by heavy vehicles was estimated by multiplying the annual ESAL for heavy trucks with the cost per ESAL.

The study estimated a PDC of \$1,727 per mile per year attributable to the beef industry. A limitation of the study was that it used estimates, rather than actual, values of traffic data (beef shipment records), thus raising possible questions about the data accuracy. Also, the traffic data covered a time period starting from 2005 while the maintenance data spans 1985–2003, thus there was temporal inconsistency. A more appropriate approach would have been to obtain the most recent traffic data available for selected roadway segments, duly adjusted using a traffic growth factor. Traffic and pavement maintenance data from a consistent time period could have been used because the study objective was to estimate how much damage was caused to pavement from a specific number of vehicles. Lastly, the authors did not account for the pavement reconstruction cost, thus arriving at a PDC estimate that may be an underestimate of the true cost.

3.4.2 MPDC Estimation Based on Engineering Approach

This approach has been termed the perpetual overlay indirect approach, indirect approach, engineering approach, or bottom-up approach, in past literature (*22,32,48*). In this approach, using theoretical knowledge, a unit dimension of the infrastructure (specifically, one lane-mile) is analyzed and a repair cost vs. usage relationship is established. Then the results are generalized for the entire network. The main concept is the derivation of an expression for the present value of recurring fixed-intensity rehabilitation (such as an overlay of constant thickness) over an infinite analysis period, as a function of annual traffic. The past studies that used this approach generally considered only a single type of overlay treatment for MPDC estimation. In doing so, they had assumed, implicitly or explicitly, that these overlays constitute the dominant share of pavement maintenance and rehabilitation (M&R) cost and that all other maintenance activities and reconstruction cost are negligible. However, the simplifying assumption of a single overlay at constant interval does not adequately reflect practical agency decision-making processing and can lead to unrepresentative estimates of M&R cost over the life cycle. A brief discussion of studies using this approach is presented in the ensuing paragraphs.

In 1988, Newbery presented the fundamental theorem for estimating marginal overlay cost using an infinite analysis period. The expression he used for determining the MPDC (or marginal overlay cost) for an additional ESAL is:

$$\text{Marginal Cost} = \vartheta\left(\frac{C}{TQ}\right) \tag{3.15}$$

Where: C is rehabilitation treatment (overlay) cost per km; T is the life of rehabilitation treatment; Q is the total annual traffic (ESALs); φ is the part of road deterioration caused by traffic.

Newbery's marginal maintenance cost formulation is based on the following assumptions (*22,49*):

- The age of all roads in the network is uniformly distributed between zero and some time interval, t.
- Traffic remains constant over the life span of a pavement segment.
- There is no weathering action on the road and all pavement deterioration can be attributed to traffic loading.
- Resurfacing constitutes a dominant part of pavement maintenance and rehabilitation cost and hence all other maintenance costs can be ignored.

Newbery (*49*) estimated the average MPDC for an additional ESAL using roughness as the performance indicator. It was further assumed that maintenance is condition-responsive and that the road will be overlaid whenever roughness reaches a certain threshold value. If weathering is ignored, then the MPDC is simply the overlay cost per lane-Km divided by the total number of ESALs during the life span of an overlay. Thus, road user charges were represented as the average cost of the overlay. Newbery further extended his study to account for pavement weathering using data from Tunisia, and concluded that the estimated MPDC would not efficiently recover road maintenance cost; on this basis, he concluded that the MPDC and congestion cost, if considered together, can help an agency design an efficient road user charging system. For roads in Tunisia with different design lives, traffic volumes, and maintenance strategies, the author estimated that the marginal overlay cost (1983 constant dollars) ranges from \$0.0013 to \$0.0258 per ESAL-Km (*49*).

Again, Newbery's work was based on a number of assumptions, some of which may be considered quite debilitating; thus, the MPDC estimation in that study may not represent the true picture. It is a truism that any highway network is comprised of pavement segments of varying ages and traffic volumes. Furthermore, traffic volume typically continues to grow over time at any given road segment. While it is true that rehabilitation constitutes a dominant part of pavement repair costs, non-consideration of reconstruction and periodic and routine maintenance costs can result in erroneous MPDC estimates. Considering the limitations of Newberry's study, it is necessary to eschew approaches that are unable to incorporate realistic highway agency MR&R practices into MPDC estimation.

Small et al. (*50*) improved Newbery's work by estimating an MPDC that accounted for both weathering and traffic. In the Small study, PDC models were estimated by deriving expressions for the net present cost of resurfacing as a function of traffic loading Q and pavement durability D. The basic formulation used by Small et al. proceeds as follows: Consider a single lane of a flexible pavement for which an agency uses an overlay of constant intensity. The highway receives an overlay in a perpetual cycle which is triggered by deterioration to a predetermined threshold level as shown in Figure 3.3.

Let Q = annual traffic loading; D = pavement durability (number of ESALs to failure); T = time interval between two rehabilitation (resurfacing) treatments; C = cost of the rehabilitation a treatment.

Then, the interval between two resurfacing actions is given by: $T = \frac{D}{Q}$

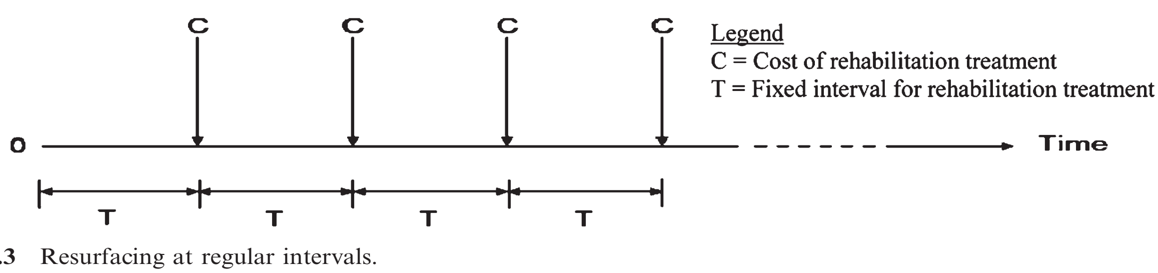


Figure 3.3 Resurfacing at regular intervals.

In order to incorporate the effect of climate, Small et al. (*50*) used the results of a World Bank study entitled "Road Deterioration and Maintenance Effects" that established relationships between pavement roughness and cumulative ESALs at any given time (*51*). Paterson assumed that pavement roughness increases linearly with cumulative loading and exponentially with time. Small et al. (*50*), using the AASHTO road test data, also established the relationship between pavement quality and pavement durability (number of ESALs to failure). Making use of these relationships, the interval between two successive resurfacing actions (rehabilitations) can be re-written as:

$$T=\frac{\mathrm{D}}{\mathrm{Q}}\left(\mathrm{e}^{-\mathrm{mT}}\right) \tag{3.16}$$

Where, m is the annual rate of increase in pavement roughness.

Small et al. (*50*) used a 4% rate of increase of roughness in their study. Suppose that the unit cost of resurfacing is C ($/Lane-mile) which is incurred every T years, and the interest rate is r. Also, assuming that the overlay interval is constant, then the present cost M, of all future resurfacing actions (infinite analysis period), using annual discounting is:

$$\mathrm{M}=\frac{\mathrm{C}}{\left(\mathrm{e}^{-\mathrm{rt}}-1\right)} \tag{3.17}$$

The marginal resurfacing cost was estimated by partially differentiating the annualized resurfacing cost (rM) by annual traffic loading as follows:

$$\begin{aligned}\mathrm{MC}&=\mathrm{r}\left(\frac{\partial\,\mathrm{M}}{\partial\,\mathrm{Q}}\right)=\mathrm{r}\left(\frac{\partial\,\mathrm{M}\;\mathrm{dT}}{\partial\,\mathrm{T}\;\mathrm{dQ}}\right)\\&=-\left(\frac{\mathrm{r}^2\mathrm{e}^{-\mathrm{rT}}\mathrm{C}}{\left(\mathrm{e}^{-\mathrm{rT}}-1\right)^2}\right)*\left(\frac{\mathrm{dT}}{\mathrm{dQ}}\right)\end{aligned} \tag{3.18}$$

The marginal cost when the effect of climate is ignored is:

$$\mathrm{MC}=-\left(\frac{\mathrm{r}^2\mathrm{e}^{-\mathrm{rT}}\mathrm{C}}{\left(\mathrm{e}^{-\mathrm{rT}}-1\right)^2}\right)*\left(\frac{T^2}{D}\right) \tag{3.19}$$

Also, the marginal cost when the effect of climate is duly accounted for is:

$$\mathrm{MC}=-\left(\frac{\mathrm{r}^2\mathrm{e}^{-\mathrm{rT}}\mathrm{C}}{\left(\mathrm{e}^{-\mathrm{rT}}-1\right)^2}\right)*\left(\frac{T^2}{D}\right)*\left(\frac{e^{mt}}{1+mT}\right) \tag{3.20}$$

As shown in Part II Appendix C of the present report, the author concluded that the MPDC (1985 constant dollars) varied between $0.0148 and $1.2545 per ESAL-mile at the existing investment levels, and 0.33 to 101.30 cents per ESAL-mile under optimal investment levels for different road functional classes. The finding, that an optimal investment decision results in a lower overall cost to each group of society, is an important contribution of the Small study. The five-axle semi-trailer with 80,000 lbs GVW would be charged approximately 2 cents per ESAL-mile (in 1985 constant dollars), on Interstates and local roads. Small et al. (*50*) further concluded that climate does not affect road deterioration independently; rather, it is the interaction of climate with axle weight that affects pavement deterioration, and climate makes pavement more vulnerable to damage by heavy loads. The positive aspects of the study are that it incorporated the effect of climate into MPDC estimation formulation. However, it did not consider reconstruction and periodic and routine maintenance costs, a failing that is discussed in Chapter 5 of the present report. The study also assumed a constant rate of increase of pavement roughness with respect to traffic loading; in actuality, however, pavement segments deteriorate at different rates, depending upon traffic and climatic loading. Furthermore, the assumption that the overlay timing intervals are the same throughout the life cycle and the derivation of a single MPDC expression for the entire network seems to be rather overly simplifying and inappropriate, as is discussed in Chapter 5.

Vitaliano and Held (*52*) estimated the MPDC in New York using data from 475 roadway segments in that state. Their study used a "theoretical" analysis for a single pavement segment to derive an expression for the present cost of recurring fixed-intensity rehabilitation over an infinite analysis period. It was assumed that 50% of pavement deterioration is caused by traffic and 50% by climate (an assumption based on work done by Paterson (*51*). This study estimated a cost (1990 constant dollars) of $0.076 per ESAL-mile as the average road user charge. The MPDC was explicitly calculated for a five-axle semi-trailer with 80,000 lbs GVW for different road functional classes (see Part II Appendix C). However, the study did not account for the cost of reconstruction and routine maintenance.

In 1996, the results of the Transportation Research Board (TRB) study "Paying Our Way" were published (*53*). The primary focus of the study was to investigate whether freight shippers were incurring the full social cost for their use of the public infrastructure (highways, railroads, and waterways) or whether they were being subsidized. For highways, the study considered the marginal cost of externalities including congestion, crashes, air pollution, energy security, and noise in addition to the MPDC. That study estimated the marginal external cost and the infrastructure damage cost (for pavements and bridges) in terms of dollars per truckload by adopting an approach similar to Newbery (*49*), but incorporating the weathering impact. The results suggested that the road-use fee per truckload paid by truck operators for a two-lane road exceeded the cost of infrastructure damage occasioned by the trucks. In the case of Interstate highways, the road-use fee paid by truck operators was almost equal to the occasioned infrastructure damage cost. Similar to the other studies, the TRB study (*53*) did not explicitly account for reconstruction and routine maintenance cost.

Using the Newbery approach, Lindberg estimated MPDC using data from the Swedish long-term pavement performance program. The study used a cracking index as the performance indicator, ignored effect of climate for simplicity, and considered rehabilitation cost only (*22,54*). The MPDC estimated in this study (2002 constant dollars) varied from $0.0007 to $0.0176 per ESAL-Km for high-quality and reduced-strength roads, respectively. In terms of VKm, the MPDC was estimated at $0.020 per VKm for combination trucks and $0.0034 per VKm for passenger cars. The authors, in acknowledging the shortcomings of their study approach stated that new overlay (categorized as rehabilitation) formed only 30% of the total maintenance budget. Thus the methodology did not yield results that indicated the actual and full cost of maintenance and rehabilitation.

Recently, Anani and Madanat (*48*) presented a methodology for estimating MPDC by considering both the rehabilitation and periodic maintenance costs. The authors adopted a formulation similar to that used by Newbery (*49*), Small et al. (*50*), and Vitaliano and Held (*52*). The only difference in the Anani and Madanat study (*48*) was their consideration of two treatment categories instead of one (rehabilitation and periodic maintenance). Similar to Small et al. (*50*), for a single pavement resurfacing activity, the MPDC was expressed as follows:

$$MC(R) = \frac{(e^r - 1) r e^{rT} C}{(e^{rT} - 1)^2} \left(\frac{T^2}{D} \right) \tag{3.21}$$

Where: MC (R) is the MPDC in the case of a highway agency that uses a single repeated overlay of constant intensity; r, T, D, and C are as defined previously in equations 3.17 to 3.20.

The authors presented a MPDC estimation formulation that involved two interrelated pavement maintenance activities (Figure 3.4): rehabilitation and periodic maintenance. It was further assumed that periodic maintenance activities are performed more frequently (and have lower cost) compared to rehabilitation activities. An expression for the present value of recurring fixed-intensity rehabilitation and periodic maintenance over an infinite analysis period was derived by the theoretical analysis of a single pavement segment. The MPDC is given by the following equation:

$$MC(r + pm) = (e^{dr} - 1) \left[\frac{\partial M}{\partial T_{(pm)}} * \frac{dT_{(pm)}}{dQ} + \frac{\partial M}{\partial T_{(r)}} * \frac{dT_{(r)}}{dQ} \right] \tag{3.22}$$

Where: MC (r+pm) = MPDC for rehabilitation and periodic maintenance activities at a fixed interval; M = present worth of all future rehabilitation and periodic maintenance activities; $T_{(pm)}$ = time interval between two consecutive periodic maintenance activities; $T_{(r)}$ = time interval between two consecutive rehabilitation activities; Q = annual traffic loading; dr = discount rate.

From the study documentation, Anani and Madanat (*48*) obviously started with earnest intentions to estimate the MPDC for MR&R, but it seems that the final research did not attain the stated objective. While the authors continuously advocated that MPDC should be based on realistic and practical highway agency maintenance strategies and should include all costs associated with pavement maintenance, their solution seemed viable to meet this requirement; thus, the research results may be rather limited in potential practical application. The developed formulation is very restrictive and does not fit into highway agency maintenance practices as it uses only two types of treatments at fixed intervals and fails to account for routine maintenance and reconstruction costs. That study also used a single representative pavement segment and infinite analysis period for MPDC estimation. The authors did not provide any MPDC estimate at the study conclusion. In what could be a possible acknowledgement of the inherent limitation of their assumptions, the authors concluded that it was difficult to generalize their study results.

The researchers in that study did not use field data to demonstrate the application of their proposed methodology; instead, using hypothetical values for periodic maintenance and rehabilitation, they demonstrated (correctly) that periodic maintenance should not be ignored as was the case in most similar past studies. The

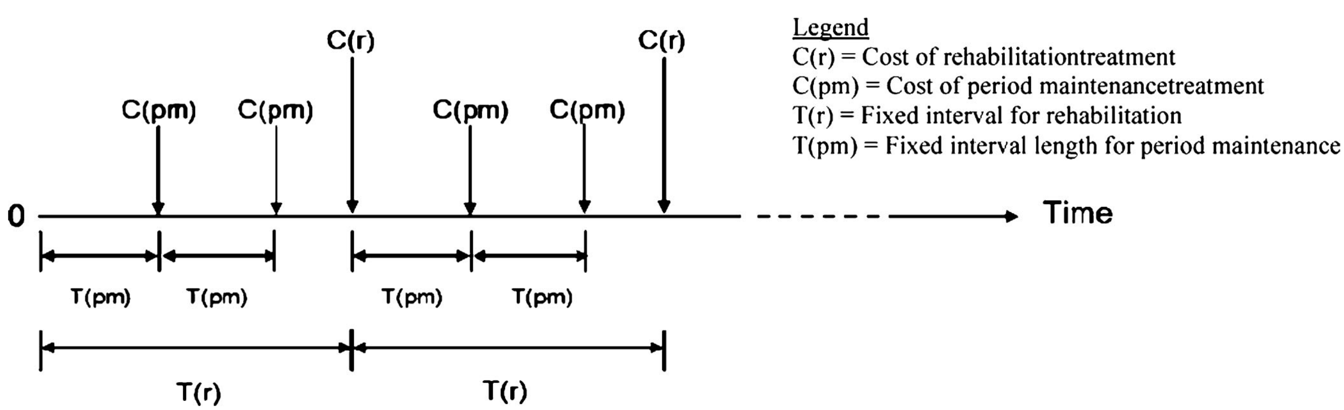


Figure 3.4 Rehabilitation and periodic maintenance at regular intervals.

lower life-cycle cost associated with a strategy that includes periodic maintenance and rehabilitation compared with one that has only periodic maintenance or only rehabilitation was proven using hypothetical data: the authors demonstrated that MPDC estimated separately for periodic maintenance or rehabilitation is greater than when rehabilitation and periodic maintenance are considered together. Details are provided in Part II Appendix C.

3.5 Miscellaneous other Approaches for HCA/PDC Estimation

Besides the two major contexts of PDC analysis, there have been a number of research efforts with other contexts or purposes such as the investigation of the impact of truck weight and size changes on infrastructure repair costs. A discussion on these studies is provided below.

3.5.1 Truck Size and Weight Studies and Pavement Repair Cost

Hewitt et al. (*55*) estimated the impact of a change in truck weight and size on the infrastructure, truck operation cost, and overall state economy of Montana. Four different maximum GVW scenarios were considered for their analysis. A reduction in in the state maximum GVW was represented by three loading scenarios (80,000 lbs, 88,000 lbs, and 105,500 lbs) while the fourth scenario proposed an increase to 128,000 lbs. The authors used hypothetical traffic and pavement maintenance cost data to determine the percentage change in pavement maintenance cost due to the change in maximum GVW. A new traffic stream was identified for each of the proposed GVW scenarios, assuming that the present GVW is replaced by the proposed GVW limit. The new traffic stream was predicted by assigning all the freight being transported in the base year (study year) to an appropriate vehicle that would be hauling the same freight under a different maximum GVW for four different scenarios. For each scenario, the PDC resulting from the new traffic stream was estimated using standard AASHTO equations. The PDC analysis was performed for a small sample of pavements and the results were applied to the entire state. The change in equivalent uniform annual maintenance cost for each scenario was estimated. The study argued that there was no marked difference in equivalent uniform annual maintenance cost due to the proposed changes in GVW limits. The authors did not provide any details about the maintenance and rehabilitation data collected for the analysis or the length of the analysis period over which the total change in pavement maintenance cost was calculated.

Using simulated data, Roberts and Djakfar (*56*) investigated the impact of increasing GVW limits from 80,000 to 100,000 lbs in the state of Louisiana. For analysis purposes, vehicles hauling four commodities (rice, timber, cotton, and sugarcane) were selected for the simulation. The analysis focused on PDC that resulted from increased GVW limits. The AASHTO design equation and the concept of ESAL were used to estimate changes in pavement M&R costs due to increased GVW limits. The routes typically used by trucks transporting the four selected commodities were selected with the help of industry personnel. The M&R data were collected for the candidate roads from the Louisiana Department of Transportation. There were 11 selected roads for which M&R data were available. Then, the payloads of trucks hauling the commodities were estimated using industry data and expert opinion. Using available statistics from federal sources, the quantities of the selected commodities that were expected to be hauled from year 1999 to 2008 were estimated. The vehicle loads established for the different weight scenarios are presented in Part II Appendix D of the present report.

The base scenario had a GVW of 86,000 lbs for a five-axle semi-trailer and 49,000 lbs for a two-axle truck. Thus, for each road segment, three traffic streams were estimated for three load scenarios. The rehabilitation costs needed to sustain the traffic were estimated using AASHTO equations for each of the traffic scenarios. Using a compound interest rate of 5%, the present worth of all rehabilitation costs for each of the three weight scenarios and 15 different traffic streams were estimated in $/lane-mile and compared. The results showed that an increase in the GVW limits had a more severe effect on non-Interstate pavements compared to Interstate pavements. The authors proposed an increase in road-use fees for heavy vehicles to compensate for the road damage. Simulated traffic load data were used in the study. The authors had rather limited pavement maintenance data for the selected highway segments; actual M&R expenditure data or simulated data that duly reflected the agency's maintenance and rehabilitation practices, could have been used.

3.5.2 Studies that used Mechanistic Models for Pavement Damage Analysis

Parker and Hussain (*57*) proposed a methodology to quantify highway pavement damage caused by vehicles on the basis of the GVW, the number of axles, and the axle load distribution on individual axles. The KENLAYER mechanistic model was used for the pavement damage analysis. This model expresses the load in terms of the axle load spectra (distributions) instead of ESALs. In the first step of using a mechanistic model, stress, strains and displacements are calculated in the pavement structure. In the second step, a mechanistic-empirical model predicts damage caused by loading. The proposed methodology was applied to compare the damage caused by four-axle and five-axle trucks using data from WIM stations (see Figure 3.5). Using the assumed pavement thickness and layer characteristics, the KENLAYER model was used to estimate tensile and compressive strains for trucks

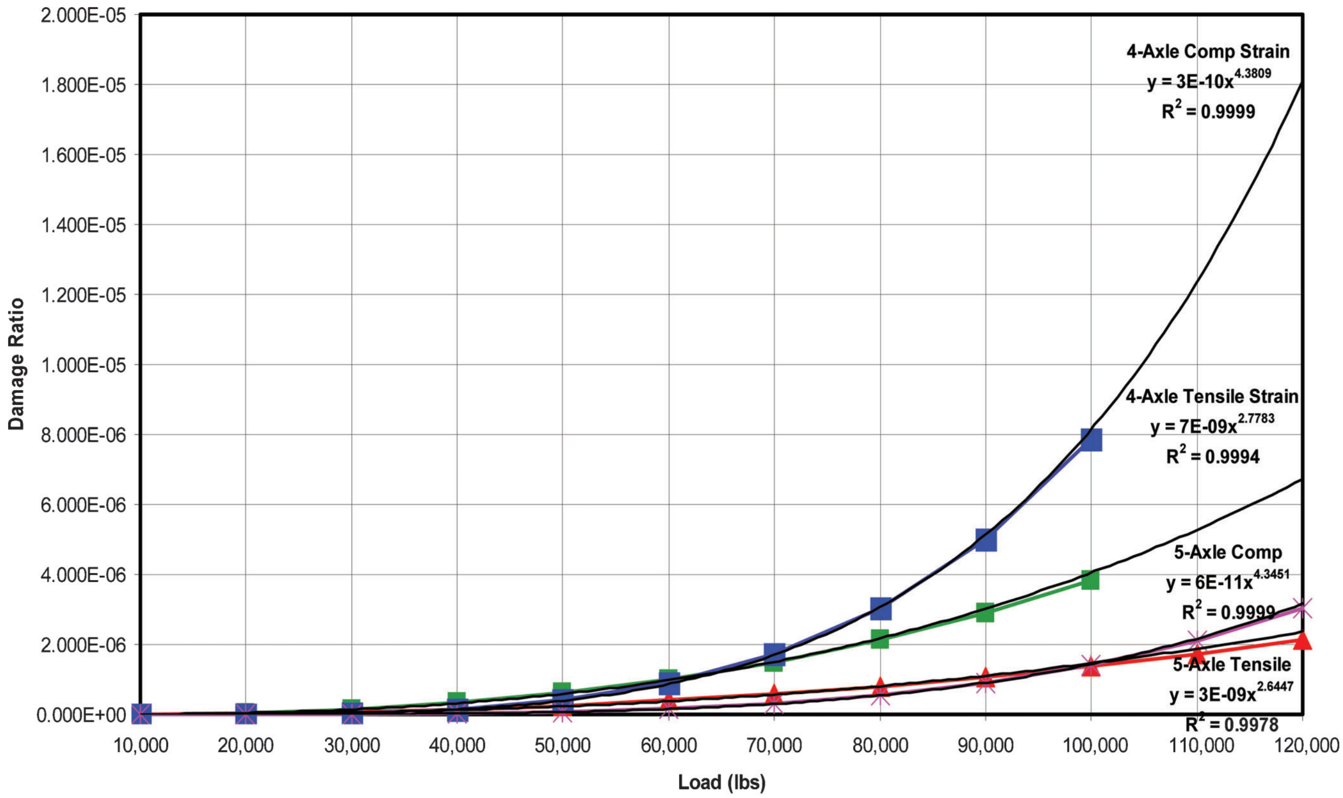


Figure 3.5 Pavement damage analysis for 4-axle and 5-axle trucks (*57*).

with different GVWs and different axles load distributions. The curves fitted to the tensile strain were more consistent with the AASHTO fourth-power curve, thus validating the AASHTO results for comparatively lower loads. On the other hand, the curves fitted to the compressive strain were closer to the third-power law, thus validating more recent research (*50*) which found that at higher loads the damaging power of an axle is closer to the third-power rather than the fourth-power.

Using maintenance data from a typical flexible pavement in New York, the PDC (in 2006 constant dollars) for a five-axle, 80,000 lbs GVW was estimated as $0.11/lane-mile. In the dataset, trucks had an average speed of 58 miles mph and an assumed 80 psi tire pressure. A typical pavement structure was assumed for analysis to compute the PDC for different truck classes. The Parker and Hussain study at the individual-vehicle-level, and with many underlying assumptions, was able to show that the PDC varies for different axle weights, axle load spectra, vehicle speeds, and other factors.

3.5.3 Studies that used Mechanistic-Empirical Pavement Design

Hong et al. (*58*) proposed a site-specific methodology for estimating the load-related cost of pavement construction using the Mechanistic-Empirical Pavement Design Guide (MEPDG) which uses axle load spectra instead of ESALs. Their proposed methodology is summarized as follows:

- Actual traffic data were collected from a single WIM station over a four-year period and were used to generate the axle load spectra.
- A typical flexible pavement structure and material used in Texas was considered for analysis purposes. Due to the very large number of possible combinations of different pavement structural layers, the authors fixed the thickness of the base and subbase layers at twelve and six inches, respectively, and used six different surface layer thicknesses (three to eight inches, in one inch increments). Thus, in total, six different pavement structures were used for analysis.
- Consistent with MEPDG capabilities, climatic data were included in the analysis.
- For pavement performance analysis, the pavement design life was taken as 20 years. Surface rutting was selected as the performance indicator, with a threashold value of 0.5 inches.
- After selecting the failure criteria, the maximum allowable number of repetitions to failure (R_i) for each truck class was determined using the MEPDG. This provided a measure of pavement damage from a vehicle class perspective. An iterative procedure was used to ensure that for the selected pavement design life of 20 years, the maximum number of passes of a particular truck class for a fixed-failure criterion was estimated. Similarly, for mixed traffic conditions, the total number of repetitions to failure was determined (R_{mix}).

- The relative damage by a single pass of each truck class i was obtained as follows:

$$D_j = \frac{R_{mix}}{R_j} \quad (3.23)$$

Where: R_i = the maximum number of repetitions for pavement failure for an individual truck class; R_{mix} = the maximum number of repetitions for pavement failure for a mixed traffic stream.

Lastly, the cost share for an individual truck class i was calculated as follows:

$$C_i = \left(\frac{V_i D_i}{\sum_{i=1}^{j} (V_n D_n)} \right) \quad (3.24)$$

Where, V_i is the volume of class i as a percentage of the total truck traffic volume.

This was a site-specific study and is very appropriate for similar future efforts at the project level, where the cost and traffic data from a single site can help to estimate the share of pavement damage by different vehicle classes. However, in the context of a network, where there is a need to have a uniform charging sytem for a certain geographical region, such as a state, province, or district, such site-specific studies have limited utility. At the particular WIM site used in the case study, there were no vehicles from FHWA classes 7 and 13 and thus these categories were excluded from analysis. This is one of the limitation of studies using small datasets and basing PDC estimates on vehicle classes instead of individual vehicles. The study reports class share and relative damage by a single pass of different vehicle classes. However, for PDC estmation, agencies are interested in total damage by a single pass of an individual vehicle with a specific GVW and axle configuration. Any study which is unable to report results based on these two criteria fails to provide an equitable way to charge different vehicles. In an ideal scenario, one could suppose that data are available from a single WIM station where a sufficent number of vehicles are present from all classes. By using the methodology proposed in the present study, it is possible to estimate the relative damage by a single pass of individual vehicle classes and the vehicle class share; however, there is no equitable way to charge individual vehicles with varying GVWs and axle configurations. Also, this study discussed only the procedure for allocating the construction cost of new pavements, which is a capacity-driven expenditure (*17*). PDC estimation studies are focused on estimating the load-driven expenditures, such as reconstruction, rehabilitation and maintenance, which are incured to strengthen the pavement structure.

Another issue with the Hong et al. (*58*) study arises from the total number of passes for each vehicle class and for the entire traffic mix. It can be noticed from Table 3.1 that when mixed traffic with load spectra for all truck classes is entered into the MEPDG, the maximum number of passses to failure was 2,306,800.

TABLE 3.1
Number of Passes to Failure, by Truck Class (*58*)

Vehicle Class	Total Number of Passes for Pavement Failure	Remarks
4	2,941,900	
5	15,198,600	
6	4,350,800	
7	—	No vehicle observed
8	4,489,500	
9	1,730,100	
10	1,452,700	
11	2,233,800	
12	1,189,900	
13	—	No vehicle observed
Mix	2,306,800	

Alternatively, when the individual classes of trucks (class 9, 10, 11, or 12) and their load spectra were entered into the MEPDG, the corresponding number of passes to failure were 1,730,100, 1,452,700, 2,233,800, and 1,189,900, respectively, which is not intutive. These results suggest that fewer passes from the individual truck classes (9, 10, 11, and 12) will result in pavement failure, than when combined traffic from all vehicle classes is used. This seems to be indicative of possible problems associated with the data entry or software code in that study.

3.5.4 Axle Load Based PDC Estimation

More recently, Alison and Walton (*59,60*) proposed a methodology for allocating the cost of new toll road construction, maintenance, and debt servicing on the basis of axle loads. The axle-load toll structure was developed using the principles of HCA. Instead of assigning the costs directly to individual vehicle classes, the proposed methodology assigns the costs to the axle-load classes (which are based on the number of axles and the load on the individual axles of different vehicle classes). Assuming a 30-year analysis period and using data from a single WIM station, the application of the methodology was demonstrated. First, the authors defined the axle-load classes using the number of axles and the axle loads of individual trucks. A common base toll was estimated simply as the total common cost divided by the number of vehicles expected to use the facility during the facility life cycle. The load-related cost of construction, maintenance, and debt servicing were allocated using the incremental method, as used in the 1997 HCA study. Thus, the load-related toll is proportional to the ESALs contributed by each axle-load class. The total toll was estimated as the sum of the base toll (common toll) and the load-related toll. The study did not consider the climatic effects on infrastructure damage. Also, no explicit results for the PDC were provided for the purpose of charging vehicles for road use.

3.5.5 Highway Development and Management Model (HDM) Approach

The World Bank's HDM software can be used to estimate pavement deterioration cost (wear and damage) and user cost (road damage externalities). The HDM method, which has the flexibility to be used for either individual roads or for an entire network, is often criticized for the lack of detailed calculations in the output and thus transparency (*22*). This software has empirical deterioration models for calculating different types of pavement distress, such as cracking, potholes, and rut depth; the method is data-intensive as detailed pavement and traffic data are needed for accurate estimation of the PDC. It also needs to be calibrated for local conditions (*61*). Bruzelius (*22*) used the HDM model for PDC estimation and obtained the results presented in Table 3.2.

The PDC estimation results presented in Table 3.2 are for a nine-meter wide road having an AADT of 6,000 vehicles, which includes 4,860 cars, 300 pick-up trucks, 360 light trucks, 360 heavy trucks, and 120 buses. These estimates are based on a 50-year analysis period and an interest rate of 4%. For the maintenance strategy, it was assumed that the pavement receives an overlay any time rutting exceeds 22 mm or there is more than 10% overall structural cracking. In HDM, a major portion of cost is the external cost associated with vehicle movement, and the road wear cost constitutes only a small portion of the total cost. The HDM analysis framework uses four models: road deterioration, works effects, road user effects, and social and environmental effects. Cracking, raveling, potholes, edge-breaks, rutting, roughness, texture depth, and skid resistance are the different distresses considered while evaluating the level of road deterioration. The critical distresses considered for pavement failure were cracking, rutting, and roughness as HDM has separate models to estimate their time of initiation and rate of progression (*62*).

3.5.6 Benefits-based Approach

Highway construction and maintenance can include a number of benefits in terms of higher mobility, safety, reduced travel time, reduced vehicle operating cost, economic development, and reduced shipping costs (*63*). A benefits-based approach for user charging is discussed in past PDC estimation literature (*17*). This approach allocates different costs, including pavement and bridge costs, on the basis of the benefits received by different vehicle classes from the highway system. A vehicle class receiving higher benefits from road-use is made to pay a higher user fee regardless of its damage contribution. The approach assumes that highways are designed to provide benefits both to highway users and non-users (that is, the society as whole). It is believed that system-use fees based on benefits will ensure fairness and efficiency. A major obstacle in the implementation of this approach is the difficulty of quantifying the non-user benefits, since the non-user community benefits (i.e., positive externalities) are mostly intertwined with user benefits. So far, this approach has not been employed fully in cost-allocation studies (*17,24,61*).

TABLE 3.2
PDC Estimation Using HDM (*22*)

Vehicle	PDC (Cents/Mile)—2004 Constant $
Bus	0.025
Heavy truck	0.241
Light truck	0.003
Car	0.003
Pick-up	0.0

3.6 Cost Issues

3.6.1 Classification of Cost Incurrence

In addition to construction of new pavements, highway agencies regularly carry out expansion and preservation activities, including pavement widening, reconstruction, rehabilitation, and periodic and routine maintenance of existing pavements. The objectives include ensuring a minimum desirable ride quality standard, structural integrity of the highway network and provision of adequate capacity. There is a need to clearly define which of these costs should be considered in PDC estimation. Different cost categories that have been used in past research are discussed briefly in the ensuing paragraphs:

New construction. New construction typically involves preliminary engineering, right-of-way acquisition, grading and earthwork, drainage, erosion control, and shoulder and pavement structure cost. New construction is a provision of highway capacity (*17,23*). In HCA, new construction cost is allocated using the incremental method but is not considered in PDC estimation because it is a capacity-driven expenditure. However, at least two past studies: Hajek et al. (*35*) and Ghaeli et al. (*39*), unfortunately, did not make any distinction between new construction and reconstruction.

Pavement reconstruction/replacement. A pavement reconstruction/replacement project includes removal of the existing pavement structure, including the subbase, and placing a new pavement structure of equivalent or increased strength over a prepared subgrade (*64*). A pavement that is structurally damaged to an extent that it cannot be restored cost-effectively using either maintenance or rehabilitation, is an appropriate candidate for reconstruction/replacement. The new pavement may have wider lanes or a different number of lanes compared with the original pavement. Also, the final cost may include expenditures on non-pavement facilities, including safety, grading, drainage, shoulders, and guardrails (*65*). Pavement reconstruction/replacement is a strength-driven expenditure and therefore appropriate for use in PDC estimation.

Pavement widening. Widening of an existing pavement is carried out either to improve safety or to enhance highway capacity and includes widening shoulders, improving curve alignment, and providing medians between opposing traffic. Also, pavement widening at curved sections can help to improve sight distance lateral clearance (*17,66,67*). Pavement widening does not add or restore structural capacity; therefore, it is treated as a capacity-driven expenditure and is typically not considered in PDC estimation.

Rehabilitation. Rehabilitation is the structural or functional enhancement of an in-service pavement with the purpose of extending service life, arresting pavement deterioration, and improving pavement condition and ride quality (*68*). The pavement work associated with rehabilitation projects may include milling of the existing pavement, PCCP slab reduction, the placement of an overlay, or a combination of these work activities (*64*). Rehabilitation cost was considered by all past PDC estimation studies, irrespective of the methodology used.

Maintenance. This is a set of activities carried out to address surface defects and to prolong pavement life by slowing its rate of deterioration. It consists of periodic (preventive) and routine maintenance. Periodic maintenance, which is a non-structural enhancement of existing pavement, can involve functional overlays (e.g., thin HMA overlay). Routine maintenance is the day-to-day activities and is comprised of routine preventive maintenance (e.g., crack sealing), routine corrective maintenance (e.g., patching) performed to prevent pavement deterioration (*69*). Most PDC estimation studies excluded maintenance cost entirely, particularly, periodic maintenance. Only those studies by Martin (*34*); Hajek et al. (*35*); Li and Sinha (*36*); and Ghaeli et al. (*39*) considered periodic maintenance cost. While Newbery (*49*); Small et al. (*50*); Vitaliano and Held (*52*); TRB (*53*); and Lindberg (*54*) excluded both periodic and routine maintenance as well as reconstruction cost. Some other studies considered maintenance but often did not provide explicit details on what comprised maintenance cost (*33,40,41,46,47*). For accurate estimation of PDC, both periodic and routine maintenance cost should be considered.

3.6.2 Purpose of Cost Incurrence (Capacity vs. Strength Expenditure)

For PDC estimation, there is a need to have a clear distinction between the costs that are incurred to strengthen the pavement structure and those that are incurred to enhance capacity. Overall pavement expenditure comprises new pavement construction, reconstruction with added lanes, reconstruction, major widening, minor widening, rehabilitation, and periodic and routine maintenance (*17*). When new pavements are constructed or lanes are added to existing highways or some widening project is undertaken, the main purpose is to relieve congestion, improve level of service and road safety, and provide enhanced travel conditions. In the 1997 federal HCA study, expenditures for new construction, reconstruction with added lanes, and widening projects were considered as capacity-driven expenditure and were allocated on the basis of the VMT, weighted by a passenger car equivalent (PCE). On the other hand, reconstruction, rehabilitation, and periodic and routine maintenance are expenditures due to direct pavement loading and are treated as strength-driven expenditures. These expenditures have been allocated on the basis of the contribution of each vehicle class to different pavement distresses in past federal HCA studies (*17,21*). All past PDC estimation studies have failed to explicitly define which costs should be included in PDC estimates; therefore, none of the past PDC estimation studies included all of the strength-driven expenditures for PDC estimation. Past PDC estimation studies either completely excluded some strength-driven expenditure from PDC estimation (*41,46–50,52–54*) or failed to distinguish between strength- and capacity-driven expenditures (*35,39*).

3.6.3 Attributable vs. Non-attributable (Load vs. Non-load) Costs

Attributable costs are those costs that can be allocated to different vehicle classes as per their road damage contributions and vary across different vehicles due to vehicle weight differences. Non-attributable costs are the common costs that are due to climate, weather, aging of the pavement structure, application of deicing salts, and other factors that are not related to vehicle loading (*23*). In PDC estimation, the purpose is to find the load-related share of pavement damage due to different vehicle classes; therefore, pavement costs are separated into load- and non-load-related categories. Besides studies by Small et al. (*50*); Martin (*34*); and Li and Sinha (*36*), no other study explicitly recognized this dichotomy of cost by separating the attributable and non-attributable costs.

3.7 Road-use Measure

The road-use measure is a traffic variable used for reporting PDC per unit of road use. Commonly-used road use measures include vehicle-mile, mile/year, GVW-mile, axle-mile, and ESAL-mile. Gibby et al. (*33*), and Liu et al. (*47*) used $/mile/year; Herry and Sedlacek (*40*), Link (*43*), and Schreyer et al. (*41*) used $/vehicle-mile; while Haraldsson (*46*) used Vehicle-Km. Newbery (*49*), Small et al. (*50*), Vitaliano and Held (*52*), Hajek et al. (*35*), and Li and Sinha (*36*) used ESAL-mile. The issues associated with the use of different road-use measures are as follows:

- **Vehicle-mile:** If vehicle-mile is used as the road-use measure for PDC estimation, the practical issue of non-homogeneity arises because this measure assumes implicitly that the same amount of damage is inflicted by each vehicle irrespective of its weight or class. Thus, studies that estimated unit PDC in terms of $/vehicle-mile do not provide results that can be considered equitable.

- **Mile/year:** Gibby et al. (*33*) and Liu et al. (*47*) estimated PDC in terms of $/mile/year. This road-use measure does not differentiate between different vehicle classes. For example, Liu et al. (*47*) estimated a PDC of $1,727 per mile per year attributed to the beef industry. This road-use measure provides general information but provides no information based on vehicle weight or class.
- **GVW-mile:** Martin (*34*) estimated PDC in terms of GVW-mile. This road-use measure has an issue of equity: it implicitly assumes that two vehicles having the same weight but different axle configurations inflict the same damage, and thus should pay the same cost, but this is not necessarily so.
- **Axle weight-mile:** Alison and Walton (*60*) used axle load per mile as the road-use measure for PDC estimation. This approach would assume that a 100% increase in axle weight could cause a 100% increase in pavement damage. However, the relationship between axle loading and pavement deterioration is non-linear and is typically characterized by the so-called "fourth-power law" (*70,71*). Therefore, this road-use measure can result in equity issues.
- **ESAL-mile:** This road measure used by most past studies is the most appropriate road-use measure because it assigns user charges to individual vehicles in direct proportion to the pavement damage they cause.

3.8 Evolution of Pavement Design and Consequences on PDC Estimation

Pavement deterioration is a complex process that is influenced by a number of factors including pavement layer types and thicknesses, geotechnical characteristics of the underlying soil, climatic conditions, maintenance practices, traffic loading, and dynamic interactions between vehicle loads and the pavement. Pavement loading is the most important factor in pavement design (*45,53*). PDC estimation approaches that involve the use of pavement design procedures depend heavily on the accuracy of traffic estimates. For accurate estimation of traffic loading on a pavement structure, there is a need to use the appropriate unit of traffic loading. PDC estimation depends heavily on how the pavement was designed initially. For this reason, any changes or refinements in pavement design procedures over the years can have a direct impact on PDC estimation. The traditional approach uses the ESAL concept to convert loading from different axles to a standard axle (*72*), while MEPDG considers traffic in terms of load spectra instead of ESALs. The evolution of pavement design and its use in PDC estimation are discussed in the next section of this chapter.

3.8.1 AASHTO Guide for Design of Pavement Structures

The AASHTO road test, which was conducted in 1958–1962 in Ottawa, Illinois, is one of the most important highway design experiments ever undertaken. This experiment involved the measurement of ESALs for pavement design purposes. The ESAL is the key component of pavement design using AASHTO procedures. There have been a few modifications to the original design procedure to facilitate the incorporation of new research findings and these changes have led to improved pavement design. The latest such effort was the 1993 AASHTO Design Guide (*72*) which helps engineers to design new and rehabilitated pavements. The ESAL concept is used to convert axles with different loads and configurations to a standard axle of 18 kip. In other words, the ESAL concept helps in converting the damage to pavements from different axle loads (vehicles having single, tandem, or tridem axles) to the equivalent damage that would be caused by a standard axle of 18,000 lbs. LEF is the ratio of the damaging effect of a non-standard axle to that of a standard axle load (*70–72*). LEF is then defined as:

$$\mathrm{LEF} = \left(\frac{W_{18}}{W_x}\right) \tag{3.25}$$

Where, W_{18} and W_x are the number of repetitions of a standard axle (18 Kip) and a given axle load respectively that attain the same serviceability level.

The following regression equation derived from the AASHTO road test for flexible pavements can be used to determine W_{18}/W_x:

$$\log\left(\frac{W_{18}}{W_x} = 4.79\log(18+1) - 4.79 log(L_x + L_2) + 4.33 log L_2) + \left(\frac{G_t}{\beta_x}\right) - \left(\frac{G_t}{\beta_{18}}\right) \right. \tag{3.26}$$

$$G_t = \log\left(\frac{4.2 - P_t}{4.2 - 1.5}\right) \tag{3.27}$$

$$\beta_x = 0.40 + \left(\frac{0.81(L_x + L_2)^{3.25}}{(SN+1)^{5.19} * (L_2)^{3.23}}\right) \tag{3.28}$$

The number of ESALs can then be computed as follows:

$$\mathrm{ESAL} = n * \mathrm{LEF} \tag{3.29}$$

Where, LEF is the equivalent number of ESALs for a certain combination of weight and axles.

Deacon (*73*) conducted theoretical analysis and proved that it is reasonable to assume that tensile strains are directly proportional to axle weights and developed the well-known relationship which says that damage caused to the pavement by a given axle is proportional to the fourth-power of the axle weight. Using the fourth-power law, the LEF can be expressed as:

$$\mathrm{LEF} = \left(\frac{W_i}{W_s}\right)^4 \tag{3.30}$$

Where, W_s and W_i are the weights of a standard axle and a given axle, respectively.

The LEF determined using fourth-power law expresses the relationship between loading and pavement deterioration in terms of the present serviceability index (PSI). For developing the AASHTO LEF, the variables used are: axle load, axle configuration (single, tandem), structural number for flexible pavements, slab thickness for rigid pavements, and terminal serviceability (*74*). Different researchers argue that the AASHTO LEF is based on empirical models which are not valid outside the scope of the material, climatic conditions, and vehicle characteristics used for the AASHTO road test. Super-single tires, new suspension systems, new axle configurations, higher tire pressures, composite pavements, new pavement materials, and advanced statistical techniques have raised concerns about the validity/accuracy of AASHTO LEF (*74*).

In light of these concerns, past researchers have explored the use of different methodologies to re-estimate LEF using either the AASHTO road test data or data from specific states/regions. Small et al. (*50*), using data from the AASHTO road test, estimated a less steep relationship between pavement life and pavement loading. Their study results showed a relationship close to the third power rather than the fourth power. Arguing against the use of some fixed/standard power, Hajek (*75*) developed a general LEF that is independent of axle configuration and pavement characteristics and obtained the 3.8^{th} instead of the standard fourth power. Huhtala et al. (*76*), in studying the effect of tire pressure on road pavements, estimated that the power value of the LEF exponent ranges between 1.80 and 6.68 depending upon the selected performance indicator. When the authors used survival analysis techniques, their study results showed a relationship close to third (3.24) rather than fourth power for the cracking index as the performance indicator. Weissmann et al. (*77*), using a Weibull distribution, estimated an exponent power closer to 3. Not long thereafter, Hudson et al. (*78*), using data from individual loops of the AASHTO road test, found that the LEF exponent ranged from 2.5 to 6.

The Organization for Economic Cooperation and Development (OECD) carried out a full-scale accelerated pavement test in the French Central Laboratory of Roads and Bridge Projects, and evaluated the performance of different pavement structures under loading. Using rutting as the performance indicator, the exponent power was found to vary from 1.47 to 5.74 (*79*). In another study that used the same performance indicator, Archilla and Madanat (*80*), using data from the AASHTO road test, developed a pavement deterioration model and obtained an exponent power of 2.98 and 3.89 for single and tandem axles, respectively. De Ponte et al. (*81*) used an accelerated pavement testing facility in New Zealand to study pavement wear due to increased axle loading and its ultimate implications on pavement damage cost estimation. Four different pavement sections with different base course material were tested. Using permanent vertical deformation as the performance indicator, the exponent value was found to range from 1 to 3. Prozzi and Madanat (*82*) estimated a pavement performance model using experimental data from the AASHTO road test and field data from the Minnesota Road Research Project and obtained an exponent power of 3.85 using roughness as the performance indicator.

3.8.2 SHRP Evaluation of AASHTO Design Equations

The design accuracy of new and rehabilitated pavements that were constructed using AASHTO design procedures was evaluated using data from the Strategic Highway Research Program (SHRP) Long-Term Pavement Performance (LTPP) in-service flexible and rigid pavement test sections (*83*). Data from 244 flexible and 120 rigid in-service pavement sections were used for the analysis. The study results suggested that there were inadequacies in the AASHTO flexible pavement design equations in predicting pavement performance. The study found that the ESAL estimates that would cause a certain loss of serviceability, as predicted by the AASHTO equations, exceeded the actual observed values. The study also found that the threshold level (2.5 PSI), which was established during the AASHTO road test, is not very consistent with the actual rehabilitation and maintenance practices of highway agencies. In fact, pavements are typically not left to deteriorate to such a level and agency decisions to undertake maintenance or rehabilitation are typically made at higher PSIs ($>$ 2.5) (*83*).

In the LTPP experiment, data from in-service test sections comprising 54 jointed plain concrete pavements (JPCP), 34 jointed reinforced concrete pavements (JRCP), and 32 continuously-reinforced concrete pavements (CRCP) with diverse traffic and climatic conditions, provided a unique opportunity to study AASHTO's rigid pavement design equations. The analysis results revealed that the original AASHTO design equations overestimated the number of ESALs that would cause a given drop in PSI loss. However, the study stated that the 1993 AASHTO design equations (*72*), which have been modified over the years, provide somewhat unbiased results, and the predicted and observed ESALs that cause a given drop in PSI loss, were not very different in value. Similar findings were obtained when the data from rigid pavements were analyzed by dividing the dataset into wet freeze, wet non-freeze, dry freeze, and dry non-freeze regions (*83*).

The LTPP study provided a number of recommendations to improve the design equation and recommended replacing the PSI concept with individual distresses. This recommendation was based on the argument that instead of a composite pavement performance indicator which lumps all distresses together, individual performance indicators (such as IRI, rut depth, and cracking index) would help in establishing direct relationships between individual distresses and the loss in pavement performance. Thus, using individual distresses, it will be possible to pinpoint whether pavement is deteriorating due to increased roughness, rutting, or cracking. Individual distress equations were developed for increases in roughness, rutting, and transverse (thermal) cracking. The equations for other performance measures, such as alligator cracking and loss of friction, could not be developed due to the unavailability of sufficient data. The general form of the developed equations is:

$$Z = N^{D} 10^{E} \tag{3.31}$$

Where: Z = Total change in distress during a specified period of time

N = Cumulative ESALs in 1000's

$$D = d_0 + d_1 X_1 + d_2 X_2 + \ldots\ldots\ldots\ldots\ldots\ldots + d_n X_n$$

$$E = e_0 + e_1 X_1 + e_2 X_2 + \ldots\ldots\ldots\ldots\ldots\ldots + e_n X_n$$

X_1, X2…X_n are the pavement design, construction standard and climate related parameters.

The distress equations were developed for predicting different distress levels and the use of these equations for designing layer thicknesses was not intended. However, having established the allowable distress threshold and by defining some new variables, these equations can be transformed to predict the required layer thickness as follows:

$$X_T = \frac{\left(log_{10}\left(\frac{Z}{N^D}\right)\right) - E_X}{E_T} \tag{3.32}$$

Where: X_T = Thickness of base or hot mix asphalt concrete

$$E_X = e_0 + e_1 X_1 + e_2 X_2 + \ldots\ldots\ldots\ldots\ldots\ldots + e_n X_n e_T X_T$$

E_T = coefficient of the term $C_i X_i$ that includes the layer thickness of interest X_T

All other variables are as defined previously.

3.8.3 Mechanistic-Empirical Pavement Design Guide (MEPDG)

Pavement engineers continue to strive for an effective analytical tool for design and analysis of pavement structures, and the latest development in that regard is the MEPDG. The MEPDG uses refined procedures as compared to AASHTO 1993 and its earlier versions, which relied heavily on the performance equations, developed from the AASHTO road test data in the late 1950s and early 1960s. Extensive research has been carried out for many years through the National Cooperative Highway Research Program (NCHRP) to develop a comprehensive guide for design of new pavements and rehabilitated structures (*84*). The MEPDG is in fact a gradual shift from the traditional empirical approach to the mechanistic approach.

The mechanistic-empirical design procedure uses both mathematical (mechanistic) and empirical models. Mathematical models or structural response models are used to compute critical stress, strain, and deflection in the pavement structure due to traffic and climatic loading. Climatic loading of pavements may be associated with a direct effect, such as strain due to thermal expansion/contraction, or indirect effects due to changes in material properties including material stiffness resulting from moisture effects. The mechanistic analysis relates the pavement response and the total effect of environment and loading. Common structural response models are based on finite element model application (rigid pavements) and multilayer liner elastic theory (flexible pavements) (*84,85*). Structural response models help to compute critical stress and/or strain values, such as tensile horizontal strain at the bottom of the hot-mix asphalt (HMA) layer and the compressive vertical stress within HMA for prediction of fatigue cracking and rutting, respectively.

In order to replicate the field conditions, MEPDG has the ability to accumulate the pavement damage on a bi-weekly or monthly basis, depending on the way climatic changes occur and the effect of the material properties at the project location. Thus, the pavement damage is simulated over a continuous time period load-by-load. The cumulative damage or distress is computed by adding the incremental distress or damage during each analysis period (two or four weeks). Performance prediction models or calibrated transfer functions (the empirical part of the MEPDG) convert the cumulative damage to physical cracking or rutting. Performance prediction models have been estimated using data from the LTPP database and other similar sources for a wide range of traffic and climatic conditions (*84,85*).

The basic difference between empirical and mechanistic design is the way traffic is considered for pavement design. Empirical pavement design procedures use ESALs as the traffic variable to convert axles with different loads to equivalent loads using LEF. The new design guide uses load spectra (axle load distribution) for single, tandem, tridem, and quad axles using detailed traffic data, including initial two-way AADT by direction and lane, traffic volume adjustment factors, axle load distribution. The traffic volume using the forecast data for design life determines the total number of axle application for each axle type. Damage and distress prediction is carried out using the total number of axle applications. The pavement response model also uses data relating to axle width, tire pressure, and tire and axle spacing to compute different distresses.

The MEPDG is capable of carrying out the analysis for new pavements, rehabilitation treatments, and composite pavements. The impact of climate on material response has been addressed by establishing a link between climatic conditions and a material library. The material characterization model has been incorporated in the design; this enables pavement engineers to analyze the efficiency of new materials, including new binders, recycled material, and unconventional gradations of aggregates. Another innovative feature in the new design guide is its ability to accumulate the pavement damage on a bi-weekly or monthly basis, thus providing a fairly reliable estimate of when rehabilitation will be needed.

The MEPDG uses three hierarchical levels for data inputs (Figure 3.6). The use of hierarchical levels of inputs ensures that the level of effort is consistent with the importance of the project. Traffic, materials and environmental inputs each have inbuilt provisions for selecting one of three hierarchical levels. Level 1 input uses refined data for pavement structure analysis and involves comprehensive testing. Characterization of traffic using WIM-collected data is part of Level 1 input. Level 2 input is an intermediate accuracy category where inputs are estimated through correlation or some limited testing. Results of tests performed on binders, aggregate gradation, and mix properties can be used for estimation of asphalt concrete modulus. Level 3 has the lowest accuracy and involves little or no testing. The inputs are regional or national default values selected by the user.

The MEPDG provides the opportunity to design and analyze pavements under varying traffic and climatic conditions using axle load spectra for each vehicle class. An effort was made by Hong et al. (*58*) to compare the impact of different vehicle classes for highway construction cost allocation using the concept of axle load spectra. The authors used data from a single WIM station and simulated the pavement damage by different vehicle classes. The percentages of construction cost share across vehicle classes were estimated as the ratio of the number of repetitions to failure for selected pavement sections by all vehicle classes to the number of repetitions to failure by the vehicle class in question. The MEPDG can be used to estimate vehicle class share as demonstrated by Hong et al. (*58*) but it is unable to provide PDC estimates for individual vehicles with varying GVWs and axle configurations. Also, Alison (*59*) argued that vehicle-based load equivalency may be obtained using typical axle loads for individual vehicles and recording the number of repetitions to failure; however, no such solution exists for individual axle loads. Recently, Bordelon et al. (*86,87*) examined whether the ESALs concept could still be used instead of load spectra for jointed plain concrete pavements (JPCP) without sacrificing the slab thickness accuracy. The authors found that there were insignificant differences in pavement slab thickness between the

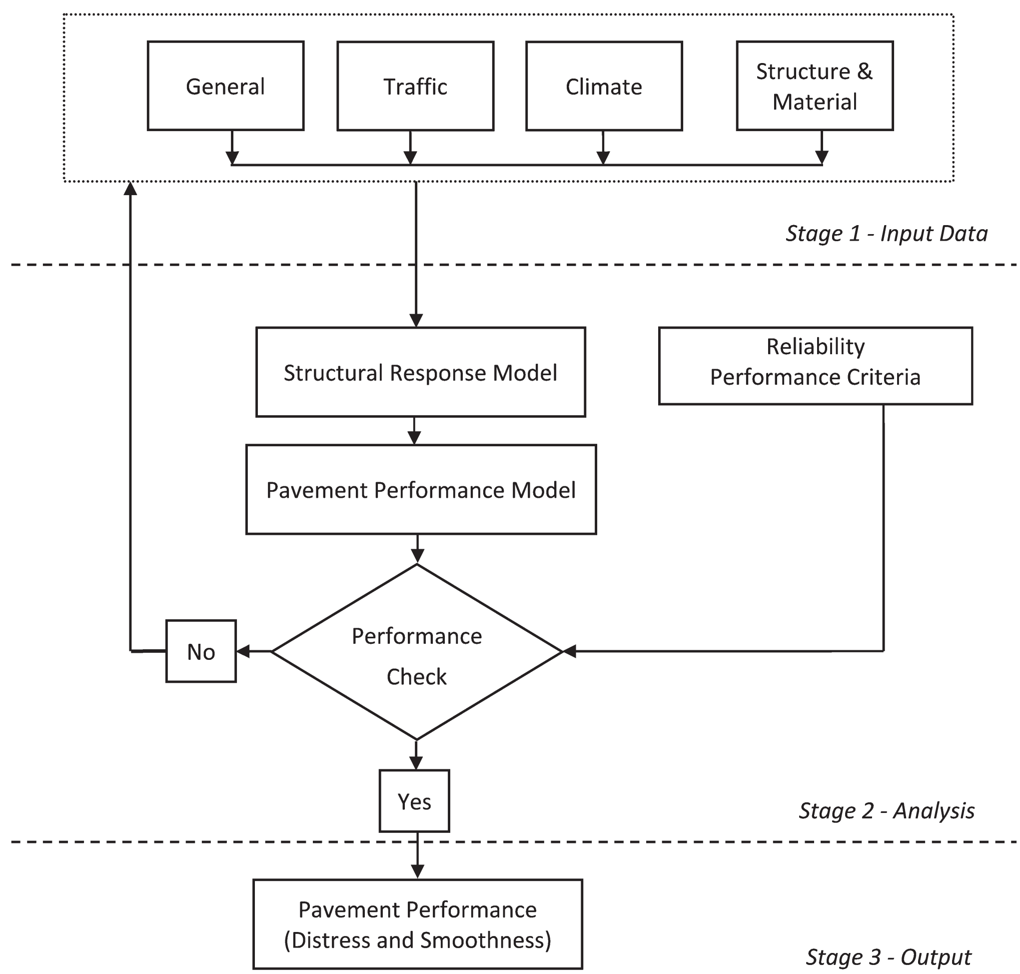


Figure 3.6 Mechanistic-empirical pavement design procedure (*84*).

two design methods and recommended that the Illinois Department of Transportation continue to use ESAL concept for JPCP design.

3.9 Discussion and Chapter Summary

The detailed review of the literature and state-of-the-art of pavement damage cost estimation provided vital information for the development of a methodology for estimating pavement damage cost that incorporates the actual practices of an agency. The general body of literature lacks a pavement damage cost estimation methodology that appropriately considers all the costs associated with pavement damage repair; namely, reconstruction, rehabilitation, and periodic and routine maintenance. Most past studies used only rehabilitation and maintenance cost but did not consider reconstruction cost. A few studies considered reconstruction cost but failed to incorporate agency practices for rehabilitation and maintenance.

3.9.1 Summary and Major Conclusions from HCA Studies

Table 3.3 summarizes the features of prominent studies that estimated PDC as part of HCA studies. The HCA studies had the primary objective of evaluating the equity and efficiency of federal highway user charges based on the costs assigned to different vehicle classes (*17*). The major issue with most HCA studies is that while estimating the cost responsibility factor for different vehicle classes, the allocated costs are not decomposed by the capacity-driven and strength-driven expenditures which reflect an agency's objective for carrying out any project. By failing to distinguish between capacity-driven and strength-driven expenditures, the road-user charges estimated by these studies included costs that were not directly related to pavement damage and thus cannot be used as a basis for establishing road-user charges to cover the damage cost.

In allocating the load-related cost of individual cost categories, such as periodic maintenance, the methods used are similar to that used by HCA estimation studies. Thus, the main difference between the HCA and PDC estimation studies arises from the differences in cost categories they consider in estimating the cost responsibility and not the differences in their cost estimation methodologies.

Another issue with past HCA studies is the variation in attributes within each user class: vehicles are grouped into different weight classes and equity was investigated separately for each vehicle class. Potentially, there could be significant variations in weight within each vehicle class, thus giving rise to the likelihood that certain vehicles will not be paying their fair share of road damage cost, as duly recognized in a TRB-sponsored study (*53*). To address this issue, the cost shares could be estimated based on some commonly-used road-use measure that varies with each vehicle class such as ESAL-mile.

TABLE 3.3
Summary of Past HCA Studies—Methods and Cost Allocators

Study	New Pavement Cost	Rehabilitation and Maintenance Cost
1965 Federal HCAS	Incremental method (traditional) •Base facility cost—VMT •Enhanced facility—traffic volume increments (ESAL)	Incremental method •VMT or incremental method •Maintenance cost not considered •Rehab formed small part of total cost
1982 Federal HCAS	Uniform removal technique (reverse incremental method) •Base facility—VMT •Enhanced facility—traffic volume decrements (ESAL)	Individual distress models (consumption method) •Cost allocated on the basis of distress contribution (not ESAL) •Maintenance cost not considered
1984 Indiana HCAS	Thickness incremental method (pavement thickness increments) •Base facility—VMT •Enhanced facility—Pavement thickness increments (ESAL) •Reconstruction—similar to new construction	Aggregate damage model (performance based methodology) •Concept of PSI-ESAL loss was introduced •Costs estimated on the basis of proportionality assumption •Load-related cost—ESAL •Non-load-related cost—VMT
1997 Federal HCAS	Thickness incremental method (pavement thickness increments) •Base facility—VMT-PCE •Enhanced facility—ESAL	NAPCOM—individual distress models •Load-related cost allocated on the basis of distress contribution (not ESAL) •Non-load-related cost—VMT
2009 Oregon HCAS	Incremental method	NAPCOM—individual distress models

NOTE: Maint = maintenance; rehab = rehabilitation; AADT = annual average daily traffic; VMT = vehicle miles travelled.

3.9.2 Major Conclusions–MPDC Estimation using Empirical Approach

MPDC estimation using the empirical approach is a two-step process. In the first step, models are estimated to explain the MR&R costs as a function of independent variables such as traffic, climate, pavement condition, and pavement structure characteristics. Then, the estimated models are differentiated with respect to the road-use variable (traffic) to yield the desired marginal cost. Past studies which have used this approach are summarized in Table 3.4 and major issues with these studies are discussed as follows:

1. Exclusion of reconstruction/routine maintenance cost. Past studies that used this approach generally did not consider the cost of pavement reconstruction or routine maintenance. Thus, the output of these studies (i.e., the estimated cost of pavement damage) was assumed, even if implicitly, to be only for maintenance and rehabilitation. This is an incomplete picture of real estimates of PDC because whenever pavements reach a very poor condition (due in part to traffic loading), they are reconstructed; there is no reason to exclude this cost from the costs to be borne by users.

2. Time span for the M&R cost data. In past studies that used the empirical approach, the PDC was estimated using historical maintenance and rehabilitation (M&R) cost and traffic data associated with individual pavement M&R activities. The total cost, which was the dependent variable in the basic model, is the overall M&R expenditure during a certain analysis period, the average annual M&R expenditure, or the M&R expenditure during one life cycle (the time between consecutive rehabilitations or between rehabilitations and reconstruction). The issue here is the manner of use of data from the individual M&R activities for the model estimation. The time interval over which the different M&R activity costs were considered were often not consistent with the time interval of the influence of the factor responsible for the cost (i.e. the total traffic and climatic loading sustained by the pavement segment). The studies (Table 3.4) that used the total M&R expenditures during a selected analysis period and the average annual M&R expenditures as the dependent variable (without regard of when the pavement segment in question last received maintenance or rehabilitation) were likely affected by such bias.

In the hypothetical illustration shown as Figure 3.7, rehabilitation actions were applied to a pavement section in years 1985 and 2000. To illustrate the issue associated with the time span of the data, consider two different studies carried out using the data from this pavement section. For the purpose of PDC estimation, Study A used data from 1988 to 1998 and thus completely missed the rehabilitation cost. Study B used data from 1995 to 2005 and thus included the cost of one rehabilitation action. Both studies covered same analysis period (10 years) and therefore the same traffic data for this period are used for estimating the pavement damage. However, because different costs are considered, the two studies will yield different results. As demonstrated by this illustration, the PDC can be significantly influenced by the temporal inconsistencies in the analysis period and its relation to the timing of the major pavement repair actions.

3. Time span for traffic data. Studies that used the concept of MR&R expenditure during one life cycle of a pavement for PDC estimation had the issue of traffic estimates that were likely incorrect. For PDC estimation, the cost of individual maintenance treatments (rehabilitation and periodic maintenance) is used as the dependent variable, and the accumulated traffic and climate effects during one life cycle are used as the independent variables. For model estimation, those studies used the appropriate measure of expenditure (the cost of the individual treatments); however, they generally had limited information on the actual individual treatment service lives and thus used historical values instead. It has been shown, though, that the use of trigger values and historical treatment service lives can lead to error, and thus it is more appropriate to estimate treatment service life for individual treatments for the specific highway functional class in question, using pavement performance data (*88*). Estimates of traffic and other variables which affect PDC can become unreliable without correct estimation of the treatment service life. For example, suppose a study uses the correct service life of a treatment of 10 years, while another uses a treatment service life of 15 years. In the first case, traffic and climate effects will span a 10-year period; and in the second case, the traffic and climate estimate effects will span a 15-year period. Thus, the two studies will have the same cost data for the pavement section but very different effects of traffic and climatic, resulting in different cost estimates. With the advancements in pavement management systems, it is envisaged that highway agencies can overcome this issue by estimating reliable treatment service lives for their standard M&R treatments.

4. Road-use measure for pavement damage cost estimation. The manner in which traffic is considered in PDC estimation can significantly influence the estimation results. A wide variety of traffic variables or road-use measures have been used in past studies: mile/year, vehicle-mile, GVW-mile, axle-mile, and ESAL-mile. It is not the total weight of vehicles, but the weight of individual axles that determines how much pavement is being "consumed" by a vehicle (*17,89*). Therefore, in reporting the PDC using an incorrect road-use measure can result in an equity issue. Traffic variables or road-use measures that account for individual axle weights and the damage they inflict, such as ESAL-mile, seems to be the most appropriate one to use.

5. Ignoring climatic effects. There are very few studies which have considered climatic effects in PDC

TABLE 3.4
PDC Estimation Studies that Used the Empirical Approach

Study	Independent Variable/Cost Model Functional Form	Traffic Variable and Performance Indicator	Maintenance Activities/Data Details	Climate/Age Variable for Estimation	Cost Estimates
Gibby et al. (*33*)	Total maint expend over 3yrs (for 1 mile section) Cobb-Douglas	AADT (cars & small trucks) AADT trucks (>5axles)	Total maint cost California (1984–1987)	Temperature Age	Trucks—$7.60/m/yr Cars—$0.08/m/yr
Martin (*34*)	Annual routine, periodic, & total maint expend Linear and non-linear	ESAL, GVW, PCU, AADT	Routine, periodic, and total maint expend Data from Australia	Age	50% (±7) load-related expend 50% (±7) load-related expend
Hajek at al. (*35*)	Total life-cycle cost over 60 yr analysis period	ESAL	Construction, maint. & rehab Ontario data	Two climatic regions	$0.0025–0.597/VKm (New pavements) $0.0013–0.307/VKm (in-service pavements)
Li & Sinha (*36–38*)	Rehab and periodic maint expend during one life cycle Annual routine maint expend OLS & system of equations	ESAL IRI	Routine maint, rehab & periodic maint expend Indiana (1994–1998) 872 highway segments	Age Freeze index Temperature	$0.0143–$0.024 per ESAL-mi 28%,78%, and 38% load-related expend for flexible, rigid and composite pavements respectively
Ghaeli et al. (*39*)	Total life-cycle cost over 30 yr analysis period	ESAL	Construction, maint. & rehab Ontario data	Two climatic regions	No estimates for PDC
Herry & Sedlacek (*40*)	Annual maint & rehab expend OLS	AADT trucks & cars Gross tons Total axle load	Annual maint & rehab cost Austria (1987–2004) 46 highway segments	—	€0.0016($.0017)/Vkm
Schreyer et al. (*41*)	Total maint & rehab expend 1985–1988 Log-linear	Total VKm Total weight-distance Total ESAL	Total maint & rehab Sweden (1985–1998) 127 highway segments	—	€0.00046 ($0.0005) per VKm (cars) €0.044 ($0.0472)/VKm (trucks)
Link (*43*)	Total rehab expend per Km (1980–1999) Log-linear	AADT cars AADT trucks	Rehab cost Germany data 1980–1999	Age	€0.008–1.87 ($0.009–2)/VKm
Ozbay et al. (2007) (*44*)	Maint & rehab expend per lane-mile Non-linear	ESAL	Maint & rehab 2004–2006	—	No estimates for PDC
Haraldsson (*46*)	Total maint expend for a region Non-linear	Heavy vehicle Km	Maint & rehab Sweden (1998–2002) 145 small regions	—	0.22 SEK ($0.0305)/heavy VKm
Liu et al. (*47*)	Annual average maint expend AASHTO equation HERS decay functions	ESAL PSR loss	Maint expend Kansas (1985–2003) 127 highway segments	HERS decay functions (non-load damage)	$1727/mi/yr

NOTE: Maint = maintenance; rehab = rehabilitation; VKm = vehicle kilometer; AADT = annual average daily traffic; PI = pavement

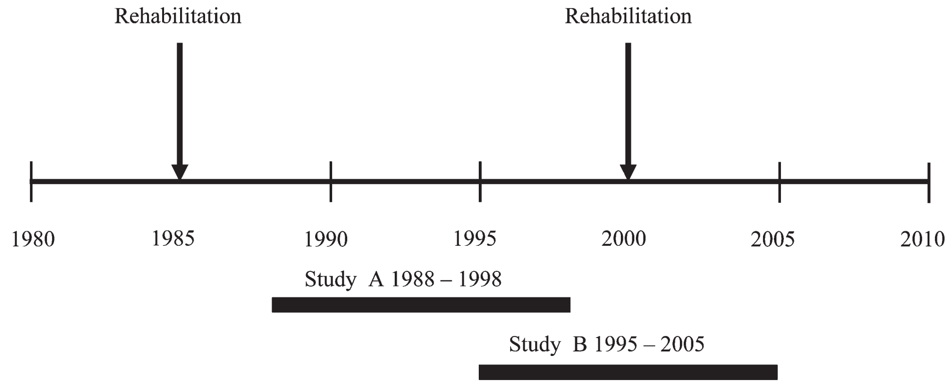


Figure 3.7 Hypothetical timelines to illustrate the impact of mismatch between time span of the MR&R data and analysis periods.

estimation. This has been an oversight as past research indicates that climate has a significant impact on pavement damage (*23,34*); therefore it is not appropriate to exclude it completely.

6. Miscellaneous issues with studies that used simulated data. Hajek et al. (*35*) and Ghaeli et al. (*39*) estimated PDC by developing models that used synthesized data from specified MR&R schedules (treatment type and timings) over life-cycle periods. Explicit details of the constituent MR&R activities and decision criteria for the treatment applications were not provided. For the MR&R schedule, Hajek et al. (*35*) escalated the costs by 25% to account for overrun. It is not certain that this was appropriate. Also, the study did not express the cost in constant dollars as recommended in the literature (*90*). Both studies did not distinguish between strength- and capacity-driven expenditure as they treated new construction and reconstruction costs without distinction. Ghaeli et al. (*39*) used a 30-year analysis period, which may be considered inadequate. For life-cycle cost analysis pavement investment, a minimum analysis period of 35 years has been recommended (*90*).

3.9.3 Major Conclusions—MPDC Estimation Using the Engineering Approach

In this approach, using theoretical knowledge, a unit dimension of the infrastructure (one lane-mile) is analyzed and a repair cost vs. usage relationship is established. Then the results are generalized for the entire network. Features of past studies that used this approach are summarized in Table 3.5 and the major issues with these studies are as follows:

1. Reconstruction and maintenance cost not considered. Studies that used this approach generally failed to account for routine maintenance and reconstruction cost and thus underestimated the cost of pavement damage. Therefore, all the results reported by past studies (Table 3.6) represent the pavement rehabilitation cost only and do not provide a comprehensive estimate of true PDC.

2. MPDC estimation based on optimal maintenance scenario. This approach estimates PDC on the basis of the assumption that a pavement promptly receives a specified treatment whenever it deteriorates to a certain threshold, thus presenting an optimal maintenance scenario. In reality, highway agency decisions may not be optimal due to insufficient funds at times for highway maintenance. Thus, the estimated cost associated with the optimal maintenance scenario does not represent the expenditure actually incurred by the highway agency; therefore, it is not appropriate to pass on such hypothetical expenditure to the users.

3.9.4 Major Conclusions from Miscellaneous Other Approaches

Apart from the two main approaches (empirical and engineering), a number of other approaches have been used to estimate the PDC per unit of road use. The HDM Model, which uses a pavement management system, can be used to estimate pavement deterioration cost (wear and damage), and user cost (road damage externality). This method is data intensive because detailed pavement and traffic data are needed for accurate estimation of PDC. Secondly, it needs to be calibrated for local conditions (*61*). Studies by Hewitt et al. (*55*) and Roberts and Djakfar (*56*) were focused more on investigating the impact of a change in GVW limits and not essentially quantifying the PDC for each vehicle class. Parker and Hussain (*57*) proposed a methodology that quantified the pavement damage caused by vehicles with different gross weights, number of axles, tire pressures, speeds, and load distribution on individual axles. Hong et al. (*58*) proposed a site-specific methodology for load-related pavement construction cost estimation using the MEPDG and provided relative pavement damage in terms of truck passes by different truck classes, but they did not report their findings in monetary values. Alison and Walton (*60*) proposed a theoretical framework for charging commercial vehicles at toll facilities on the basis of axle weights and number of axles rather than using the operating weight.

TABLE 3.5
MPDC Estimation Based on Engineering Approach

Study	Independent Variable (Cost per Km or per Mile of Road Segment)	Traffic Variable & PI	Maintenance Activities/Data	Climate Effect	Cost Estimates
Newbery (*49*)	Rehab cost over an infinite planning period Non-linear cost model	ESAL IRI	Rehab Tunisia data	Not considered	$0.0013–0.0258/ESAL-Km
Small et al. (*50*)	Rehab cost over an infinite planning period Non-linear cost model	ESAL PSI	Rehab US data	Considered	$0.0148–1.125/ESAL-Km (non-optimal practice) $0.0033–1.01/ESAL-Km (optimal practice)
Vitaliano & Held (*52*)	Rehab cost over an infinite planning period Non-linear cost model	ESAL PCR	Rehab New York data	Assumption—50% damage by climate	$0.030–0.742 per ESAL-mile (for a 5-Axle Truck)
TRB (*53*)	Rehab cost over infinite planning period	ESAL	Rehab	Considered	No estimates for PDC
Lindberg (*54*)	Rehab cost over an infinite planning period Non-linear cost model	ESAL Cracking index	Rehab Sweden data	Not considered	€0.00065–0.0162 ($0.0007–0.0176)/ESAL-Km
Anani & Madanat (*48*)	Rehab and periodic maint cost over an infinite planning period Non-linear cost model	ESAL	Periodic maint & rehab Assumed data	Not considered	No estimates for PDC

NOTE: Maint = maintenance; rehab = rehabilitation; PI = pavement performance indicator; expend = expenditure; PCR = pavement condition rating.

TABLE 3.6
Studies Using Miscellaneous Methods for PDC Estimation

Study	Maintenance Activities/Data	Traffic Variable	Performance Indicator	Climate Effect	Cost Estimates
Hewitt et al. (*55*)	Maint & rehab cost 20 yr analysis period	ESAL	—	Not considered	No estimates for PDC
Roberts and Djakfar (*56*)	Maint & rehab cost Difference in cost for alternative scenarios 1999–1918	ESAL	—	Not considered	No estimates for PDC
Parker & Hussain (*57*)	Life-cycle maint cost Maint data for a typical flexible pavement in NY	Axle load spectra	Fatigue cracking Rutting	Considered	For a truck with 5-axle, 80000 lbs GVW—$0.11/lane-mile at avg. speed of 60 mph
Hong et al. (*58*)	New construction	Axle load spectra	Surface rutting	Considered	Relative damage by single pass of each truck class was estimated
Alison & Walton (*91*)	New construction Maintenance Debt servicing	Axle Axle-weight	—	Not considered	No explicit estimates for PDC

NOTE: Maint = maintenance; rehab = rehabilitation; PI = pavement performance indicator; expend = expenditure; PCR = pavement condition rating.

These studies had their respective significant contributions by pointing toward new directions for enhanced PDC estimation. However, their results are difficult to generalize for an entire network for equitable road user charging as they were based on limited datasets and are unable to incorporate a highway agency's maintenance strategy into PDC estimation. Studies by Parker and Hussain (*57*), Hong et al. (*58*) and Alison and Walton (*60*) used site-specific data. Therefore, the results can be useful for facilites such as toll roads, but they have limited application for state agencies that deal with thousands of miles of road network characterized by wide traffic variations, different functional classes and road surfaces and heterogeneous vehicle mixes. Also, a maintenance strategy for a single road segement cannot necessarily represent the maintenance strategy used by a highway agency for all segments of an entire network.

The literature review shows that very few studies have adopted a comprehensive approach for PDC estimation. Most of the studies have either used data from a few WIM stations or considered only a single overlay applied at regular interval. None of the studies is based on actual MR&R practices, which are characterized by different treatments to different pavement surface types and at different timings. Also, the methodology should not be for a single point or link only and then generalized for the entire network. Rather, it should be carried out using data from the entire network, appropriately categorized into families of similar characteristics. Thus, it is necessary to collect cost, performance, and traffic data from representative pavement sample sections in each family. Further, there should be a clear dichotomy between strength- and capacity-driven expenditure. For strength-driven expenditure, the shares of load and non-load damage, and hence, expenditure, must be established. An appropriate time span for the analysis must be established so that long-term expenditures, traffic and performance trends can be established with minimum bias. Also, an appropriate road-use measure should be selected that is consistent with the objective of analysis (in this case, pavement damage). Another important issue is that all the categories, not just one or a select few, of the costs associated with pavement damage repair, must be considered: routine and periodic maintenance, rehabilitation, and reconstruction. Also, an appropriate exponent for LEF must be determined on the basis of the agency-specified performance indicator and threshold values for each family of pavements under consideration. Finally, the effectiveness of individual pavement repair treatments, on the basis of service life, must be ascertained according to the agency's performance indicator and performance threshold, for the analysis.

Having identified the gray areas in past studies, a comprehensive methodology was developed in this study which duly addresses the deficiencies identified in the past literature. The proposed methodology is presented in Chapters 4 and 5.

4. MAINTENANCE, REHABILITATION AND RECONSTRUCTION STRATEGY FORMULATION AND MARGINAL PAVEMENT DAMAGE COST ESTIMATION

4.1 Introduction

The general framework developed in this study for marginal pavement cost damage estimation using pavement MR&R strategies over an infinite analysis period is shown in Figure 4.1. Details of the framework elements are discussed in this chapter. Typical (past practice) or anticipated types and timings of MR&R can be used to formulate long-term strategies or schedules, for highway pavement preservation. If the cost of each MR&R activity is known, then the overall life-cycle cost can be calculated. Then, if the total number of users or the extent of their use is known, this cost can be divided among the number of users to obtain the cost to be shared by each user.

As discussed in Chapter 3, highway MPDC has been estimated in past studies using either empirical or so-called "engineering" approaches. In the studies that used the latter approach (*33,34,36,40,41,44,46,47*), M&R expenditures and traffic data from historical records (in pavement management system databases) were used for estimating the MPDC. In studies that used the "engineering" approach (*49,50,52,54*) theoretical analysis of a single representative pavement segment was used to derive an expression for the present value of recurring fixed-intensity rehabilitation over an infinite analysis period for MPDC estimation. Only one study, Hajek et al. (*35*) considered maintenance strategies for PDC estimation; however, it did not provide explicit details of the constituent MR&R activities nor did the study explain the decision criteria for the treatment applications. The study report provided no details on whether the developed strategies were based on agency practice or on optimal practice. Also, they did not distinguish between strength-driven and capacity-driven expenditures because they did not indicate a dichotomy between new construction and reconstruction costs.

Further, in the costing aspects of their analysis, none of the past studies explicitly considered the entire range of highway pavement preservation categories, namely, reconstruction, rehabilitation, and routine and periodic maintenance that occur during the life cycle of a pavement. Similarly, no past study formulated a methodology for PDC estimation that explicitly incorporates practical and realistic highway agency MR&R strategies. There seemed to be little or no realization of the fact that for a given family and pavement design, several alternative M&R treatments are available that could be applied over the pavement life cycle. The total cost of constituent M&R treatments can be estimated and summed up to yield the total cost over the pavement life cycle. The rest period (time between reconstruction and the first periodic maintenance treatment) can be estimated for different road functional classes. Also, the effectiveness of periodic M&R

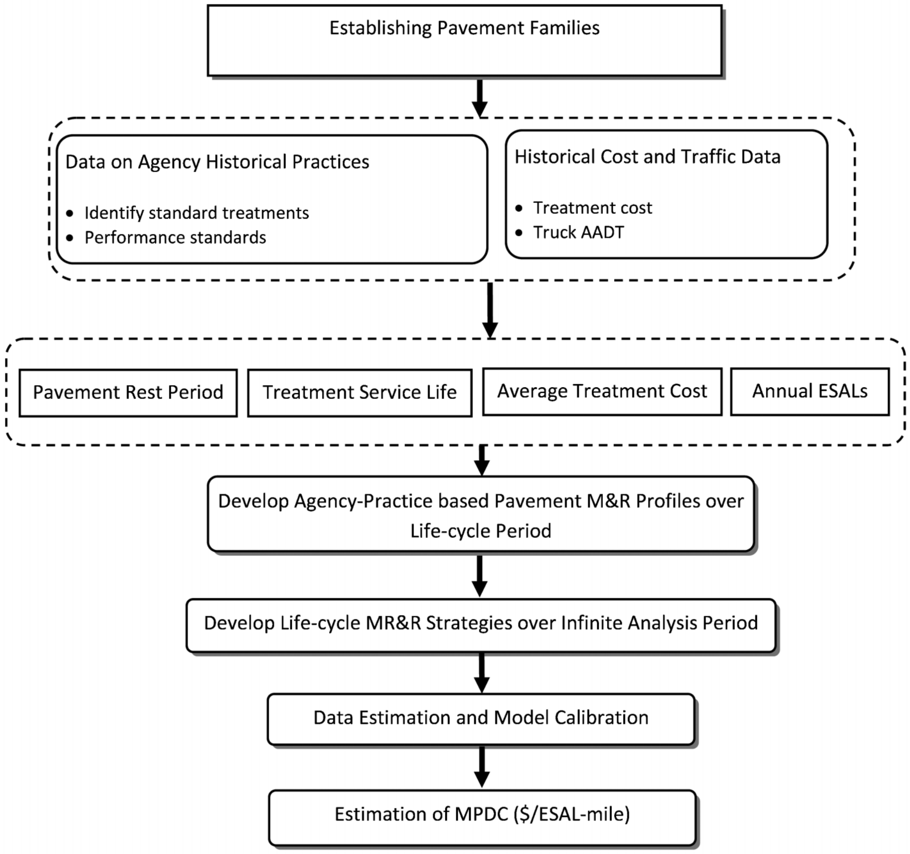


Figure 4.1 Framework for MPDC estimation using practical highway agency MR&R strategies.

treatments can be determined in terms of service life or the time taken by a treatment to reach the threshold condition. The total traffic and climatic effects over the entire life cycle of a pavement can be estimated using historical records and appropriate traffic growth factors.

Information on the total cost of reconstruction, rehabilitation and maintenance; rest periods; the service life of individual treatments; and the total traffic and climatic effect over the entire life cycle of a pavement segment can be used to estimate the PDC per unit traffic ($/ESAL-mile). The formulation of the PDC estimation methodology using highway agency MR&R strategies is discussed in the remaining sections of this chapter.

4.2 Past Research on the Formulation of Highway Pavement MR&R Strategies

An effective pavement preservation program specifies the appropriate times at which different M&R treatments should be applied to the pavement structure. To establish treatment types and timings, different studies in the past have used different timing criteria (age or condition) and different mechanisms for establishing these criteria levels (historical trends, expert opinion or optimization). The commonly-used procedures are as follows:

4.2.1 Time-based MR&R Strategy Formulation

A time-based strategy is one where treatments are applied on the basis of pavement age. Such a strategy usually involves the use of the treatment service life and is also termed as a strategy based on established time intervals (*92*). These intervals may be large or small depending upon the asset age, traffic, and climate. Age can be considered as a surrogate for accumulated climatic and traffic loading (*93*). In situations where it is difficult to collect and manage data on traffic and condition for individual pavement segments, age-based strategies may be considered reasonable (*94*).

Zimmerman et al. (*95*), in a study that incorporated chip sealing, patching, and crack sealing into South Dakota's pavement management system, developed various time-based strategies for pavement preservation. The life-cycle strategies were developed for different road types and road functional classes by a team of experts (Table 4.1).

Hicks et al. (*96*) investigated the case of application of flexible pavement preventive maintenance in order to address three main issues: (1) when and where a preventive maintenance treatment should be used; (2) the cost-effectiveness of different preventive maintenance treatments and methodology to determine the most effective treatments; and (3) different factors to be considered in formulating a preventive maintenance

TABLE 4.1
Pavement Life-Cycle Strategies for New HMA Pavements by Functional Class (*95*)

Year	Functional Class		
	Interstate	Major Arterial	Minor Arterial
1			
2	Crack seal	Crack seal	Crack seal
3	Chip seal	Chip seal	Chip seal
4			
5			
6			
7	Crack seal	Crack seal	Crack seal
8	Chip seal	Chip seal	Chip seal
9			
10			
11			
12		Crack seal	
13		Chip seal	Crack seal
14			Chip seal
15	Overlay		
16			
17	Crack seal	Overlay	
18	Chip seal		
19		Crack seal	
20		Chip seal	Overlay

strategy for a particular pavement. Table 4.2 presents the generalized optimal times Hicks et al. suggested for applying preventive maintenance treatments to asphaltic concrete pavements.

Lamptey et al. (*92*) developed time-based strategies for asphalt concrete and rigid pavements in Indiana. These strategies were developed using the treatment service life suggested by the Indiana Department of Transportation (INDOT) Pavement Design Manual, the responses of pavement engineers to a questionnaire survey of the INDOT districts, and treatment service life information synthesized from different past studies. Figure 4.2 presents a time-based strategy developed by Lamptey et al. (*92*) for new HMA pavements on the national highway system (NHS).

Labi and Sinha (*69*) formulated different time-based strategies for flexible and rigid pavements to carry out long-term cost-effectiveness evaluation of maintenance treatments. Each strategy consisted of rehabilitation and preventive maintenance treatments. Table 4.3 presents a time-based strategy reported by Labi and Sinha for a non-Interstate pavement.

TABLE 4.2
General Optimal Times for Applying Selected Treatments on AC Pavements (*96*)

Treatment	Years
Fog seals	1–3
Crack seals	2–4
Chip seals	5–7
Slurry seals	5–7
Thin overlays (including surface recycling)	5–10

Currently, INDOT uses time-based strategies for use in life-cycle cost analysis (LCCA) to carry out assessment of competing alternatives by considering pavement MR&R costs only. LCCA requires reconstruction (initial construction), rehabilitation, and maintenance costs; interest rate; salvage value; analysis period; and service life of the individual treatments as main inputs (*97*). Table 4.4 presents the anticipated service lives of various treatments used in LCCA as defined in the INDOT Pavement Design Manual. INDOT has also adopted certain guidelines for pavement M&R; and the preventive M&R treatments guidelines adopted by INDOT for asphalt and Portland cement concrete (PCC) pavements respectively are discussed in Section 4.4.2 of this study. The INDOT Pavement Design Manual recommends that, for asphalt pavements, preventive maintenance treatments should be applied generally to pavements with relatively low-to-moderate cracking and IRI of less than 150 in/mi (2.370 m/Km). For PCC pavements, there are no explicit guidelines based on IRI or friction; however, preventive maintenance treatments are recommended for PCC pavements with significant surface distresses (*98*).

4.2.2 Performance-based MR&R Strategy Formulation

In performance-based strategy formulation, the pavement threshold condition is the deciding factor for pavement intervention. As soon as the pavement reaches a certain threshold condition in terms of a selected performance indicator, an appropriate preventive maintenance, rehabilitation, or reconstruction is carried out to restore the pavement condition. Performance-based approaches involve constant monitoring of assets so that an appropriate treatment is applied to the pavement at the appropriate time. Pavement condition is monitored typically by highway agencies by collecting data on performance indicators that may be aggregate (e.g., PCR and IRI) or disaggregate (e.g., asphalt cracking index (ACI) and rutting index (RI)) (*94*).

Various studies in the past have developed performance-based thresholds and strategies using engineering judgment and past experience (*92,99*). Hicks et al. (*96*) presented a conceptual discussion of establishing thresholds for various categories of treatments for application to a pavement at different stages of its lifecycle. Figure 4.3 provides the proposed thresholds based on a pavement condition survey, on a scale of 1–100.

Lamptey (*100*) developed a performance-based methodology for applying various preventive maintenance treatments in the rehabilitation life cycle (the time interval between two consecutive rehabilitations). The developed project-level optimization methodology in that study demonstrated the superior overall benefits of applying various preventive maintenance treatments at optimal points during the rehabilitation interval. Integer programming was used to compare the costs and benefits of different candidate strategies for

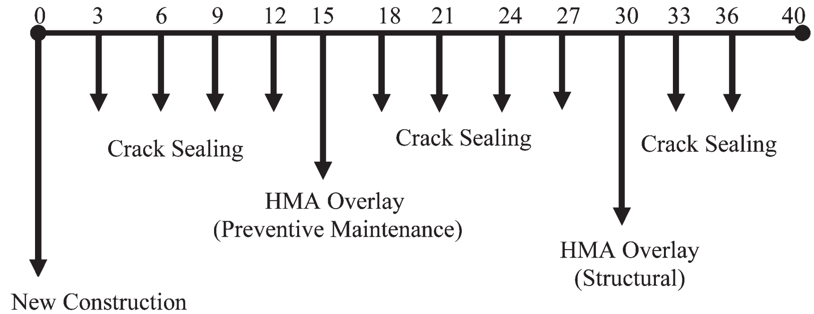


Figure 4.2 Time-based strategy for new HMA pavement, NHS (*92*).

preventive maintenance within the rehabilitation cycle. The authors developed the optimization program using performance and budgetary constraints, and formulated a preventive maintenance strategy that minimized the agency and user costs over the analysis period. A preventive maintenance strategy developed for non-Interstate using IRI as the performance measure and the corresponding anticipated performance trend, is shown in Figure 4.4.

Khurshid et al. (*101*) developed a methodology for establishing optimal performance thresholds for flexible pavement rehabilitation and periodic maintenance treatments using data from the state of Indiana. The cost-effectiveness analysis concept was used to develop the optimal thresholds. The optimal thresholds were established using agency cost only and, agency and user cost combined; and they found that the cost-effectiveness was lower when an intervention is applied to any asset either too early (asset is in relatively good condition) or too late (asset is highly deteriorated) compared to the optimal time of application. A case study using functional HMA overlay was used to demonstrate that the developed optimal thresholds (Table 4.5) represent the points where an agency derives maximum benefit at minimum possible cost by applying an intervention at that point. Comparison of

TABLE 4.3
Time-Based Strategy Formulation for Non-Interstate Pavements (*69*)

	Overall Maintenance Scenario				
	Details of Strategy (Preventive Maintenance Elements)				
Strategy #	**Thin HMA Overlay**	**Micro-surfacing**	**Crack Sealing**	**Underdrain Maintenance**	**Default Actions: Corrective Maintenance Elements (as needed, but 3-year intervals is assumed)**
0	—	—	—	—	—
1	—	—	—	—	Shallow patching, deep patching, premix leveling bump planning
2	—	—	FA: 6 years FT: 6 years	Every year	Same as above
3	—	—	FA: 3 years FT: 3 years	Every year	Same as above
4	—	FA: 6 years FT: 6 years	—	Every year	Same as above
5	—	FA: 6 years FT: 6 years	FA: 3 years FT: 3 years	Every year	Same as above
6	FA: 6 years FT: 6 years	—	FA: 3 years FT: 3 years	Every year	Same as above
7	—	FA: 3 years FT: 3 years	—	Every year	Same as above
8	—	FA: 4 years FT: 4 years	—	Every year	Same as above
9	—	FA: 8 years FT: 8 years	FA: 3 years FT: 3 years	Every year	Same as above
10	FA: 9 years FT: 9 years	—	6 years after rehab or microsurfacing	3 years after thin overlay	Same as above
11	FA: 8 years FT: 6 years	—	6 years after rehab or microsurfacing	Every year	Same as above
12	FA: 5 years FT: 5 years	—	6 years after rehab or microsurfacing	1 year after microsurfacing	Same as above

FA: Age of first application, FT: Frequency thereafter (after first application).

TABLE 4.4
Recommended Design Lives for LCCA (*64*)

Pavement—Work Type	Design Life (Years)
New PCCP pavement	30
PCC over existing pavement	25
HMA pavement with SMA (stone matrix asphalt)	25
HMA with SMA surface overlay on rubblized PCC	25
New full depth HMA pavement	20
HMA overlay on continuously reinforced concrete pavement (CRCP)	20
HMA overlay on rubblized PCCP	20
HMA overlay on cracked and seated PCCP	15
HMA overlay on perpetual asphalt	
Structural	n/a
Functional	18
Preventive maintenance	15
HMA overlays on built-up asphalt	
Structural	18
Functional	15
Preventive maintenance	9
HMA overlays on PCC	
Structural	15
Functional	12
Preventive maintenance	5
HMA overlays on JRCP or JPCP	
Structural	15
Functional	12
PCCP joint sealing	8
Ultrathin bonded wearing course (UBWC)	8
Microsurfacing	8
Concrete pavement rehabilitation (CPR) techniques	6
Chip seal	4
Asphalt crack sealing, route and seal	3
Asphalt crack sealing	1

the optimal threshold with current agency practices revealed some variability and inconsistency in the latter.

Recently, Irfan (*88*) developed a methodology for establishing optimal project-level, life-cycle M&R strategies for flexible and rigid pavements. This was done using mixed-integer nonlinear programming. For determining the effectiveness of each M&R strategy, four different objective functions were used and effectiveness was expressed as either the area bounded by the performance curve, the savings in annualized user VOC due to improved pavement performance relative to a base case, or the sum of the annualized VOC and the agency basic routine maintenance cost savings. For deriving the expression for effectiveness, treatment-specific models were developed separately for flexible and rigid pavements. The author estimated the treatment service lives for individual treatments commonly used in the state of Indiana using pavement condition and traffic data from 2001 to 2006. Cost models were estimated to determine the cost of each candidate M&R strategy. The study results can help an agency to select which treatments to apply to a certain pavement segment and at which years, for maximum cost-effectiveness. Figure 4.5, an example of the strategies developed by that study, shows that for annual average truck traffic of 2.5 million, and an annual average freeze index of 461 (degree-days), a thin HMA overlay applied at year 11 and a functional HMA overlay applied at year 20 is the optimal maintenance strategy.

INDOT has adopted certain performance standards for selecting the application thresholds for various M&R treatments (see Table 4.11). The threshold performance level of a pavement is the minimum (or maximum) acceptable performance level below (or above) which the pavement performance is unacceptable. Most agencies establish threshold values for their M&R treatments on the basis of either expert opinion or historical practices. More recently, studies using Indiana data (*98,101*) have found that preventive maintenance treatments should be applied when the IRI is between 125–150 inches/mile, and rehabilitation treatments should be applied when the IRI $>$ 150, which is generally consistent with current INDOT practices.

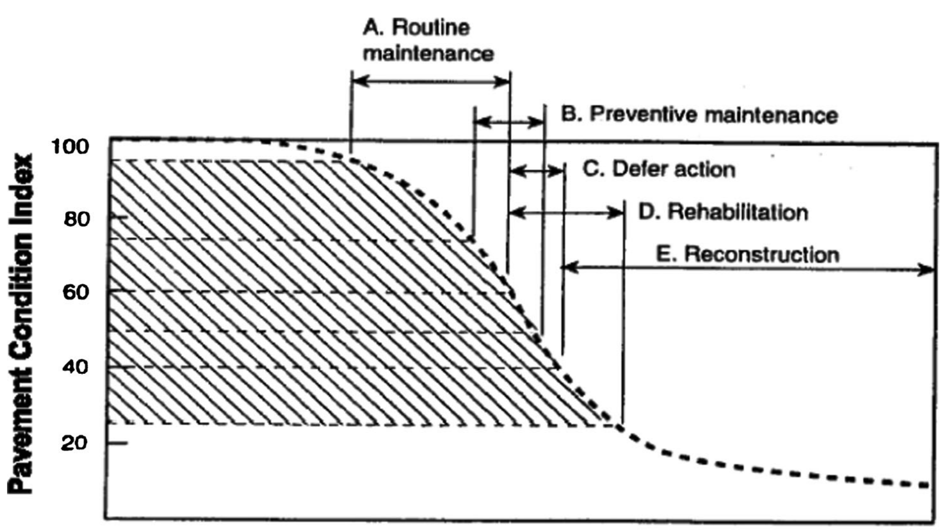


Figure 4.3 Performance thresholds for maintenance and rehabilitation treatments (*96*).

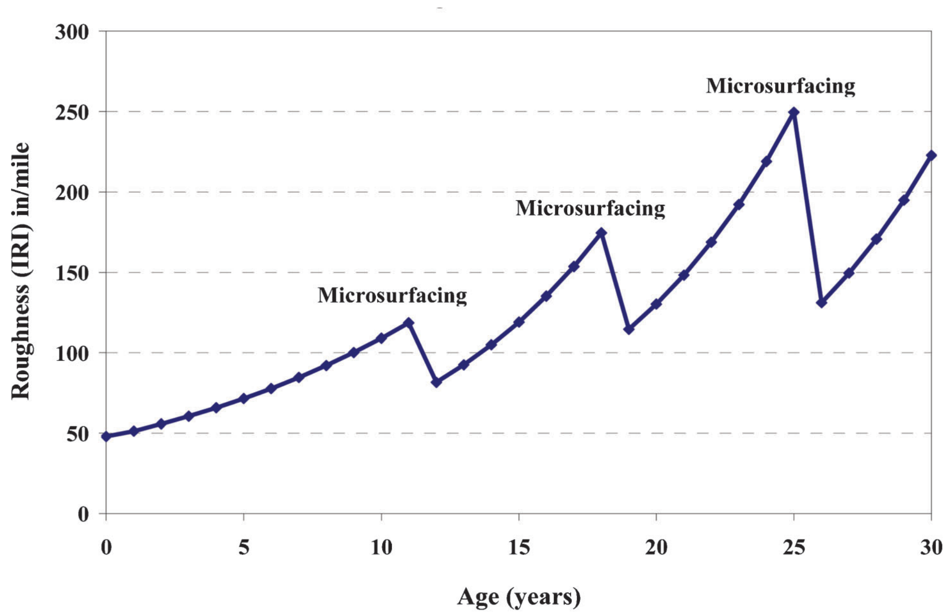


Figure 4.4 Surface roughness trend corresponding to an optimal project-level preventive maintenance strategy (*100*).

TABLE 4.5
Optimal Thresholds for Functional HMA Overlay (*101*)

	OTH Based on Non-Monetized Benefits (AOC)			OTH Based on Overall Annualized Costs (EUAC)		
Highway Functional Class	**IRI (in/mile)**	**PCR**	**Rut**	**IRI (in/mile)**	**PCR**	**Rut**
Interstate	145	74	7.1	151	78	6.1
NHS (NIS)	151	72	7.9	156	75	7.1
NNHS	157	70	9.1	162	73	8.2

NOTE: OTH = optimal threshold; AOC = area over the curve; EUAC = equivalent uniform annual cost.

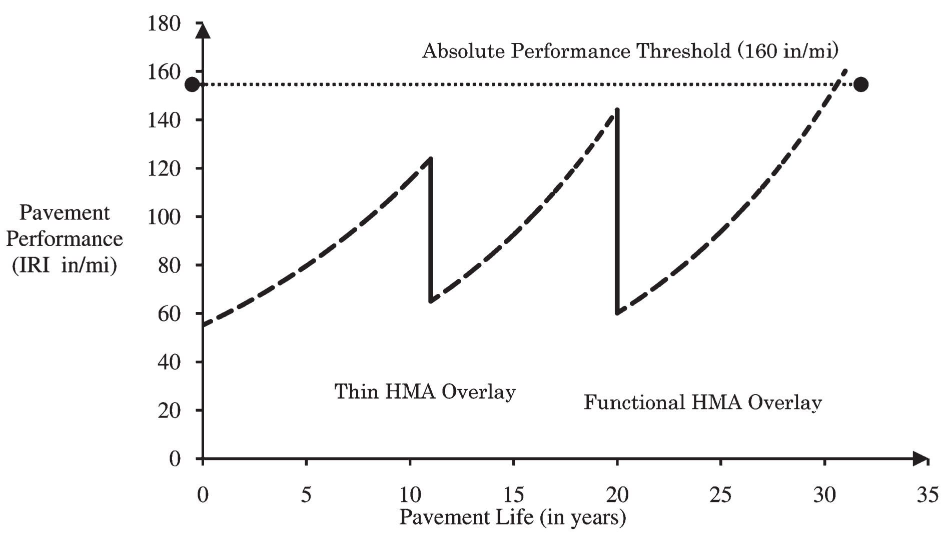


Figure 4.5 Optimal M&R strategy for flexible Interstate pavements (*88*).

4.2.3 Use of Decision Trees and Matrices for MR&R Strategy Formulation

Condition-based decision trees and matrices are a set of rules and criteria which are established using either expert opinion or past experience in pavement management. These are used for selecting appropriate M&R treatment strategies and have been developed by a number of studies in the past (*102,103*). By incorporating a set of criteria, decision trees help to select an appropriate pavement maintenance or rehabilitation treatment under a specific set of conditions such as pavement type and its distress level, traffic volume and functional class of highway (*96*). Decision trees and matrices are based primarily on the decision process historically used by a highway agency (*92*). The major advantages of decision trees and matrices are: (1) they are based on decision practices used by a highway agency; and (2) they incorporate the experience of pavement experts. However, this method of strategy formulation has certain disadvantages: (1) they incorporate only those treatments that might have worked well at a particular highway agency in past, and may not be an effective guideline for new and improved treatments that have been used more recently; and (2) the decision process cannot incorporate all the factors/ distress types that may influence treatment service life and strategy formulation (*69,92,96,97*).

In 2001, the Minnesota Department of Transportation (MnDOT) developed decision trees for treatment applications using PSR and structural condition as performance indicators (*102*). Besides decision trees, tables for trigger values of PSR and structural condition were also prepared to facilitate decision-making.

The Alberta Infrastructure & Transportation (*99*) developed guidelines for pavement preservation in 2006. In that study, decision trees and matrices for various categories of pavement treatments were developed. The decision matrices for low-cost preventive maintenance treatments were developed on the basis of IRI and the severity and extent of pavement distress (cracking). The thresholds for high-cost rehabilitation treatments were based on IRI, cracking thresholds, and structural strength requirements. The threshold values of IRI and cracking were established using past practice and expert opinion.

Ahmad (*103*), using age and the performance threshold from the INDOT pavement management system, developed a decision matrix (Figure 4.6) for formulating a pavement M&R strategy.

Ahmad's study presented a basic approach to combine expert opinion and distress indices to formulate strategies. For strategy formulation, a 40-year life cycle was used and the selected solutions were segregated into three subgroups: the cycles for preventive maintenance, functional rehabilitation and structural rehabilitation.

Wade et al. (*104*), in a South Dakota study designed to evaluate the suitability of chip seal for high-volume high-speed roads, developed a decision matrix for selecting surface treatments for rural and urban roads. Using threshold values for significant pavement distresses, the criteria for selecting appropriate pavement maintenance treatments were developed. The threshold values used for developing a decision matrix were established using past experience and expert opinion. A sample decision matrix for selecting surface treatments for rural roads is presented in Table 4.6.

4.2.4 MR&R Strategy Formulation in Past PDC Estimation Studies

Different studies in the past have used data from simulated MR&R strategies for MPDC estimation. In the time-based simulated strategies, treatment types and timing were based either on expert opinion or agency practice. Strategies were formulated over either a finite or infinite analysis period. The typical MR&R strategy formulation techniques used in past studies are discussed in the following paragraphs.

4.2.4.1 MR&R strategy formulation using an infinite analysis period. The literature review showed that for MR&R strategy formulations, past MPDC studies used an infinite analysis period, and assumed the application of a single type of rehabilitation treatment (resurfacing of a fixed thickness) to the pavement after fixed time intervals. Several studies did not consider the costs of reconstruction, and of periodic and/or routine maintenance. Also, practical M&R strategies used at highway agencies were not considered. The general procedure used by such studies for strategy formulation is as follows.

Consider a single lane of a flexible pavement for which a highway agency uses an overlay of constant intensity. Assume that the pavement receives an overlay in a perpetual cycle whenever it deteriorates to a predetermined threshold level (Figure 4.7). Let C = Unit cost ($/Lane-mile) for overlay used by highway agency; Q = Annual traffic loading of a given pavement segment in ESAL; D = Pavement durability (number of ESAL to failure).

Then the interval between any two successive resurfacing actions (rehabilitation), T is:

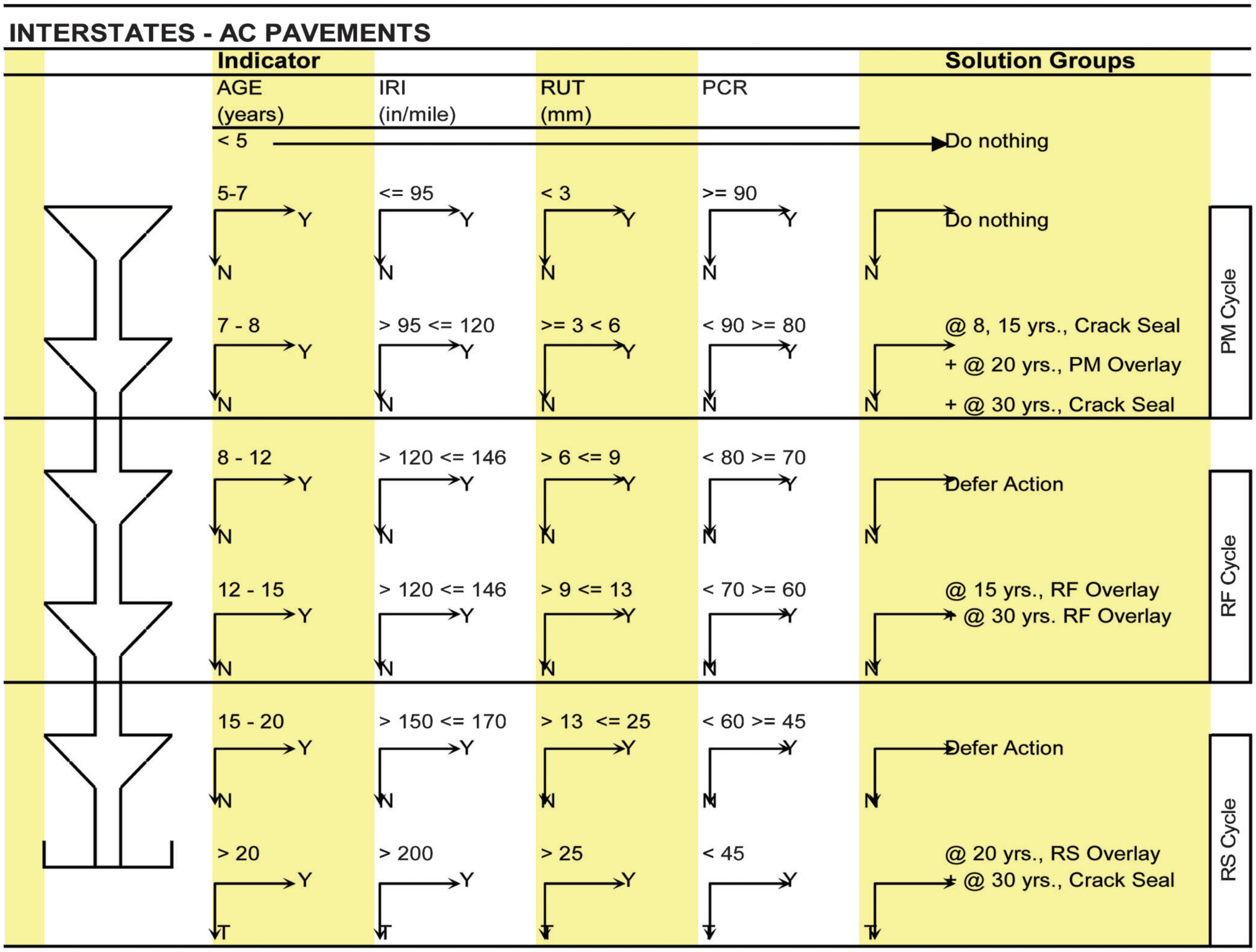
$$T = D/Q \tag{4.1}$$

The real compound interest rate is "r," and present value of all future overlays is "P." An overlay is assumed to be just laid (pavement is in new condition). The interest rate per compounding period m (number of interest periods in a year) is r/m. The continuously-compounded value, Z, of a single pavement C after every T:

$$Z = \frac{C}{(1 + r/m)^{mT}} \tag{4.2}$$

$$Z = \frac{C}{(1 + r/m)^{(m/r)rT}} \tag{4.3}$$

When m approaches ∞, 1/m approaches zero, therefore $(1 + r/m)^{(m/r)}$ approaches e.



Y=Yes, N=No, T=Terminate process, PM=Preventive Maintenance, RS=Structural Rehabilitation, RF=Functional Rehabilitation

Figure 4.6 Strategy matrix for AC Interstate pavements (*103*).

Thus, the present worth of a continuously-compounded single pavement C after T years is:

$$Z = \frac{C}{e^{rT}} \tag{4.4}$$

Similarly, the present worth, P, of all future overlays:

$$P = \frac{C_1}{e^{rT(1)}} + \frac{C_2}{e^{rT(2)}} + \frac{C_3}{e^{rT(3)}} + \ldots\ldots\ldots\ldots \frac{C_1}{e^{rT(n)}} \tag{4.5}$$

As these studies assumed that a highway agency uses an overlay of constant intensity, Equation 4.5 can be rewritten as:

$$P = C\left[\frac{1}{e^{rT(1)}} + \frac{1}{e^{rT(2)}} + \frac{1}{e^{rT(3)}} + \ldots\ldots\ldots\ldots \frac{1}{e^{rT(n)}}\right] \tag{4.6}$$

$$P = C\sum_{n=1}^{\infty}\left[\frac{1}{e^{rT(n)}}\right] \tag{4.7}$$

Assuming that (rT) is strictly negative and finite, the finite geometric series converges and can be re-written as:

$$P = C\sum_{n=1}^{\infty}\left[e^{-rT}\right]^{n} \tag{4.8}$$

$$P = C\left[\frac{e^{-rT}}{(1-e^{-rT})}\right] \tag{4.9}$$

$$P = \frac{C}{(e^{rT}-1)} \tag{4.10}$$

If P is the present worth of all future overlays, using continuous discounting, the annualized cost (AC) of all future overlays is given by:

$$AC = P(e^{r}-1) \tag{4.11}$$

TABLE 4.6
Decision Matrix for Selecting Surface Treatments for Rural Roads (*104*)

Significant Distresses	Rural Roadway		
	Low Volume	Medium Volume	High Volume
Rutting 12–25 mm (0.5–1.0 in)	Microsurfacing, mill/inlay, thin overlay	Microsurfacing, mill/inlay, thin overlay	Microsurfacing, mill/inlay, thin overlay
Bleeding > 10%	Microsurfacing, thin overlay, sand seal, chip seal	Microsurfacing, thin overlay, chip seal	Microsurfacing, thin overlay, chip seal
Roughness (IRI) 100–160 in/mi	Sand seal, chip seal	Sand seal, chip seal	Chip seal, friction course, thin overlay
Alligator cracking 0–2% high 2–10% med 4–25% low	Scrub seal, sand seal, chip seal	Sand seal, chip seal	Chip seal, friction course, thin overlay
Long./trans. cracking 0–2% high > 2% med > 4% low	Scrub seal, sand seal, chip seal	Sand seal, chip seal	Chip seal, friction course, thin overlay
Poor surface Friction SN < 40	Flush seal, scrub seal, sand seal, chip seal	Sand seal, chip seal	Chip seal, friction course, thin overlay
Raveling 0–2% high 5–25% med 10–50% low	Flush seal, scrub seal, sand seal, chip seal	Chip seal, friction course, thin overlay	Chip seal, friction course, thin overlay
Oxidation (asphalt hardening)	Fog seal, flush seal, scrub seal, sand seal, chip seal	Flush seal, sand seal, chip seal	Chip seal, friction course, thin overlay

The annualized cost is differentiated w. r. t annualized traffic to yield the PDC for a unit road-use measure.

$$\mathrm{MC} = \frac{\mathrm{d}}{\mathrm{dQ}}(\mathrm{AC}) = \frac{\mathrm{d}}{\mathrm{dQ}}\left[\mathrm{P}(\mathrm{e}^{\mathrm{r}} - 1)\right] \tag{4.12}$$

$$\mathrm{MC} = \left(\frac{\mathrm{dP}}{\mathrm{dT}}\right)\left(\frac{\mathrm{dT}}{\mathrm{dQ}}\right)(\mathrm{e}^{\mathrm{r}} - 1) \tag{4.13}$$

From Equation 4.10,

$$\frac{dP}{dT} = -rC\left[\frac{e^{rT}}{(e^{rT}-1)^2}\right] \tag{4.14}$$

Using Equation 4.1,

$$\frac{\mathrm{dT}}{\mathrm{dQ}} = \frac{-\mathrm{D}}{\mathrm{Q}^2} = \frac{-\mathrm{TQ}}{\mathrm{Q}^2} = \frac{-\mathrm{T}}{\mathrm{Q}} \tag{4.15}$$

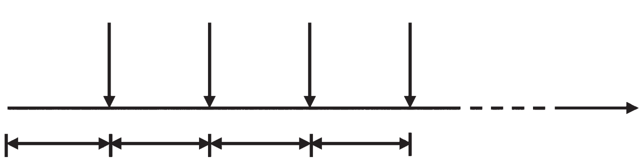


Figure 4.7 MR&R strategy assumed in most past PDC estimation studies.

Using Equations 4.13, 4.14, and 4.15, the MPDC ($/ESAL-mile) is given by:

$$MC = \frac{(e^r - 1)rCTe^{rT}}{Q(e^{rT} - 1)^2} \tag{4.16}$$

Equation 4.16 presents the basic formulation used by Small et al. (*50*), Vitaliano and Held (*52*) and Anani and Madanat (*48*). The simplified MR&R strategy formulation and data simulation, using an infinite analysis period, is very problematic. Most of these studies assumed that pavement M&R costs are dominated by the resurfacing cost and thus completely failed to consider the cost of routine and periodic maintenance and reconstruction. In reality, every highway agency uses a very wide range of different treatments for effective management of its highway network. Agencies carry out rehabilitation, periodic maintenance and routine maintenance activities, such as crack sealing and patching, to prevent rapid deterioration of the pavement structure. Also, when a pavement completes a life cycle, it is reconstructed.

The simplified strategy for pavement preservation, as implied in Equation 4.16, yields a tractable and convenient mathematical formulation but fails to reflect the actual maintenance strategies used by highway agencies. Therefore, studies that used this methodology for estimation of PDC obviously and seriously underestimated the PDC because only one category of maintenance activity, rehabilitation, was considered.

4.2.4.2 MR&R strategy formulation using a finite analysis period. There are very few past studies that formulated MR&R strategies using a finite analysis period for MPDC estimation. A prominent study in this category is Hajek et al. (*35*) which formulated time-based strategies for 20 representative categories of Ontario roads separately for new pavements and in-service pavements. From the developed strategies, data were simulated for PDC estimation. Hajek et al. (*35*) used a 60-year analysis period and 4% interest rate for the strategy formulation. The authors did not provide any detail about the M&R activities (rehabilitation and periodic maintenance) that were considered over the analysis period. Similarly, no detail was provided on the cost of individual treatments and their application criteria. Also, the study failed to establish the difference between strength-driven and capacity-driven expenditures.

4.3 Highway Pavement MR&R Strategy—the Concept

Highway structures are constructed with the purpose of providing service for several decades. Besides the initial facility construction costs, there are other costs incurred during the facility life cycle. As the facility is intended to be perpetual, the life-cycle cost will be repeated after a certain number of years. The initial investment may include one-time costs including right-of-way acquisition, grading and earthworks, drainage and erosion control, relocation of utilities, environmental mitigation, and certain other costs that are not found in recurring investments (*23,63*). The life-cycle cost includes reconstruction, rehabilitation, periodic maintenance, and routine maintenance activities that are repeated after a certain number of years. This study deals with the costs that occur during the life cycle of a pavement and which are the direct result of traffic loading and climate; therefore, the initial (new) construction cost has been excluded from PDC estimation.

Consider a hypothetical pavement structure which is constructed in year zero with an initial cost $P as shown in Figure 4.8. It is assumed that this facility will be kept in service to perpetuity; and thus will be reconstructed at regular intervals, as it will ultimately deteriorate (due to traffic and climate) to a point where M&R alone may not be sufficient to restore it to a desirable level. Also, rehabilitation and maintenance will also be carried out between the initial construction and reconstruction or between two consecutive reconstructions (pavement reconstruction life cycle, N). The life-cycle cost (the sum of the cost of reconstruction, rehabilitation, and maintenance) will be repeated every N-year period. All costs that occur during the replacement cycle of the pavement can be discounted to the initial year to yield into a single amount ($R). The interval between two reconstruction activities (N) can be either fixed or may vary depending on the loading experienced in that interval and the quality standards. Higher traffic and climatic severity will result in a decreasing value of N while higher rehabilitation standards and superior construction materials will result in higher values of N (*63*).

The interval between two reconstruction activities can be referred to as a reconstruction life cycle, replacement life cycle, or simply the life cycle. This study deals with all those costs that occur during the reconstruction life cycle of a pavement; therefore, the reconstruction, rehabilitation, and periodic and routine maintenance costs form a key aspect of this study and are considered herein for estimating the cost of pavement damage.

Highway agencies use different types of pavement structure for pavement design purposes. Also, in order to maintain pavements in satisfactory condition, agencies use different rehabilitation and maintenance treatments. Depending on the design alternatives, agency practices, and the availability of construction materials, there are typically a limited number of rehabilitation and maintenance treatments that could be applied.

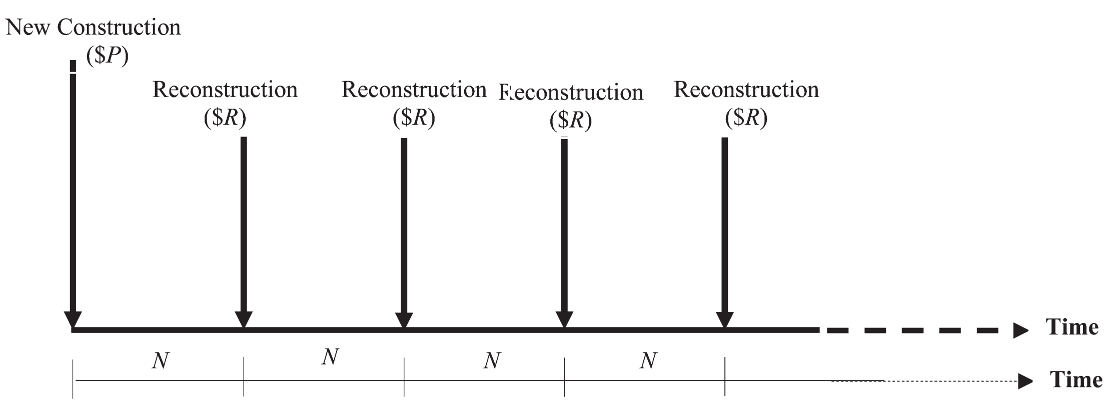


Figure 4.8 Initial and periodic costs to perpetuity for a typical pavement structure.

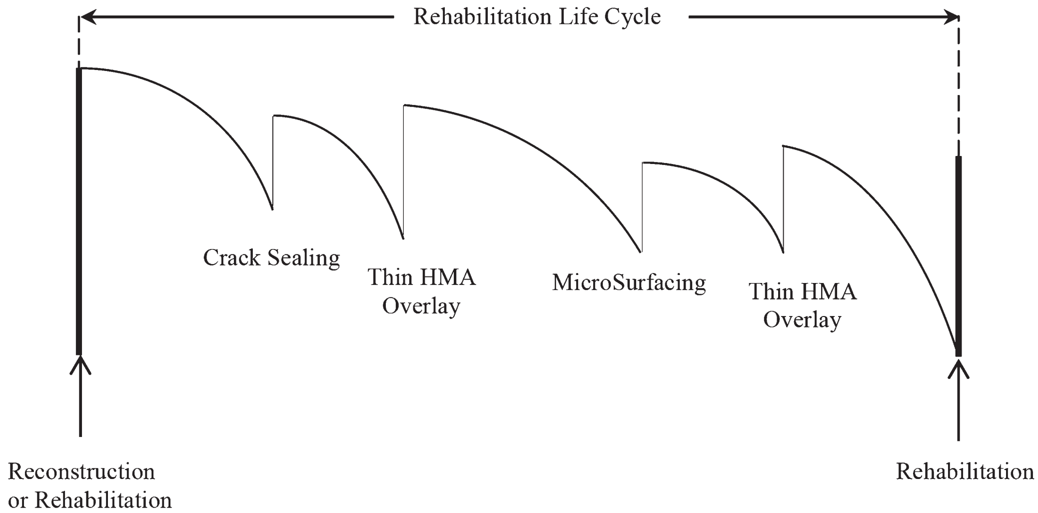


Figure 4.9 A typical maintenance activity profile within a rehabilitation life cycle.

A maintenance and rehabilitation (M&R) profile is a combination of treatment types and their application timings during the life cycle of a pavement. Other synonymous terms in the literature are "schedule," "activity profile," and "activity time line" (*92,94*). A preventive maintenance activity profile is a set of different preventive maintenance treatments applied to a pavement structure at different times between the rehabilitation life cycle (Figure 4.9), that is, between two consecutive rehabilitations or between reconstruction and rehabilitation (*94*).

Different rehabilitation and maintenance treatments can also be applied to a pavement structure during the reconstruction life cycle, replacement life cycle, or simply, life cycle, that is, the period between two consecutive reconstructions (Figure 4.10). The combination of different resurfacing activities applied to a pavement structure at various times during the reconstruction life cycle has been termed as "M&R profile" in this study. Also in this study report, the term "MR&R strategy" refers to the combination of maintenance; rehabilitation and reconstruction (life-cycle M&R profiles between successive reconstructions) over an infinite analysis period.

4.4 MR&R Strategy Formulation Developed in this Study

The following steps used in this study for developing MR&R strategies are discussed in the ensuing paragraphs.

- Group pavements into families
- Establish highway agency MR&R practices
- Establish the effectiveness of M&R treatments
- Establish pavement rest periods
- Establish the cost of MR&R treatments
- Establish road-use measure and road-use trends
- Establish MR&R strategy parameters
- Formulate MR&R strategies for each family
- Estimate cost and traffic data from MR&R strategies

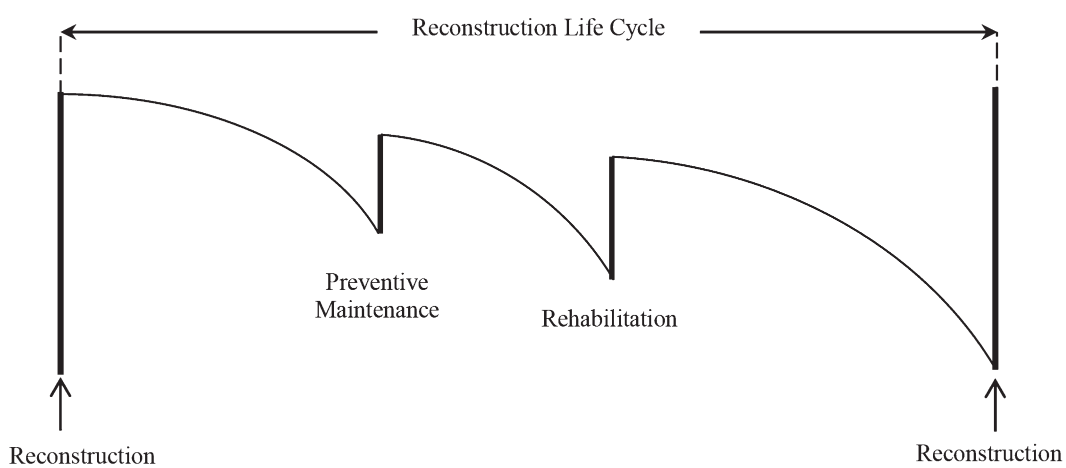


Figure 4.10 A typical M&R profile within a reconstruction life cycle.

- Develop models to relate road-use to expenditure
- Estimate MPDC for different highway functional classes

4.4.1 Grouping of Pavements into Families

A group of pavement segments with similar deterioration characteristics can be referred to as a pavement family (*105*). A pavement family usually has similar material type and traffic characteristics. Different families of pavement need to be considered separately for pavement preservation strategy formulation because a treatment or strategy that is suitable for one family may not be suitable for others. For this reason, agencies use certain preservation treatments to address only certain specific pavement distresses in specific pavement families. For example, chip seal is a preventive maintenance treatment that is inappropriate for high-speed and high-volume roads such as Interstate highway systems but is suitable for non-Interstates (*64,96*). Therefore, it is appropriate that different pavements be placed into families on the basis of their attributes (e.g., material type, road functional class, traffic volume, and climatic regions).

The development of pavements families is carried out to reflect the inherent differences between the families, mainly in order to incorporate the effect of the design and construction features for which data are typically unavailable. Also, grouping pavements into different families creates surrogate variables on the basis of functional class and surface type (*100*). It is hypothesized that pavements with similar design and construction features grouped into families will exhibit similar responses to different M&R treatments (*88*).

4.4.1.1 Grouping of pavement on the basis of surface types. On the basis of surface type, pavements can be broadly classified into three types: (1) flexible pavements (2) rigid pavements, and (3) composite pavements. These pavements have different structural responses under loading and are designed using different loading theories (*13,45*). Flexible pavements, also referred to as asphalt pavements, bend or flex under loading and have bituminous or asphalt material as the top course. Flexible pavements are of two major types: conventional flexible pavements and full-depth asphalt pavements. Conventional flexible pavements are composed of a layered system having superior quality material to sustain high stress at the top layers and relatively low quality material to sustain the low stress at the bottom layers. In the case of full-depth asphalt pavements, one or more layers of HMA are placed directly over a subgrade or improved subgrade. Full-depth asphalt pavements are suitable for areas having high traffic levels and where other materials are not available locally (*45*).

Rigid pavements, also referred to as Portland cement concrete pavements (PCCP), are comprised of a PCC surface course as a principal structural layer placed directly over the prepared subgrade or over a single layer of stabilized material (*45*). A rigid pavement consists of stiff material and therefore distributes the load over a relatively wider area compared to a flexible pavement. Also, unlike flexible pavements where the combined strength of all layers is considered in the design, rigid pavement design considers the structural strength of the concrete slab as the only major factor. Therefore, minor variations in subgrade strength have little influence on the overall strength or capacity of the pavement structure (*106*). Rigid pavements can be broadly classified as follows: (1) jointed plain concrete pavements (JPCP); (2) jointed reinforced concrete pavements (JRCP); and (3) continuously reinforced concrete pavements (CRCP). Rigid pavements have a higher initial cost and traffic noise, but are stronger and durable, and can provide a more skid-resistant surface (*88,106*).

A composite pavement is a combination of rigid and flexible pavement. It is considered an ideal pavement because it combines some of the desirable characteristics of both types of pavements. When a HMA overlay is placed over a PCC layer, the result is a strong base and smooth riding surface. This type of pavement as new construction is seldom used due to its high cost; however, some concrete pavements, after many years of service, are overlaid by an asphalt layer to yield this pavement type (*45*). In this study, a composite pavement is not considered as a separate pavement family, rather flexible and composite pavements are considered as one family for the MR&R strategy formulation.

4.4.1.2 Grouping of pavement by functional class. Functional classification is the grouping of different highways on the basis of the mobility and accessibility services they provide to travelers. The functional classification helps in assigning jurisdictional responsibility, conducting fiscal planning, and establishing design standards for different types of roads (*107*). Besides surface types and functional classes, road networks can also be grouped on the basis of whether or not they are located on the National Highway System (NHS), a network of approximately 160,000 miles of U.S. roadways that are important for mobility, and defense and economic vitality of the nation (*107*). Interstates which are part of the NHS, have the highest level of traffic loading, as well as superior mobility, access control, and design and construction standards compared to other roadways (*92*). Also, a fraction of U.S. roads and selected state roads form part of the NHS; these are termed National Highway System non-Interstate (NHS (NIS)). The basis of construction, safety, and design standards of NHS (NIS) are superior to non-National Highway System (NNHS) roads but inferior to those of the Interstate system. NNHS roads are mostly minor arterial or collector roads having lower standards of design, construction, maintenance, and safety compared to the NHS roads (*88*).

On the basis of surface type and functional classification, the highway distribution in the state of Indiana is shown in Table 4.7. It can be noticed that NNHS roads comprise the majority of U.S. roads and flexible pavements are a dominant surface type category.

TABLE 4.7
Distribution of Pavement Families and Sizes by Surface Type and Road Functional Class (*108*)

Pavement Classification		Road Functional Class		
		Interstate	NHS (NIS)	NNHS
Pavement surface type (miles)	Flexible	95	571	8595
	Rigid	184	282	61
	Composite	889	883	1748
Total (miles)		**1168**	**1736**	**10404**

4.4.2 Highway Agency MR&R Practices

In formulating MR&R strategies in the study, the objective is not to compare the competing alternatives and select the best one, but rather to assemble data points to establish a relationship between the total cost of the treatments in a given MR&R strategy and the traffic loading and other explanatory variables. For preserving each family of pavements in their jurisdiction, different highway agencies use different M&R treatments. There is no standard list of treatments that are applied universally across the states. However, from time to time, agencies provide guidelines on the basis of their latest practices. Before discussing the types of treatments, it is appropriate to define certain terms which are associated with pavement M&R strategy formulation.

A FHWA memorandum (*109*) regarding pavement preservation definitions provides a standard platform for interpreting pavement preservation to all local and state highway agencies, thus helping to ensure some degree of consistency. On the basis of this, FHWA memorandum and other literature (*65,69,92,98*), pavement preservation and related terminologies are presented below:

- **Pavement Preservation:** This refers to all activities undertaken to maintain serviceable pavements and includes corrective and preventive and minor rehabilitation (Figure 4.11). It excludes new construction, reconstruction and major rehabilitation. Pavement preservation is a long-term strategy aimed at preserving investment in the highway pavement infrastructure, cost effective extension of pavement life, improving safety, reducing delay and meeting users' expectations (*98,109*).
- **Preventive Maintenance:** FHWA defines preventive maintenance as a planned strategy of cost-effective treatments to an existing pavement network to correct minor defects, retard future deterioration, and improve the functional condition without enhancing structural capacity. Preventive maintenance extends the service life of structurally sound pavements, typically applied to pavements in good condition, and forms a major component of pavement preservation (*69,98,109*).
- **Corrective Pavement Maintenance:** These are reactive and unscheduled activities that are performed to restore a pavement to an acceptable level of service after an unforeseen situation. Pothole repairs or patching of localized pavement deterioration are examples of flexible pavement corrective maintenance. In the case of rigid pavements, slab replacement at an isolated location is an example of corrective maintenance. Corrective maintenance at times requires an immediate response to avoid serious consequences (*98,109*).
- **Routine Maintenance:** Planned work performed on a routine basis to preserve the condition of highway pavements. These activities which are typically carried out at relatively short interval, include crack sealing (routine preventive maintenance), and patching (routine corrective maintenance) (*69,109*).
- **Minor Rehabilitation:** This is the non-structural enhancement of an existing pavement structure aimed at reducing aging and restoring pavement serviceability. For example, these treatments can help to eliminate cracking in flexible pavements caused by environmental factors, thus extending the life of the pavement. Minor rehabilitation techniques are non-structural in nature and therefore fall into the category of pavement preservation (*109*).
- **Major Rehabilitation:** Major rehabilitation is defined as structural enhancements of a pavement with the intention of extending the service life of the pavement structure and to improve its load-carrying capacity (*109*).
- **Pavement Reconstruction/Replacement:** Pavement reconstruction/replacement often consists of removal of the existing pavement structure, including the subbase and placing a new pavement structure of equivalent or increased strength over a prepared subgrade (*64*). A pavement that is so structurally damaged that it cannot be restored, either by maintenance or rehabilitation, is a candidate for reconstruction/replacement. Thus, the existing mainline pavement is replaced with a complete new pavement structure. The width and number of lanes of new pavements may differ from those of the original pavement. The final cost may also include the costs of enhanced drainage and facility safety (e.g., grading, drains, widened shoulders, and guardrails (*92*).
- **Pavement Rehabilitation 3R:** This treatment involves pavement rehabilitation or reconstruction, shoulder work such as patching and/or replacement, and limited safety improvement and drainage work. 3R rehabilitation treatments may also include curb or sidewalk work and minor realignment of the road centerline at specific locations. 3R rehabilitation projects do not include right-of-way acquisition (*65*).
- **Pavement Rehabilitation Partial 3R:** This treatment involves placing of a new surface on the existing road to improve service. It does not involve alignment work and therefore uses construction standards that differ from those of 3R/4R standards. Road widening and modernization or a significant facility upgrade are not included in 3-R rehabilitation treatments. The primary focus is to restore the pavement surface. 3-R rehabilitation treatments may also include incidental related work items such as improvements to curbs, drains, shoulders, or guardrails (*65*).
- **Pavement Rehabilitation 4R:** This treatment is a major rehabilitation project which involves complete replacement of the entire pavement structure. Correction of all safety defects and reconstruction of items outside the

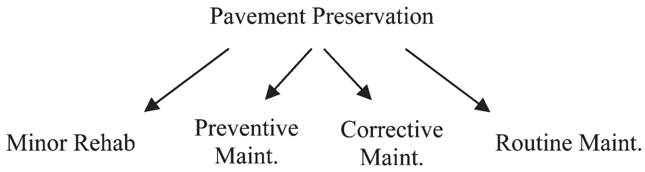


Figure 4.11 Components of pavement preservation (*109*).

pavement structure are part of all 4R projects. The purpose of 4R projects is to bring the road up to current geometric standards and to upgrade safety and drainage features. Work may include lane additions if necessary (*65*).

In the case of flexible pavements, the most widely-used preventive maintenance treatments include thin HMA overlay, microsurfacing, crack seal, and fog seal. For rigid pavements, the most frequently-used preventive maintenance treatments include undersealing, crack sealing, and saw-and-sealing joints. Flexible and rigid pavement preventive maintenance treatments, which are used to address specific pavement distresses, are summarized in Tables 4.8 and 4.9.

For pavement rehabilitation a number of treatments are applied by INDOT in practice. However, no explicit guidelines similar to those in Table 4.9 were provided for rehabilitation treatments. Table 4.10 provides a general overview of different types of preventive M&R treatments used by INDOT in the recent past for flexible and rigid pavement. The details were extracted from available INDOT contract record files.

These tables provide an overview of M&R treatments that are applied frequently. This table does not cover the data for reconstruction activities. It can be noticed that in the case of flexible pavements, thin HMA overlay was the most common choice for preventive maintenance of flexible pavements. For rehabilitation of flexible pavements, besides 3R/4R rehabilitation, HMA overlay (structural) and resurfacing of asphalt pavements (partial 3R) were common choices. In the case of rigid pavements, PCC patching has been widely used as preventive maintenance treatment while Repair PCC and HMA Overlay, Crack-and-seat PCC and HMA overlay, Rubblize PCC and HMA Overlay were common selections for rehabilitation. These choices were also influenced by the nature of the existing surface defects and the overall pavement condition at the time of the decision.

Every agency has a certain set of performance levels that warrant application of different preventive M&R treatments. For MR&R strategy formulation, it is necessary that performance thresholds are clearly established as to when to apply which treatment and at what level of initial condition. A treatment applied too early when the asset is in the superior performance stage or applied too late when the asset's performance is relatively inferior is not cost-effective (*94*). INDOT has established the actions that should not be applied when 100<IRI>200 (Table 4.11). When IRI<100, the pavement is in relatively good condition and when pavement IRI > 200, then it is a suitable candidate for reconstruction. Also, the INDOT Pavement Design Manual recommends that no preventive maintenance treatment should be applied when IRI<130 (*64*). Khurshid et al. (*20*) using data for the state of Indiana, established optimal thresholds for thin HMA overlay and functional HMS overlay. The established thresholds are consistent with current INDOT standards.

TABLE 4.8
INDOT HMA Preventive Maintenance Treatment Guidelines (*64*)

Treatment	AADT[1]	Pavement Distress	Rutting (in)	IRI (in/mi)	Friction Treatment	Surface Aging
Crack seal	Any	Low to moderately severe surface cracks	N/A	N/A	No	N/A
Fog seal	< 5,000[2]	Low-severity environmental surface cracks	N/A	N/A	No[3]	Reduces aging and oxidation; arrests minor raveling
Seal coat (chip seal)	< 5,000[2]	Low-severity environmental surface cracks	< 0.25[4]	N/A[4]	Yes	Reduces aging, oxidation and minor raveling
Microsurfacing	Any	Low-severity surface cracks	Any	< 130	Yes	Reduces aging, oxidation and minor raveling
Ultrathin bonded wearing course (UBWC)	Any	Low to moderately severe surface cracks	< 0.25	< 140	Yes	Reduces aging, oxidation and moderate raveling
HMA inlay	Any	Low to moderately severe surface cracks	Any	< 150	Yes	Reduces aging, oxidation and raveled surface
HMA overlay	Any	Low to moderately severe surface cracks	Any	< 150	Yes	Reduces aging, oxidation and moderate raveling

[1]For mainline pavement.
[2]Unless traffic can be adequately controlled.
[3]Treatment may reduce skid numbers.
[4]Treatment does not address this.

TABLE 4.9
INDOT PCC Preventive Maintenance Treatment Guidelines (*64*)

Treatment	AADT*	Pavement Distress	IRI (in/mi)	Friction Treatment	Surface Aging
Crack seal	Any	Mid-panel cracks with aggregate interlock	N/A	No	N/A
Saw and seal joints	Any	> 10% joints with missing sealant; otherwise joints in good condition	N/A	No	N/A
Retrofit load transfer	Any	Low to medium severity mid-panel cracks; pumping or faulting at joints < 0.25 in.	N/A	No	N/A
Surface profiling	Any	Faulting < 0.25 in.; poor ride; friction problems	N/A	No	N/A
Partial-depth patch	Any	Localized surface deterioration	N/A	Yes	N/A
Full-depth patch	Any	Deteriorated joints; faulting ≥ 0.25 in.; cracks	N/A	No	N/A
Underseal	Any	Pumping; voids under pavement	N/A	No	N/A
Slab jacking	Any	Settled slabs	N/A	No	N/A

*For mainline pavement.

TABLE 4.10
Historical Trends—INDOT Maintenance and Rehabilitation Treatments

Activity	Treatment	No. of Records
Flexible preventive maintenance	Crack seal	4
	Asphalt patching	51
	Micro-surfacing	24
	Thin HMA overlay	269
	Wedge and level	70
Flexible rehabilitation	HMA overlay functional	787
	HMA overlays structural	1715
	Resurfacing of asphalt pavement (partial 3R)	816
	Mill full-depth and asphalt concrete overlay	6
	Road rehabilitation (3R/4R standards)	148
Rigid preventive maintenance	PCC patching	146
	PCC cleaning and sealing joints	14
	Diamond grinding	4
Rigid rehabilitation	PCC repair and HMA overlay	50
	Crack and seat PCC and HMA overlay	20
	Rubblize PCC and HMA overlay	18
	PCC overlay on PCC	3
	Resurface PCC pavement (partial 3R standards)	8
	Road rehabilitation (3R/4R standards)	148
Composite rehabilitation	Crack and seat composite pavement and HMA overlay	30
	Rubblize composite and HMA overlay	8

TABLE 4.11
Pavement Performance Standards (*110*)

	INDOT Standards—Pavement Performance Indicator Value		
Performance Indicator	(m/km)	(in/mi)	Performance
International Roughness Index (IRI)	< 1.6	< 100	Excellent
	1.6–2.37	100–150	Good
	2.37–3.15	150–200	Fair
	> 3.15	> 200	Poor
Pavement Condition Rating (PCR)	> 90		Excellent
	90–80		Good
	80–70		Fair
	< 70		Poor

4.4.3 Effectiveness of Asset Interventions

A number of studies have been carried out in the recent past to assess the effectiveness of standard pavement M&R treatments. Treatment service life, increase in the area bounded by performance curve, or increased average pavement condition over treatment service life are widely-used measures of effectiveness (*94*). However, treatment service life has more intuitive meaning and is widely used by agencies.

The effectiveness of the initial pavement construction and of subsequent M&R activities can have a significant impact on MR&R strategy formulation. For similar traffic and climatic loadings, MR&R strategies with longer intervals between M&R activities will generally have lower total agency costs (the sum of reconstruction, rehabilitation and maintenance activities) as compared to strategies with shorter intervals. A number of studies in the past have estimated the effectiveness of different M&R treatments (*67–69*); however, relatively little effort has been made to estimate the initial performance period of newly-constructed pavements, which is referred to as the "rest period" in this study (the time from opening the newly-constructed road to traffic (or pavement reconstruction) to the time of application of the first periodic maintenance) (Figure 4.12). Also, different studies have provided time-based estimates for the design life of flexible and rigid pavements (*64,92,111*). INDOT recommends a rest period of 20 years for flexible pavements and 30 years for PCC pavements (*64*). These estimates are based on expert opinion and the personal judgment of pavement engineers.

In the present study, an analytical approach was used to estimate the rest period. Maintenance and rehabilitation treatments are commonly applied by highway agencies to extend pavement life and to improve pavement ride quality (*112*). Reconstruction is carried out when a pavement has structural deficiencies to such an extent that any maintenance or rehabilitation treatment will not be cost-effective. The effectiveness of M&R treatments can be measured by the extent to which they extend the pavement life or enhance ride quality in the short or long term (*113*). On the other hand, the effectiveness of a newly-constructed or reconstructed pavement can be estimated by determining the time from construction/reconstruction to the application of the first periodic maintenance treatment (i.e., the rest period). The effectiveness can be measured in either the short-term or the long term or can be quantified as monetized benefits or non-monetized benefits (*97*). The three commonly-used measures of long-term effectiveness (*93*) for M&R treatments are discussed briefly in the ensuing paragraphs.

Service life of reconstruction, rehabilitation, or periodic maintenance. This can be measured directly as the time elapsed between the pavement reconstruction or treatment application and the time taken to reach some threshold as shown in Figure 4.13.

Increase in average pavement performance over pre-treatment performance. This measure of long-term effectiveness has been used in a number of past studies (*93,97,114*) and makes use of increase in average asset condition upon intervention. Pre-intervention performance and average post-intervention performance can be used to estimate the increase in average pavement performance.

$$\text{Effectiveness}(\%) = 100 \times \left(\frac{\text{Initial}_{\text{Performance}} - \text{Average}_{\text{Performance}}}{\text{Initial}_{\text{Performance}}}\right) \tag{4.17}$$

This approach can be used easily for estimating the effectiveness of periodic maintenance and rehabilitation

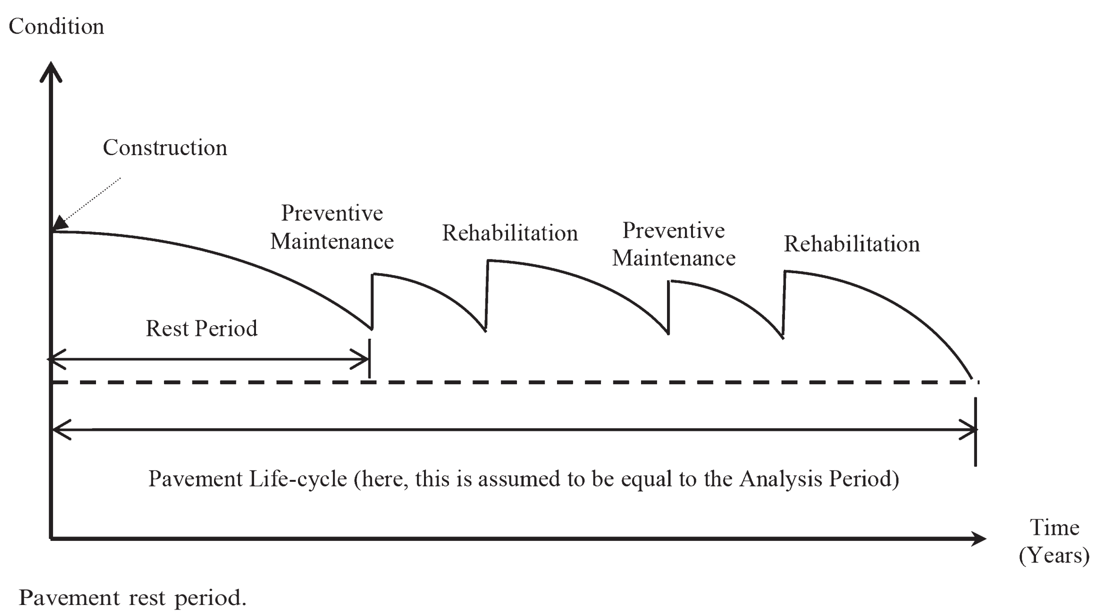


Figure 4.12 Pavement rest period.

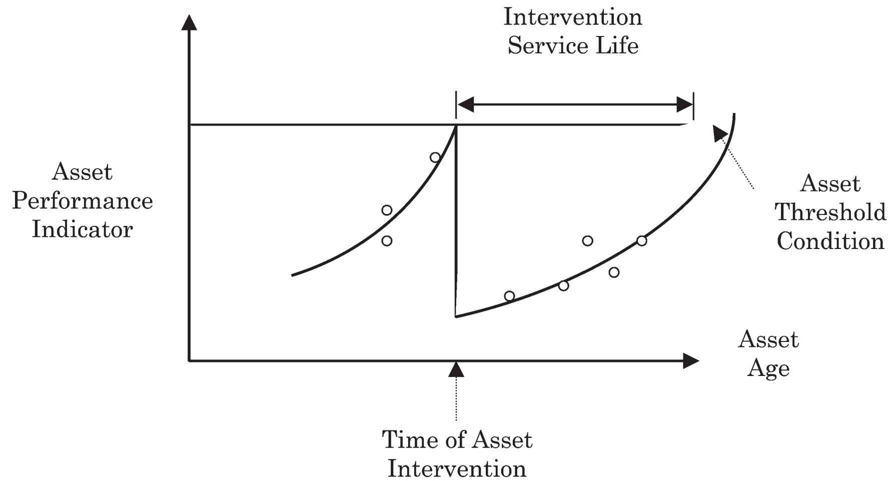


Figure 4.13 Schematic representation of intervention service life.

treatments. However, in the case of pavement reconstruction, it is inappropriate because the old pavement is removed and hence its initial condition is inconsequential. In the case of the periodic maintenance and rehabilitation treatments, the temporal span between treatment applications is relatively short and a large number of pavement segments receive this treatment type; therefore, there often are sufficient data points for model building. In the case of reconstruction, not only is the temporal span between two reconstructions activities long, but also relatively few assets are reconstructed every year.

The area bounded by the performance curve (ABPC). This is another measure for evaluating the long-term effectiveness of pavement intervention that combines the benefits of both service life and an increase in average pavement condition over service life (*93,114,115*) (Figure 4.14). ABPC can be used as a surrogate for the overall intervention benefits, which are difficult to otherwise quantify, such as reduced travel time, enhanced safety and reduced vehicle operating cost (*88,115,116*).

Every agency has an important task of establishing guidelines for pavement M&R. Having proper pavement M&R guidelines help in selecting the proper treatments for both flexible and rigid pavements. Also, agencies need to have quality data for asset intervention effectiveness analysis. Where data are available, it is possible not only to estimate treatment service life for different rehabilitation and preventive maintenance treatments, but also to estimate the rest period for newly-reconstructed pavements. This study makes use of the intervention service life as the measure of effectiveness.

Information on the treatment service life and the rest period can help in the formulation of pavement MR&R strategies for various agency tasks, including PDC estimation. A number of studies have been carried out in Indiana and elsewhere in the U.S. (in the last two decades) where efforts have been made to estimate the treatment service life. Information on the treatment service life can help to approximate how on average different treatments will withstand specific prevailing traffic and climatic loading. In the present study, pavement strategies were formulated for Indiana using

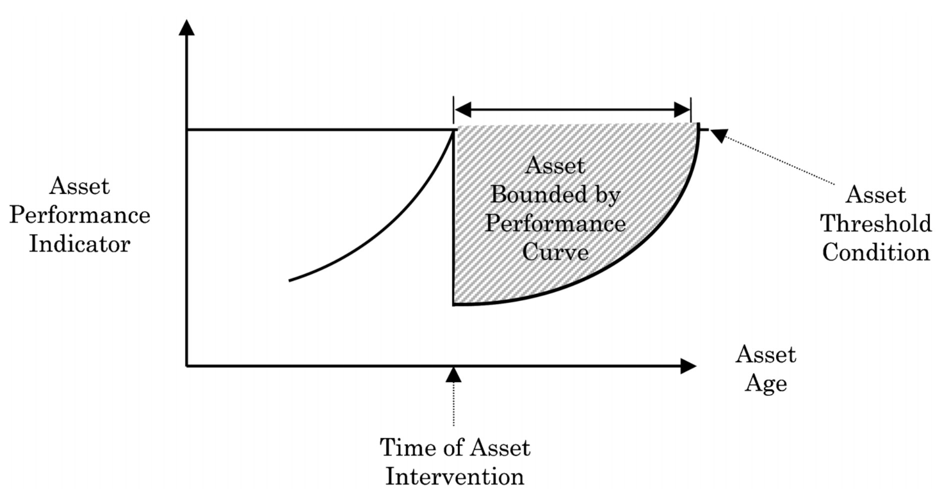


Figure 4.14 Schematic representation of area bounded by performance curve.

the treatment service lives developed for Indiana or recommended by INDOT. Treatment service life values of rehabilitation and preventive maintenance treatments used by INDOT have been estimated in the recent past (*69,88,97,117*). For treatments where there are insufficient data, certain guidelines have been provided by INDOT (*64*) based on historical record. The results from these studies are summarized in Table 4.12.

4.4.4 Collection of Historical Cost Data for MR&R Intervention

For pavement life-cycle costing and prioritization, it is necessary to have a fair estimate of the agency cost of different pavement treatments. Agency cost is the direct cost of labor, equipment and material that is incurred by the road agency in reconstruction, rehabilitation, or maintenance, implemented in-house or by contract.

In past studies, the agency cost has been estimated using one of two broad approaches as shown in Figure 4.15: (1) a disaggregate approach where unit prices are assigned to individual components of the work activities on the basis of the historical average costs of these individual pay items; and (2) an aggregate approach which uses either an average value, such as dollar per unit dimension or cost models which express the total cost as a function of the asset length, width, area, or condition (*63,92,118*). These two broad approaches for cost estimation are shown in Figure 4.15.

For pavement planning purposes and life-cycle cost analysis, the use of average costs (dollars per unit mile) can provide satisfactory results. Average costs have been used in a number of past studies for different rehabilitation and preventive maintenance treatments. In 2002, the Washington State Department of Transportation (WSDOT) conducted a survey for highway construction cost comparison using data from 25 states and estimated the average highway construction costs in units of $/lane-mile (*119*). That study found that the construction cost of a single lane-mile of highway varies between $1million and $8.5 million (*119*). A similar study was carried out by Collura et al. (*120*) to estimate the service life and cost of M&R treatments used on local roads in Massachusetts and other parts of New England; the cost of overlay was estimated as $30.36/ton of material. A FHWA study (*121*), using data from different states, established estimates for pavement widening and construction projects separately for rural and urban areas and found that the construction cost of one lane-mile of a typical four-lane divided highway ranged from $3.1 to $9.1 million. Lamptey et al. (*92*), using data from the INDOT Contracts Division, estimated the cost in $/lane-mile of various rehabilitation and preventive maintenance treatments.

Recently, Irfan et al. (*118*) investigated the functional relationships between treatment cost and project attributes. Using road functional class, highway location, year of the treatment, project size, treatment intensity, and asset condition prior to the treatment as explanatory variables, that study developed separate cost models for Interstate, NHS (NIS), and NNHS systems and showed that project size, number of lanes, and initial condition at the time of the preservation treatment had significant influence on treatment costs.

TABLE 4.12
Treatment Service Lives for Rehab and Maintenance Treatments

			Other Indiana Studies	
Treatment	**Treatment Type**	**INDOT**	**Avg. SL**	**Range of SL**
Flexible rehabilitation	New construction	20	—	—
	HMA overlay, structural	18	11	6–18
	HMA overlay, functional	15	12	6–14
	Resurfacing (partial 3R standards)	—	11	7–19
	Mill full-depth and asphalt concrete overlay	—	9	7–14
Flexible preventive maintenance	Thin HMA overlay	9	9	7–14*
	Microsurfacing	8	7	5–9
	Seal coat (chip seal)	4	5	—
	Asphalt crack seal (route and seal)	3	3	—
Rigid rehabilitation	New construction	30	—	—
	Repair PCCP & HMA overlay	15	14	10–19
	PCC overlay of PCC pavement	25	22	17–25
	Crack and seat PCCP and HMA overlay	15	18	14–20
	Rubblize PCCP and HMA overlay	20	13	10–16
Rigid preventive maintenance	HMA overlay, functional	12	—	—
	PCCP patching	—	10	8–14
	Crack seal	—	4	—
	Concrete pavement restoration (CPR) techniques	6	—	—
	PCCP patching	8	—	—

*Source: (*64,69,88,97,117*).

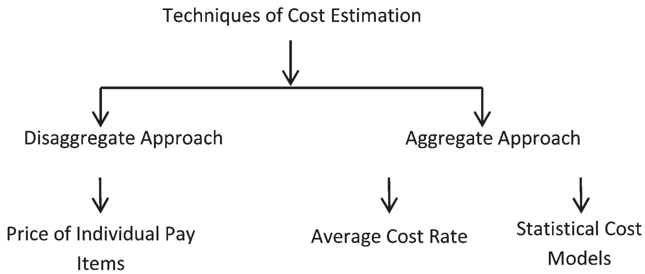


Figure 4.15 Techniques for cost estimation.

In this study, the focus is on estimating how much damage, on average, each vehicle causes to the pavement structure. Therefore, it is more appropriate to use the average cost (cost/lane-mile) as it can provide a superior representation of actual highway agency spending on a lane-mile of a pavement segment.

4.4.5 Historical Traffic Data and PDC Estimation

AADT, the average daily number of vehicles passing a specific road segment, is obtained by dividing the total yearly vehicle traffic volume by 365 days (total number of days in a year). Indiana has 114 continuous traffic counters (CTC) all over the state that collect traffic speed and volume 24 hours a day throughout the year. Of the 114 CTC sites, 50 are equipped with weigh-in-motion (WIM) technology to collect truck weight data. There is also a coverage count program that operates on a three-year cycle: one third out of a total of 30,000 count locations are covered each year through this program. At coverage count locations, at least 48 hours of traffic data are collected and subsequently used to estimate AADT using different adjustment factors developed through CTC (axle, week-day, and seasonal). INDOT classifies all vehicles into 13 different vehicles classes (Scheme F), depending upon the axle spacing and number of axles. All vehicles from Classes 4 through 13, as per the FHWA classification system (Part II Appendix E), are counted as commercial vehicles (*122*). For purposes of MR&R strategy formulation in this study, the traffic loading was calculated using the most recent AADT and the Truck AADT's.

4.4.6 Parameters Involved in Highway Pavements MR&R Strategy Formulation

4.4.6.1 Pavement life-cycle length. Pavements are designed and constructed for providing service for a long period of time. There is hardly any occurrence where a highway is constructed and subsequently abandoned. Like most other civil structures and facilities, it can be assumed that highways are built to provide land transportation services for an infinite time period even if it needs to be rebuilt successively after reaching its design life. After construction, there are a number of activities that are performed to ensure that the highway pavement continues to provide reasonable serviceable conditions, including rehabilitation, periodic and routine maintenance, and reconstruction. Service life, a concept that depends on the context in which it is used, can be defined generally as the time elapsed between the treatment application and the time when the pavement condition reaches some threshold or the time interval between applications of successive treatments with the subsequent treatment often at the same or a higher level. With regard to construction life-cycle, service life can be defined generally as the time between highway construction and its reconstruction or the time between two consecutive reconstructions. It can be considered as the aggregation of the rest period and the service life of different individual rehabilitation and periodic maintenance treatments that are applied during the remaining life (*92*) (Figure 4.16).

When different M&R strategies are formulated for either life-cycle cost analysis (LCCA), estimation of PDC, or carrying out sensitivity analysis for any of the factors affecting the total cost of competing M&R strategies, the analysis period should be of sufficient length to accommodate all representative activities (rehabilitation and periodic maintenance) needed to maintain the pavement at a reasonable level of service. FHWA also recommends that the analysis period for economic efficiency analysis should be sufficiently long

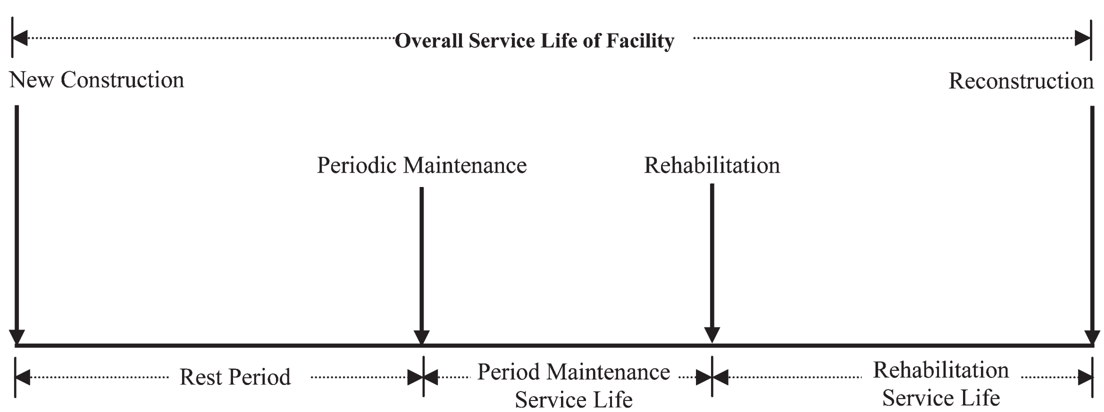


Figure 4.16 Pavement life-cycle illustration.

to reflect the long-term cost differences between competing alternatives (*90*). FHWA recommends that the selected analysis period should include at least one rehabilitation activity and should be at least 35 years. However, the analysis period may range between 30–50 years depending upon the time of application of the rehabilitation activity (*90,123*).

Dickey and Miller (*124*) recommended trade-off analysis between two considerations while selecting an appropriate analysis period: (1) a long analysis period is considered appropriate for highway facilities as these are intended to serve many future generations and may last for over hundred years; and (2) an excessive analysis period becomes inappropriate when the effect of the discounted facility rehabilitation and maintenance cost overwhelms the facility construction cost.

Sinha and Labi (*63*) emphasized that the factors that should be given due consideration while selecting the analysis period are: (1) length of the service life (project type); (2) nature of the regional or national economy (stable or fluctuating economic trends); (3) forecast of uncertainties; (4) rate of technology change; (5) social discount rate and its stability; and (6) likelihood of construction/implementation delays.

When the different MR&R strategies formulated for flexible and rigid pavements have different analysis periods, the equivalent uniform annual cost (EUAC) is the most appropriate economic efficiency criterion (*63*). However, when the overall analysis period for different MR&R strategies is the same, but individual treatments have different service lives, there are some alternatives that may have residual value at the end of analysis period, which must be accounted for in monetary value (*63*). For LCCA, INDOT recommends that analysis period should preferably be 50 years and should include at least one rehabilitation treatment (*64*).

4.4.6.2 Remaining service life. Remaining service life (RSL) is the additional time period during which a highway facility can provide reasonable service at the end of analysis period (*64*). MR&R strategies should be evaluated over an equivalent analysis period so that the cost comparison is fair. It is possible that when MR&R strategies are formulated, some of the strategies will have service lives that will exceed the designated service life, which is termed as RSL. Failing to account for RSL may result in biased evaluations. A graphical representation of RSL is shown in Figure 4.17.

From Figure 4.17, it is clear that at the end of the analysis period, there can still be some remaining useful service life due to the last rehabilitation. To calculate the RSL, a straight line function may be used from the time of application of the rehabilitation until the end of its expected useful life. RSL is added as a negative cost in calculating the total net present value (NPV) of all MR&R activities during the analysis period. There is a difference between RSL and salvage value: Salvage value is the actual value realized from the sale or reuse of recovered material at the termination or removal of a transportation facility from service; RSL is obtained at the end of the analysis period when the facility is still in operation (*63,125*).

4.4.6.3 Discounting and inflation. The cost and benefits occurring at different points in time during the service life of a MR&R strategy should be compared only after accounting for the opportunity cost. The value of money erodes over time due to the combined impact of inflation and opportunity cost. Inflation is defined as an increase in the prices of goods and services with time or a general trend of higher prices of goods with time. Opportunity cost is the economic return or income that is not earned in some future year by deciding not to invest in the current year (*63,125*).

In formulating MR&R strategies and carrying out subsequent economic analysis, all the future costs and benefits of a project should be expressed in constant dollars using price indices and then discounted to a base year (year 0) using a real interest rate in order to account for the effects of inflation. FHWA (*125*) states that public-sector projects benefits should depend upon

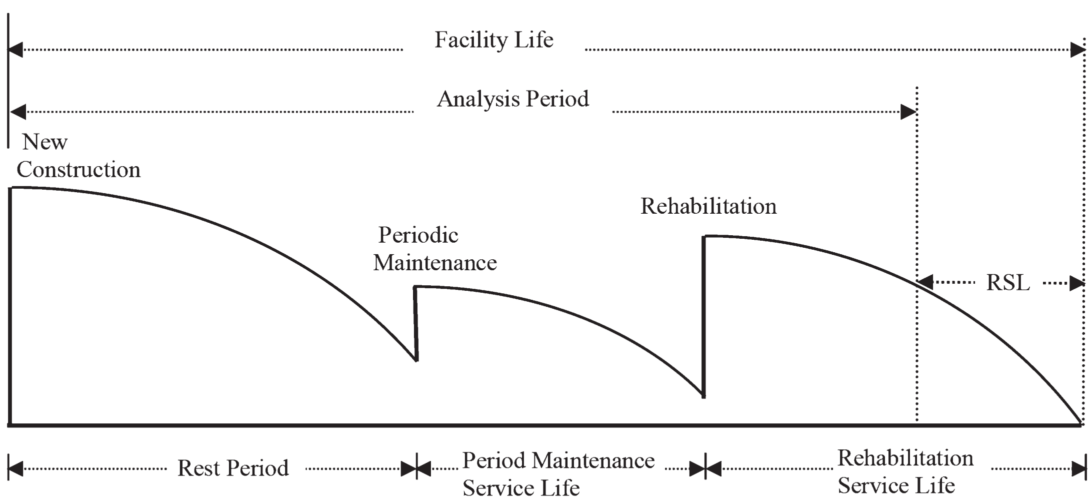


Figure 4.17 Remaining service life calculation.

real gains only (cost saving), and not on purely price effects. Walls and Smith (*90*) and Sinha and Labi (*63*) argue that since all benefits and cost of different alternative MR&R strategies will be equally affected by inflation, therefore it is a reasonable assumption to ignore the impact of inflation.

FHWA recommends the use of a real interest rate in the range of 3–5%. INDOT recommends a 4% real rate of interest, but also emphasizes that sensitivity analysis should be carried out for different interest rates in the 0–10% range to observe the impact of varying interest rate (*64*).

4.5 Chapter Summary

This chapter explained the general framework developed and used in this study for PDC estimation. The steps were explained in detail, with the exception of the pavement life-cycle M&R profile, the MR&R strategy formulation, and the actual model estimation; these are discussed in detail in Chapter 5. An important part of the framework is the definition of all costs associated with pavement damage so that all pavement-related expenditures can subsequently be accounted for and appropriately allocated to users. Also, the prevailing agency maintenance practices, specifically, the types of pavement preservation and their effectiveness, costs, and application timing criteria are key aspects of the framework. The framework also uses detailed traffic and cost data information to help mimic realistic practices of MR&R and their influence, among other factors, on pavement damage.

5. ESTIMATION OF MARGINAL PAVEMENT DAMAGE COST ON THE BASIS OF FORMULATED MR&R STRATEGIES

5.1 Introduction

The framework for MPDC estimation was discussed in Chapter 4 of this study. In the present chapter, the applicability of the developed framework is demonstrated using data from in-service pavements in Indiana. The chapter begins with a discussion of the pavement families, standard maintenance and rehabilitation treatments in the state, treatment cost and traffic data, and the effectiveness of the treatments that comprise the M&R activity profiles. This chapter discusses results of the cost vs. usage models that used data generated from the formulated strategies and shows how the MPDC were derived from the cost vs. usage models.

5.2 Pavement Families for this Study

In this study, pavements were classified on the basis of their surface type and functional classes (Figure 5.1), which is consistent with past studies in Indiana that classified pavements on the basis of surface type (flexible and rigid) and functional class (Interstate, NHS (NIS), and NNHS) (*92,97*). For consistency with

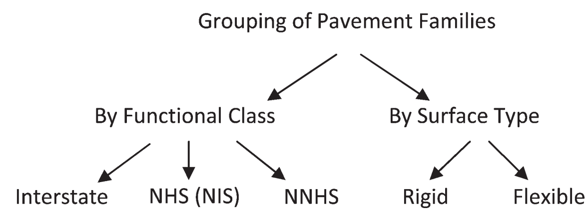


Figure 5.1 Pavement families considered in this study.

INDOT Life-Cycle Cost Analysis (LCCA) policy, composite pavements were not considered as a separate class (*64*). The M&R profiles for each life cycle and MR&R strategies comprising multiple life cycles, were established for each pavement family as shown in Figure 5.1. Further details of sub-grouping based on traffic loading are discussed in subsequent sections.

5.3 Maintenance and Rehabilitation Treatments Considered in this Study

The routine and periodic maintenance and rehabilitation treatments for flexible and rigid pavements considered in this study's MR&R strategy formulation, are discussed below.

5.3.1 Flexible Pavement Treatments

For flexible pavements, following routine and periodic maintenance and rehabilitation treatments were considered:

- **Crack Sealing:** Crack sealing is the placing of specialized material into the working cracks of an asphalt pavement to prevent the water from entering the pavement structure, thus extending the pavement service life. This is a routine pavement maintenance activity that is carried out by most highway agencies. INDOT recommends that crack sealing should be carried out when surface cracks are of low-to-moderate severity, irrespective of the AADT levels (*64,98*).
- **Chip Sealing:** Chip sealing is a preventive maintenance technique used to reduce the rate of pavement deterioration. The treatment is applied to the entire pavement surface using a combination of hot asphaltic cement and coarse aggregate. First, the asphalt emulsion is sprayed on the prepared surface, followed by the spreading of a thin layer of crushed stone. INDOT recommends this treatment for application to pavements that have low-severity environmental cracking and AADT less than 5,000. Chip sealing can help in reducing the aging and oxidation of pavement as well as reduce raveling (*64,126*).
- **Thin Hot-mix Asphalt (HMA) Overlay:** This treatment is used as a non-structural preventive maintenance treatment for reducing the rate of deterioration of a pavement structure. This treatment, which is suitable for pavements with low-to-moderate cracking, can help reduce aging and oxidation, restore a raveled surface, and help address problems of rutting, surface defects, skid resistance, road-tire noise, and drainage (*64,88,98,127,128*). The overlay is placed in thin lifts ranging from 12.5 mm (0.5 in.) to 37.5 mm (1.5 in.) and adds little to pavement structural capacity (*129*). Thin HMA overlays are

considered a cost-effective method of preserving and maintaining flexible pavements. The design of a thin HMA overlay generally depends on the expected traffic volume and purpose for which it is being used. This treatment is applied to all classes of highways irrespective of traffic volume (*64,98*).

- **Microsurfacing:** This treatment involves a mixture of dense-graded aggregate, asphalt emulsion, water, and mineral fillers used as preventive maintenance for asphalt pavements. It can increase skid resistance, provide color contrast, repair slight to moderate surface defects, reduce aging, oxidation, and minor raveling (*64,98,130,131*). Microsurfacing can be applied to any road for quick friction-restoration treatment, irrespective of traffic volume. Microsurfacing is resistant to cracking in the winter months and rutting and shoving in the summer and can be applied in a broad range of temperature and weather conditions. Therefore, it can assist in lengthening the paving season. Also, microsurfacing has low energy requirements and is relatively environmentally safe (*131*).
- **Functional HMA Overlay:** This treatment is used to restore the pavement condition on structurally-sound pavements. It consists of an intermediate course and a surface course (*64*) but is non-structural and contributes little to the pavement structure. The treatment improves ride quality, enhances appearance, reduces road tire noise, corrects minor surface defects, and improves skid resistance (*132*).
- **Structural HMA Overlay:** This treatment is designed to add structural support to an existing pavement. It consists of a base course, an intermediate course, and a surface course that are placed after milling the existing pavement. This rehabilitation treatment not only strengthens the existing pavement but also restores smoothness (*64*).
- **Mill Full-Depth and Asphalt Concrete (MFD & AC) Overlay:** This is a rehabilitation treatment where the existing pavement surface is milled to remove the top distressed material and overlaid with asphalt concrete. A milled surface also ensures that the new layer of asphalt concrete is laid to the same level of the curb as that of the pre-milled pavement (*133*).
- **Resurfacing over Existing Asphalt Pavement (Partial 3R):** Partial 3R rehabilitation treatment involves the placement of a new surface on an existing pavement to improve serviceability. This treatment does not involve alignment work; therefore, the construction standards are not equivalent to the 3R/4R standards. Also, road widening, modernization or significant facility upgrade are excluded from Partial 3R. The primary focus is to restore the road surface condition, but rehabilitation contracts may also include incidental work such as curbs, drains, shoulders, guardrail improvement, minor lane and shoulder widening, and minor alterations to vertical grades and horizontal curves (*65,88*). Thus, the cost of Partial 3R projects may partially include costs other than the main work on the pavement.

5.3.2 Rigid Pavement Treatments

For rigid pavements, the following routine and periodic maintenance and rehabilitation treatments were considered in this study:

- **Crack Sealing:** This treatment involves significant preparation of any existing cracks, followed by application of high quality sealant into or on top of the crack. This treatment reduces water infiltration into the pavement and protects cracks from intrusion of incompressible material. The entry of incompressible material into cracks can hinder slab expansion that could lead to blowups or buckling of PCC slabs. Also, sealing reduces the amount of water entering the pavement structure as water may cause pumping, reduced support, and corner breaks. Crack sealing is recommended for transverse or longitudinal cracks of low-to-moderate severity and widths smaller than 0.5 in. (*134*).
- **Cleaning and Sealing of Joints:** Joint resealing consists of routing (sawing to remove the old sealant and to reshape the joint seal reservoir), followed by cleaning and sealing of the joint. INDOT's Pavement Design Manual recommends that contraction and longitudinal joints be inspected periodically, particularly for pavements that are eight to ten years old, so that cleaning and sealing of required joints can be carried out when needed. Where a PCCP inspection shows over 10% of joints having loose, missing, or depressed sealant, the pavement is considered a candidate for joint cleaning and sealing. This preventive maintenance technique prevents the entry of water and incompressible material into pavement joints (*64,134*).
- **Concrete Pavement Restoration (CPR):** This treatment is a set of corrective and preventive maintenance techniques to restore the condition of a moderately distressed PCCP. CPR techniques that are used to repair isolated areas of deterioration in a rigid pavement include diamond grinding, full-depth repair, partial-depth repair, slab stabilization, load-transfer, retrofitting of concrete shoulders, retrofitting of edge drains, dowel bar retrofit, and joint resealing. CPR techniques are used to address a variety of PCCP distresses that include corner deflection, edge distress, faulting, load transfer problems, pumping, bumps, and profile defects. CPR techniques help improve pavement rideability, driving comfort, and structural integrity and also restore deteriorated portions and thus extend pavement life (*106*).
- **Repair PCCP and HMA Overlay:** This is a PCCP rehabilitation technique involving either partial-depth or full-depth patching of a deteriorated pavement segment, followed by an HMA overlay. In the case of partial-depth patching, the slab is not removed to its full depth; in the case of full-depth patching, the entire slab is removed and replaced. Repaired PCCP could receive either a structural or non-structural overlay depending upon the level of pavement deterioration (*97,134*).
- **PCC Overlay of Existing PCC Pavement:** This treatment involves placing a PCC overlay on an existing deteriorated PCCP in order to restore the pavement structural capacity. PCC overlays are a suitable option for all types of rigid pavement designs including jointed plain cement concrete pavements (JPCP), jointed reinforced cement concrete pavements (JRCP), and continuously reinforced cement concrete pavements (CRCP). PCC overlay can be used either as a relatively thick unbonded PCC overlay of 5–12 inches or a relatively thin bonded PCC overlay of four-inch thickness. Unbonded overlays are used for badly deteriorated pavements without removing the original pavement, while bonded overlays are used for relatively less-deteriorated pavements (*135,136*).

- **Crack-and-Seat PCCP and HMA Overlay:** This rehabilitation technique is used for a badly deteriorated PCCP pavement with the purpose of minimizing reflective cracking. Cracking and seating of the existing slab into smaller sections minimizes slab movements at joints and cracks, thus preventing reflective cracking on an HMA overlay. Using mechanical means, the PCC slab is broken down into approximately one to three sq. ft. pieces. Then, the broken PCC slabs are seated using pneumatic rollers and overlaid with HMA (*66*).
- **Rubblize PCCP and HMA Overlay:** In this PCCP rehabilitation technique, a badly deteriorated rigid pavement is reduced completely using a resonant pavement breaker or multi-head breaker to yield a base aggregate, which is then overlaid using HMA. The reduction of the slab into aggregate virtually eliminates the incidence of reflective cracking. A recent study in Alabama found that rubblization is an effective rehabilitation technique for an aged concrete pavement (*66,137*).

5.4 Treatment Costs

For estimating the costs of the MR&R strategies, this study used the unit cost of the different asset interventions. The unit costs ($/lane-mile) for road reconstruction, routine and periodic maintenance, and rehabilitation treatments were calculated for Interstates, NHS (NIS), and NNHS, for flexible and rigid pavements. Data were collected from the contract data file in INDOT's database, which included contract ID, total agency cost, date and year of construction, fiscal year of contract, length (in miles), number of lanes, surface type, functional class, etc. for all projects undertaken during 2001–2006. Cost data were collected for crack sealing, microsurfacing, thin HMA overlay, functional HMA overlay, structural HMA overlay, resurfacing (Partial 3R), mill full-depth and AC overlay, and reconstruction for flexible pavements. For rigid pavements, cost data were collected for pavement cleaning and joint sealing, CPR technique, functional HMA overlay, repair PCCP and HMA overlay, PCC overlay on PCC pavement, crack-and-seat PCCP and HMA overlay, and rubblize PCCP and HMA overlay. Where the database entries indicated the functional class of the project, the unit costs ($/lane-mile) were calculated separately for all of the three functional classes; and where records were not available separately for each functional class, the same unit cost was used across the functional classes. All costs were brought to their equivalent 2010 constant dollar values using FHWA's construction price indices (CPI) as follows:

$$C_{AY} = C_{BY} \frac{CPI_{AY}}{CPI_{BY}} \tag{5.1}$$

Where: C_{BY} and C_{AY} = cost of the treatment in the analysis and base years, respectively; CPI_{AY} and CPI_{BY} = construction price indices in the analysis and base years, respectively.

The cost for road reconstruction, rehabilitation, and routine and periodic maintenance treatments in $/lane-mile for the three functional classes are presented in Tables 5.1 through 5.5.

5.5 Traffic Data Collection and Collation

5.5.1 Traffic Estimates for MR&R Strategy Formulation

For this study, traffic (AADT) data were obtained for 6,265 road segments on Indiana's road network. The most recent traffic volume estimates covering the entire state, from year 2007, were updated to the analysis year (2010) using yearly adjustment factors provided by INDOT (Part II Appendix F). Since trucks are the major focus of this analysis, truck AADT was estimated separately. The summary statistics of the AADT and truck AADT for the three functional classes are provided in Table 5.6.

This study used FHWA's 13-vehicle classification system. In this classification system, trucks are placed in nine classes (class 5 to class 13). Data on truck traffic composition (percentage of truck for each class) were obtained from 38 WIM stations on the Indiana state highway network (twenty-five on Interstates, seven on NHS (NIS), and six on NNHS). These data were collected during the months of March and April of 2011. The summary of the truck traffic composition data is presented in Table 5.7 and is further explained graphically in Figure 5.2. It can be noticed that each of the highway functional classes are dominated by class 5 (two-axles, single unit trucks) and class 9 trucks (five-axles, combination trucks). On Interstates, approxi-

TABLE 5.1
Average Agency Costs of Flexible Pavements Treatments—Interstate

Treatment Type	Unit Cost ($/Lane-Mile)—2010 Constant $				Sample Size
	Mean	Minimum	Maximum	Std. Dev.	
Thin HMA overlay	$94,907	$46,737	$180,340	$47,689	10
Microsurfacing	$22,380	$15,525	$27,424	$6,153	3
Crack sealing	$2,815	$240	$14,463	$3,094	17
Chip seal (seal coating)	$8,131	$2,534	$19,051	$9,458	3
Functional HMA overlay	$89,481	$47,824	$409,619	$93,376	14
Structural HMA overlay	$370,412	$44,347	$2,714,978	$659,441	14
Resurfacing (partial 3R)	$152,905	$11,892	$408,182	$119,254	13
Mill full depth & AC overlay	$171,846	$17,618	$380,455	$148,257	6
Road reconstruction	$2,504,774	$517,855	$4,471,955	$1,125,679	9

TABLE 5.2
Average Agency Costs of Flexible Pavements Treatments—NHS (NIS)

Treatment Type	Unit Cost ($/Lane-Mile)—2010 Constant $				Sample Size
	Mean	Minimum	Maximum	Std. Dev.	
Thin HMA overlay	$88,107	$31,645	$206,770	$36,452	31
Microsurfacing	$39,653	$20,422	$77,905	$21,911	7
Crack sealing	$2,815	$240	$14,463	$3,094	17
Chip seal (seal coating)	$8,131	$2,534	$19,051	$9,458	3
Functional HMA overlay	$127,041	$56,667	$209,792	$46,198	31
Structural HMA overlay	$179,513	$38,096	$537,124	$156,287	21
Resurfacing (partial 3R)	$119,351	$14,125	$392,450	$69,534	160
Mill full depth & AC overlay	$171,846	$17,618	$380,455	$148,257	6
Road reconstruction	$1,706,498	$483,124	$2,469,084	$563,879	9

TABLE 5.3
Average Agency Costs of Flexible Pavement Treatments—NNHS

Treatment Type	Unit Cost ($/Lane-Mile)—2010 Constant $				Sample Size
	Mean	Minimum	Maximum	Std. Dev.	
Thin HMA overlay	$84,635	$26,840	$250,695	$38,377	100
Microsurfacing	$39,653	$20,422	$77,905	$21,911	7
Crack sealing	$2,815	$240	$14,463	$3,094	17
Chip seal (seal coating)	$8,131	$2,534	$19,051	$9,458	3
Functional HMA overlay	$125,601	$20,332	$250,378	$52,368	81
Structural HMA overlay	$207,831	$30,451	$448,338	$151,771	7
Resurfacing (partial 3R)	$102,935	$8,695	$301,676	$56,552	396
Mill full depth & AC overlay	$171,846	$17,618	$380,455	$148,257	6
Road reconstruction	$1,706,498	$483,124	$2,469,084	$563,879	9

TABLE 5.4
Average Agency Costs of Rigid Pavement Treatments—Interstate

Treatment Type	Unit Cost ($/Lane-Mile)—2010 Constant $				Sample Size
	Mean	Minimum	Maximum	Std. Dev.	
Cleaning and joint sealing	$212,847	$97,146	$36,280	$56,420	8
CPR	$150,057	$24,027	$550,022	$173,050	7
HMA functional overlay on concrete	$89,481	$47,824	$409,619	$93,376	14
Repair PCCP & HMA overlay	$491,865	$2,883	$844,367	$345,803	15
PCCP overlay on PCCP pavement	$737,585	$737,585	$737,585	—	1
Crack and seat PCCP & HMA overlay	$519,405	$117,711	$209,844	$864,941	11
Rubblize PCCP & HMA overlay	$757,057	$425,913	$1,256,176	$239,717	12
Road reconstruction	$2,793,015	$358,469	$10,665,746	$2,918,320	12

TABLE 5.5
Average Agency Costs of Rigid Pavements Treatments—Non-Interstate

Treatment Type	Unit Cost ($/Lane-Mile)—2010 Constant $				Sample Size
	Mean	Minimum	Maximum	Std. Dev.	
Cleaning and joint sealing	$212,847	$97,146	$36,280	$56,420	8
CPR	$150,057	$24,027	$550,022	$173,050	7
HMA functional overlay on concrete	$127,041	$56,667	$209,792	$46,198	31
Repair PCCP & HMA overlay	$491,865	$2,883	$844,367	$345,803	15
PCCP overlay on PCCP pavement	$737,585	$737,585	$737,585	—	1
Crack and seat PCCP & HMA overlay	$440,847	$143,415	$324,704	$1,114,233	7
Rubblize PCCP & HMA overlay	$757,057	$425,913	$1,256,176	$239,717	12
Road reconstruction	$1,902,876	$334,427	$5,888,838	$1,461,856	16

TABLE 5.6
AADT and Truck AADT—Summary Statistics (*110*)

Details	Interstate Segments		NHS (NIS) Segments		NNHS Segments	
	AADT	Truck AADT	AADT	Truck AADT	AADT	Truck AADT
Mean	45,477	10,396	12,696	1,282	4,316	402
Std. dev.	36,426	7,414	9,180	1,135	4,131	482
Minimum	3,900	243	500	17	15	10
Maximum	189,467	45,390	81,901	11,440	33,960	9,897
Total segments	**429**		**2,075**		**3,761**	

TABLE 5.7
Truck Percentage by Functional Class

Functional/Truck Class	5	6	7	8	9	10	11	12	13
Interstate	17.38	2.49	0.33	2.94	72.09	0.54	3.07	1.08	0.08
NHS (NIS)	24.53	3.34	1.57	6.06	60.61	1.53	1.25	0.58	0.53
NNHS	43.91	3.71	0.96	7.48	42.40	0.82	0.45	0.16	0.13

mately 90% trucks are class 9 or class 5. On NHS (NIS) and NNHS, 85% and 87% respectively are trucks in class 9 or 5. The next dominant classes are class 6 and 8.

5.5.2 Grouping of Pavement Families on the Basis of Traffic Loading

In addition to surface type and functional classes, pavements can also be classified on the basis of traffic volume (AADT or truck AADT). Traffic loading intensity can be measured in terms of the total number of trucks or the total ESALs sustained by a pavement section. Traffic loading affects the service life of individual rehabilitation and maintenance treatments (*97*). Generally, very high traffic levels are associated with short pavement service life.

From the summary statistics presented in Table 5.6, it can be noticed that there is wide variation in truck

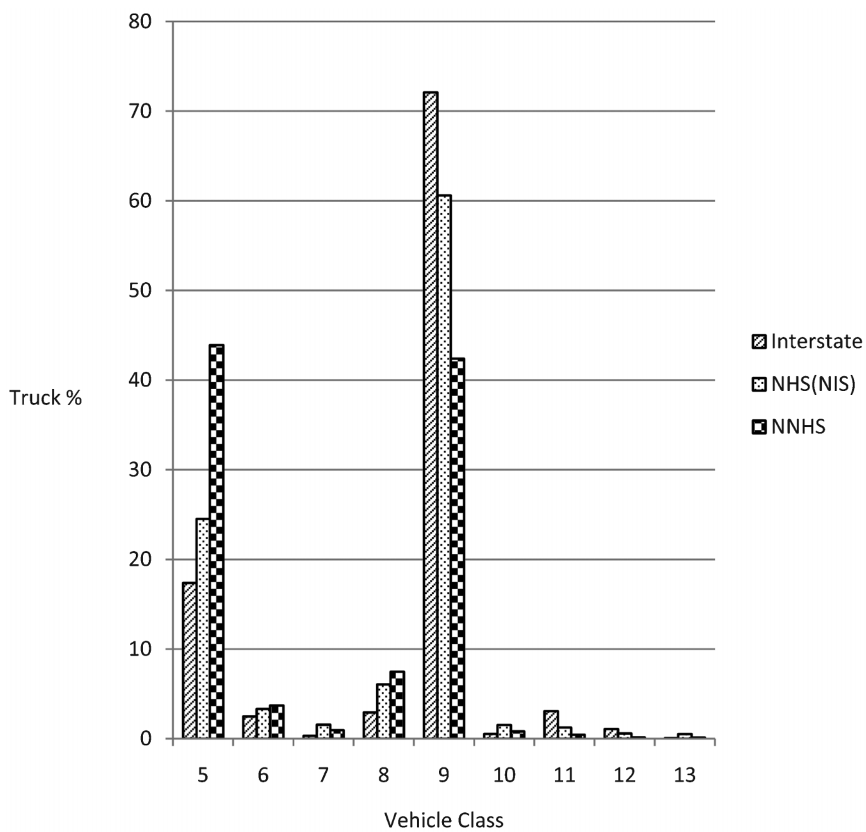


Figure 5.2 Truck traffic percentage on different highway functional classes.

traffic on the different highway functional classes in Indiana. Thus, using a single traffic volume for all MR&R strategies in each functional class will lead to bias. Thus, in this study, each highway functional class was further divided into four traffic sub-categories (very high, high, medium, and low (Table 5.8)). Sub-dividing the functional classes on the basis of truck traffic can help generate surrogate variables for pavement groups with different traffic loading levels, and thus can yield more representative estimates of MPDC.

5.5.3 Traffic Growth Factor

A correct estimation of traffic loading is necessary for reliable estimation of marginal pavement damage cost. For this study, traffic estimates were obtained from the average daily traffic and commercial vehicles interactive map provided by INDOT (*110*). For estimating the future traffic, the appropriate traffic growth factor was determined. The annual average traffic growth rates were estimated using past traffic growth trends in Indiana. Using the total traffic growth information from year 2001–2010 (*110*), the compounded annual growth rate of traffic was estimated using Equation 5.2. The compounded annual growth rate of traffic on Interstate, NHS (NIS), and NNHS was found to be, +1.227%, −0.185% and −0.510% respectively.

$$\mathrm{CAGR}(0,t_n) = \left(\frac{\mathrm{Truck\ AADT}(t_n)}{\mathrm{Truck\ AADT}(t_0)}\right)^{\frac{1}{n}} - 1 \quad (5.2)$$

Where: CAGR = Compound annual growth rate; Truck AADT(t_n) = Truck AADT in year n; Truck AADT(t_o) = Truck AADT in base year; n = number of years.

It can be noticed that the statewide traffic growth has generally remained low for the last ten years. Interstate highways have seen an increase (average 1.227% yearly traffic growth in last nine years). For NHS (NIS) and NNHS highways, the traffic volume has decreased, as indicated by their negative annual growth rate, which could be due to the economic recession in the last few years. For pavement design purposes, INDOT recommends the use of 2.8% to 3.3% as the compound annual growth rate (*64*). In view of the traffic growth pattern noted for the past ten years in Indiana, this study used a growth factor of 1.5%.

5.5.4 Road-use Measure

The selection of an appropriate road-use measure is a vital step in the estimation of MPDC. Most past studies have used vehicle-mile, mile/year, GVW-mile, and ESAL-mile. The most commonly-used road-use measure is ESAL-mile or ESAL-Km. ESAL is the ratio of the damaging effect of a non-standard axle load to that of a standard axle load (*72*). The ESAL concept helps in converting axles with different loads and configurations to a standard axle of 18 kip. Thus, the damage to pavement due to different loads (vehicles having single and multiple axles) is converted to the damage from a standard axle of 18,000 lbs. The data in the present study were obtained from the "total ESAL class by hour" monthly report generated from INDOT's WIM equipment. The estimated ESAL values for flexible and rigid pavements are summarized in Table 5.9.

5.6 Effectiveness of Reconstruction, Rehabilitation, and Maintenance Treatments

For the purpose of formulating MR&R strategies for PDC estimation, it is necessary to establish the effectiveness of different rehabilitation and periodic maintenance treatments and also to specify the rest period (i.e., when to apply the first periodic main-

TABLE 5.8
Sub-Groupings of Highway Functional Classes on Basis of Traffic Loading

Functional Class	Categories (Truck Traffic)	Truck Traffic Range	No. of Road Segments	Sub-group Truck AADT
Interstate	Very high	Truck AADT > 10,000	190	16,768
	High	10,000 > truck AADT > 8,000	57	8,694
	Medium	8,000 > truck AADT > 6,000	48	6,964
	Low	Truck AADT < 6,000	133	3,322
	Total No. of road segments		**429**	
NHS (NIS)	Very high	Truck AADT > 4,000	185	5,072
	High	4,000 > truck AADT > 3,000	163	3,378
	Medium	3,000 > truck AADT > 2,000	607	2,360
	Low	Truck AADT < 2000	1109	858
	Total No. of road segments		**2075**	
NNHS	Very high	Truck AADT > 1,000	306	1,566
	High	1,000 > truck AADT > 500	661	692
	Medium	500 > truck AADT > 250	1049	356
	Low	Truck AADT < 250	1746	120
	Total No. of road segments		**3761**	
Grand total No. of road segments			**6,265**	

TABLE 5.9
ESAL Factors for Different Highway Functional Classes

Truck Class	Highway Functional Class					
	Interstate		NHS (NIS)		NNHS	
	Flexible	Rigid	Flexible	Rigid	Flexible	Rigid
5	0.0646	0.1014	0.0638	0.1002	0.0837	0.1314
6	0.5245	0.8235	0.5765	0.9051	0.8053	1.2643
7	2.5597	4.0187	2.0927	3.2855	2.8600	4.4902
8	0.5758	0.9040	0.2741	0.4303	0.7942	1.2469
9	1.3676	2.1471	1.1658	1.8303	1.2020	1.8871
10	1.5687	2.4629	1.6285	2.5567	1.9547	3.0689
11	1.1356	1.7829	0.8341	1.3095	1.0558	1.6576
12	0.8923	1.4009	1.3460	2.1132	3.9537	6.2073
13	3.0816	4.8381	3.7477	5.8839	3.0727	4.8241

tenance treatment to a newly-reconstructed pavement). In this study, pavement performance modeling was carried out to establish the rest periods.

5.6.1 Estimation of Rest Period for Newly-Reconstructed Pavements

For establishing the rest period, separate models were developed for each pavement family using the following steps:

- **Data Collection and Preparation:** Data were collected from different sources for a number of road segments. The major data items included road inventory, pavement condition, contract information, traffic, and climate. The road inventory data provided basic information about contract identification, start and ending points, functional class, and county and district locations. Contract data from the INDOT database, which provided information on newly-(re)constructed pavements included: contract cost, fiscal and letting year, contract identification number and location, number of lanes, and length of (re)constructed pavement. Pavement condition data included the IRI. Traffic data, which included the AADT, truck AADT, and traffic growth rate for the selected pavement segments, were obtained from INDOT traffic monitoring sections (*110*). Climate data, which included the freeze index, annual number of freeze thaw cycles, average annual precipitation, and average number of wet days in a year, were obtained from INDIPAVE 2000, a database established using data from the National Oceanic and Atmospheric Administration (NOAA) database (*138*).
- **Selection of Response and Explanatory Variables:** For effectiveness evaluation, an appropriate performance indicator needed to be selected as a first step. INDOT collects data on IRI, Pavement Condition Rating (PCR), friction, and rutting. In this study, IRI was used as the performance indicator because it generally represents the road-user perception and also serves as a basis for repair decisions at many highway agencies (*139*). IRI is a measure of pavement bumpiness in terms of the number of inches/mile. IRI data are relatively inexpensive and easy to collect (*103*) and is therefore widely used for highway asset performance modeling. The explanatory variables considered for performance modeling are functional classification (surrogate variable for construction and maintenance quality), pavement age (surrogate for combined traffic and climatic loading), truck traffic, and climatic conditions.
- **Selection of Measure of Effectiveness:** The intervention service life, the increase in the area bounded by the performance curve, or the increased average pavement condition over the intervention service life, are the three most widely-used non-monetized measures of effectiveness (*97*). For rest period estimation, service life was used as the measure of effectiveness because it is consistent with the concept of a rest period. This service life gives an estimate of the time when a newly (re)constructed pavement needs a periodic maintenance in order to preserve the structural integrity of the pavement.
- **Mathematical Form:** Ordinary least square (OLS) regression was used to develop performance models for both flexible and rigid pavement. Separate models were developed for Interstate, NHS (NIS), and NNHS. The functional form of the pavement performance models developed in this study is shown in Equation 5.3. Using the developed performance models, the expected time from (re)construction of a pavement to the application of the first periodic maintenance was estimated using Equation 5.4. The results are summarized in Table 5.10.

$$y_i = EXP(\beta_0 + \beta_1 \times AATT \times t + \beta_2 \times AAFI \times t) \qquad (5.3)$$

Where: y_i is the value of the pavement performance measure (IRI) for a (re)constructed pavement segment i, in year t; AATT (t) = is the product of the annual truck traffic (in millions) and the time since the pavement was (re)constructed, thus representing the total impact of traffic on the pavement since reconstruction; AAFI (t) = is the product of the average annual freeze index (in thousands of degree-days) and the time since the pavement was reconstructed, thus representing the total impact of climate on the pavement since (re)construction; β_0, β_1 and β_2 are model parameters.

Making t the subject of the equation, it is possible to estimate the rest period for an established threshold, if the average traffic and climatic loading are known, as follows:

$$t = \frac{\ln(y_i) - \beta_0}{\beta_1 \times (AATT) + \beta_2 \times (AAFI)} \qquad (5.4)$$

This approach has been widely used in pavement performance modeling in Indiana in the recent past (*69,92,98*). Statistical Analysis Software (SAS) (*140*) was used for the model estimation, and standard model building procedures were used. The summary of the model results and estimated rest periods are presented in Tables 5.11 to 5.13.

5.6.2 Effectiveness of Rehabilitation and Maintenance Treatments

The effectiveness of individual rehabilitation and periodic/routine maintenance treatments that comprise an MR&R strategy is another evaluation variable

TABLE 5.10
Range of Treatment Service Lives for MR&R Strategy Formulation

Pavement Type	Treatment Type	Range of Service Life			
		Overall	Interstate	NHS (NIS)	NNHS
Flexible	Structural HMA overlay	7–18	7–9	10–14	15–18
	Functional HMA overlay	6–14	6–9	10–11	12–14
	Resurfacing (partial 3R)	7–15	7–9	10–12	13–15
	Mill full depth and AC overlay	7–14	7–9	10–11	12–14
	Thin HMA overlay	6–12	6–7	8–9	10–12
	Microsurfacing	5–9	5	6–7	8–9
	Chip seal	4	4	4	4
	Asphalt crack seal	3	3	3	3
Rigid	Repair PCCP & HMA overlay	10–19	10–14	15–19	
	PCCP overlay on PCC pavement	17–25	17–20	21–25	
	Crack & seat PCCP & HMA overlay	10–16	10–15	16–20	
	Rubblize PCCP & HMA overlay	10–16	10–14	15–16	
	Crack seal	3	3	3	
	CPR techniques	6–8	6	7–8	
	Cleaning and sealing of joints	8	8	8	

Source: (*64,69,88,97,117*).

TABLE 5.11
Pavement Performance Models for Flexible Pavement

Highway Class	Coefficient	Coefficient Value	t-value	P-value	R^2	N
Interstate	Constant	4.073	202.16	<0.0001	0.56	230
	AATT	0.015	5.43	<0.0001		
	AAFI	0.075	9.43	<0.0001		
NHS (NIS)	Constant	4.118	98.10	<0.0001	0.39	75
	AATT	0.102	6.81	<0.0001		
NNHS	Constant	4.092	252.80	<0.0001	0.88	103
	AATT	0.018	3.98	0.0001		
	AAFI	0.053	14.01	<0.0001		

TABLE 5.12
Pavement Performance Models for Rigid Pavement

Highway Class	Coefficient	Coefficient Value	t-value	P-value	R^2	N
Interstate	Constant	4.386	261.01	<0.0001	0.82	126
	AATT	0.015	18.82	<0.0001		
	AAFI	0.005	2.59	<0.0108		
Non-IS	Constant	4.131	249.85	<0.0001	0.85	88
	AATT	0.009	2.09	0.0394		
	AAFI	0.089	9.24	<0.0001		

TABLE 5.13
Estimated Rest Periods (Years) for Different Traffic Loads

Flexible Pavement						Rigid Pavement			
Interstate		NHS (NIS)		NNHS		Interstate		Non-IS	
Truck Traffic	Rest Period	Truck Traffic	Rest Period	Truck Traffic	Rest Period	Truck Traffic	Rest Period	Truck Traffic	Rest Period
16,768	10	5,072	10	1,566	20	16,768	10	3319	17
8,694	14	3,378	12	692	20	8,694	19	2035	17
6,964	15	2,360	17	356	20	6,964	23	1358	18
3,322	18	858	20	120	20	3,322	25	489	18

which can significantly impact the results of MPDC estimates. There has been extensive research in Indiana and elsewhere on the estimation of treatment effectiveness. The most widely-used measure of effectiveness for LCCA and MPDC estimation is treatment service life. The treatment service life for various periodic maintenance and rehabilitation treatments commonly-used in Indiana are presented in Table 4.12 in Chapter 4. For this study, different service lives of a given treatment were used for different highway functional classes (Table 5.13), depending on the intensity of traffic loading. Within a highway functional class, treatment service lives were made to vary with traffic loading (shorter treatment service lives for higher traffic loading and vice versa).

5.7 Formulation of MR&R Strategies

After establishing pavement families, collecting cost and traffic data, estimating intervention effectiveness, and selecting the road-use measure, pavement MR&R strategies were formulated. Pavement MR&R strategies were established for each functional class. For each traffic level, five MR&R strategies for flexible pavements and four MR&R strategies for rigid pavements were established. Thus, a total of 60 MR&R strategies were established for flexible pavements and 32 for rigid pavements (Table 5.14). For a given pavement segment, different MR&R strategies represent a combination of different M&R treatments over one life cycle. The traffic loading levels (very high, high, medium, and low) that were used for the MR&R strategies are the same as those presented in Table 5.8 of this study. The life-cycle M&R profiles established in this study are provided in Part II Appendix G.

For each of these pavement groups, MR&R strategies were developed over a 50-year analysis period. Figure 5.3 presents the case of a pavement segment with a 50-year life cycle. P is the initial construction cost and the cost of all other maintenance activities during the first life cycle (first 50 years of pavement life). R is the total cost during the subsequent life cycle of the pavement. The cost in the subsequent life cycle (next 50 years) is the sum of reconstruction, rehabilitation, and periodic (preventive) and routine maintenance costs. Figure 5.4 presents a typical pavement MR&R strategy, which shows that all of the pavement maintenance activities that can take place during a single life cycle, N. It is assumed that the pavement is reconstructed every 50 years (thus incurring a cost R, every 50 years) to perpetuity. Typical pavement MR&R strategies formulated in this study for flexible pavement Interstate, NHS (NIS), NNHS and rigid pavement Interstate and non-Interstate are shown in Figures 5.4 to 5.8. The remaining MR&R strategies for flexible and rigid pavements are provided in Part II Appendix G.

5.8 Calculation of Life-Cycle Costs and Traffic Loadings Using the Formulated Strategies

The MR&R strategies presented in the previous section were formulated to provide a broad but realistic picture of the actual trends of pavement maintenance expenditures and the consumption of pavements by truck loads. These strategies reflect the highway agency decision-making process typically made to address deteriorating pavements. Interstate highways generally attract higher truck traffic and therefore receive a higher frequency of treatment applications. It must be noted, however, that the high traffic volume on Interstate highways might be compensated by their superior construction standards. On Interstate highways, the deleterious effects of high traffic loads outweigh the redeeming virtues of superior design standards. This probably explains the high frequency of M&R treatment application observed at Interstate highways compared to non-Interstate highways. From the formulated strategies, the total cost and traffic experienced over the pavement life cycle were determined.

5.8.1 Estimating the Overall Cost of MR&R Strategies

For each pavement family, the cost of each MR&R strategy over a 50-year analysis period was determined. For this estimation, an interest rate of 4% was used as recommended by INDOT and FHWA (*64,90*). Figure 5.4 represents a typical MR&R strategy over a 50-year analysis period. For this pavement, the total MR&R cost over the analysis period is the sum of the reconstruction, rehabilitation and periodic and routine maintenance costs over that period. Using interest equations, the present worth (PW) of the MR&R cost can be found as follows:

TABLE 5.14
Life-Cycle M&R Profiles for Different Highway Functional Classes

Surface Type	Functional Class	No. of M&R Profiles for Each Traffic Loading Level: Very High	High	Medium	Low
Flexible	Interstate	5	5	5	5
	NHS (NIS)	5	5	5	5
	NNHS	5	5	5	5
Rigid	Interstate	4	4	4	4
	Non-Interstate	4	4	4	4

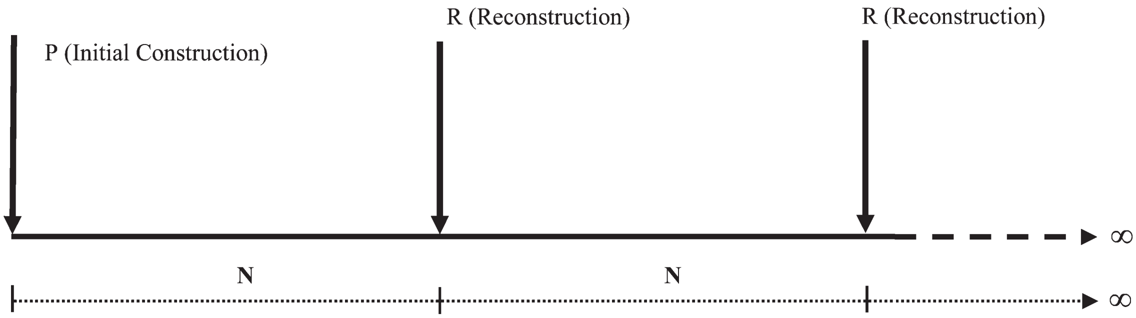


Figure 5.3 Typical MR&R strategy over an infinite analysis period.

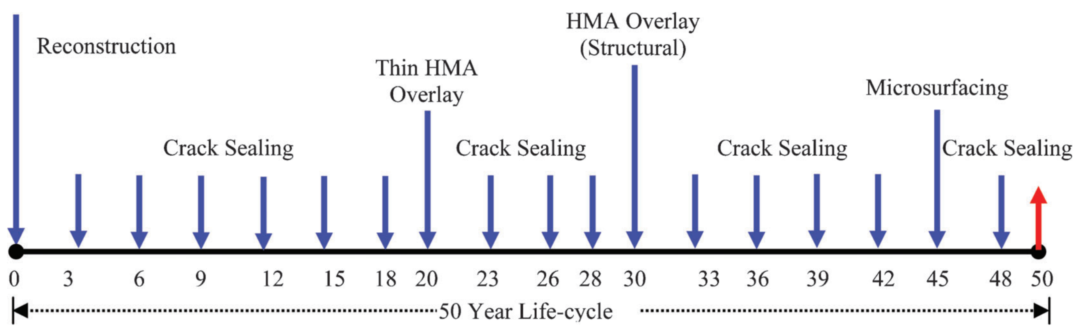


Figure 5.4 MR&R strategy—flexible pavement (Interstate).

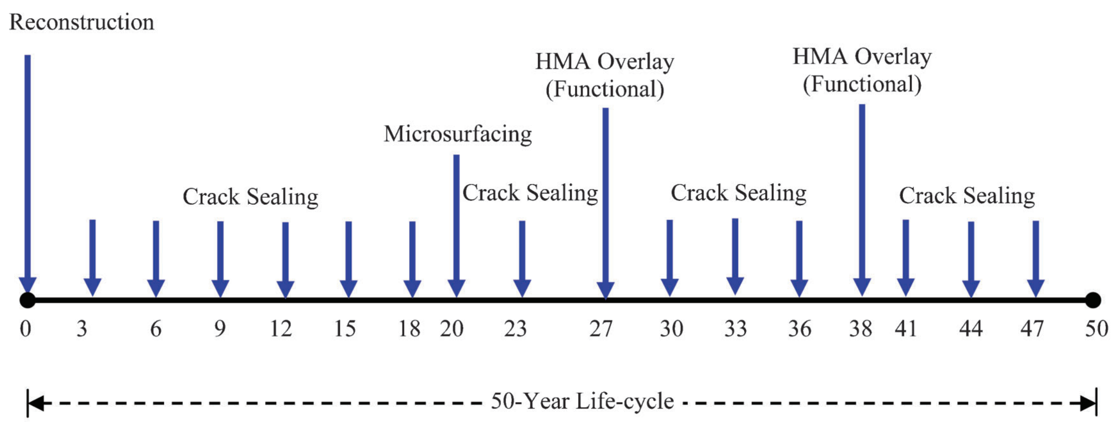


Figure 5.5 MR&R strategy—flexible pavement (NHS non-Interstate).

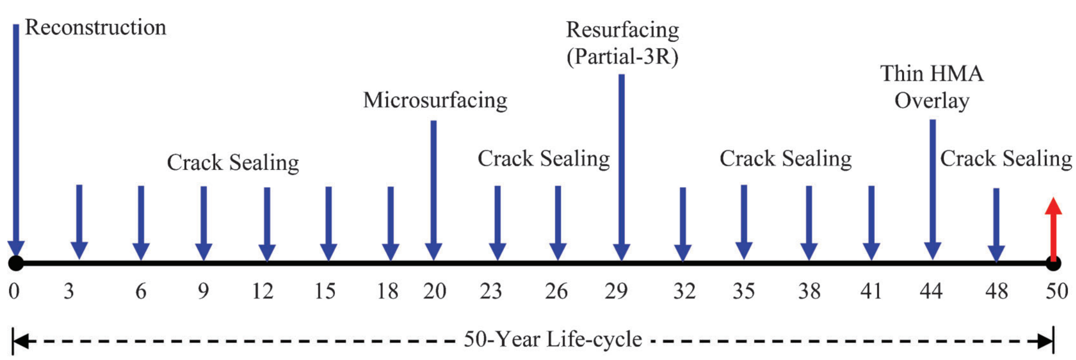


Figure 5.6 MR&R strategy—flexible pavement (non-NHS).

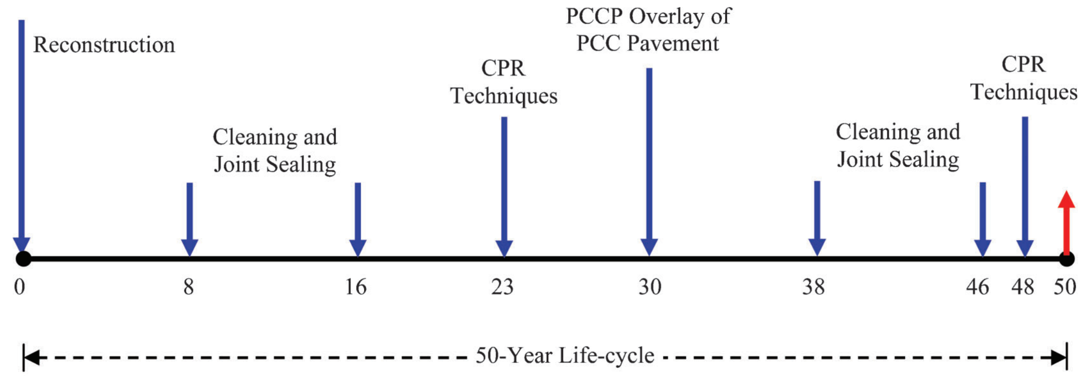


Figure 5.7 MR&R strategy—rigid pavement (Interstate).

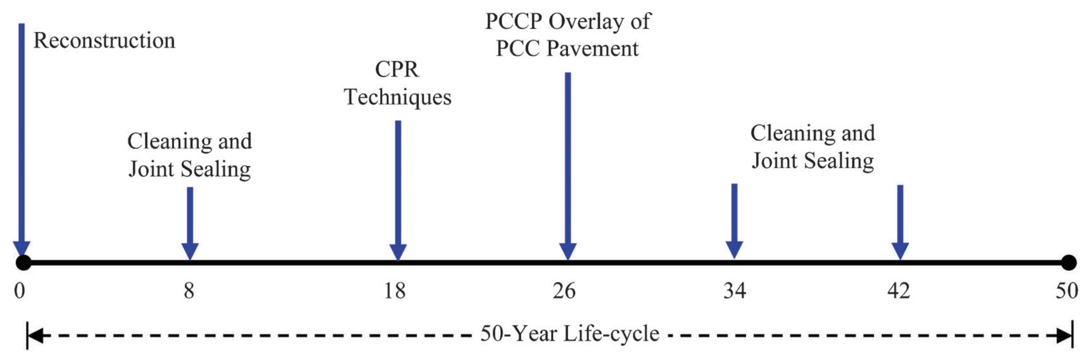


Figure 5.8 MR&R strategy—rigid pavement (non-Interstate).

$$PW(P)_{MR\&R} = R + \sum_{i=1}^{m} Rehab\left[\frac{1}{(1+r)^{t_i}}\right] + \sum_{i=1}^{m} PM\left[\frac{1}{(1+r)^{t_i}}\right] + \sum_{i=1}^{m} RM\left[\frac{1}{(1+r)^{t_i}}\right] \quad (5.5)$$

Where: $PW(P)_{M\&R}$ = present worth of total reconstruction, rehabilitation and maintenance costs of a MR&R strategy over a 50-year analysis period; r = real discount rate; t = year of application of rehabilitation, periodic or route maintenance treatment; m = number of rehabilitation, and periodic or routine maintenance applied to the pavement during the partial life cycle.

After estimating the cost of all MR&R strategy over a 50-year analysis period, the equivalent uniform annual cost (EUAC) to perpetuity is calculated as follows:

$$EUAC_{MR\&R} = \left[PW(P)_{MR\&R}\right] \times r \quad (5.6)$$

Where: $EUAC_{MR\&R}$ = equivalent uniform annual cost of MR&R strategy over a 50-year analysis period.

5.8.2 Traffic Loading Estimation for MR&R Strategies

The estimation of traffic loading was focused on the determination of the annual average number of ESALs experienced by the pavement. The ESALs estimation involved the sum of the ESALs experienced during the 50-year analysis periods. This study used a growth factor of 1.5% to estimate the total ESALs over 50-year analysis periods. The total ESALs applied to the pavement is estimated as the sum of the ESALs of individual vehicles. Thus, the ESALs for one pavement life cycle (50-year period) were estimated as follows:

$$\sum_{k=1}^{50} ESAL = Truck\ AADT * 365 * D_d * G_f * L_d * \sum_{i=1}^{L} (LEF_i * \%Class_i) \quad (5.7)$$

Where: ESAL = Total ESAL during one pavement life cycle; k = Analysis period (50-years); truck AADT = Annual Average Daily Truck Traffic; D_d = Directional distribution factor; G_f = Growth factor during the analysis period; L_d = Lane distribution factor; LEF_i = Load equivalency factor contributed by truck belonging to class i; $\%Class_i$ = Percentage of trucks in Class i; L = number of truck classes.

5.9 Pavement Damage Cost Estimation

Sixty MR&R strategies for flexible and thirty-two for rigid pavements were established in this study. Each MR&R strategy helped to generate one observation for the pavement damage cost model development. For each formulated strategy, the data and the estimated impacts include the total life-cycle cost and total life-cycle usage (loading). From the total life-cycle cost, the annualized life-cycle cost was determined. Also, from the total life-cycle loading, the annual average loading was calculated. By relating the two parameters, the marginal pavement damage cost was derived. This calculation was done for each pavement family. The various data items used for model development are presented below:

- **EUAC:** The EUAC was used as the dependent variable, and the data for this variable were obtained as the cost of the individual MR&R strategies.
- **Annual ESAL:** For each MR&R strategy, the average annual ESALs sustained by the pavements were estimated and used as one of the explanatory variables.
- **Pavement Type:** MR&R strategies were developed separately for flexible and rigid pavements. The type of pavement was represented as an indicator variable (1 if rigid pavement, 0 otherwise).
- **Number of Rehabilitation Treatments:** Each MR&R strategy had a different number of rehabilitations treatments during one full life cycle, depending on the traffic loading and pavement type. The number of rehabilitation treatments was used as one of the explanatory variables.
- **Number of Periodic Maintenance Treatments:** The frequency of periodic maintenance depends upon the traffic loading, type of pavement, and highway functional class. The number of periodic maintenance treatments during the full life cycle was simply determined from the MR&R strategy and used as an explanatory variable in the model.
- **Highway Functional Class:** Separate MR&R strategies were formulated for different highway functional classes. Therefore, the functional class was used as an indicator variable in the model.

Having generated the data for EUAC and annual ESALs experienced by the pavement, models were estimated for the marginal pavement damage cost using OLS regression techniques and SAS software (*140*) (Table 5.15). Several alternative functional forms were tested and evaluated for the model. The general functional forms of the investigated models are:

$$\text{Annualized Cost} = f\overline{(X)} \tag{5.8}$$

Where: $\overline{(X)}$ is a vector of pavement loading and other attributes such as pavement age and surface type. The functional form that was selected is:

$$EUAC_{MR\&R} = \beta_0 + \beta_1 * \ln(ESALs) + \beta_2 * PTYPE \tag{5.9}$$

Where: β_0, β_1, β_2 = Constant term and parameter estimates for model explanatory variables; $EUAC_{(MR\&R)}$ = Equivalent uniform annual cost per lane-mile of pavement segment over a 50-year analysis period; ESALs = Average annual number of equivalent single axle load per lane-mile; PTYPE = Pavement type indicator variable (1 if pavement is rigid, 0 otherwise).

The estimated model suggests that the pavement MR&R cost depends on traffic loading (average annual ESALs), and pavement type and age. The model estimates are all intuitive. The model indicates that, all else being equal, higher traffic loadings (higher number of annual ESALs) result in higher pavement repair costs. Pavements that sustain high annual traffic loadings generally have higher maintenance and rehabilitation costs. The model results show that the pavement type has a significant correlation with the pavement repair cost; namely, rigid pavements were found to have higher EUAC (MR&R) compared to flexible pavements. This is intuitive because the reconstruction cost of rigid pavements is relatively high.

The estimation of marginal pavement damage cost involves two steps: (1) estimation of a suitable EUAC (MR&R) model as a function of different explanatory variables, and (2) differentiation of the estimated model with respect to the road-use measure (ESAL). The estimated function (Equation 5.9) was differentiated with respect to annual average ESALs to obtain the marginal pavement damage cost as follows:

$$MPDC = \frac{\beta_1}{ESALs} \tag{5.10}$$

Where: MPDC = Marginal pavement damage cost ($/ESAL-mile); ESALs = Average annual number of equivalent single axle load per lane-mile.

Using the developed function, the MPDC were estimated for any highway functional class and traffic level. The average annual ESALs for three highway functional classes were calculated using available traffic data. The estimated MPDC are presented in Table. 5.16.

Overall, the marginal pavement damage cost estimates range from $0.006 per ESAL-mile on the Interstate system to $0.218 per ESAL-mile on NNHS (state route). The marginal pavement damage costs are low for NHS Interstate, but high for NNHS. These results are consistent with findings from past studies (*50,52*). The results are also consistent with those of a Louisiana study that showed that an increase in truck

TABLE 5.15
Model Estimates for PDC Estimation Using MR&R Strategy

Coefficient	Coefficient Value	t-value	P-value	R^2	N
Constant	−55,545	−3.94	<0.0001	0.74	92
ln(ESALs)	11,732	11.16	<0.0001		
PTYPE	26,318	8.19	<0.0001		

TABLE 5.16
Estimates by Highway Functional MPDC Class

Highway Functional Class	Marginal PDC in $/ESAL-mile (2010 Constant $)
Interstate	0.0072
NHS (NIS)	0.0652
NNHS	0.2559
Mean	0.1095

loading limits had a more deleterious effect on non-Interstate pavements compared to Interstate pavements (*56*). The primary reasons for this difference in unit cost include the traffic volume and design standards between lower class and higher class highway pavements. The traffic volume on Interstates is almost eight times more than that on NHS (NIS) and 25 times higher than that on NNHS. Since the Interstates have far more users, the cost of pavement damage is spread out over their broader base of users. On the other hand, the number of users on NHS (NIS) and NNHS are relatively fewer, thus resulting in a higher cost share per user.

All highway pavements are designed to carry a traffic loading that is forecast at the planning or design phase, for the design life of the pavement for rigid or flexible pavements. The major design consideration for pavement thickness is the expected number of ESALs over the entire design life. Since Interstate pavements are expected to carry higher traffic volumes (more ESALs) over their design life, these pavements have higher thicknesses and superior design standards compared to NHS (NIS) and NNHS pavements. Since the relationship between pavement thickness and traffic loading is non-linear (i.e., the pavement strength increase with the seventh power of thickness), Interstate pavements can sustain a much higher number of ESALs compared to non-Interstate pavements (*53,141,142*).

Figure 5.9 presents an overall picture of the change in MPDC with a change in the annual ESALs. When the traffic volume is low, there is reduced deterioration; however the lower cost of this damage is shared by fewer vehicles, resulting in a higher MPDC compared to a high traffic volume. When traffic levels are high, economies of scale starts to kick in, resulting in a lower MPDC. Similarly for all three functional classes, the MPDC decreases with an increase in annual ESALs. For Interstate pavements, on average, the total cost (construction plus life-cycle maintenance) per lane-mile is 1.5 times higher compared to NNHS (Table 5.17). However, (a) there are far more users of Interstates, which distributes the cost to a larger base of users, and (b) the pavement thickness on Interstate highways is greater compared to other highways, thus resulting in a lower MPDC.

In comparing marginal pavement damage costs across the different highway functional classes, another point of consideration is the average GVW vs. the average ESALs for different vehicles. If the GVW of trucks on Interstates highways is considerably higher than the GVW of trucks on non-Interstates, then the total ESALs generated on Interstates highway will be higher, resulting in a lower MPDC (since the cost will be spread out to more users). To illustrate this point, consider a hypothetical scenario in which both an Interstates highway and a state route each carry 2,000 trucks per day. Trucks moving on these two different highway systems have the same configuration but higher loads are allowed on the Interstate compared to the state route. Trucks carrying heavier loads on Interstate translate into higher number of ESALs. Assume that each truck on the Interstate generates 3 ESALs, while each truck on the state route generates 2 ESALs. If traffic remains constant, then the Interstate and state route will approximately sustain 109.5M and 73M ESALs, respectively, over the 50-year life cycle. This shows that the total ESALs on the Interstate are about 1.5 times the ESALs on the state route. As the total 50-year spending on Interstate is about 1.5 times higher than state highway (Table 5.17), the impact of additional ESALs on Interstates is offset. Consider a similar hypothetical scenario in which the GVW limits are the same as the Interstate and state highway systems. In that case, the same total number of ESALs will be generated on both highway types, assuming the same annual traffic. Since the total spending during one life cycle (50 years) on the Interstate highway is greater than the spending on the state route, the former will have a higher MPDC.

In this study, the average truck traffic and GVW were used for different highway functional classes for MPDC estimation. The GVWs for different vehicle classes are graphically shown in Figure 5.10. For each truck class, there is no marked difference in truck GVW across the highway functional classes; therefore, the average ESALs generated in each class is expected to be approximately the same across the highway classes. When the individual vehicles have the same average ESALs for different highway functional classes, then the deciding factors for MPDC are the total truck

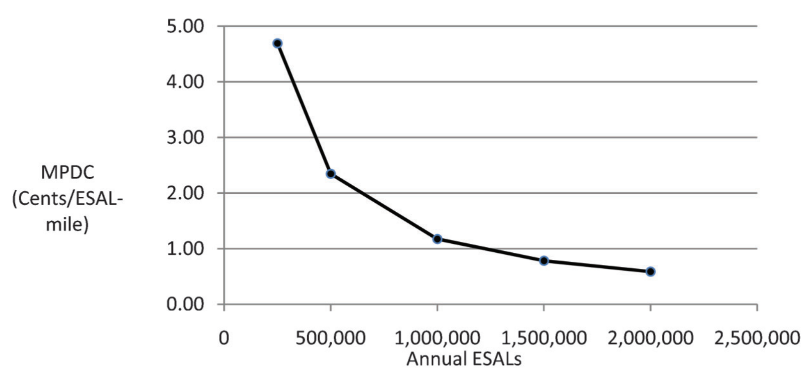


Figure 5.9 Variation of MPDC with ESALs.

TABLE 5.17
Summary of Average Cost Data for Pavement Life Cycle

Route Type	Present Worth of MR&R Cost for 50-Year Life Cycle ($2010)					EUAC ($2010)
	Total	Reconstruction	Rehab	Periodic Maintenance	Routine Maintenance	
Interstate	$2,762,000	$2,505,000	$178,101	$63,318	$15,472	$55,223
NHS (NIS)	$1,873,000	$1,707,000	$92,268	$45,232	$15,669	$37,460
NNHS	$1,809,000	$1,707,000	$38,725	$46,262	$17,550	$36,180

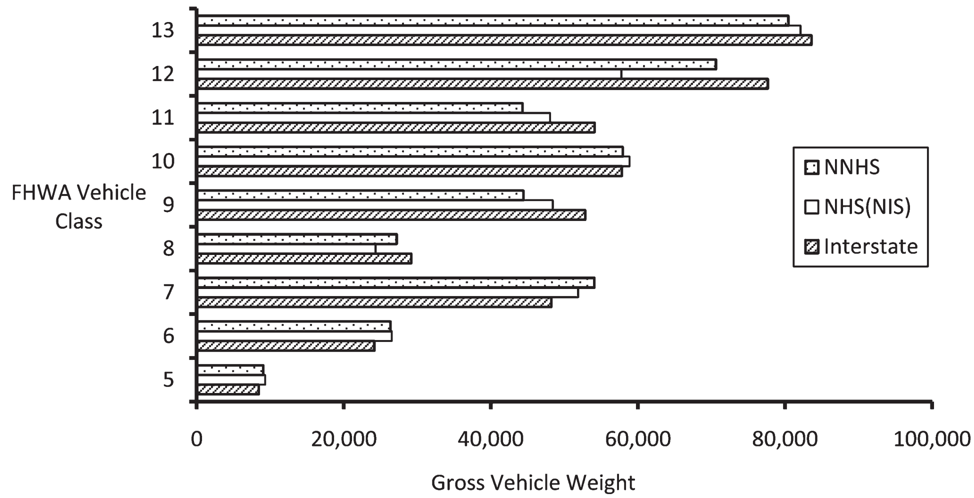


Figure 5.10 Comparison of GVW on different highway functional classes.

traffic and the total spending over a selected analysis period. As mentioned earlier in this chapter, the average spending for Interstates is 1.5 times higher than for non-Interstates but Interstates have traffic that is eight and 25 times higher than for NHS (NIS) and NNHS, respectively. Thus, the higher spending for Interstates is offset by their high traffic volume, thus resulting in a lower MPDC for that functional class compared to others.

To illustrate this point further, consider two pavement segments A and B in the same highway functional class with similar strength, design standards, and average spending but carry different levels of truck traffic over a selected analysis period of 50 years. It is further assumed that trucks moving on these two segments have the same configuration and same average GVW. The average daily truck traffic on pavement A is 4,000 and on pavement B is 6,000; and, on average, each truck generates 2 ESALs. Assuming constant traffic over the analysis period, approximately 146 million and 219 million ESALs will be sustained by pavements A and B respectively, over the 50-year analysis period. Segment B sustained a higher number of ESALs compared to pavement A (more users to share cost); thus, the MPDC for B is lower than for A. The logic is similar to that of the present study. The model estimated in this study for EUAC (MR&R) is based on average traffic and expenditures on different highway functional classes over an infinite analysis period; therefore, the estimated MPDCs are the average values for each functional class.

5.10 MPDC Estimation for Flexible and Rigid Pavements

In the previous section, for proof-of-concept purposes, the MPDC was estimated using a single model for both flexible and rigid pavements. In this section, separate models and MPDC estimates are presented for both pavement types. The data estimation, model building, and MPDC estimation steps are the same as explained in Sections 5.8 and 5.9 of this study. Tables 5.18 and 5.19 present the models developed for flexible and rigid pavements; and the MPDC estimates are presented in Table 5.20.

The findings are consistent with overall model results in Section 5.9. The estimated models show that pavement MR&R costs depend on pavement type and ESALs. The MPDC results suggest that using the available data rigid pavements seemingly have a higher

TABLE 5.18
Model Estimates for MPDC Estimation—Flexible Pavement

Coefficient	Coeff. Value	t-value	P-value	R^2	N
Constant	−42755	−2.60	<0.011	0.57	60
ln(ESALs)	10771	8.78	<0.0001		

TABLE 5.19
Model Estimates for MPDC Estimation—Rigid Pavement

Coefficient	Coefficient Value	t-value	P-value	R^2	N
Constant	−55576	−2.008	<0.053	0.62	32
ln(ESALs)	13601	6.966	<0.0001		

overall life-cycle cost (EUAC (MR&R)) compared to flexible pavements. The results also suggest that young pavements have lower repair costs (EUAC (MR&R)) compared to old pavements, which is intuitive.

5.11 Impact of Climate on MPDC Estimates

It is a well-established fact that the climate has a significant impact on pavement performance. Rutting can occur in flexible pavements due to plastic deformation of bitumen in warm regions. Similarly, low temperature can make flexible pavements brittle and can result in thermal cracking (*129*). Rigid pavements are more vulnerable to expansion and contraction forces due to temperature changes. Freezing in cold weather and thawing in the spring months results in the loss of subgrade strength in both flexible and rigid pavements. Besides temperature, precipitation plays a significant role in pavement deterioration. Not only can subgrade heaving take place due to increased moisture content, but also rain water can enter the subgrade through cracks and joints and can result in pothole formation and removal of fine particles, thus resulting in loss of pavement strength (*13,143–146*).

A number of past studies have used empirical data to confirm and quantify the impact of climate on pavement performance (*34,36*). Also, a number of studies in PDC estimation recognized this issue (*17,23–25,36,50*). It is important to recognize that the state of Indiana has significant differences in its climate due to variations in physical geographical features which extend from the Great Lakes areas in the north to mountain ranges in the south. To allow for climatic variations across different parts of the state, climatic variables, such as the mean annual temperature, the average annual precipitation, the average number of wet days, and the average annual freeze index have been used in past studies (*69,94*). For incorporating the impact of climate on PDC estimation, different methodologies have been adopted in past studies. Also, different studies have found different load and non-load-related shares of PDC. Martin (*34*) found that load-related PDC varied from 88% to 98%. The Federal HCA study of 1997 determined that load-related PDC varied from 78% to 89% for different pavement types and different pavement repair expenditures (*17*). Li and Sinha (*36*) in an Indiana study that was focused on estimation of load- and non-load-related share of pavement rehabilitation and maintenance expenditure found that load-related pavement rehabilitation and maintenance expenditure varies from 28% to 78% depending on pavement type. In past PDC estimation studies, the climatic effects were not accounted for (*40,41,48,50*), considered as some percentage of total PDC (*52*), or incorporated explicitly (*34,36,50,53*). The present study on the basis of the results from the past studies, uses an 85–15% split of pavement damage between traffic loading and climate, respectively. The MPDC estimates with recommended split to be charged on different highway classes are summarized as shown in Table 5.21.

5.12 Impact of Non-Consideration of Reconstruction or Maintenance Costs on MPDC Estimates

Most of the past MPDC estimation studies considered rehabilitation only and thus did not account for the cost of reconstruction and maintenance. Details of these studies are discussed in Section 3.4 of this report. Some of those studies used the so-called theoretical approach to analyze a single pavement segment for MPDC estimation, based on the assumption that MPDC is comprised of overlay cost only (rehabilitation at fixed intervals) and thus excluded all other categories of pavement damage repair (*48–50,52,54*). Also, these studies may have used a single repeated overlay (applied at regular intervals) in order to have a more tractable mathematical formulation; however, by not incorporating reconstruction and periodic and routine maintenance and their associated costs, it seems that these studies underestimated the true MPDC. A number of studies that used empirical approaches generally considered both maintenance (periodic and routine) and rehabilitation cost for MPDC estimation but did not consider reconstruction cost. Only Hajek et al. (*35*) and Ghaeli et al. (*39*) considered reconstruction cost for MPDC estimation; however, both studies did not distinguish between strength-driven and capacity-driven expenditures as they did not distinguish between

TABLE 5.20
MPDC Estimates for Flexible and Rigid Pavements

	Marginal PDC ($/ESAL-mile)—2010 Constant $	
Highway Functional Class	Flexible	Rigid
Interstate	0.0066	0.0083
NHS (NIS)	0.0599	0.0756
NNHS	0.2349	0.2967
Mean	0.1005	0.1269

TABLE 5.21
Load- and Non-Load-Related MPDC Estimates

	Marginal PDC ($/ESAL-mile)—2010 Constant $	
Highway Functional Class	Load Share	Non-Load Share
Interstate	0.006	0.001
NHS (NIS)	0.055	0.010
NNHS	0.218	0.038
Mean	0.093	0.016

TABLE 5.22
Different Cost Consideration Scenarios for MPDC Estimation

Cost Scenario	Pavement Damage Related Cost Considered
Scenario 1	All relevant pavement damage repair costs considered
Scenario 2	Non-consideration of reconstruction cost
Scenario 3	Non-consideration of reconstruction and routine maintenance cost
Scenario 4	Rehabilitation at fixed intervals

new construction and reconstruction costs. In order to study the impact of non-consideration of reconstruction and/or maintenance cost on MPDC estimation, this study considers four different scenarios for pavement repair categories (Table 5.22) as discussed below.

5.12.1 Scenario 1—MPDC Estimation Considering All Relevant Pavement Damage Repair Costs

For MPDC estimation purposes, all pavement damage-related costs were considered. The steps involved are summarized as follows:

- The MR&R strategies over a 50-year analysis period were developed considering all of the costs associated with pavement damage repair (reconstruction, rehabilitation, and periodic and routine maintenance) for 92 different cases of flexible and rigid pavements. The M&R strategies are identical to those discussed in Section 5.7.2 of this study.
- From the developed MR&R strategies, life-cycle costs and usage levels were estimated as discussed in Section 5.8 of this study.
- Model calibration and MPDC estimation followed the same steps as discussed in Section 5.9 of this study.
- The estimated model and MPDC estimates are summarized in Tables 4.25 and 4.26.

5.12.2 Scenario 2—Non-Consideration of Reconstruction Cost

Scenario 1 differs from Scenario 2 only in terms of cost, as the former considers reconstruction cost. Figure 5.11 represents an MR&R strategy over a 50-year life cycle for a flexible pavement where reconstruction cost was not considered. In this scenario, rehabilitation, and periodic and routine maintenance costs were considered for estimating MPDC. Similar MR&R strategies for other cases of flexible and rigid pavements were developed. The model calibration and MPDC estimation steps remained the same as discussed in the previous section and the estimated model and MPDC estimates are presented in Tables 5.23 and 5.24.

5.12.3 Scenario 3—Non-Consideration of Reconstruction and Routine Maintenance Cost

In this scenario, the reconstruction and routine maintenance costs were not considered (only rehabilitation and periodic maintenance costs were considered). Figure 5.12 represents a MR&R profile for a flexible pavement where reconstruction and routine costs were not considered. Similar MR&R strategies for other cases of flexible and rigid pavements were developed. Using these MR&R strategies, models were developed for MPDC estimation. All other steps for MPDC estimation remain the same as discussed in Sections 5.8 and 5.9. The estimated model and MPDC estimates are summarized in Tables 5.23 and 5.24, respectively.

5.12.4 Scenario 4—Rehabilitation at Fixed Intervals

This scenario has been used in a number of past studies (*49,50,52,54*). This scenario only considers rehabilitation cost and ignores all other pavement damage-related costs. Figure 5.13 represents a MR&R strategy for a flexible pavement where reconstruction and routine and periodic maintenance cost were not considered. In this MR&R strategy, only rehabilitation cost is considered. Similar MR&R strategies for other cases of flexible and rigid pavements were developed depending on traffic loading, the time of application of the first periodic maintenance treatment (the rest

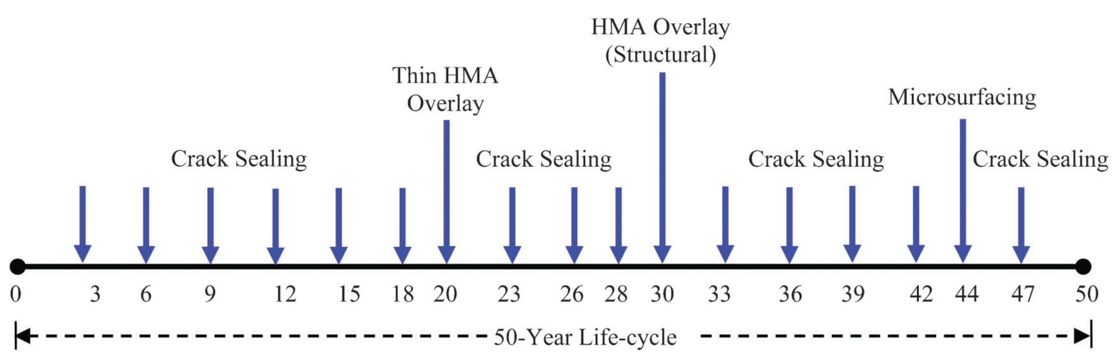


Figure 5.11 Scenario 2—Non-consideration of reconstruction cost in MPDC estimation.

TABLE 5.23
Model Estimates for Different Cost Scenarios of Pavement Repair Category

Cost Scenario	Coefficient	Coefficient Value	t-value	P-value	R^2	N
Scenario 1: All relevant costs considered	Constant	−55545	−3.93	<0.0001	0.74	92
	ln(ESALs)	11732	11.16	<0.0001		
	PTYPE	26318	8.19	<0.0001		
Scenario 2: Non-consideration of reconstruction cost	Constant	−23696	−7.84	<0.0001	0.90	92
	ln(ESALs)	2420	10.62	<0.0001		
	PTYPE	16093	23.11	<0.0001		
Scenario 3: Non-consideration of reconstruction and routine maintenance cost	Constant	−18573	−5.58	<0.0001	0.64	92
	ln(ESALs)	1967	7.85	<0.0001		
	PTYPE	5802	7.57	<0.0001		
Scenario 4: Rehabilitation cost at fixed intervals	Constant	−15828	−5.97	<0.0001	0.64	92
	ln(ESALs)	1572	7.87	<0.0001		
	PTYPE	4480	7.34	<0.0001		

TABLE 5.24
MPDC Estimates for Different Cost Scenarios of Pavement Repair Category

	MPDC ($/ESAL-mile—2010 Constant $			
Cost Scenario	Interstate	NHS (NIS)	NNHS	% Difference in MPDC with respect to Scenario 1
Scenario 1: All relevant costs considered	0.0072	0.0652	0.2559	—
Scenario 2: Non-consideration of reconstruction cost	0.0015	0.0135	0.0528	79%
Scenario 3: Non-consideration of reconstruction and routine maintenance cost	0.0012	0.0109	0.0429	83%
Scenario 4: Rehabilitation cost at fixed intervals	0.0010	0.0087	0.0343	86%

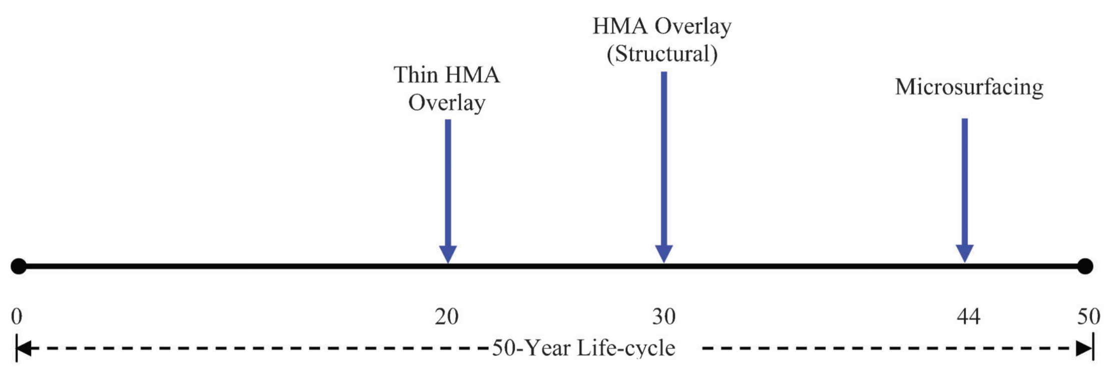


Figure 5.12 Scenario 3—Non-consideration of reconstruction and routine maintenance costs in MPDC estimation.

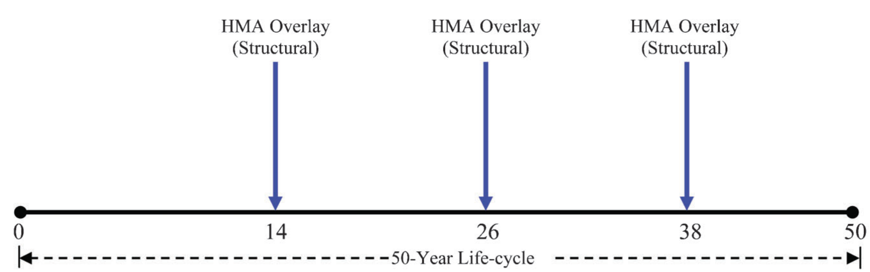


Figure 5.13 Scenario 4—MPDC estimation for rehabilitation at fixed intervals only.

period) and subsequent treatments. Using the developed MR&R strategies, models were developed for MPDC estimation. All other steps for MPDC estimation remain the same as discussed in the previous section. The estimated model and MPDC estimates are summarized in Tables 5.23 and 5.24.

The MPDC estimates (Table 5.24) suggest that the studies that did not consider reconstruction cost obtained results that underestimate the true MPDC by 79%. Since reconstruction cost is a strength-driven expenditure, it can be argued that it must be a part of MPDC estimates. In the third scenario, both reconstruction cost and routine maintenance cost were not considered, and the MPDC was estimated for periodic maintenance and rehabilitation only. By just considering rehabilitation and periodic maintenance only, the results suggest that the MPDC was almost 83% lower compared to Scenario 1. Also, the results of Scenario 3 suggest that routine maintenance cost contributes to the MPDC and should therefore form a part of MPDC estimation.

The last scenario (Scenario 4) where only rehabilitation cost was considered for MPDC estimation revealed that the MPDC was almost 86% lower compared to Scenario 1. In reality, highway agencies do not use this strategy but rather use a mix of rehabilitation, periodic and routine maintenance, and reconstruction at different times to ensure that their highways have a satisfactory level of service. Thus, it could be argued that the past studies that assumed a strategy where rehabilitation treatments were applied at regular interval for MPDC estimation, used an unrealistic approach. The estimated results are not only lower than MPDC estimates based on all costs but also are derived from maintenance strategies that are not realistic from a pavement maintenance management standpoint.

Thus, it can be argued that the most realistic approach which can lead to accurate estimation of MPDC is that which incorporates explicitly practical highway agency MR&R schedules and therefore considers all pavement repair costs for MPDC estimation.

5.13 Impact of Non-Consideration of Non-Truck Traffic on MPDC Estimates

For the MPDC estimation in the present study, only truck traffic was considered because past research suggested that the non-truck contribution to pavement damage is insignificant (*50*). INDOT uses the FHWA vehicle classification system for classifying all vehicles into 13 different classes depending upon their axle spacing and number of axles. INDOT further classifies vehicles from Class 4 through Class 13 as commercial vehicles, while vehicles from Class 1 through Class 3 (motorcycles, cars, pickup trucks, and light van traffic) as non-commercial vehicles (*110*). For simplicity, the present study refers to commercial vehicles as truck traffic and non-commercial vehicles as non-truck traffic.

To test the validity of the assumption that the non-truck traffic contribution is insignificant in MPDC estimation and thus may be excluded from analysis, a simple methodology was adopted as follows:

- **Estimation of Non-Truck Traffic Volume:** The volume of non-truck traffic was obtained from INDOT sources (*110*). The most recent year (2007) traffic volume estimates were updated to the analysis year (2010) using appropriate growth factors. The percentages of truck and non-truck traffic for different vehicle classes are shown in Table 5.25.
- **Estimation of ESALs Contribution by Non-Truck Traffic:** The total ESALs contributed by non-truck traffic were estimated using non-truck traffic volume and the fourth power law. Non-truck traffic is excluded in WIM station standard reports, thus no real weight estimates were available for these vehicles. Different studies provide different weights for small and medium-size cars, small and large SUVs and light duty trucks. On Indiana highways, approximately 60% of the non-truck traffic falls into FHWA Class 2 (cars) and 40% falls into FHWA Class 3 (SUV, light duty trucks) (Table 5.26). Using the national average weight of FHWA Classes 2 and 3, we assumed that FHWA Class 2 weighs 3,500 lbs and FHWA Class 3 weighs 4,700 lbs (*147*). Since all of these vehicles have two single axles, we further assumed that each axle carries half of the vehicle weight. Thus, each car and light duty truck axle weighs approximately 1,750 lbs and 2,350 lbs, respectively. Using the non-truck traffic volume data and fourth power law, the total ESALs contributed by non-truck traffic were estimated. Then, by comparing the results with the ESALs contributed by the truck traffic (Section 5.8.2) the percentage of ESAL contribution for non-truck traffic was estimated (Table 5.27). Note that for Table 5.27, the truck traffic categories are defined in Table 5.8.

From Table 5.27, it can be easily concluded that the non-truck traffic contribution to pavement damage is insignificant. Clearly, the total ESALs contributed by

TABLE 5.25
Traffic Composition on Indiana Highways

Highway Functional Class	Vehicle in Individual Classes (FHWA Vehicle Classification System) 1	2	3	4	5	6	7	8	9	10	11	12	13
Interstate	0.52	46.08	29.05	0.36	4.17	0.60	0.08	0.71	17.29	0.13	0.74	0.26	0.02
NHS (NIS)	0.49	54.43	29.63	0.33	3.71	0.50	0.24	0.92	9.16	0.23	0.19	0.09	0.08
NNHS	0.28	55.49	34.45	0.27	4.17	0.35	0.09	0.71	4.03	0.08	0.04	0.02	0.01
Average	0.43	52.00	31.04	0.32	4.02	0.48	0.14	0.78	10.16	0.15	0.32	0.12	0.04

TABLE 5.26
Actual Cost of Pavement Damage vs. Permit Fee, by Vehicle Class, for 85% Load Share of Damage

Details	Avg. GVW (lbs)	Avg. ESAL	Avg. Additional ESAL	85% Load-Related Damage		
				IS	NHS-NIS	Non-NHS
Cost ($/ESAL-mile)				**0.006**	**0.055**	**0.218**
GVW Range: 80001–108000 (Current Permit Fee = $0.35/mile)						
4 Axles	91,501	7.51	5.13	0.031	0.282	**1.118**
5 Axles	92,838	4.79	2.42	0.015	0.133	**0.527**
6 Axles	99,154	3.02	0.64	0.004	0.035	0.14
7+ Axles	100,474	1.68	−0.69	—	—	—
GVW Range: 108001–150000 (Current Permit Fee = $0.60/mile)						
4 Axles	120,000	16.04	13.66	0.082	**0.751**	**2.978**
5 Axles	116,455	9.63	7.25	0.044	0.399	**1.581**
6 Axles	119,686	6.56	4.18	0.025	0.23	**0.912**
7 Axles	125,896	4.64	2.26	0.014	0.124	0.492
8 Axles	131, 228	4.75	2.37	0.014	0.13	0.516
9+ Axles	126,153	2.95	0.57	0.003	0.032	0.125
GVW Range: More Than 150000 (Current Permit Fee = $1.0/mile)						
7 Axles	152,567	11.26	8.83	0.053	0.489	**1.937**
8 Axles	161,191	11.09	8.71	0.052	0.479	**1.898**
9 Axles	168,800	9.59	7.21	0.043	0.393	**1.572**
10 Axles	171,057	10.16	7.78	0.047	0.428	**1.697**
11 Axles	183,300	11.87	9.49	0.057	0.522	**2.069**
12+ Axles	201,700	10.5	8.12	0.049	0.447	**1.77**

non-truck traffic are negligible compared to truck traffic. Thus, the assumption that non-truck traffic can be excluded from MPDC estimation, can be considered valid.

5.14 Comparison of Pavement Damage Cost with Existing Permit Fee

5.14.1 Current Permit Fee

At the present time, INDOT charges a permit fee to overweight trucks. For charging vehicles on Indiana's highways, it must be established first that vehicles are over the weight and dimensions limits established by the law. To travel legally, the followings are the dimensions and weight limits:

a. Dimension Limits

- 13 feet 6 inches in height
- 8 feet 6 inches in width
- 40 feet in length for a single vehicle
- 60 feet in length for a two-vehicle combination. If two-vehicle combination is connected by a fifth wheel hook-up, there is no overall length limit, but the trailer and load length cannot exceed 53 feet

b. Weight Limits

- 80,000 pounds gross vehicle weight
- 12,000 pounds on the steering axle
- 20,000 pounds on a single axle
- 34,000 pounds on a tandem axle

Since present study is focused on determining the actual damage being inflicted by overweight vehicles only, oversize limits are outside the scope of this study. Only charges based on overweight limits are computed and compared with existing road-use charges (permit fee). For charging most overweight trucks, INDOT has established three broad categories. The weight limits and permit fee charged for each overweight truck category are summarized as follows:

a. Overweight Truck Category 1: GVW 80,000–108,000 lbs = $0.35 per mile
b. Overweight Truck Category 2: GVW 108,000–150,000 lbs = $0.60 per mile
c. Overweight Truck Category 3: GVW >150000 lbs = $1.0 per mile

In addition to these fees, $10 executive fee is charged to vehicles weighing over 120,000 lbs. Also, vehicles over 200,000 lbs pay $25 design and review fee in addition to $10 executive fee (*122*).

5.14.2 Comparison of Pavement Damage Cost with Existing Permit Fee

For comparison of pavement damage cost (actual damage which is being incurred) by different overweight truck classes to Indiana's highways, the following procedure was adopted:

- **Step 1:** Estimation of Unit Pavement Damage Cost. The details have been covered in Section 5.9 of this report. Further, it was assumed that 85% pavement damage is

TABLE 5.27
Percent ESAL Contribution by Non-Truck Traffic

Functional Class	Truck Traffic Categories	Non-Truck AADT	Truck AADT	Non-Truck ESALs	Truck ESALs	% Contribution of Non-Truck ESALs
Interstate	Very high	49,453	16,768	6130	4,217,603	0.15
	High	33,748	8,694	4184	2,186,775	0.19
	Medium	22,991	6,964	2850	1,751,633	0.16
	Low	15,110	3,322	1873	835,572	0.22
NHS (NIS)	Very high	13,358	5,072	1656	1,057,401	0.16
	High	16,722	3,378	2073	704,239	0.29
	Medium	13,772	2,360	1707	492,008	0.35
	Low	8,317	858	1031	178,874	0.57
NNHS	Very high	8,143	1,566	1009	265,367	0.38
	High	4,973	692	617	117,263	0.52
	Medium	3,325	356	412	60,326	0.68
	Low	1,551	120	192	20,335	0.94

load related and 15% is caused by climate. Therefore, on Interstate, NHS (NIS) and non-NHS, overweight trucks cause 0.0060,0.055 and 0.218 $/ESAL-mile, respectively

- **Step 2:** Estimation of GVW and average Truck ESALs for overweight truck classes. Overweight truck data was obtained from INDOR for month of September 2010. Trucks were broadly classified into three overweight groups as per INDOR current practice for permit fee. In each group, trucks were further classified on the basis of number of axles. For different axle configuration and GVW, the total ESAL generated by each truck class were determined. The detailed classification of these trucks is presented in Table 5.26.
- **Step 3:** Estimation of Average ESALs for 80,000 lbs, 5-axle Truck: Since all trucks with load 80,000 lbs or less use highway without permit, it was concluded that overweight trucks should be charged for highway use if they exceed 80,000 lbs. For example, if a truck weighs 100,000 lbs, it should be charged a permit fee for excess 20,000 lbs and not for its GVW. For subtracting the 80,000 lbs damage from the GVW of a truck, the number of ESALs generated by a standard 5-axle semi-trailer carrying 80,000 were estimated using AASHTO fourth power law. Assuming that this truck carries 12,000 lbs on steering axle and 34,000 lbs on each tandem axle, a total of 2.37 ESALs were estimated for this truck type.
- **Step 4:** Estimation of additional pavement damage due to load carried over the limit of 80,000 lbs: Knowing the total ESAL generated by an overweight truck, the additional damage was estimated by subtracting the ESALs generated by an 80,000 lbs, 5-axle truck, from the total ESALs of an overweight truck as follows: Additional pavement damage = Total ESALs of OW Truck – 2.37 (ESALs of a 80,000 lbs, 5-axle Truck).
- **Estimation of $ Value of Additional Pavement Damage by an Overweight Truck:** Having estimated the total additional damage caused by an overweight truck, its damage cost was estimated by multiplying the additional ESALS of an overweight truck with the cost per ESAL-mile as follows: Additional Damage ($) = Additional ESALs × $/ESAL-mile.

The current permit fee and actual cost of pavement damage for each truck class are presented in Table 5.26. In the case of the first overweight truck category (80,000–108,000 lbs GVW) for all trucks (4, 5, 6 and 7+ axles), the existing permit fee exceeds the actual pavement damage incurred on Interstate and NHS-NIS (Figure 5.14). In the case of NNHS, 4-axle and 5-axle trucks are underpaying (existing permit fee is less than the actual pavement damage incurred).

In the case of the second overweight truck category (108,000–150,000 lbs GVW), all trucks (4, 5, 6, 7, 8, 9+ axles) are overpaying on Interstate (Table 5.26). In the case of NHS-NIS, with the exception of 4-axle trucks, all trucks are paying a higher permit fee than the actual pavement damage they inflict. In the case of NNHS, trucks with 4, 5, and 6 axles are underpaying while other truck categories are overpaying. Thus for 4, 5, and 6-axle trucks, the existing permit fee is less than the actual pavement damage these trucking are inflicting on non-NHS roads (Figure 5.15).

In the case of the third overweight truck category (GVW greater than 150,000 lbs), all trucks (7, 8, 9, 10, 11, 12+ axles) are overpaying for both Interstate and NHS-NIS (Table 5.26). In case on NNHS, all trucks are underpaying. A comparison of the estimated pavement damage cost with the existing fee for each truck category suggests that all of the truck classes are paying more permit fee compared to pavement damage they inflict (Figure 5.16). The damage here does not include bridge damage or other costs associated with overweight truck operations and their enforcement.

5.15 Chapter Summary

This chapter presented the application of the framework developed in this study for MPDC estimation. The chapter started with a brief description of pavement families and maintenance and rehabilitation treatments considered for the MPDC estimation. This was followed by a discussion on the treatment cost and traffic data, the selection of a road-use measure, the estimation of a pavement rest period, and the effectiveness of rehabilitation and maintenance treatments used for MPDC estimation. Sixty pavement MR&R strategies for

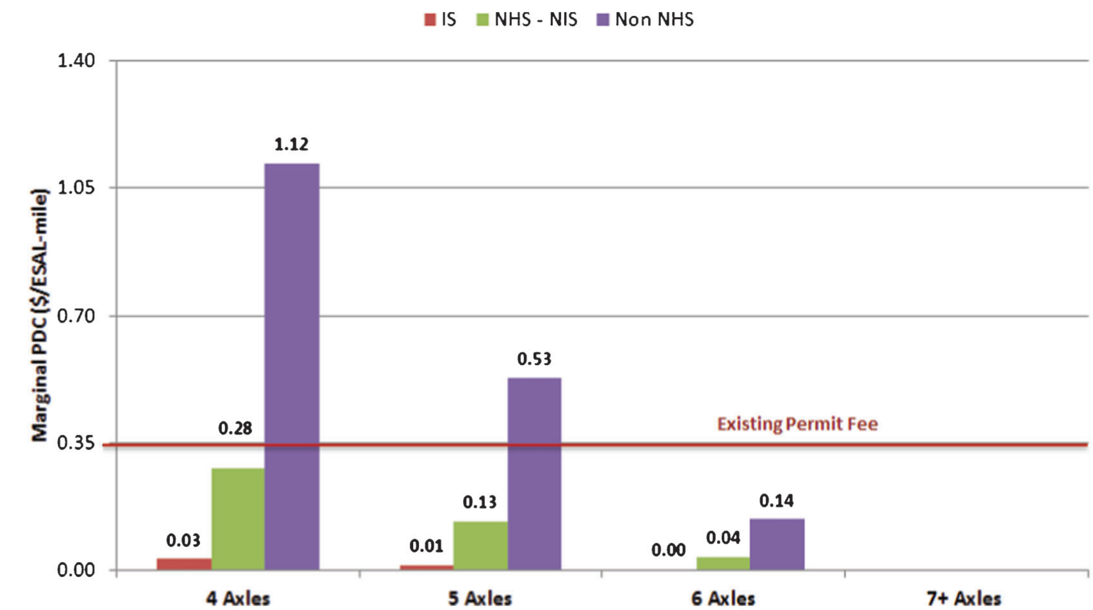


Figure 5.14 Total pavement damage cost for trucks with GVW 80,000–108,000 lbs.

flexible pavements and thirty-two for rigid pavements were presented and models were estimated for MPDC estimation. The developed models revealed that annual ESALs and pavement type were the two factors having a significant impact on MR&R cost. The model results revealed that the MPDC is greater for non-national highways and lower for Interstate highways, indicating that highway users experience economies of scale at roads with high traffic volumes.

The impacts of non-consideration of reconstruction cost, reconstruction and routine maintenance cost, and reconstruction and routine and periodic maintenance cost were analyzed. The evaluation of the MPDC results estimated by considering different cost components revealed that failure to account for any category of pavement damage-related cost can have a significant impact on MPDC estimation. It was concluded that MPDC results will likely be unsatisfactory unless (i) all categories of pavement repair, namely, reconstruction, rehabilitation, and routine and periodic maintenance cost are considered, and (ii) the analysis duly reflects the actual and practical decision-making processes of the

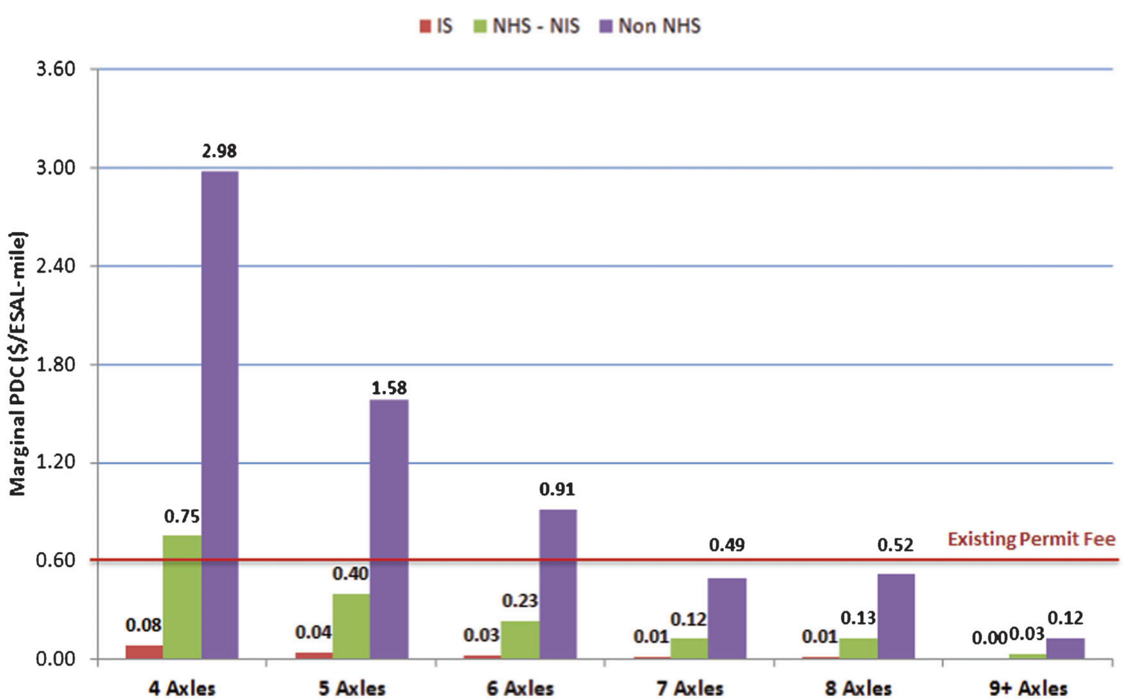


Figure 5.15 Total pavement damage cost for trucks with GVW 108,000–150,000 lbs.

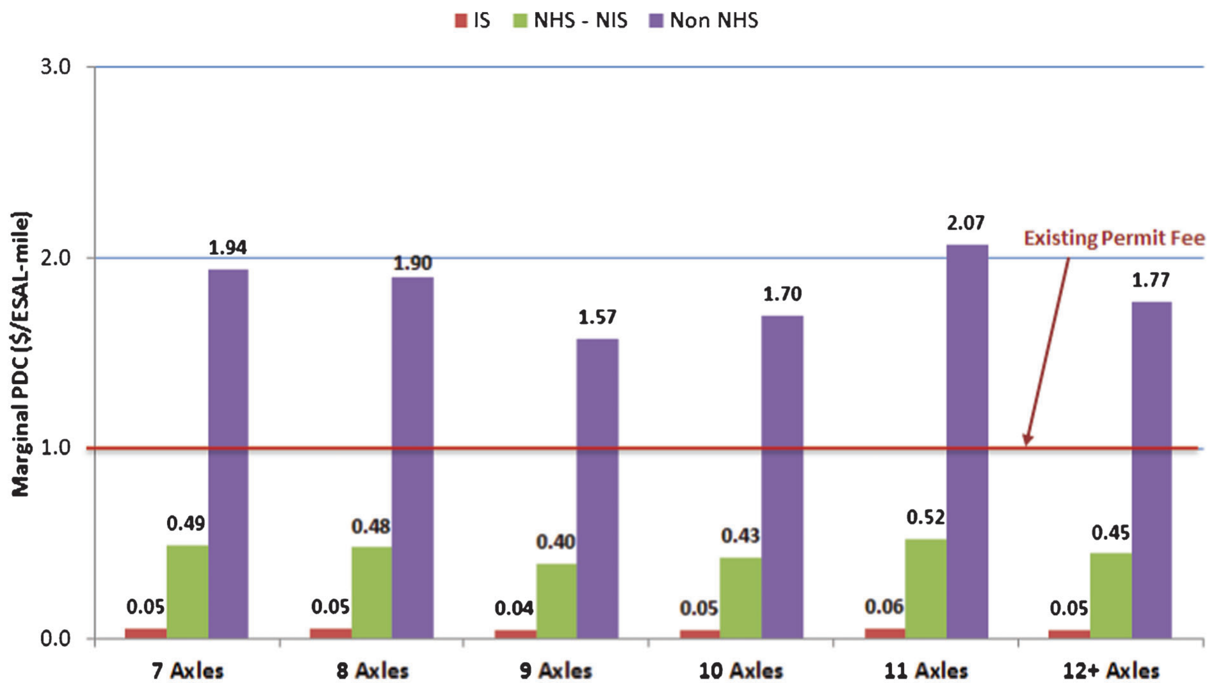


Figure 5.16 Total pavement damage cost for trucks with GVW exceeding 150,000 lbs.

highway agency. Also, it was concluded that MPDC results are not significantly compromised when non-truck traffic is excluded from the analysis. Finally, a comparison of the existing permit fee paid by different truck classes and actual pavement damage incurred revealed that trucks are paying less or more than the actual pavement damage they cause to pavements at the different highway functional classes.

6. SENSITIVITY ANALYSIS

Sensitivity analysis was carried out in this study to investigate the changes in the overall MPDC estimation results with the variation of the key input variables, including pavement life-cycle length, interest rate, pavement rest period, service life of rehabilitation treatments, and the unit costs of reconstruction and rehabilitation. The sensitivity analysis helped to validate the overall framework developed for MPDC estimation in this study.

6.1 Effect of Pavement Life-Cycle Length on MPDC Estimates

MPDC estimation in this study is based on a 50-year pavement life cycle. MPDC can vary, depending on the length of the pavement life cycles considered for analysis. The most recent INDOT Pavement Design Manual recommends a 50-year pavement life cycle (*64*). In recent years, state departments of transportation (DOTs) have been moving towards longer pavement life cycles. The increase in the length of the pavement life cycle can be attributed to the recent advances made in pavement design and the adoption of enhanced construction techniques and materials. Also, state DOTs are striving to construct long-lasting pavements in order to lower long-term maintenance cost and reduce the frequency and duration of the maintenance work zone. A recent survey by the South Carolina Department of Transportation (SCDOT) revealed that the states of Minnesota, Nebraska, New York, Virginia, Washington, and Wisconsin and the Canadian Province of Ontario are already using a 50-year pavement life-cycle for LCCA purposes (*124*).

In order to study the impact of variations of the pavement life-cycle length on MPDC, the developed methodology involved the following steps:

- MR&R strategies were formulated using 50, 45, 40, and 35-year life-cycle lengths for both flexible and rigid pavements. The four life-cycle lengths were considered as they are the most commonly used by highway agencies in the U.S. (*124*). The MR&R strategy formulation steps are discussed in Section 5.7.
- From the formulated strategies, traffic and cost data (the average annual ESALs and the EUAC for each MR&R strategy) were estimated for the four different cases of pavement life-cycle lengths. The data estimation steps are explained in Section 5.8.
- From the estimated data, separate models were developed for the pavement life-cycle lengths of 50, 45, 40, and 35 years using an infinite analysis period. The developed models are presented in Table 6.1.
- From the developed models, the MPDC was estimated for each of the three highway functional classes. The estimates for MPDC are presented in Table 6.2. The model and MPDC estimation steps are in line with the methodology explained in Section 5.9.

The MPDC estimates suggest that the pavement life-cycle length has a significant impact on the estimated cost (Figures 6.1 to 6.3). For all three functional classes, the MPDC estimates are the minimum for a

TABLE 6.1
Model Estimates—MPDC Estimation Using Different Pavement Life-Cycle Lengths

Life-Cycle Length (Years)	Coefficient	Coefficient Value	t-value	P-value	R^2	N
50	Constant	−55545	−1.99	<0.046	0.74	92
	ln(ESALs)	11732	14.93	<0.0001		
	PTYPE	26318	12.51	<0.0001		
45	Constant	−56379	−1.99	<0.046	0.75	992
	ln(ESALs)	12120	67.09	<0.0001		
	PTYPE	26367	13.04	<0.0001		
40	Constant	−59723	−2.10	<0.037	0.74	92
	ln(ESALs)	12687	15.55	<0.0001		
	PTYPE	26385	13.23	<0.0001		
35	Constant	−61020	−3.156	<0.0001	0.78	92
	ln(ESALs)	13354	13.41	<0.0001		
	PTYPE	26410	14.17	<0.0001		

TABLE 6.2
MPDC Estimates for Different Pavement Life-Cycle Lengths

	MPDC ($/ESAL-mile)—2010 Constant $		
Pavement Life Cycle (Years)	Interstate	NHS (NIS)	NNHS
50 years*	0.0072	0.0652	0.2559
45 years	0.0074	0.0674	0.2643
40 years	0.0077	0.0705	0.2767
35 years	0.0082	0.0742	0.2913

*50 years = base case.

50-year pavement life-cycle length and the maximum for a 35-year pavement life-cycle length. Thus, with the increasing length of the pavement life cycle, the MPDC estimates decreases. This is intuitive in that, for the longer pavement life-cycle length, the discounted maintenance costs occurring farther from the base year are small, thus resulting in a low EUAC (MR&R). A low EUAC (MR&R) results in a lower MPDC. Thus, adequate attention should be paid by highway agencies in selection of their appropriate pavement life-cycle length for MPDC estimation. MPDC estimates using different life-cycle lengths revealed that long-lasting pavements can result in agency cost savings. Long-lasting pavements result not only in lower maintenance, accidents, and environmental costs, but also lower MPDC. In this study, a 50-year pavement life cycle was used for MPDC estimation based upon highway agency trends and recommendations, as well as on the basis of pavement design and construction improvements. The selected length of pavement life cycle therefore should represent the current agency practices in pavement construction and maintenance.

6.2 Effect of Discount Rate on MPDC Estimates

The discount rate can be an important factor in MPDC estimation. MPDC estimates depend upon the EUAC (MR&R) of individual MR&R strategies. Different discount rates will result in different EUAC (MR&R) for individual MR&R strategies, which

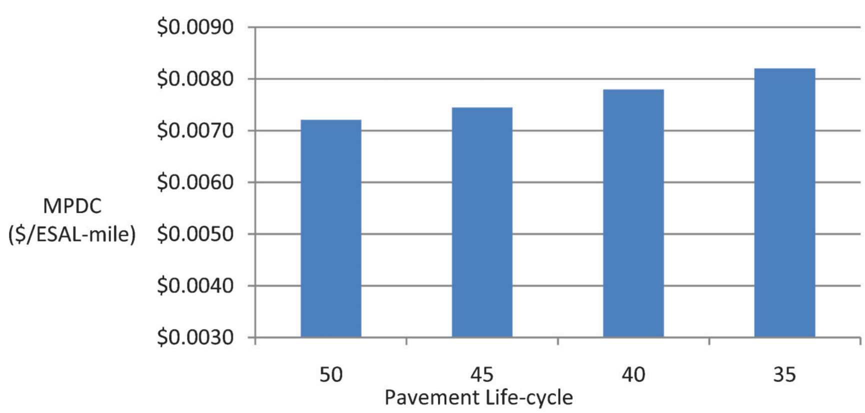


Figure 6.1 Variation of MPDC with length of pavement life cycle—Interstate.

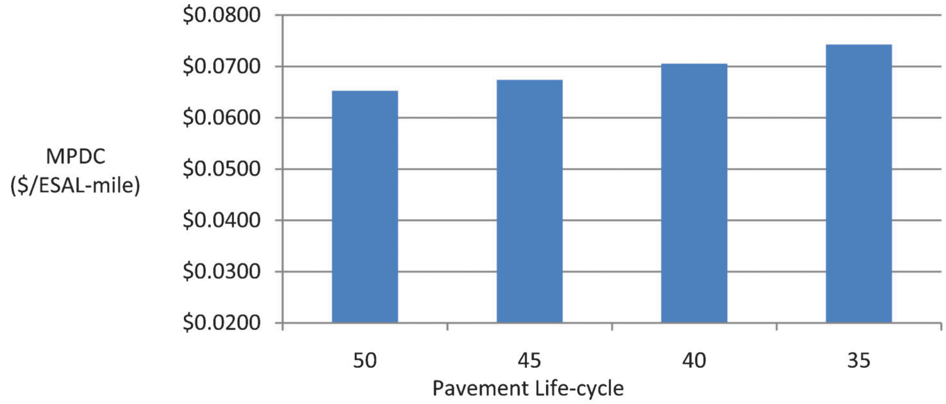


Figure 6.2 Variation of MPDC with length of pavement life cycle—NHS (NIS).

ultimately will yield different MPDC estimates. In this study, MPDC was estimated using a 4% real discount rate. Using a higher discount rate would result in a lower EUAC (MR&R) and thus lower MPDC, and vice versa. In order to study the impact of discount rate on MPDC estimation, the developed methodology involved the following steps:

- Using a 50-year life-cycle length, MR&R strategies were formulated over an infinite analysis period for new flexible and rigid pavements. The discount rate was made to vary from 0 to 10%. For each of the 11 different cases of discount rate, 92 different MR&R strategies were formulated. The MR&R strategy formulation steps are consistent with Section 5.7.
- From the formulated strategies, costs and traffic data were estimated for 11 different cases of discount rate. For doing this, the steps are in line with the methodology previously explained in Section 5.8.
- From the data estimates, separate models were developed for 11 different cases of discount rate (Table 6.3).
- MPDC was estimated from the developed models for three functional classes. The estimates for MPDC are presented in Table 6.4. The model and MPDC estimation steps are in line with the methodology explained in Section 5.9.

Figures 6.4 to 6.6 suggest that the discount rate can have a significant influence on MPDC estimates. MPDC decreases with increasing discount rates, and vice versa. The discount rate used in this study, 4%, is the real long-term rate that is recommended by FHWA and used by INDOT. Using a different rate can significantly influence the MPDC results. Therefore, any deviations from this rate should be based on the latest recommendations and practices in the industry. A recent survey by Rangaraju et al. (*124*) indicated that most state DOTs are using a 4% discount rate for their analysis. Since the discount rate can have a significant impact on MPDC estimates, it should be given due consideration when comparing the results of any two studies that used different discount rates in their analysis.

6.3 Effect of Pavement Intervention Effectiveness on MPDC Estimates

In the present study, the MR&R strategies were formulated using the estimated rest periods and service lives of rehabilitation and periodic maintenance treatments for different highway functional classes. The rest periods and service lives were estimated using Indiana data (see Chapter 4 of the present report for details). MR&R strategies with longer rest periods and more effective rehabilitation and periodic maintenance treatments are generally to have a lower EUAC (MR&R) compared to MR&R strategies with shorter rest periods and less effective rehabilitation and periodic mainte-

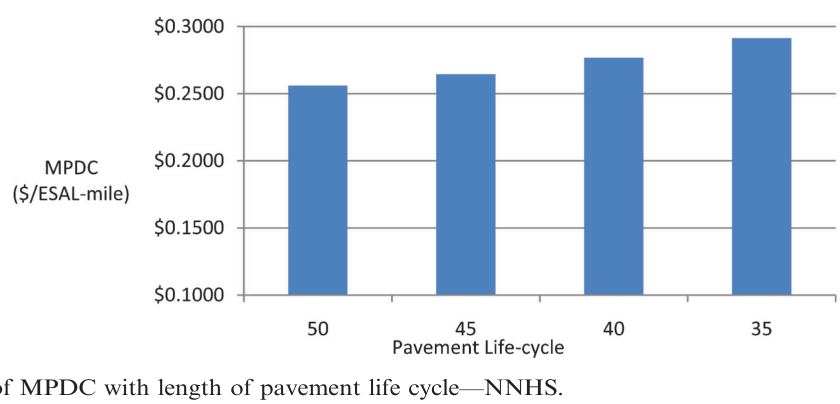


Figure 6.3 Variation of MPDC with length of pavement life cycle—NNHS.

TABLE 6.3
Model Estimates—PDC Estimation Using Different Interest Rates

Interest Rate	Coefficient	Coefficient Value	t-value	P-value	R^2	N
0%	Constant	−81456	−5.38	<0.0001	0.82	0.92
	ln(ESALs)	14715	12.91	<0.0001		
	PTYPE	40107	11.51	<0.0001		
1%	Constant	−71035	−4.87	<0.0001	0.81	92
	ln(ESALs)	13639	12.43	<0.0001		
	PTYPE	34524	10.29	<0.0001		
2%	Constant	−63141	−4.42	<0.0001	0.79	92
	ln(ESALs)	12826	11.94	<0.0001		
	PTYPE	30214	9.20	<0.0001		
3%	Constant	−57072	−4.05	<0.0001	0.77	92
	ln(ESALs)	12203	11.51	<0.0001		
	PTYPE	26856	8.28	<0.0001		
4%*	Constant	−52341	−3.74	<0.0001	0.75	92
	ln(ESALs)	11720	11.13	<0.0001		
	PTYPE	24217	7.52	<0.0001		
5%	Constant	−48607	−3.49	<0.0001	0.72	92
	ln(ESALs)	11340	10.82	<0.0001		
	PTYPE	22123	6.90	<0.0001		
6%	Constant	−45625	−3.28	<0.0001	0.70	92
	ln(ESALs)	11039	10.56	<0.0001		
	PTYPE	20447	6.39	<0.0001		
7%	Constant	−43219	−3.18	<0.0001	0.93	92
	ln(ESALs)	10797	10.35	<0.0001		
	PTYPE	19093	5.98	<0.0001		
8%	Constant	−41260	−2.97	<0.0001	0.67	92
	ln(ESALs)	10602	10.17	<0.0001		
	PTYPE	17989	5.64	<0.0001		
9%	Constant	−39653	−2.86	<0.0001	0.65	92
	ln(ESALs)	10442	10.02	<0.0001		
	PTYPE	17080	5.36	<0.0001		
10%	Constant	−37412	−2.71	<0.0001	0.65	92
	ln(ESALs)	10282	9.77	<0.0001		
	PTYPE	16690	5.01	<0.0001		

*4% = base case.

nance treatments. The impact of changes in the rest period of newly reconstructed pavement and the service lives of rehabilitation and periodic maintenance treatments on MPDC estimates is discussed in the ensuing paragraphs.

TABLE 6.4
MPDC Estimates for Different Discount Rates

	MPDC		
Interest Rate	**Interstate**	**NHS (NIS)**	**NNHS**
0%	0.0090	0.0818	0.3210
1%	0.0084	0.0758	0.2975
2%	0.0079	0.0713	0.2798
3%	0.0075	0.0678	0.2662
4%*	0.0072	0.0652	0.2557
5%	0.0070	0.0631	0.2474
6%	0.0068	0.0614	0.2408
7%	0.0066	0.0600	0.2355
8%	0.0065	0.0589	0.2313
9%	0.0064	0.0581	0.2278
10%	0.0063	0.0572	0.2243

*4% = base case.

6.3.1 Length of the Rest Period

For establishing the rest period, performance trend models were developed in this study. From the developed performance models, rest periods were established as the time interval between pavement construction to the first periodic maintenance (see Section 5.6 of this report for further detail). In order to study the impact of changes in estimates of rest period on MPDC estimation, the developed methodology involved the following steps:

- Using the 50-year pavement life-cycle length, MR&R strategies were formulated over an infinite analysis period for a new flexible pavement for five different cases (i.e., lengths of rest period). The methodology for strategy formulation with different rest periods is explained in Figures 6.7 and 6.8. Figure 6.7 represents the base case where the first periodic maintenance treatment (thin HMA overlay) was applied to a newly reconstructed pavement in year 20. Thus, in this case, the rest period was 20 years. Figure 6.8 represents the case where the same pavement had a two-year smaller rest period compared to the base case (thin HMA overlay was applied to a newly-reconstructed pavement in year

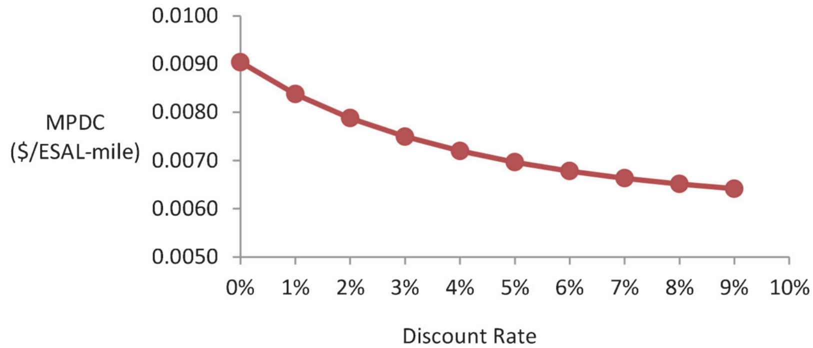


Figure 6.4 Variation of MPDC with discount interest rate—Interstate.

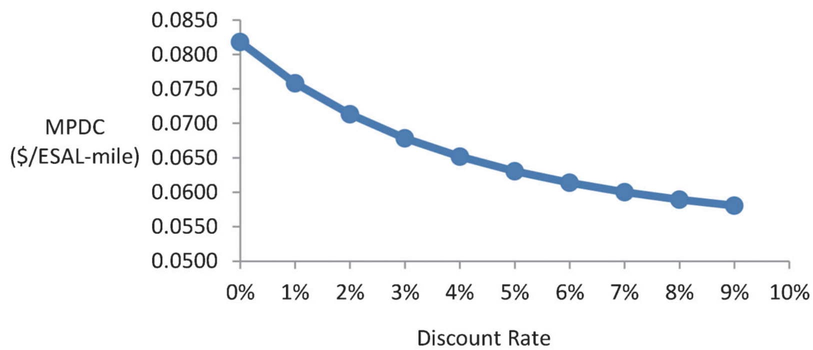


Figure 6.5 Variation of MPDC with discount interest rate–NHS (NIS).

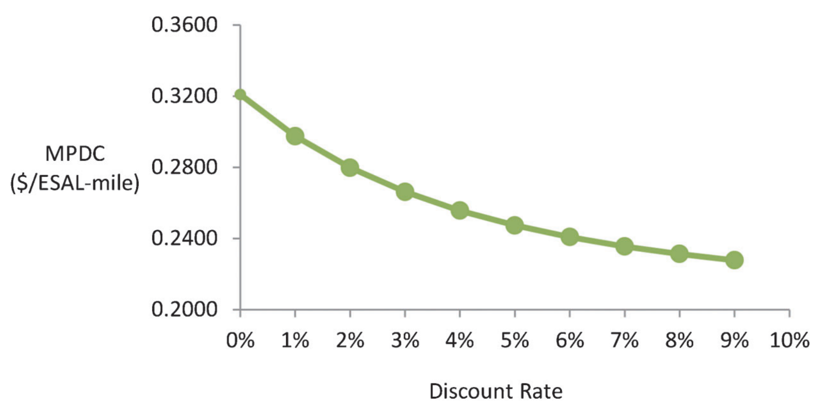


Figure 6.6 Variation of MPDC with discount interest rate—NNHS.

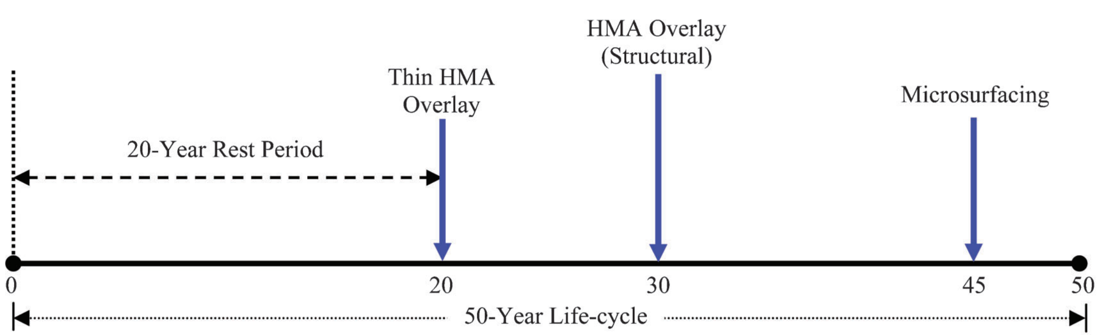


Figure 6.7 Base case—Life-cycle M&R profile based on mean rest period.

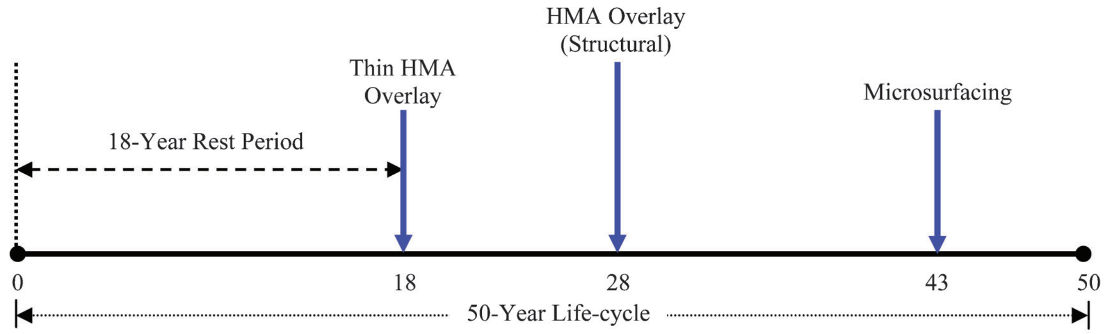


Figure 6.8 Life-cycle M&R profile with two years deviation of rest period from base case.

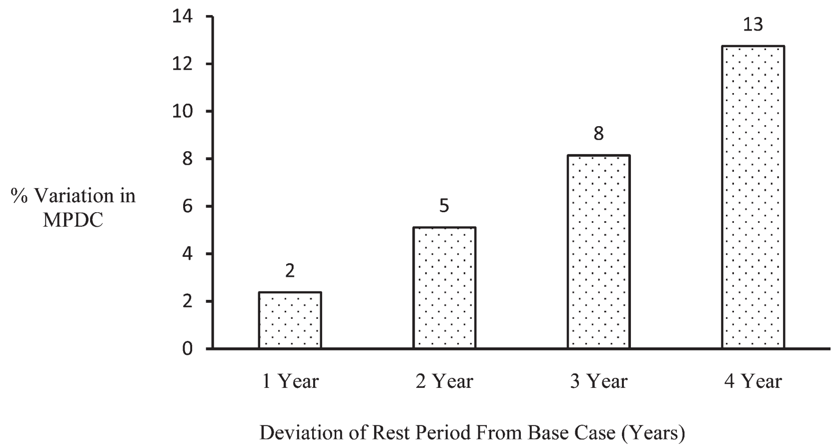


Figure 6.9 Percent variation of MPDC with variation in rest period.

18). Such reduction in the length of the rest period resulted in a shift of all maintenance activities by two years towards year zero, thus resulting in a higher EUAC (MR&R). The rest of the details (life-cycle length, effectiveness of rehabilitation and periodic maintenance, and interest rate) were identical for strategy formulation. Similarly, strategies can be formulated where the rest period exceeds the mean value. The five different cases for which strategies were formulated are shown in Table 6.5.

- From the formulated strategies, cost and traffic data were developed for five different cases of pavement rest periods. For doing this, the steps are in line with the methodology explained in Section 6.8.
- From the data, separate models were developed for five different cases of pavement rest periods (Table 6.6).
- MPDC was estimated from the developed models for three functional classes. The estimates for MPDC are presented in Table 6.7. The model and MPDC estimation steps are in line with the methodology explained in Section 6.9.

TABLE 6.5
Length of the Rest Period—Scenarios for MPDC Estimation

Scenario	Rest Period Used for Strategy Formulation
Base case	MR&R strategies based on study estimated rest period
Case -1	Rest period 1 year less than mean value
Case -2	Rest period 2 years less than mean value
Case -3	Rest period 3 years less than mean value
Case -4	Rest period 4 years less than mean value

A comparison of the MPDC estimates (Table 6.7 and Figure 6.9) showed that, with changes in the pavement rest period, the estimated MPDC also changes. The higher the deviation from the estimated rest period, the greater the difference in MPDC. Thus, if the rest period deviates by one year from the mean value, then there is an approximately 2% change in the MPDC estimates. However, if the rest period deviates by four years from the mean value, then there is an approximately 12% change in the MPDC estimates. Past studies have used expert opinion in estimating the pavement rest period for different pavement classes, therefore, the results might have had wide error bounds. In the present study, the rest periods were estimated using pavement performance models developed using real field data, thereby ensuring more reliable MPDC estimates.

For the case study, it was assumed that the rest periods are one, two, three, and four years less than the mean values, and the changes in the MPDC estimates for the reduced rest periods were determined and compared. In these scenarios, all the maintenance and rehabilitation costs occurring during the pavement life cycle were moved two years earlier, thus resulting in higher EUAC (MR&R) and higher MPDC. In alter-

TABLE 6.6
MPDC Estimation Using Different Rest Periods

Rest Period	MPDC ($/ESAL-mile)			% Difference From Base Case
	Interstate	NHS (NIS)	NNHS	
Base case rest period	0.0066	0.0599	0.2350	—
1-year deviation from base case	0.0068	0.0613	0.2405	2.38%
2-year deviation from base case	0.0071	0.0644	0.2528	5.11%
3-year deviation from base case	0.0077	0.0697	0.2734	8.15%
4-year deviation from base case	0.0087	0.0786	0.3083	12.75%

nate scenarios, if rest periods were increased by one, two, three, and four years for each MR&R strategy and MPDC was estimated, then the deviation from the base case was expected to be lower. Increased rest periods will defer all maintenance and rehabilitation costs (by the number of years the rest period is increased), thus resulting in lower EUAC (MR&R) and MPDC estimates. Thus, even if the rest period was either four years less or more from the mean value, the deviation of MPDC estimates from base-case would remain at 12.75% or lower.

6.3.2 Effectiveness of Rehabilitation Treatments

In this study, the treatment service life was used as a measure of the effectiveness of a rehabilitation treatment for MR&R strategy formulation. The service lives of different rehabilitation treatments were summarized earlier in Table 4.12. In order to study the impact of inaccuracy in the rehabilitation treatment effectiveness (service life) estimates on MPDC estimation, the developed methodology involved the following steps:

- Using a 50-year pavement life-cycle length, MR&R strategies were formulated over an infinite analysis period for new flexible pavements for five different cases of rehabilitation treatment effectiveness.
- The methodology for strategy formulation with different rehabilitation treatment effectiveness is explained with the help of Figures 6.10 and 6.11. Figure 6.10 represents the base case where the service life of a rehabilitation treatment is 15 years. Figure 6.11 represents an alternative case where the same pavement has a two-year less rehabilitation treatment service life. This reduced service life will shift backward by two years only those maintenance activities which are performed after this rehabilitation treatment. This backward shifting of maintenance activities will result in a higher EUAC (MR&R).
- The remaining details (life-cycle length, length of rest period, effectiveness of periodic maintenance, and interest rate) were kept similar for strategy formulation. The five different cases for which strategies were formulated are shown in Table 6.8.
- From the formulated strategies, the cost and traffic data were estimated for five different cases of pavement rehabilitation treatment effectiveness. For doing this, the steps are in line with the methodology explained in Section 5.8.
- From the data estimates, separate models were developed for five different cases of rehabilitation treatment effectiveness (Table 6.9).
- MPDC was estimated from the developed models for three functional classes. The estimates for MPDC are presented in Table 6.10. The model estimation and MPDC estimation steps are in line with the methodology explained in Section 5.9.

The MPDC estimates suggest that, with a change in rehabilitation treatment effectiveness, MPDC changes significantly (Table 6.10 and Figure 6.12). The larger the deviation from the mean estimated values, the greater the difference in MPDC from the base case. Figure 6.12 indicates that with one, two, three, and four years deviations of the rehabilitation treatment service life from the base case results in approximately 1%, 1.8%, 2.6%, and 3.9% changes in the MPDC estimates, respectively. The analysis results suggest that the consequences of treatment life misspecification are relatively little compared to inaccuracies in rest period estimation. Most of the past PDC estimation studies have used expert opinion in estimating the rehabilitation treatment effectiveness; this may have led to incorrect PDC estimates. For accurate estimation of MPDC,

TABLE 6.7
Rehabilitation Treatment Effectiveness—Scenarios for MPDC Estimation

Scenario	Service Life of Rehabilitation Treatment
Base case	MR&R strategies based on mean service life (used in this study)
Case 1	Service life 1 year less than mean value
Case 2	Service life 2 years less than mean value
Case 3	Service life 3 years less than mean value
Case 4	Service life 4 years less than mean value

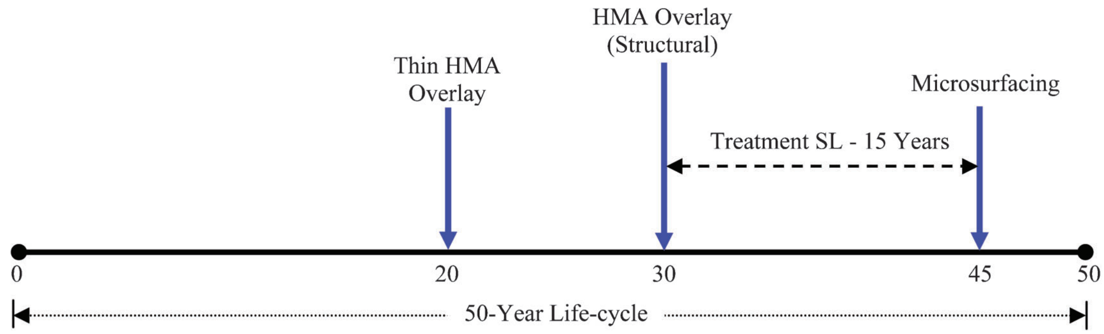


Figure 6.10 Life-cycle M&R profile based on mean treatment effectiveness.

TABLE 6.8
MPDC Estimates for Different Service Lives of Rehabilitation Treatment

	MPDC			
Service Life of Rehabilitation Treatment	**Interstate**	**NHS (NIS)**	**NNHS**	**% Difference from Base Case**
Base case SL	0.0066	0.0599	0.2350	—
1-year deviation from base case	0.0067	0.0605	0.2375	1.08%
2-year deviation from base case	0.0068	0.0616	0.2418	1.80%
3-year deviation from base case	0.0070	0.0632	0.2480	2.59%
4-year deviation from base case	0.0073	0.0657	0.2577	3.91%

TABLE 6.9
MPDC Estimates for Different Reconstruction Costs

	MPDC ($/ESAL-mile)			
Reconstruction Cost Scenario	**Interstate**	**NHS (NIS)**	**NNHS**	**% Difference from Mean Reconstruction Cost**
Base case	0.0066	0.0599	0.2350	—
+2%	0.0066	0.0595	0.2333	+0.72
+4%	0.0065	0.0591	0.2317	+1.41
+6%	0.0065	0.0586	0.2301	+2.10
+8%	0.0064	0.0582	0.2285	+2.80
+10%	0.0064	0.0578	0.2268	+3.49
+12%	0.0063	0.0574	0.2251	+4.21
+14%	0.0063	0.0570	0.2235	+4.90
+16%	0.0062	0.0566	0.2219	+5.59
+18%	0.0062	0.0561	0.2203	+6.28
+20%	0.0062	0.0557	0.2186	+6.98
−2%	0.0067	0.0603	0.2367	−0.69
−4%	0.0067	0.0607	0.2383	−1.38
−6%	0.0068	0.0611	0.2399	−2.07
−8%	0.0068	0.0616	0.2415	−2.77
−10%	0.0068	0.0620	0.2432	−3.46
−12%	0.0069	0.0624	0.2449	−4.18
−14%	0.0069	0.0628	0.2465	−4.87
−16%	0.0070	0.0632	0.2481	−5.56
−18%	0.0070	0.0637	0.2497	−6.25
−20%	0.0071	0.0641	0.2514	−6.98

TABLE 6.10
MPDC Estimation Using Different Rehabilitation Costs

Rehabilitation Cost Scenario	MPDC ($/ESAL-mile) Interstate	NHS (NIS)	NNHS	% Difference from Mean Rehabilitation Cost
Base case	0.0066	0.0599	0.2350	—
+2%	0.0066	0.0594	0.2330	+0.84
+4%	0.0065	0.0589	0.2311	+1.68
+6%	0.0065	0.0584	0.2291	+2.53
+8%	0.0064	0.0579	0.2271	+3.37
+10%	0.0063	0.0574	0.2251	+4.24
+12%	0.0063	0.0569	0.2232	+5.11
+14%	0.0062	0.0564	0.2212	+5.89
+16%	0.0062	0.0559	0.2192	+6.79
+18%	0.0061	0.0554	0.2172	+7.64
+20%	0.0061	0.0549	0.2153	+8.45
−2%	0.0067	0.0604	0.2369	−0.84
−4%	0.0067	0.0609	0.2389	−1.65
−6%	0.0068	0.0614	0.2409	−2.50
−8%	0.0068	0.0619	0.2429	−3.34
−10%	0.0069	0.0624	0.2449	−4.18
−12%	0.0070	0.0629	0.2470	−5.02
−14%	0.0070	0.0634	0.2488	−5.86
−16%	0.0071	0.0640	0.2509	−6.70
−18%	0.0071	0.0645	0.2529	−7.55
−20%	0.0072	0.0649	0.2548	−8.39

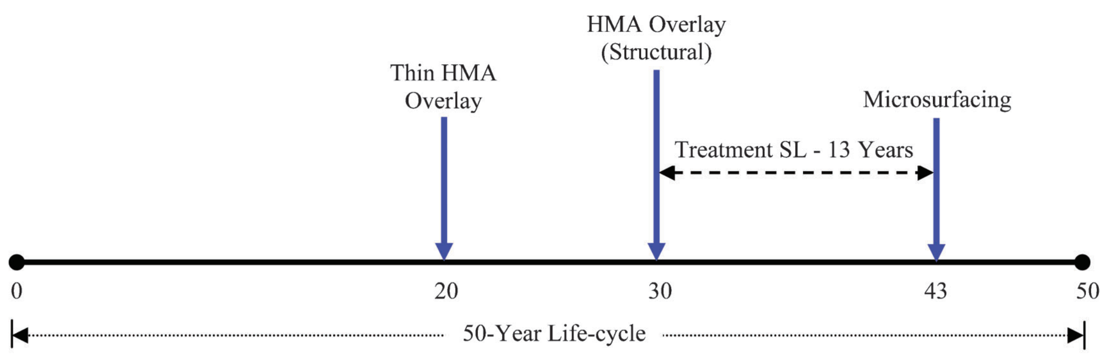


Figure 6.11 Life-cycle M&R profile with two-year deviation of service life from base case.

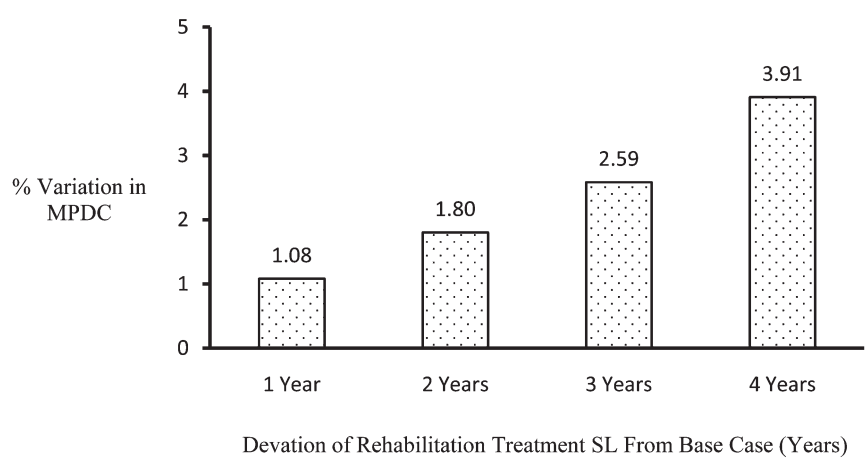


Figure 6.12 Percent variation of MPDC with variation in rehabilitation treatment effectiveness.

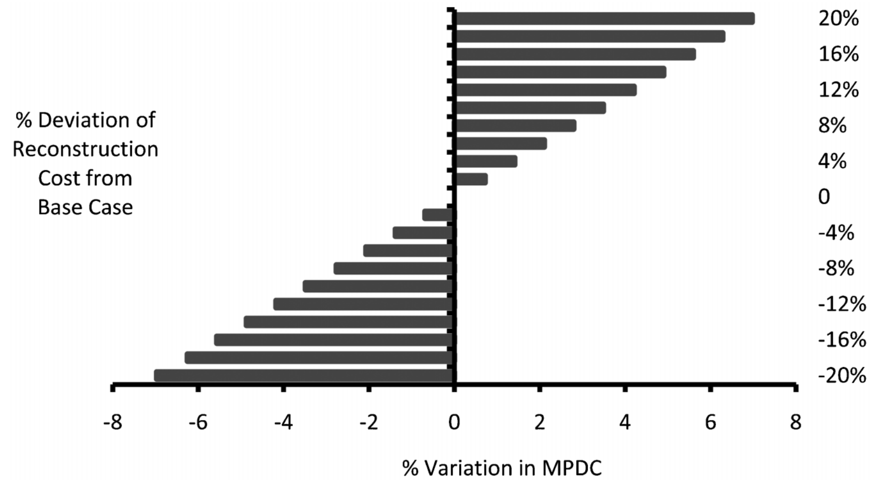


Figure 6.13 Percentage variation of MPDC with reconstruction cost changes.

rehabilitation treatment effectiveness should be estimated using the best available data and the use of expert opinion should be resorted to only where there is no other option.

From the discussion in previous paragraphs, it was assumed that the service lives were one, two, three, and four years less than the mean values, and changes in the MPDC estimates resulting from such reduced effectiveness were determined and compared. In these scenarios, all the maintenance and rehabilitation costs occurring after the first rehabilitation treatment during the pavement life cycle were moved one, two, three, and four years earlier, and resulted in a higher EUAC (MR&R) and a higher MPDC. In another scenario, if the service lives were increased by one, two, three, and four years for each MR&R strategy and MPDC was estimated, then the deviation from the base case was expected to be lower. Increasing the rehabilitation treatment service life will delay all maintenance activities (by the number of years the rehabilitation treatment service life was increased), thus resulting in lower EUAC (MR&R) and MPDC estimates. Thus, if the service life is misinterpreted by either four years less or more from the mean value, the deviation of the resulting MPDC estimates from the base case would remain 3.91% or lower.

6.4 Sensitivity of MPDC with Respect to Reconstruction and Rehabilitation Cost

Reconstruction, rehabilitation, and periodic maintenance are the three major activities that are carried out during the pavement life cycle. This study used the unit cost ($/lane-mile) of reconstruction, rehabilitation, and periodic maintenance treatment from the contract data file of INDOT's database. All costs were brought to their equivalent 2010 constant dollar values using FHWA's CPI. Since the data were obtained from projects undertaken during 2001–2006, an investigation of the changes in MPDC with respect to changes in the unit cost of reconstruction and rehabilitation from their mean value (base case) was carried out. This is discussed in the following section.

6.4.1 Sensitivity of MPDC with Respect to Reconstruction Cost

Separate reconstruction costs for Interstate and non-Interstate highway systems for both flexible and rigid pavements were used for the MR&R strategy formulation. The reconstruction costs used for MR&R strategy formulation are provided in Section 5.4. In order to study the impact of changes in MPDC with change in reconstruction cost, using a 50-year life-cycle length, MR&R strategies were formulated over an infinite analysis period for new flexible pavements. MR&R strategies were formulated for 21 different cases of reconstruction cost. The reconstruction costs considered in this study were 0%, 2%, 4%, 6%, 8%, 10%, 12%, 14%, 16%, 18%, and 20% from the base case. From the formulated strategies, the cost and traffic data were estimated for 21 different cases of pavement reconstruction cost. From the data estimates, separate models were developed for the 21 cases. The MPDC was estimated from the developed models for the three functional classes (Table 6.9).

It was shown in Figure 6.13 that MPDC changes with changes in the reconstruction cost, and the changes in MPDC with respect to the reconstruction cost is linear. Slight variations in the estimation of the reconstruction cost, however, were not significant in that an approximately 10% error in estimation of reconstruction cost only led to about a 3.5% error in the MPDC estimates.

6.4.2 Sensitivity of MPDC with Respect to Rehabilitation Cost

The rehabilitation cost can have a major impact on MPDC estimates as it is typically many times more than the periodic maintenance cost and also rehabilitation activities usually take place at least one to three times as often in a pavement life cycle. Different rehabilitation costs for Interstate, NHS (NIS) and NNHS for flexible and rigid pavements were used for the MR&R strategy formulation (shown in Section

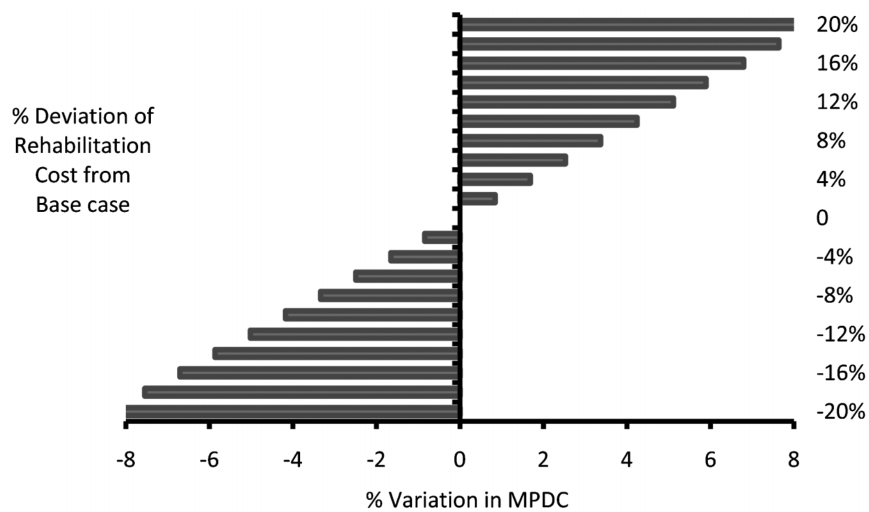


Figure 6.14 Percentage variation of MPDC with rehabilitation cost changes.

5.4). In order to study the impact of changes in MPDC with changes in the rehabilitation cost, using a 50-year life-cycle length, MR&R strategies were formulated over an infinite analysis period for new flexible pavements. MR&R strategies were formulated for 21 different cases of rehabilitation cost. The rehabilitation costs considered were 0%, 2%, 4%, 6%, 8%, 10%, 12%, 14%, 16%, 18% and 20% from the base case. From the formulated strategies, the cost and traffic data were estimated for 21 different cases of pavement rehabilitation cost. From the data estimates, separate models were developed for 21 different cases. MPDC was estimated from the developed models for the three functional classes (Table 6.10).

It was shown (Figure 6.14) that MPDC changes linearly with changes in the rehabilitation cost. Similar to the case of reconstruction cost, slight inaccuracies in the estimation of rehabilitation cost are not that alarming because it was observed that a 10% error in the estimation of the rehabilitation cost only led to only 4% error in the MPDC estimates.

6.5 Chapter Summary

This chapter presented a detailed discussion of the sensitivity of MPDC estimates with respect to the pavement life-cycle length, discount rate, effectiveness of rehabilitation treatments, rest period, and cost of pavement reconstruction and rehabilitation. For the sensitivity analysis, the developed MR&R strategies were adjusted to incorporate different values of each input factor, keeping other factors the same (pavement life-cycle length, interest rate, rest period, rehabilitation treatment effectiveness and reconstruction and rehabilitation treatment cost). Using the adjusted strategies, OLS regression models were estimated to describe the change in MPDC with respect to changes in the input variables.

The results suggest that the pavement life-cycle length has a significant impact on MPDC estimates. MR&R strategies for pavement life-cycle lengths of 35, 40, and 45 years were formulated to estimate MPDC for comparison with MPDC based on a 50-year life-cycle. It was observed that, for longer pavement life-cycles, MPDC estimates were lower, and vice versa. It is important to select carefully the pavement life-cycle length guided by the current highway agency MR&R practices. It was also observed that the discount rate can have a significant impact on the MPDC estimation results. MPDC changes in a non-linear fashion with changes in the discount rate (MPDC decreases with increases in the discount rate, and vice versa). MPDC estimates with the 4% real discount rate used in this study was compared with discount rates ranging from 0% to 10%. Since changes in the discount rate can significantly influence MPDC estimates, the selected discount rate should be based on the latest recommendations and practices in the highway industry.

The sensitivity of MPDC with respect to the rest period and also to the effectiveness of rehabilitation treatments was also evaluated. The results suggest that incorrect estimation of the rest period and the effectiveness of the rehabilitation treatment can change MPDC estimates. It was observed that MPDC estimates could vary by about 2–12% with a one- to four-year incorrect estimation of the rest period. However, in the case of rehabilitation treatments, a one- to four-year incorrect estimation of rehabilitation effectiveness can cause an approximately 1–4% change in MPDC estimates. Lastly, the impact of the accuracy of estimating the pavement reconstruction and rehabilitation treatment cost on MPDC estimates was investigated. The results seem to indicate that incorrect estimates of either the reconstruction or rehabilitation cost can change the MPDC estimates but the results are not critical in that a 10% error in the estimation of the reconstruction or rehabilitation cost led to only 4% error (approximately) in MPDC estimates.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 Synopsis of the Research

This study addressed the vital issue of marginal pavement damage cost estimation that highway agencies worldwide continue to grapple with. An analytical framework was developed for estimating the marginal pavement damage cost on the basis of practical and realistic strategies for highway maintenance. The study began with an extensive review of the literature on the subject, thus facilitating identification of the gaps in the existing practice and research and the establishment of pavement families on the basis of surface type, functional class, and traffic loading. The framework, which can be applied for pavements in different families, incorporates pavement MR&R treatment types, costs, timing, traffic volumes, and growth projections from an entire state's highway network, pavement classification based on surface type, functional classes and traffic loading distribution, and age-based pavement MR&R strategies. Using the developed framework, the marginal cost of pavement damage was estimated for each pavement family and age group. Also, the consequences of non-consideration of reconstruction, routine maintenance, and/or periodic maintenance cost were quantified in terms of underestimation of the pavement damage cost. Similarly, the consequences of not considering non-truck traffic and also of a possible mathematical misspecification of the load-damage functional relationship, were investigated. Furthermore, the variation of marginal pavement damage cost with respect to key policy and analysis variables (i.e., length of pavement life cycle, discount rate, MR&R treatment effectiveness, and MR&R treatment cost) was explored using sensitivity analysis.

7.2 Recapitulation of the Problem Statement and Summary of the Findings

The literature review confirmed that very few studies adopted a truly comprehensive approach for marginal pavement damage cost estimation on the basis of practical and realistic practices of maintenance, rehabilitation and reconstruction. Most past studies used data from a few WIM stations that did not adequately represent the loading patterns across the different functional classes. Also, many studies considered only a single type of overlay applied at fixed intervals, thereby missing the practical reality that there are many overlay types, depending on the overlay material types and thickness, and that application intervals are not (and should not be) constant. Also, it was shown that the methodology adopted by a number of past studies involved just a single highway segment and then generalized for the entire network without accounting for the significant heterogeneity that is encountered across different segments, in practice. Thus, it is necessary to use data on treatment cost and performance and traffic volumes and trends from representative sample pavement sections in each established family. Further, there should be a clear dichotomy between strength- and capacity-driven expenditure so that damage-based costs are not unfairly or unduly inflated by the inclusion of capacity-based costs. Also, an appropriate time span for the analysis must be established so that long-term expenditures, traffic, and performance trends can be established with minimum bias. In addition, an appropriate road-use measure should be selected that is consistent with the objective of the analysis (which, in the context of this study, is related to pavement damage). Another important issue is that all of the categories, not just one or a two, of the costs associated with pavement damage repair, must be considered in order to reflect the true and practical nature of agency repair decision making.

It is also important for pavement damage cost estimation studies to duly recognize that the length of the pavement rest period can be different from the service lives of rehabilitation and periodic maintenance treatments as well as for different pavement families depending upon the traffic loading and climate. Therefore, an appropriate approach is needed to establish the rest periods and the effectiveness of the maintenance and rehabilitation treatments prior to MR&R strategy formulation.

On the basis of the identified gaps in the existing practices of pavement damage cost estimation, this study developed a framework with MR&R strategies that incorporated not only reconstruction, rehabilitation and maintenance costs, but also the treatment selection and timing criteria, as a matter of practicality. This study applied the developed framework to estimate the cost of pavement damage for different families and ages. The study results showed that pavement damage cost is influenced significantly by traffic loading levels and age. It was seen that the marginal pavement damage cost increased with increasing traffic and pavement age. Overall, the marginal pavement damage cost estimates were found to range from \$0.006 per ESAL-mile on Interstate highways to \$0.218 per ESAL-mile on non-national highway system.

The results showed that non-consideration of reconstruction and maintenance cost can have serious consequences on the estimated marginal pavement damage cost. To show this, the marginal pavement damage cost for four different cost scenarios were estimated: (i) by considering all relevant pavement damage repair costs (reconstruction, rehabilitation, and periodic and routine maintenance); (ii) by considering all relevant pavement damage repair costs except reconstruction; (iii) by considering all relevant pavement damage repair costs except reconstruction and routine maintenance; and (iv) by considering rehabilitation only, applied at fixed intervals of time. The results showed that non-consideration of reconstruction or reconstruction and routine maintenance cost can result in 79% and 83% underestimation of the actual marginal pavement damage cost, respectively. The analysis also showed that the unrealistic approach of considering only rehabilitation treatments applied at fixed intervals can lead to as much as 86% underestimation of the actual marginal pavement damage cost. The results also suggested that non-consideration of non-truck traffic has insignificant impact on marginal pavement damage cost estimates; therefore, it is concluded that it is appropriate to exclude automobiles from pavement damage cost analysis.

This study conducted a sensitivity analysis of the pavement damage cost with respect to the pavement life-cycle length, discount rate, rest period, effectiveness of rehabilitation treatments and the cost of pavement reconstruction and rehabilitation treatment. The results suggested that the marginal pavement damage cost estimates are highly sensitive to the pavement life-cycle length. All else being equal, the marginal pavement damage cost was found to be low for longer pavement life cycles and vice versa. It was concluded that it is very important to select an appropriate pavement life-cycle length that reflects the particular highway agency's MR&R practices. Similarly, it was determined that the marginal pavement damage cost estimates are very sensitive to the discount rate used for analysis. As such, the appropriate discount rate should be selected on the basis of the current policies of the highway agency. The study also evaluated the sensitivity of marginal pavement damage cost with respect to the length of the rest period of a reconstructed pavement and also to the effectiveness (treatment service life) of the rehabilitation treatments. It was shown that incorrect estimation of either the rest period or the rehabilitation treatment service life can significantly alter the estimated marginal pavement damage cost; and the consequences are more severe in the case of the rest period compared to the rehabilitation treatment service life. An assessment of the impact of inaccuracy in the pavement reconstruction and rehabilitation treatment costs revealed that such inaccuracies can cause some variations in the marginal pavement damage cost estimates, albeit to a relatively minor degree compared to the other factors.

7.3 Contribution of this Research

This study is of interest to highway agencies that face maintenance funding shortages and, thus are seeking options to raise revenue such as establishing or updating highway user charges on the basis of the damage incurred to highway infrastructure. This research effort was aimed at developing a comprehensive marginal pavement damage cost estimation methodology that could help transportation agencies in overcoming the limitations in existing techniques. The major contributions of this research are summarized as follows.

As duly recognized in the literature, the first step in any effort towards marginal pavement damage cost estimation is to correctly identify the various repair cost categories that are related to pavement damage. In most of the past studies, a parochial range of cost categories, namely, rehabilitation, or rehabilitation and periodic maintenance, only were considered. However, it is a truism that reconstruction, rehabilitation, and periodic and routine maintenance are expenditures that are incurred due to pavement loading and, consequently, pavement damage, and thus are strength-driven expenditures. Most past studies on pavement damage cost estimation failed to explicitly define which cost categories should be included in pavement damage cost estimates and therefore did not include all of the pavement damage repair categories that are associated with strength-driven expenditures for pavement damage. This report documents a study effort that is probably the first pavement damage cost estimation study that explicitly defines strength-driven and capacity-driven expenditures and explicitly considers all of the expenditures in the former category (reconstruction, rehabilitation, and maintenance) for the analysis.

Unlike most past studies where the marginal pavement damage cost was estimated without considering the realistic and practical highway agency MR&R strategies, this study incorporated actual and practical highway agency decision making processes and guidelines with regard to treatment types and timings into marginal pavement damage cost estimation. Most past studies did not adequately consider such practical realities and instead adopted untenable strategies that involved a single type of rehabilitation treatment applied at fixed intervals or rehabilitation and periodic maintenance treatments only, without considering actual treatment service lives.

To reflect the state of practice as well as engineering practicality, this study duly carried out the analysis for different pavement families, that is, for the different surface types (rigid and flexible), the highway functional classes (Interstate, national highway system non-Interstate, and non-national highway system) and the different levels of traffic volume. The detailed pavement classification used in this study enabled capturing the impact of pavement deterioration and the resulting expenditures more reliably for various pavements that are designed differently and deteriorate differently, and necessarily receive different repair actions.

Unlike most of the past marginal pavement damage cost estimation studies that either completely failed to account for pavement age or did not explicitly consider that attribute, this study carried out the analysis for five different pavement age groups and demonstrated analytically the impact of pavement age on marginal pavement damage cost estimates. The results show that the cost of pavement damage, and consequent user charges, are generally higher for old pavements compared to new ones.

PART II. APPENDIX A. SUMMARY OF HCA STUDIES AND RELATED CONCEPTS

1. 1982 Federal Highway Cost Allocation Study

The U.S. Department of Transportation conducted a highway cost allocation study in 1982 to allocate federal highway program cost among the various vehicle groups responsible for road wear. The purpose of study was to assess the equity of federal user fee structure and to recommend changes if necessary. In the study, a new procedure was adopted for allocating pavement rehabilitation and resurfacing costs. Mathematical models were developed to relate the degree to which different vehicle classes "consumed" the pavement structure and contributed to the pavement deterioration. This is also called consumption method. The models helped to estimating the contribution of vehicle axle loads to different pavement distresses that necessitate the rehabilitation activities. Similarly, changes were made to procedure for allocation of new pavement cost. Unlike 1965 Federal HCA study which used an incremental method for allocation of new pavement cost, the 1982 study allocated new pavement cost to different vehicle classes in using a reverse incremental or uniform removal technique. The 1982 study did not account for the maintenance cost.

In the 1982 Federal HCA study, analysis was carried out for eight highway classes. Urban and rural Interstates, other arterials, collectors, and local roads represented these highway classes. The analyses were carried out for 38 vehicle classes but results were reported for 15 vehicles classes only. The study determined the share of total cost attributable to various vehicle classes. Common costs, which were allocated to different vehicle classes on basis of vehicle miles travelled, constituted 46.7% of total cost. The attributable cost which represented 53.3% of total cost was assigned to different vehicle classes depending upon their contribution to a particular cost. The study results showed that autos and motorcycles, combination vehicle and single-unit truck and buses were responsible for 16.8%, 56.9% and 26.7% cost for the forecast period.

2. 1984 Indiana HCA Study

In 1984, the Indiana Department of Transportation sponsored a cost allocation study to determine the cost responsibilities of different vehicle classes for highway use. The study scope covered six highway classes: urban and rural Interstate, primary and secondary state routes, country roads, and city roads. Costs were allocated for each of fourteen vehicle classes. That study used the thickness incremental method instead of traditional incremental method. The latter involves traffic volume increment or uniform removal technique (traffic volume decrements) used in the 1982 Federal HCA study. The pavement thickness increment procedure proposed in that study eliminated the need for the iterative procedure for calculating cost responsibilities of different vehicles. Four and one-half inches for rigid pavement and eight and one-half inches for flexible pavements were established as the minimum base thicknesses. The base facility cost was allocated to all vehicles on the basis of facility use (vehicle-miles travelled). In the thickness incremental method, the total pavement thickness (in addition to minimum thickness) is divided into different increments. Pavement thickness increments are added to base facility successively, and the cost responsibility factor for each vehicle class is estimated using AASHTO equations. When all the thickness increments have been added the total cost responsibility of each vehicle class is computed as simple addition of its cost responsibility for all thickness increments and base facility (*23,26*).

The pavement rehabilitation cost allocation method used in 1982 Federal HCA study, did not explicitly consider the effect of maintenance cost in its analysis or the interaction between different distresses (*28*). These limitations of federal methods were identified by Fwa and Sinha (*28*) who proposed an aggregate damage model for relating pavement performance to pavement maintenance.

3. I997 Federal HCA Study

The last major HCA study at federal level was conducted in 1997 and further updated by an addendum in 2000. The purpose of that study was to estimate cost responsibilities of different vehicle classes for federal highway program cost and to evaluate whether different vehicle classes paid a proportionate share of their cost responsibility. It was also aimed at studying the impact of changes in Federal-aid highway program and different user fees on the equity of Federal highway user fee structure (*17*).

For the pavement cost allocation, in addition to new pavement cost and rehabilitation cost, maintenance cost was also considered. New pavement cost allocation approach used in 1997 Federal HCA study is similar to 1982 Federal HCA study. Uniform removal technique or reverse incremental method was used to allocate construction cost of new pavement. However, unlike 1982 Federal HCA study, the base facility cost was allocated to different vehicle classes in proportion to vehicle miles travelled weighted by passenger car equivalent (PCE) for each vehicle class. The enhanced facility cost of the new pavement was allocated using the procedure similar to 1982 Federal HCA study (where costs were assigned on the basis of ESAL contribution).

For allocation of rehabilitation and maintenance costs, the national pavement cost model (NAPCOM) was adopted. NAPCOM uses the basic framework (individual distress models) of the 1982 Federal HCA study but with significant improvements. NAPCOM helps to establish the applicable types of pavement deterioration and the responsible vehicle. Pavement deterioration analysis was carried out using data from Highway Performance Monitoring System (HPMS) pavement sections. The study considered load- and non-load-related cost for pavement rehabilitation and maintenance. The load-related costs are determined using NAPCOM instead of the fourth-power law. The non-load portion of cost was attributed to climatic and aging effects and hence was shared among all vehicle classes based on their VMT contribution. The load-related portion of cost was estimated on the basis of share of each vehicle class to pavement distresses resulting from that particular vehicle class for different road functional classes. The pavement distress model also estimated the cost share due to climate and aging. All expenditures in a particular year were allocated to road users. Unlike previous studies, the 1997 federal HCA study also considered marginal social costs, i.e., air pollution, noise, congestion, crash costs and waste disposal cost (*17,22*). The incremental pavement deterioration cost associated with an extra mile of travel, was found to vary with pavement design and condition. The pavement damage cost attributable to each additional mile of travel, for different vehicles, is summarized in Table II.A.1.

4. 2009 Oregon HCA Study

In 1937, the first highway cost allocation study in the nation was carried in Oregon, and to date, the state has conducted sixteen highway cost allocation studies so far. The latest study, in 2009 used the FHWA road classification system. All vehicles weighing less than 10,000 pounds gross weight were placed in light or "basic" vehicles group, while all other vehicles were classified as heavy vehicles. The cost of new pavement construction was allocated using incremental method. For allocation of load-related portion of maintenance and rehabilitation cost NAPCOM equations were used. Non-load-related or common costs were allocated using a number of cost allocators. The study results found that light vehicles (vehicles weighing less than 10,000 lbs) were projected to pay 67.1% of the state highway users' revenue while heavy vehicles were estimated to contribute 32.9% during the projected period. The equity ratio for light and heavy vehicles was found to be 0.9915 and 1.0173, respectively. The equity ratio for individual heavy vehicles was found to vary for different vehicles: certain classes were found to be overpaying while others were underpaying their fair share.

5. Performance-Based Methodology

According to the performance-based methodology presented by Fwa and Sinha (*28*), the pavement damage due to load factors and explained by AASHTO equations is bounded between no-loss line and design equation curve (represented by area A in Figure II.A.1); the pavement damage due to non-load factors and interaction between load-related and non-load-related is bounded between design equation curve and zero-maintenance curve (represented by area B in Figure II.A.1). The load and non-load-related cost shares were estimated using the proportionality assumption and equations presented as follows (*27,28*):

$$\frac{a}{(a+b+c+d)} = \frac{b}{(b+c+d)} \qquad \text{(II.A.1)}$$

$$\frac{d}{(a+b+c+d} = \frac{c}{(a+b+c)} \qquad \text{(II.A.2)}$$

These equations assume that the load share of the interaction damage is directly proportional to the load share of the overall damage. A similar assumption is made for the non-load share (Figure II.A.2). That study found that load-related costs accounted for up to 70 percent of total maintenance expenditure. The load-related cost was assigned on the basis of ESAL while non-load portion of cost was allocated on the basis of vehicle-miles travelled. Traffic loading, environmental effects, pavement characteristics and routine maintenance were identified as the four major factors influencing pavement performance.

6. National Pavement Cost Models

The improvements to individual distress model or federal method for pavement damage cost estimation continued during eighties and nineties. The mechanistic pavement distress models developed for 1982 federal HCA study were based on a small number of hypothetical pavement sections (*17*). Original models were improved by using actual pavement section data from Highway Performance Monitoring System (HPMS) and also in addition to models used in 1982

TABLE II.A.1
Unit PDC for Various Truck Types by Functional Class (*18*)

Road Type	Vehicle Class	Pavement Damage Cost (Cents per Mile, $1997)
Rural Interstate	40,000 4-axle single unit truck	1.0
Urban Interstate	40,000 4-axle single unit truck	3.1
Rural Interstate	60,000 4-axle single unit truck	5.6
Urban Interstate	60,000 4-axle single unit truck	18.1
Rural Interstate	60,000 5-axle combination truck	3.3
Urban Interstate	60,000 5-axle combination truck	10.5
Rural Interstate	80,000 5-axle combination truck	12.7
Urban Interstate	80,000 5-axle combination truck	40.9

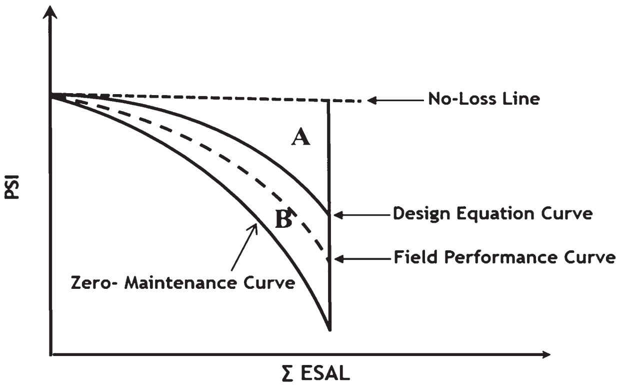


Figure II.A.1 PSI-ESAL loss as a representation of pavement damage (*28*).

Federal HCA study, some new models for both flexible and rigid pavements were developed which resulted into National Pavement Cost Model (NAPCOM).

NAPCOM was first used in 1997 Federal HCA study. NAPCOM also helped to develop load equivalency factors (LEF) at national and state level using data from HPMS pavement sections. Pavement deterioration curves developed using NAPCOM are less steep sloped unlike the approximate 4^{th} power relationship established by AASHTO. In NAPCOM separate pavement wear relationship for different distresses have been developed, unlike a single pavement deterioration relationship based on a subjective criterion (Present Serviceability Index (PSI)) used by AASHTO.

Pavement deterioration analysis is applied to a large number of representative pavement sections to determine the pavement condition at end of each year of analysis. When a pavement section reaches threshold level of any specific distress, distress level, its contribution to rehabilitation and reconstruction decision and, vehicle responsible for distress are recorded by NAPCOM. NAPCOM outputs vehicle class responsibility for 20 different vehicle classes, and for 10 different road functional classes. NAPCOM uses individual distress model for flexible and rigid pavement. For flexible pavements NAPCOM has individual distress models for traffic-related Present Serviceability Rating (PSR) loss, expansive-clay-related PSR loss, fatigue cracking, thermal cracking, rutting, and loss of skid resistance, and for rigid pavement the distress models includes traffic related PSR loss, faulting, loss of skid resistance, fatigue cracking, spalling and soil-induced swelling and depression.

TABLE II.A.2
Deduction Point System Used by NAPCOM

Distress Type	Flexible Pavement	Rigid Pavement
PSR Loss	50	50
Cracking	25	30
Rutting	30	—
Skid resistance loss	20	20
Faulting	—	30
Spalling	—	10
Swelling and depression	—	20

The number of lanes, pavement type and thickness, pavement condition, average daily traffic, percentage of heavy vehicles, estimated 20-year traffic levels and some basic pavement information needed for NAPCOM are extracted from HPMS pavement sections data. Addition data items like freeze-thaw cycles, freezing index, modulus of subgrade reaction and thickness of base layer are obtained from other sources. In its pavement analysis, NAPCOM uses HPMS sections PSR and International Roughness Index (IRI) data to estimate the age of different pavement sections (as PSR and IRI are the only two pavement condition data which are reported by HPMS). NAPCOM estimates the level of other distresses like rutting and cracking etc. using age and accumulated traffic. NAPCOM uses an overall pavement condition rating (OPCR) which is calculated by applying "deduction point" for different distress level. The current deterioration levels of a pavement segment are multiplied with maximum deduction points allowed for a particular distress and subtracted from 100. A pavement is considered candidate for rehabilitation when OPCR is 10 or less. The different deduction points considered in NAPCOM are summarized in Table II.A.2.

A national model that was developed using data from individual states, NAPCOM is unable to tailor all specific parameters of the model to best match the conditions in each state (*148*). Although the NAPCOM

a		Load-related Effects
b	Interaction Effect	Load-related Effects
c		Non-load-related Effects
d		Non-load-related Effects

Figure II.A.2 Load and non-load-related pavement damage (*28*).

uses data from HPMS pavement section, missing pavement information is imputed for PDC estimation purposes. NAPCOM estimated PDC is at aggregate level as it uses aggregate value of annual highway expenditure by road functional class and vehicles miles of travel by vehicle configuration and road functional class. Also, NAPCOM is not tailored to be consistent with specific maintenance strategies typically used by highway agencies. Highway agencies use different trigger criteria for maintenance and rehabilitation decision making; NAPCOM's use of only one criterion may not be appropriate.

PART II. APPENDIX B. MODELS AND MPDC ESTIMATES USING ECONOMETRIC APPROACH

1. Gibby et al. (*33*) Maintenance Cost Model

Using pavement maintenance cost data from randomly selected pavement sections, the following maintenance cost model was developed:

$$TOTALCOST = \left(47 * 10^{6}\right) * \left(\mathrm{HT\_AADT}^{0.21}\right) * \left(\mathrm{PL\_AADT}^{0.06}\right) * \left(AGE^{0.17}\right) * \left(\mathrm{AATEMP}^{-2.11}\right) * \left(\mathrm{SHD}^{-0.36}\right) * \left(e^{NOSHD}\right)^{-0.61} * \left(e^{MTN}\right)^{-0.38} * \left(e^{BR}\right)^{-14.9} * \left(e^{MNCL}\right)^{-1.23} * \left(e^{DIST2}\right)^{0.66} * \left(e^{DIST11}\right)^{0.60}$$

Where: TOTALCOST is the total pavement maintenance cost for a one-mile section over three fiscal years (1984–1987), in dollars; HT_AADT is the daily volume of trucks with at least 5 axles; PL_AADT is the daily volume of passenger cars and trucks with less than 4 axles; AGE is the pavement age (the time since last major pavement work), in years; AATEMP is the average annual temperature, in degree Fahrenheit; SHD is the Shoulder width, in ft; NOSHD (1= no shoulder; 0=shoulder); MTN (l = Mountain climate; 0 = not Mountain climate); BR (l = the one mile is entirely bridge section; 0=at least part of the section not a bridge); MNCL(l = minor collector; 0 = not minor collector); DIST2 (l = Caltrans District 2; 0 = not District 2); DIST11 (l = Caltrans District 11; 0 = not District 11).

2. Martin (*34*) Maintenance and Construction Expenditure Models

Maintenance Expenditure Model

$$\text{Maint EXPEND} = \alpha + \beta_1 * (\text{RUV}) + \beta_2 * \text{Pavement Age}$$

Where: Maint EXPEND = the annual average total maintenance expenditure/annual average routine maintenance expenditures or annual average periodic maintenance expenditure; RUV = the road use variable and has forms (1) Cumulative ESAL/lane/year (Heavy Vehicles) (2) Cumulative Gross Vehicle mass/lane/year (Heavy Vehicles) (3) Cumulative passenger car units/lane/year (All Vehicles), and (4) AADT/lane (All Vehicles).

Construction Expenditure Model

For estimating pavement construction costs ($/lane-mile), Martin (*34*) developed relationship between total pavement construction cost and pavement design variable. The general functional form of the model is as follows:

$$\text{Const EXPEND} = \alpha + \beta_1 * \text{PDV} + \beta_2 * \text{PDV}^2 + \beta_3 * \text{PDV}^3$$

Where: Const EXPEND = the total expenditure for pavement construction or replacement per lane-Km; PDV is the pavement design variable and has three forms: (1) Cumulative ESAL/lane over pavement design life, (2) Cumulative Gross Vehicle mass/lane over pavement design life, and (3) Cumulative passenger car units/lane over pavement design life.

3. Hajek et al. (*35*) Maintenance Cost Models and PDC Estimates

The following models were developed by Hajek et al. (*35*):

$$\text{EUAC}_{\text{New Pavements}} = 1601 + 311(Log_{10}ESAL)^2 + 1394N + \varepsilon$$

$$\text{EUAC}_{\text{In-Service Pavements}} = 100 + 160(Log_{10}ESAL)^2 + 558N + \varepsilon$$

The two ESAL cost functions were differentiated to obtain the marginal cost as follows:

$$\text{MCOST}_{\text{New Pavements}} = 622\left(\frac{\text{Log10ESALs}}{\text{ln 10.ESALs}}\right)$$

$$\text{MCOST}_{\text{In-service Pavements}} = 322\left(\frac{\text{Log10ESALs}}{\text{ln 10.ESALs}}\right)$$

Where: $\text{EUAC}_{\text{New Pavements}}$ = Equivalent uniform annual cost (EUAC) per lane (new pavements); $\text{EUAC}_{\text{In-Service Pavements}}$ = EUAC per lane for in-service pavements; ESALs = annual number of equivalent single axle loads per lane; N = indicator variable (0 for southern and 1 for northern Ontario); ε = error; $\text{MCOST}_{\text{New Pavements}}$ = MPDC per ESAL-km for a new pavement; $\text{MCOST}_{\text{In-service Pavements}}$ = MPDC per ESAL-km for a in-service pavement.

The pavement maintenance and rehabilitation cost per ESAL-km estimated by Hajek et al. (*35*) for different road classes are summarized in Table II.B.1.

TABLE II.B.1
Pavement Damage Cost—Ontario, Canada (*35*)

	Marginal Pavement Cost Per ESAL-Mile ($)		Marginal Pavement Cost Per Mile for 5-Axle Truck ($)	
	Pavement Type		Pavement Type	
Highway Class	**New**	**In-Service**	**New**	**In-Service**
Urban freeway	0.0025	0.0013	0.004	0.002
Major arterial	0.0092	0.0047	0.014	0.007
Minor arterial	0.0158	0.0082	0.024	0.012
Collector	0.01401	0.0206	0.060	0.031
Local	0.5968	0.3070	0.895	0.461

3. Li and Sinha (*36*) Load- and Non-Load-Related Rehabilitation and Maintenance Cost Models

Rehabilitation and Periodic Maintenance Models for Flexible Pavements

$$\begin{aligned}\text{EXPEND}_{(\text{R})} = {} & 172{,}430 + 0.3113\left(\frac{\text{CESALs}}{\text{THICK}}\right) \\ & + 300.8(\text{P200} * \text{MOIST} * \text{FZI}) \\ & - 145{,}380 * \mathit{DRAINCO} \\ & + 701.2(\mathit{AGE} - 10) * \text{DM}\end{aligned}$$

$$\begin{aligned}\text{EXPEND}_{(\text{MR})} = {} & 170{,}310 + 0.3110\left(\frac{\text{CESALs}}{\text{THICK}}\right) \\ & + 300.7(\text{P200} * \text{MOIST} * \text{FZI}) \\ & - 143{,}240 * \mathit{DRAINCO} \\ & + 700.4(\mathit{AGE} - 10) * \text{DM}\end{aligned}$$

Rehabilitation and Periodic Maintenance Models for JCP

$$\begin{aligned}\text{EXPEND}_{(\text{R})} = {} & -629{,}000 + 0.038(\text{CESALs}) - \\ & 40{,}020(\text{SLABTH}) + \\ & 13{,}274(\text{Days} > 32C) + 34{,}760 * \text{AGE}\end{aligned}$$

$$\begin{aligned}\text{EXPEND}_{(\text{MR})} = {} & -665{,}900 + 0.0374(\text{CESALs}) - \\ & 38{,}800(\text{SLABTH}) + \\ & 13{,}409(\text{Days} > 32C) + 37{,}610 * \text{AGE}\end{aligned}$$

Rehabilitation and Periodic Maintenance Models for Composite Pavements

$$\begin{aligned}\text{EXPEND}_{(\text{R})} = {} & +540{,}900 + 0.2409\left(\frac{\text{CESALs}}{\text{THICK}}\right) \\ & + 71.03(\text{MOIST} * \text{FZI}) \\ & - 10{,}393 * \text{MINTEM} \\ & + 10{,}593 * (\text{AGE} - 10) * \text{DM}\end{aligned}$$

$$\begin{aligned}\text{EXPEND}_{(\text{R})} = {} & +448{,}400 + 0.2327\left(\frac{\text{CESALs}}{\text{THICK}}\right) \\ & + 71.05(\text{MOIST} * \text{FZI}) \\ & - 8{,}337 * \text{MINTEM} \\ & + 8{,}962 * (\text{AGE} - 10) * \text{DM}\end{aligned}$$

Where: EXPEND (R) = expected rehabilitation expenditures after the service of a life cycle ($/lane-mile); EXPEND (MR) = expected periodic maintenance and rehabilitation expenditures after the service of a life cycle ($/lane mile); CESALs = Total ESALs (18 kips) applied to the pavement during a life cycle; THICK = total thickness of flexible and composite pavements (inches); SLABTH = slab thickness of JCP pavements (inches); P200 = subgrade material percent passing a No. 200 sieve (weight%); MOIST = subgrade moisture content (%); FZI = average freeze index during one life cycle (in degree-days); DRAINCO = drainage coefficient; DAYS > 32°C = annual average number of days greater than 32°C during one life cycle; MINTEM = annual average minimum temperature in one life cycle (°F); AGE = pavement age at time of rehabilitation (in years); DM = dummy variable (1 if age ≥11 years, 0 otherwise).

Marginal Pavement Maintenance and Rehabilitation Expenditure for flexible Pavements

$$\text{MEXPEND}_{(\text{R})} = \frac{0.3133}{\text{THICK}}$$

$$\text{MEXPEND}_{(\text{MR})} = \frac{0.3110}{\text{THICK}}$$

For Jointed Concrete Pavements

$$\text{MEXPEND}_{(\text{R})} = \frac{0.038}{\text{THICK}}$$

$$\text{MEXPEND}_{(\text{MR})} = \frac{0.0374}{\text{THICK}}$$

For Composite Pavements

$$\text{MEXPEND}_{(\text{R})} = \frac{0.2409}{\text{THICK}}$$

$$\text{MEXPEND}_{(\text{MR})} = \frac{0.2327}{\text{THICK}}$$

5. MPDC Estimation by Link (*43*)

Link (*43*) used the logarithm of the sum of rehabilitation cost as dependent variable for his model. The estimated model has following functional form:

$$\text{LnC}_\text{i} = \text{c} + \sum_{j=1}^{m} (\alpha_\text{j}\text{DS}_\text{ij}) + \alpha_k Cpast_i$$
$$+ \beta_1 lnLN_i + \beta_2 ln\left(\frac{u_{1i}}{u_{2i}}\right) + \beta_3 lnage_i$$
$$+ 0.5\left(\beta_4 ln^2\left(\frac{u_{1i}}{u_{2i}}\right) + \beta_5 ln^2 age_i\right) +$$
$$+ 0.5\left(\beta_6 ln\left(\frac{u_{1i}}{u_{2i}}\right) + lnage_i\right)$$

Where: i = index for motorway sections; j = index for state; c = constant; C_i = sum of renewal costs from 1980 to 1999, expressed as costs per km; DS_{ij} = dummy variable for the federal state where section i is located (j= 1…10); Cpast = renewal costs before 1980 (categorical variable with 0, 1, 2, 3); LN= number of lanes; u_1 = passenger cars AADT u_2 = goods vehicles (trucks) AADT; Age = age of motorway section.

The Link study used the ratio of AADT of passenger cars to AADT of trucks to estimate the marginal cost using following expression:

$$\frac{\partial C}{\partial \gamma} = e^{\beta_2} r^{\beta_4} age^{0.5*\beta_6}$$

PART II. APPENDIX C. MPDC ESTIMATES USING ENGINEERING APPROACH

1. MPDC Estimates—Small et al. (*50*)

TABLE II.C.1
Pavement Maintenance Cost by Road Classification (*50*)

	MPDC Cents per ESAL-mile ($1985)	
Road Functional Class	**Current Investment**	**Optimal Investment**
Rural Interstate	1.48	0.46
Rural principal arterial	4.38	1.13
Minor arterial	10.02	2.60
Major collector	16.49	9.96
Minor collector	31.18	16.09
Local	101.30	101.30
Urban Interstate	2.38	0.33
Urban freeway	4.32	0.61
Urban principal arterial	10.92	0.87
Minor arterial	33.92	3.23
Collector	125.45	13.66
Local	40.92	40.92

2. MPDC Estimates—Vitaliano and Held (*52*)

TABLE II.C.2
Pavement Maintenance Cost—New York Roads (*52*)

	PMDC $ per mile ($1990)	
Road Functional Class	**5-axle Tractor-trailer**	**$ Per ESAL-mile**
Rural and urban Interstate	0.030	0.0115
Urban expressway	0.069	0.026
Rural expressway	0.064	0.024
Urban arterial	0.138	0.052
Rural minor arterial	0.106	0.04
Urban minor arterial/collector	0.387	0.146
Rural collector	0.742	0.280

3. MPDC Estimates—Anani and Madanat (*48*)

TABLE II.C.3
Assumptions for MPDC Estimation in the Anani and Madanat Study (*48*)

Details	Default Values
ESALs to failure for periodic maintenance treatment	200,000
ESALs to failure for rehabilitation	500,000
Annual traffic loading	100,000
Unit cost for periodic maintenance ($/lane-mile)	20,000
Unit cost for rehabilitation ($/lane-mile)	200,000
Discount rate	0.05
No. periodic maintenance treatments between two rehabilitations	2

TABLE II.C.4
MPDC Estimates in the Anani and Madanat Study (*48*)

Marginal Pavement Damage Cost ($/ESAL-mile)		
Periodic Maintenance and Rehabilitation	**Periodic Maintenance Only**	**Rehabilitation Only**
0.4902	0.1025	0.4080

PART II. APPENDIX D. MISCELLANEOUS APPROACHES FOR PDC ESTIMATION

TABLE II.D.1
Vehicle Load for different Commodities and Weight Scenarios (*56*)

Commodity/Scenario	Highway Type	5-Axle Semitrailer			
		Steering Axle (lbs)	Tandem Axle (lbs)	Tandem Axle (lbs)	GVW (lbs)
Rice and Sugarcane					
Scenario 1	State route	12,000	37,000	37,000	86,000
	Interstate	12,000	34,000	34,000	86,000
Scenario 2	State route	12,000	44,000	44,000	100,000
	Interstate	12,000	44,000	44,000	100,000
Scenario 3	State route	12,000	44,000	44,000	100,000
	Interstate	12,000	44,000	44,000	100,000
Timber					
Scenario 1	State route	12,000	37,000	37,000	86,000
	Interstate	12,000	34,000	34,000	86,000
Scenario 2	State route	12,600	37,000	37,000	86,600
	Interstate	12,000	35,700	35,700	83,400
Scenario 3	State route	12,000	44,000	44,000	100,000
	Interstate	12,000	44,000	44,000	100,000
Commodity/Scenario	**Highway Type**	**2-Axle Truck**			
		Steering Axle (lbs)	**Tandem Axle (lbs)**	**GVW (lbs)**	
Cotton*					
Scenario 1	State route	12,000	37,000	49,000	
Scenario 2	State route	12,000	48,000	68,000	
Scenario 3	State route	12,600	48,000	68,000	

*Cotton transportation on state route only.

PART II. APPENDIX E. VEHICLE CLASSES FOR MPDC ESTIMATION

TABLE II.E.1
FHWA Vehicle Classes

Vehicle Class	Description
1	Motorcycles
2	Passenger cars
3	Other 2 axle, 4 tire single units
4	Buses
5	2 axle, 6 tire single units
6	3 axle single units
7	4 or more axle single units
8	4 or less axle single trailers
9	4 axle single trailers
10	6 or more axle single trailers
11	5 or less axle multi-trailers
12	6 axle multi-trailers
13	7 or more axle multi-trailers

Source: (*149*).

YEAR TO	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Urban - Interstate (11), Freeways and Expressways (12)										
2001	-	0.966	0.937	0.926	0.903	0.887	0.853	0.872	0.855	0.852
2002	1.035	-	0.970	0.958	0.934	0.919	0.883	0.902	0.885	0.882
2003	1.067	1.031	-	0.988	0.963	0.947	0.911	0.930	0.913	0.909
2004	1.080	1.043	1.012	-	0.975	0.958	0.922	0.941	0.924	0.920
2005	1.108	1.070	1.038	1.026	-	0.983	0.945	0.966	0.948	0.944
2006	1.127	1.089	1.056	1.043	1.017	-	0.962	0.982	0.964	0.960
2007	1.172	1.132	1.098	1.085	1.058	1.040	-	1.021	1.002	0.998
2008	1.147	1.108	1.075	1.062	1.035	1.018	0.979	-	0.981	0.977
2009	1.169	1.130	1.096	1.083	1.055	1.038	0.998	1.019	-	0.996
2010	1.174	1.134	1.100	1.087	1.059	*1.042*	1.002	1.023	1.004	-
Urban - Principal Arterials (14), Minor Arterials (16), Collectors (17), Local (19)										
2001	-	0.943	0.956	0.967	0.966	0.960	0.972	1.003	1.008	1.001
2002	1.060	-	1.013	1.025	1.024	1.017	1.031	1.064	1.068	1.061
2003	1.046	0.987	-	1.012	1.011	1.004	1.017	1.050	1.054	1.047
2004	1.034	0.975	0.988	-	0.999	0.992	1.005	1.037	1.041	1.034
2005	1.035	0.976	0.989	1.001	-	0.993	1.006	1.038	1.042	1.035
2006	1.042	0.983	0.996	1.008	1.007	-	1.013	1.046	1.050	1.042
2007	1.028	0.970	0.983	0.995	0.994	0.987	-	1.032	1.036	1.029
2008	0.997	0.940	0.952	0.964	0.963	0.956	0.969	-	1.004	0.997
2009	0.993	0.936	0.949	0.960	0.959	0.953	0.965	0.996	-	0.993
2010	0.999	0.943	0.955	0.967	0.966	0.959	0.972	1.003	1.007	-
Rural - Interstate (01)										
2001	-	0.953	0.949	0.936	0.932	0.924	0.917	0.933	0.941	0.945
2002	1.049	-	0.995	0.982	0.977	0.970	0.962	0.979	0.987	0.996
2003	1.054	1.005	-	0.987	0.982	0.974	0.967	0.983	0.992	0.996
2004	1.068	1.018	1.013	-	0.995	0.987	0.979	0.996	1.005	1.009
2005	1.073	1.023	1.018	1.005	-	0.992	0.984	1.001	1.010	1.014
2006	1.082	1.031	1.026	1.013	1.008	-	0.992	1.009	1.018	1.022
2007	1.091	1.040	1.034	1.021	1.016	1.008	-	1.017	1.027	1.031
2008	1.072	1.022	1.017	1.004	0.999	0.991	0.983	-	1.009	1.013
2009	1.062	1.013	1.008	0.995	0.990	0.982	0.974	0.991	-	1.004
2010	**1.058**	**1.009**	**1.004**	**0.991**	**0.986**	**0.978**	**0.970**	**0.987**	**0.996**	**-**
Rural - Principal Arterials (02), Minor Arterials (06)										
2001	-	0.987	1.009	0.982	0.983	0.974	0.974	1.024	1.029	1.033
2002	1.013	-	1.022	0.995	0.996	0.987	0.987	1.038	1.043	1.046
2003	0.991	0.978	-	0.973	0.974	0.965	0.965	1.015	1.020	1.023
2004	1.018	1.005	1.028	-	1.001	0.992	0.992	1.043	1.048	1.052
2005	1.017	1.004	1.027	0.999	-	0.991	0.991	1.042	1.047	1.051
2006	1.027	1.013	1.036	1.008	1.009	-	1.000	1.052	1.057	1.060
2007	1.027	1.013	1.036	1.008	1.009	1.000	-	1.052	1.057	1.060
2008	0.976	0.964	0.985	0.959	0.960	0.951	0.951	-	1.005	1.008
2009	0.971	0.959	0.981	0.954	0.955	0.946	0.946	0.995	-	1.003
2010	0.968	0.956	0.978	0.951	0.952	0.943	0.943	0.992	0.997	-
Rural - Major Collectors (07), Minor Collectors (08), Locals (09)										
2001	-	0.978	0.976	0.972	0.984	0.989	0.983	1.051	1.042	1.047
2002	1.022	-	0.997	0.993	1.006	1.011	1.004	1.074	1.065	1.070
2003	1.025	1.003	-	0.996	1.009	1.014	1.007	1.077	1.069	1.073
2004	1.029	1.007	1.004	-	1.013	1.018	1.011	1.081	1.073	1.077
2005	1.016	0.994	0.991	0.987	-	1.005	0.998	1.067	1.059	1.063
2006	1.011	0.989	0.986	0.982	0.995	-	0.993	1.062	1.054	1.058
2007	1.018	0.996	0.993	0.989	1.002	1.007	-	1.070	1.061	1.065
2008	0.952	0.931	0.928	0.925	0.937	0.942	0.935	-	0.992	0.996
2009	0.959	0.939	0.936	0.932	0.944	0.949	0.942	1.008	-	1.004
2010	0.955	0.935	0.932	0.928	0.941	0.945	0.939	1.004	0.996	-

Figure II.F.1 INDOT traffic volume adjustment factors (*110*).

MR&R Strategies - Flexible Pavement (Interstate)

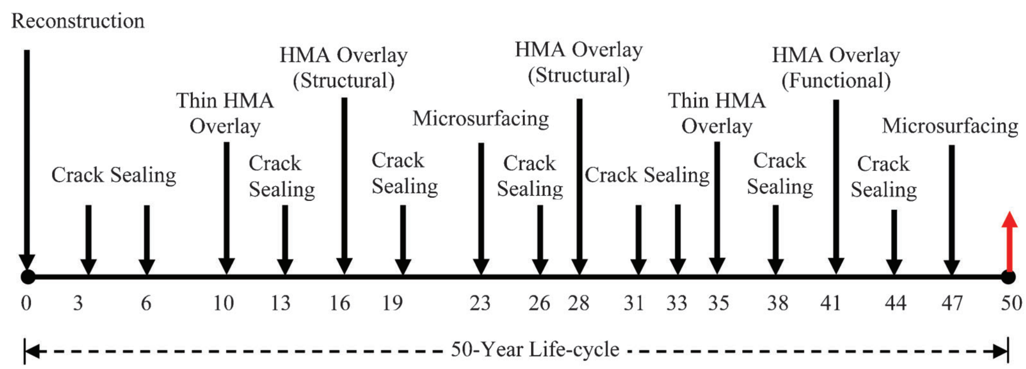


Figure II.G.1 M&R Profile for Flexible Pavement (Interstate) –1 (Very High Traffic).

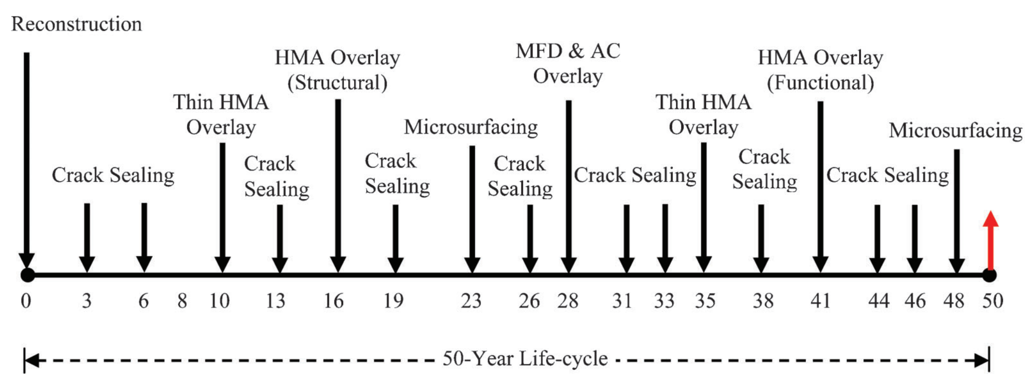


Figure II.G.2 M&R Profile for Flexible Pavement (Interstate) –2 (Very High Traffic).

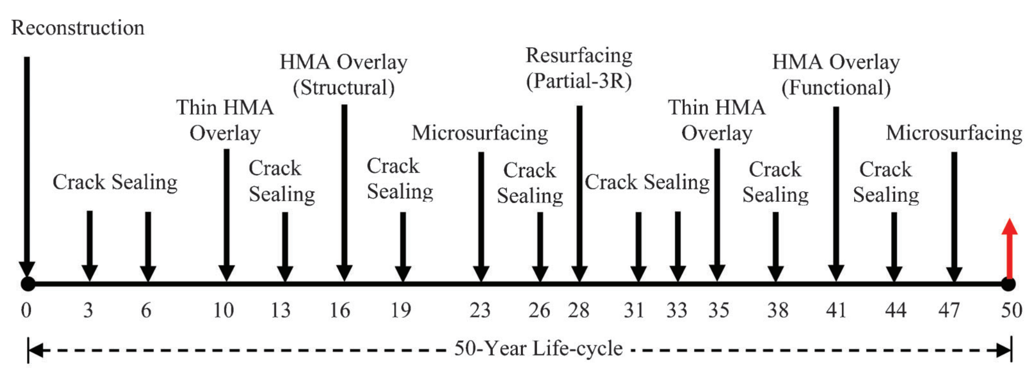


Figure II.G.3 M&R Profile for Flexible Pavement (Interstate) –3 (Very High Traffic).

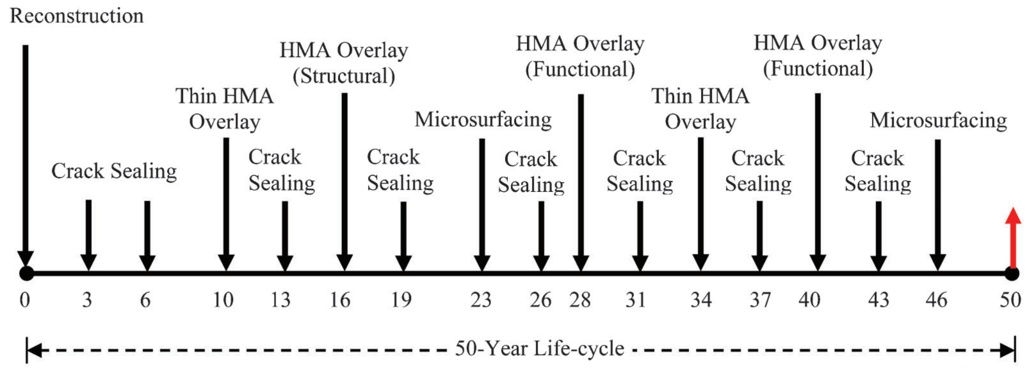


Figure II.G.4 M&R Profile for Flexible Pavement (Interstate) –4 (Very High Traffic).

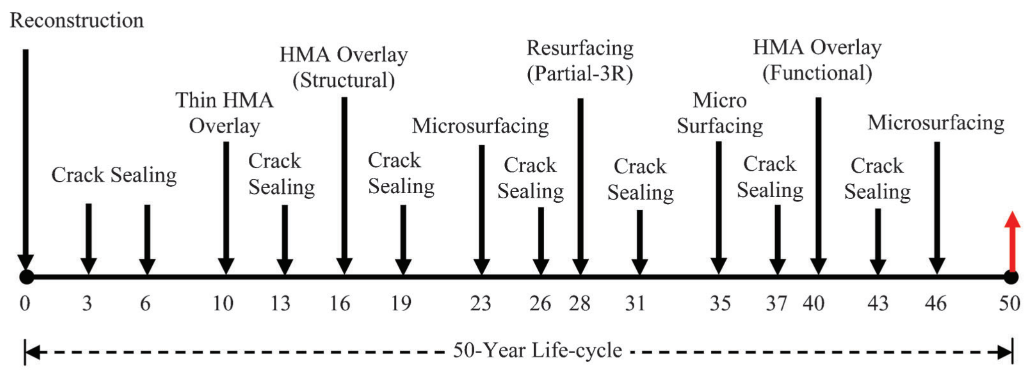


Figure II.G.5 M&R Profile for Flexible Pavement (Interstate) –5 (Very High Traffic).

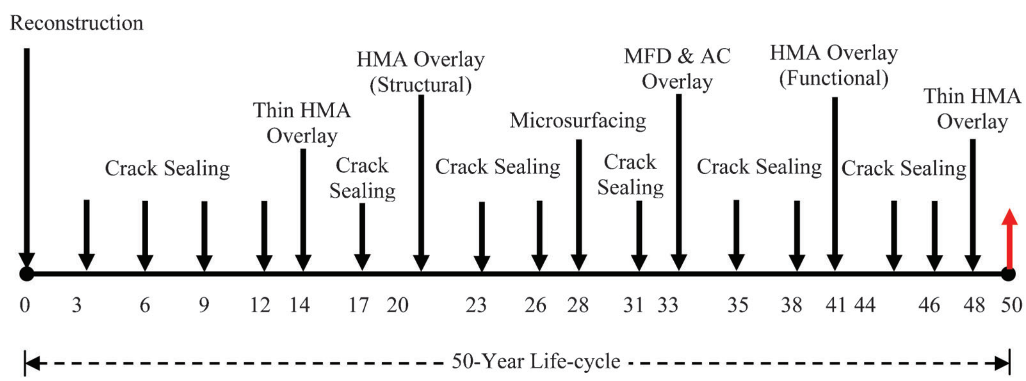


Figure II.G.6 M&R Profile for Flexible Pavement (Interstate) –6 (High Traffic).

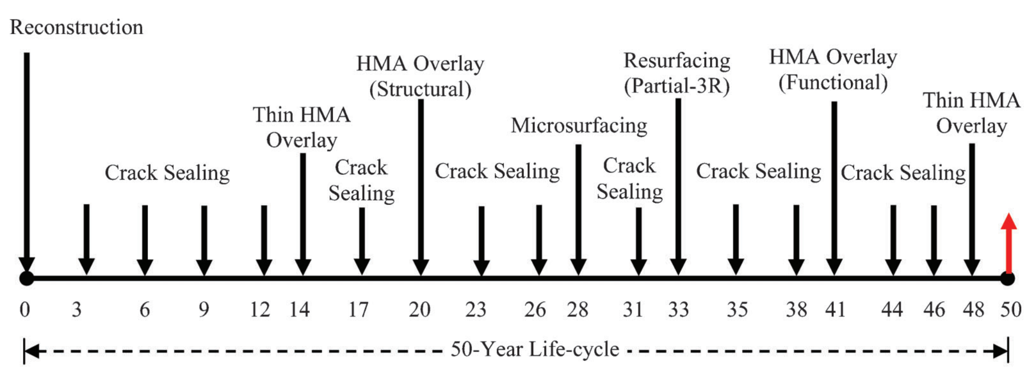


Figure II.G.7 M&R Profile for Flexible Pavement (Interstate) –7 (High Traffic).

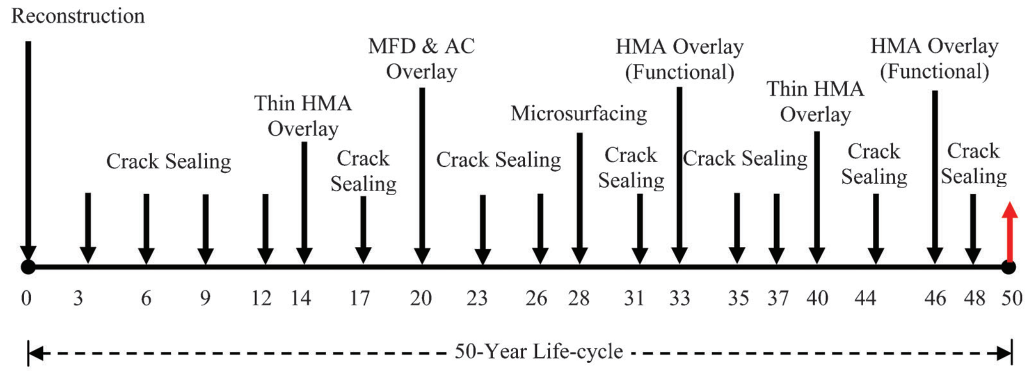


Figure II.G.8 M&R Profile for Flexible Pavement (Interstate) –8 (High Traffic).

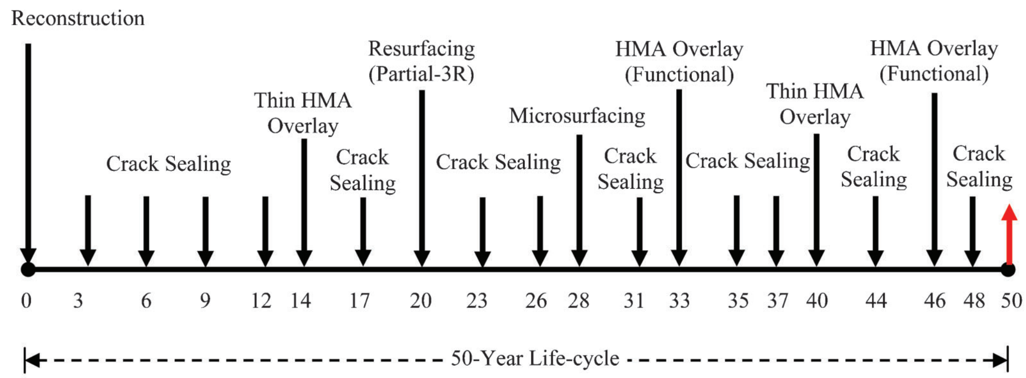


Figure II.G.9 M&R Profile for Flexible Pavement (Interstate) –9 (High Traffic).

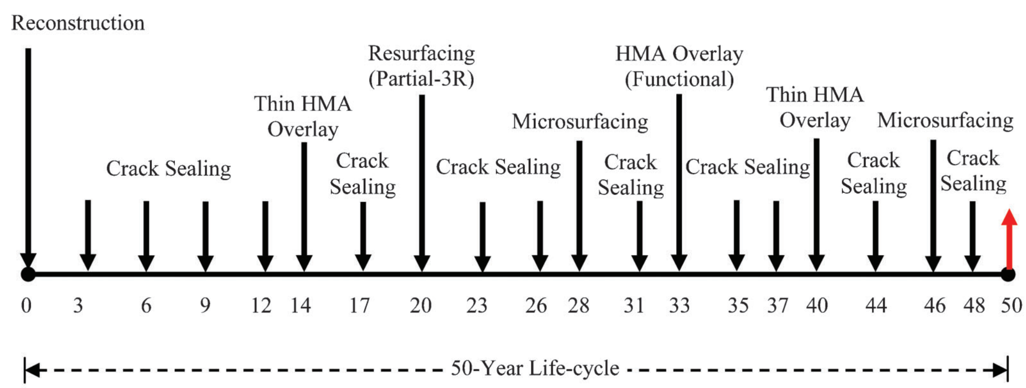


Figure II.G.10 M&R Profile for Flexible Pavement (Interstate) –10 (High Traffic).

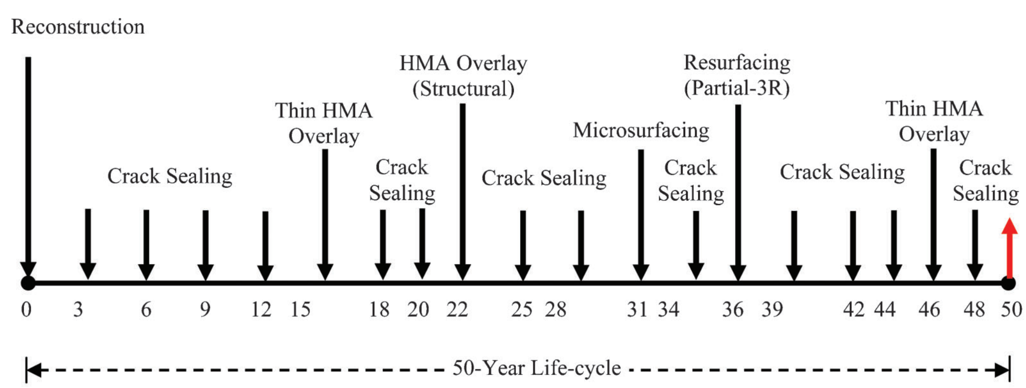


Figure II.G.11 M&R Profile for Flexible Pavement (Interstate) –11 (Medium Traffic).

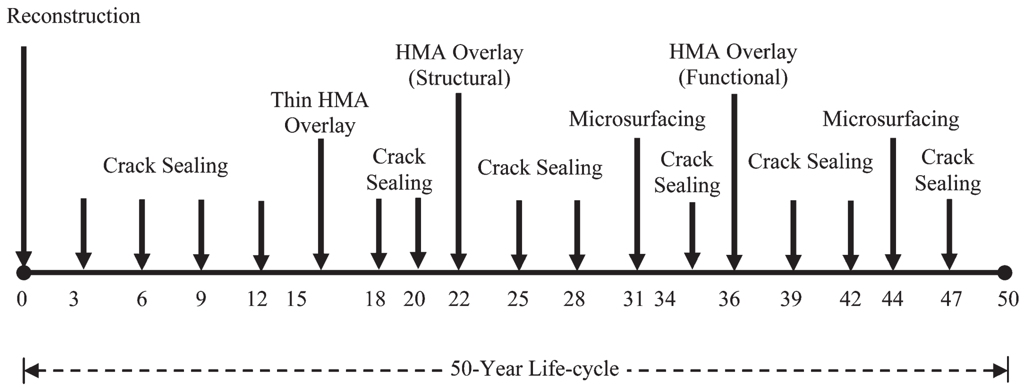


Figure II.G.12 M&R Profile for Flexible Pavement (Interstate) –12 (Medium Traffic).

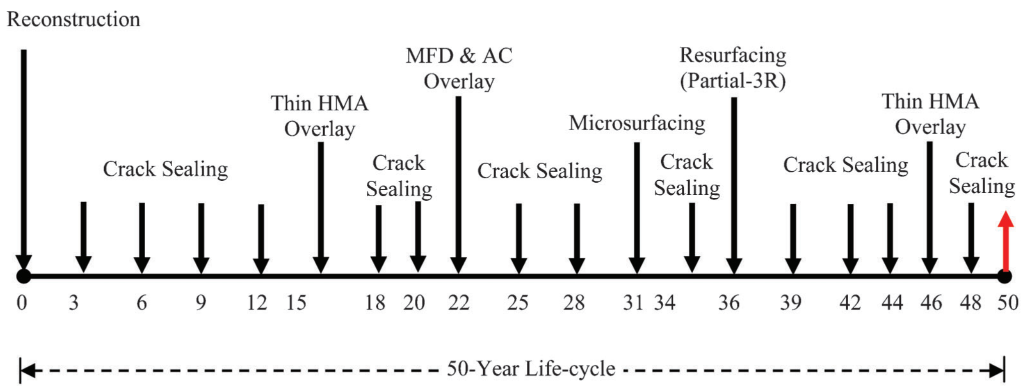


Figure II.G.13 M&R Profile for Flexible Pavement (Interstate) –13 (Medium Traffic).

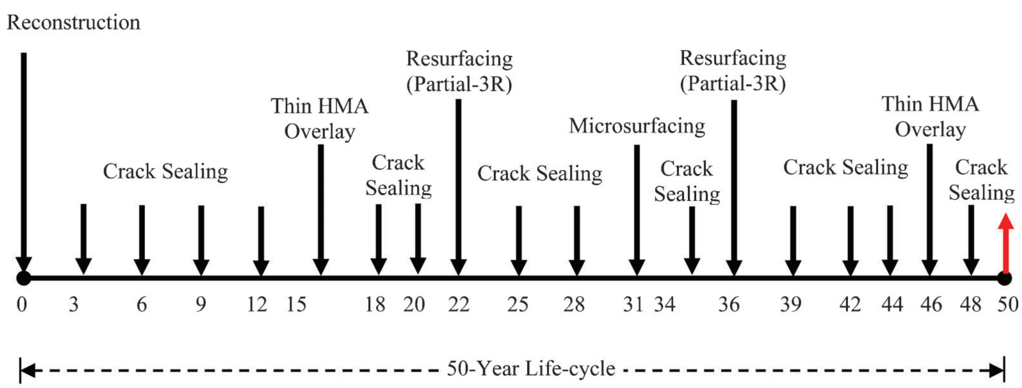


Figure II.G.14 M&R Profile for Flexible Pavement (Interstate) –14 (Medium Traffic).

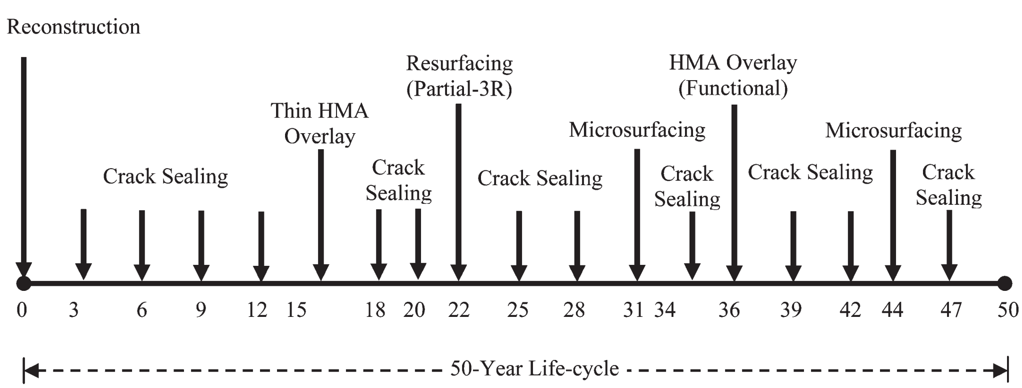


Figure II.G.15 M&R Profile for Flexible Pavement (Interstate) –15 (Medium Traffic).

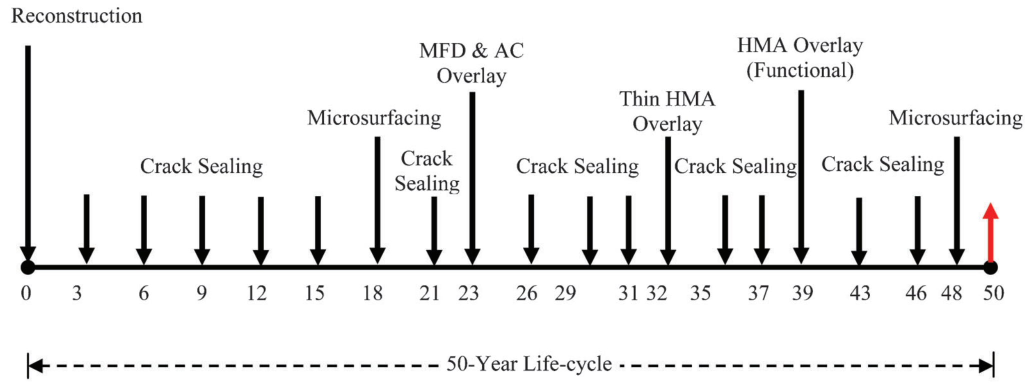


Figure II.G.16 M&R Profile for Flexible Pavement (Interstate) –16 (Low Traffic).

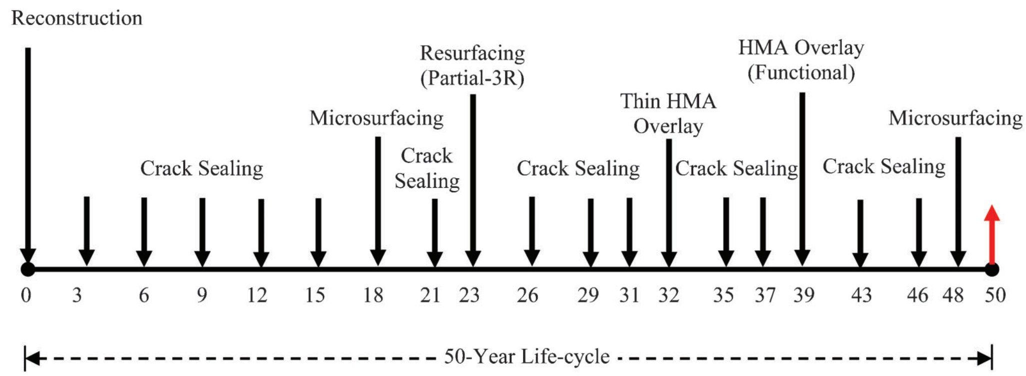


Figure II.G.17 M&R Profile for Flexible Pavement (Interstate) –17 (Low Traffic).

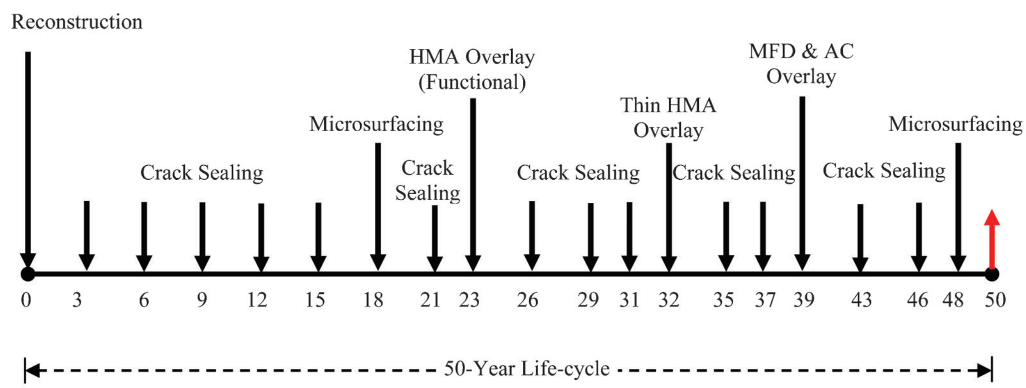


Figure II.G.18 M&R Profile for Flexible Pavement (Interstate) –18 (Low Traffic).

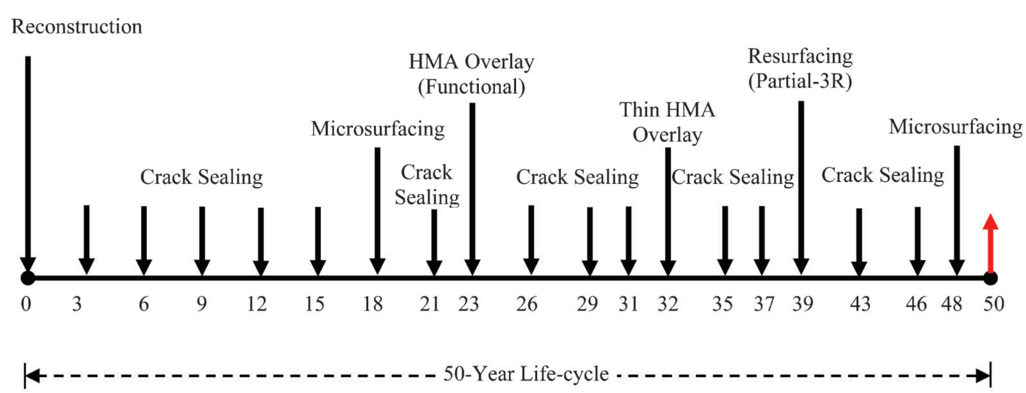


Figure II.G.19 M&R Profile for Flexible Pavement (Interstate) –19 (Low Traffic).

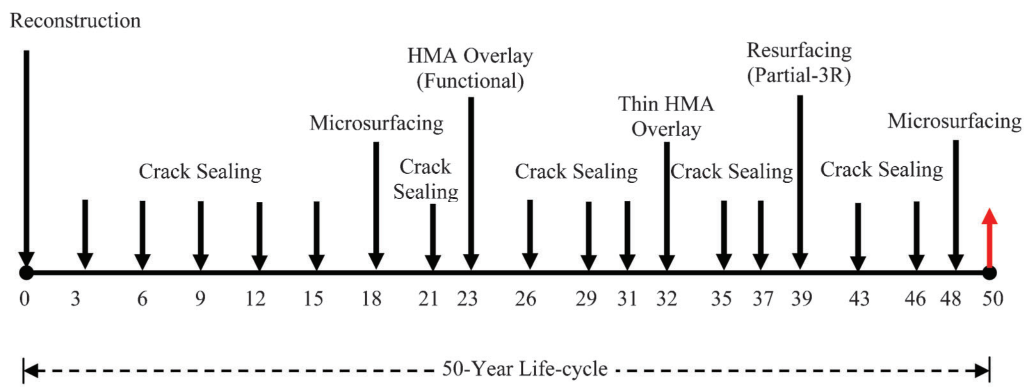


Figure II.G.20 M&R Profile for Flexible Pavement (Interstate) –20 (Low Traffic).

MR&R Strategy – HMA NHS (NIS)

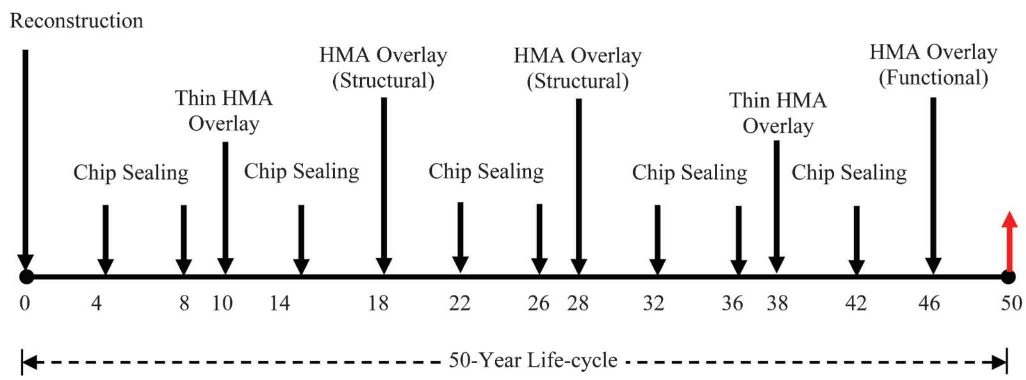


Figure II.G.21 M&R Profile for Flexible Pavement (NHS (NIS)) –1 (Very High Traffic).

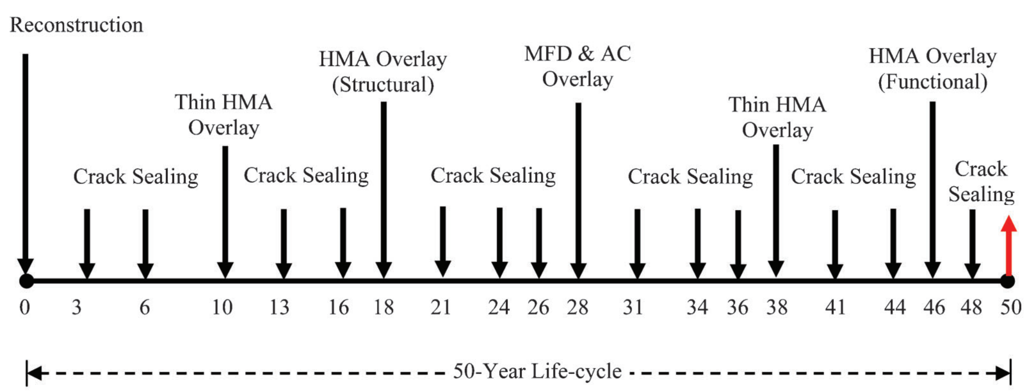


Figure II.G.22 M&R Profile for Flexible Pavement (NHS (NIS)) –2 (Very High Traffic).

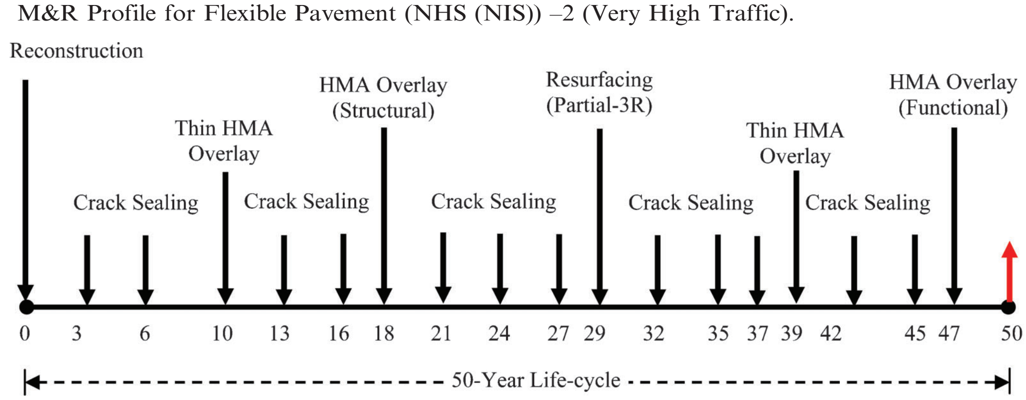


Figure II.G.23 M&R Profile for Flexible Pavement (NHS (NIS)) –3 (Very High Traffic).

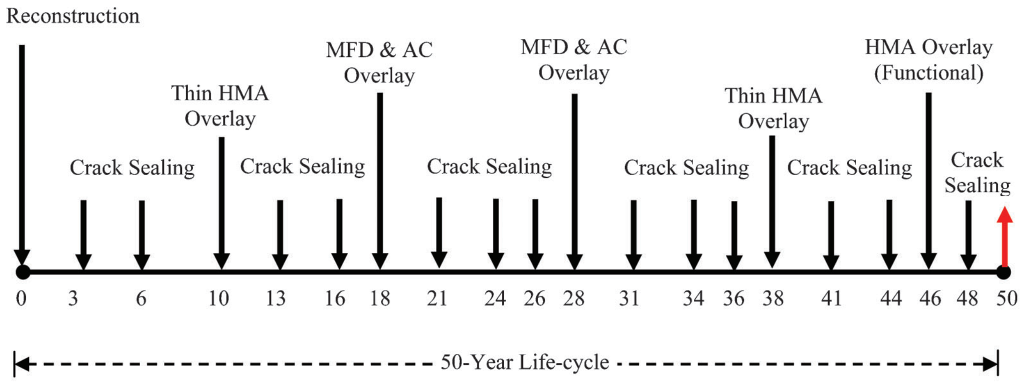


Figure II.G.24 M&R Profile for Flexible Pavement (NHS (NIS)) –4 (Very High Traffic).

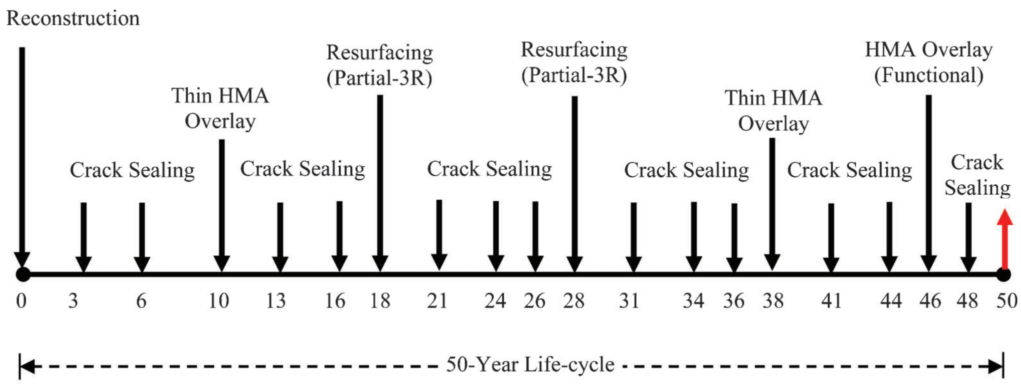


Figure II.G.25 M&R Profile for Flexible Pavement (NHS (NIS)) –5 (Very High Traffic).

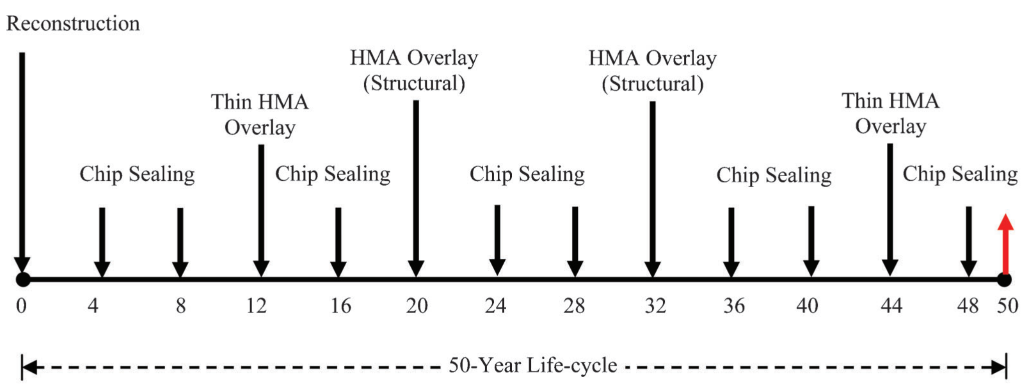


Figure II.G.26 M&R Profile for Flexible Pavement (NHS (NIS)) –6 (High Traffic).

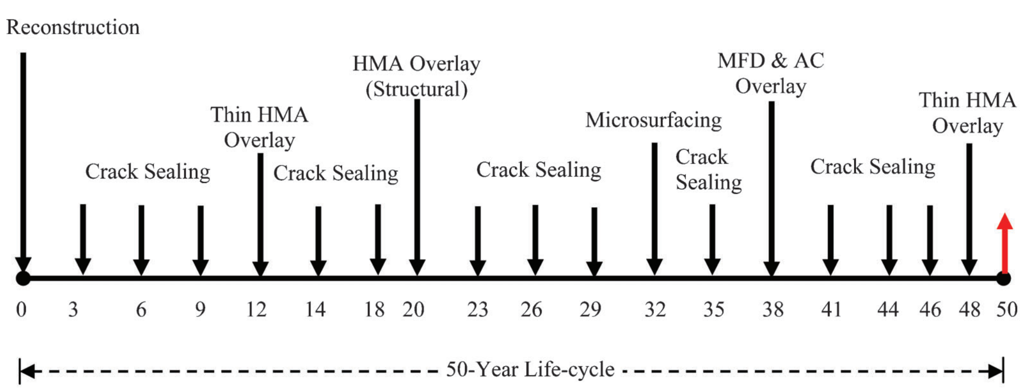


Figure II.G.27 M&R Profile for Flexible Pavement (NHS (NIS)) –7 (High Traffic).

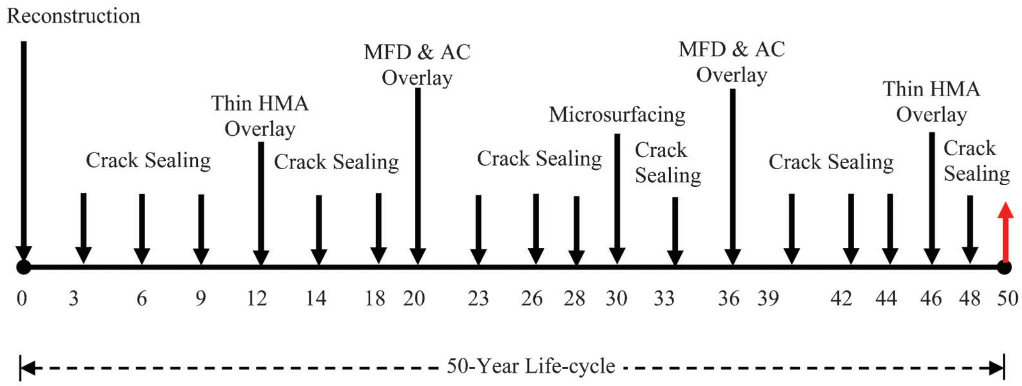


Figure II.G.28 M&R Profile for Flexible Pavement (NHS (NIS)) –8 (High Traffic).

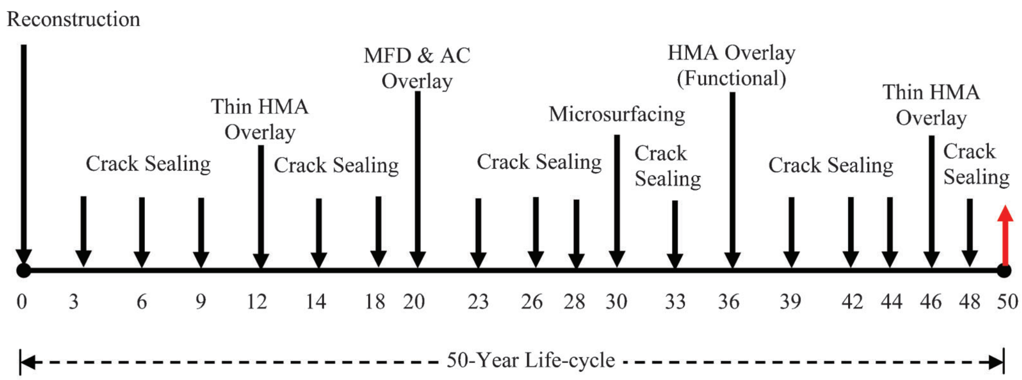


Figure II.G.29 M&R Profile for Flexible Pavement (NHS (NIS)) –9 (High Traffic).

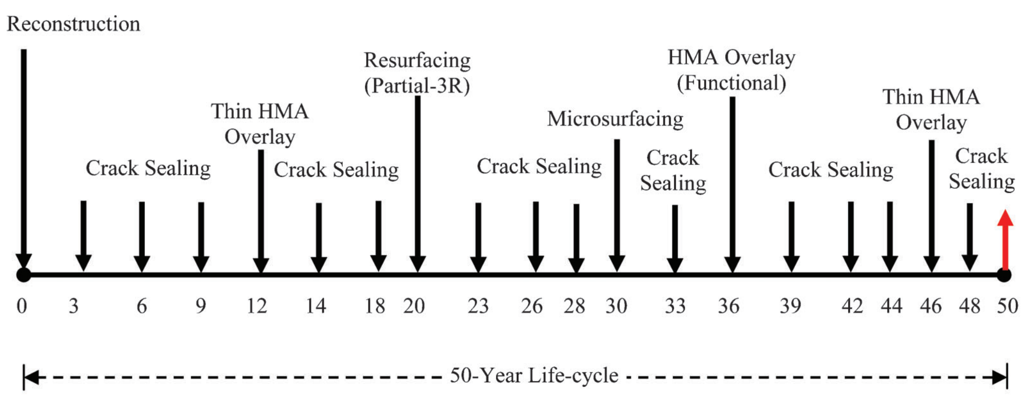


Figure II.G.30 M&R Profile for Flexible Pavement (NHS (NIS)) –10 (High Traffic).

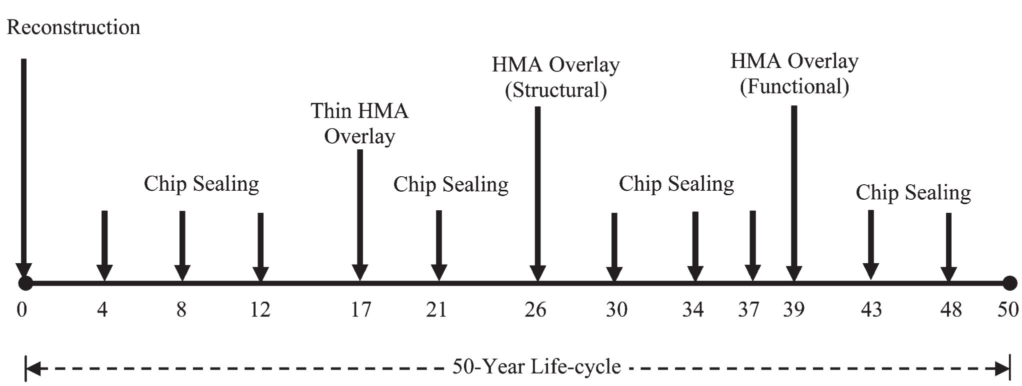


Figure II.G.31 M&R Profile for Flexible Pavement (NHS (NIS)) –11 (Medium Traffic).

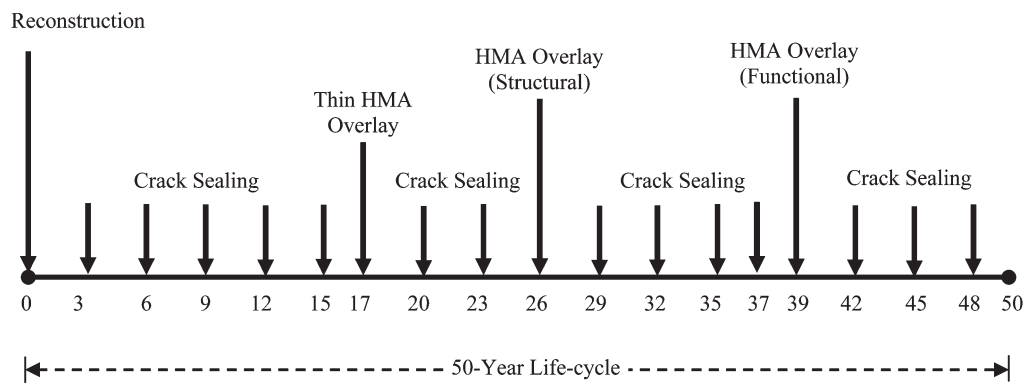


Figure II.G.32 M&R Profile for Flexible Pavement (NHS (NIS)) –12 (Medium Traffic).

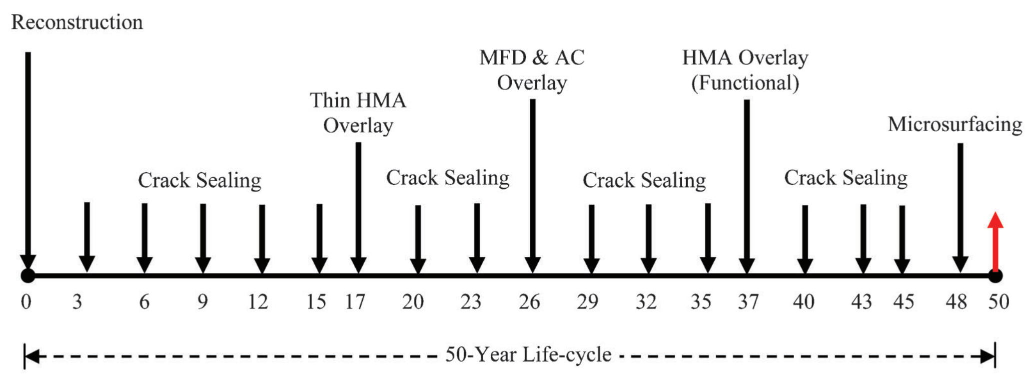


Figure II.G.33 M&R Profile for Flexible Pavement (NHS (NIS)) –13 (Medium Traffic).

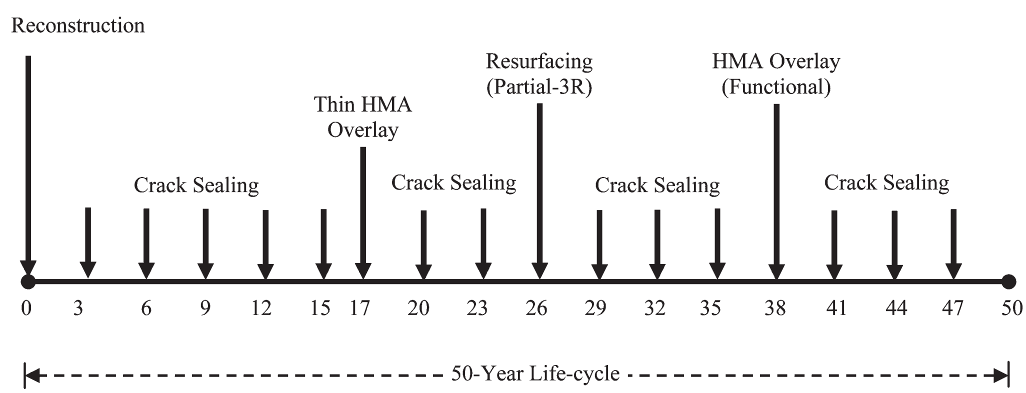


Figure II.G.34 M&R Profile for Flexible Pavement (NHS (NIS)) –14 (Medium Traffic).

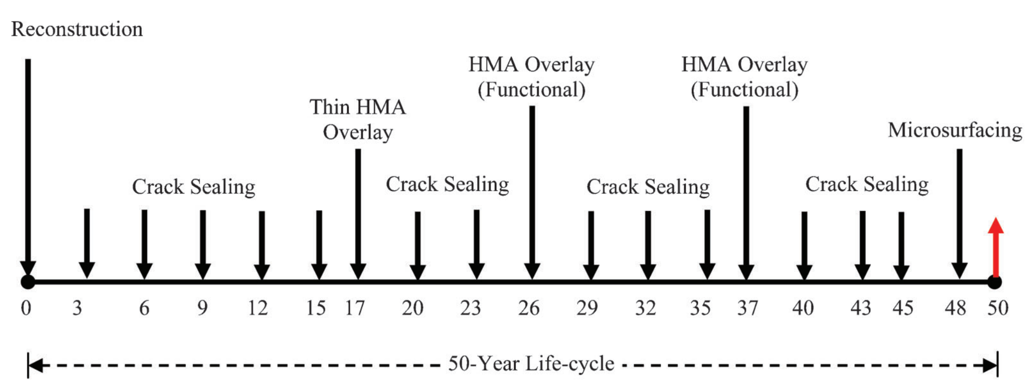


Figure II.G.35 M&R Profile for Flexible Pavement (NHS (NIS)) –15 (Medium Traffic).

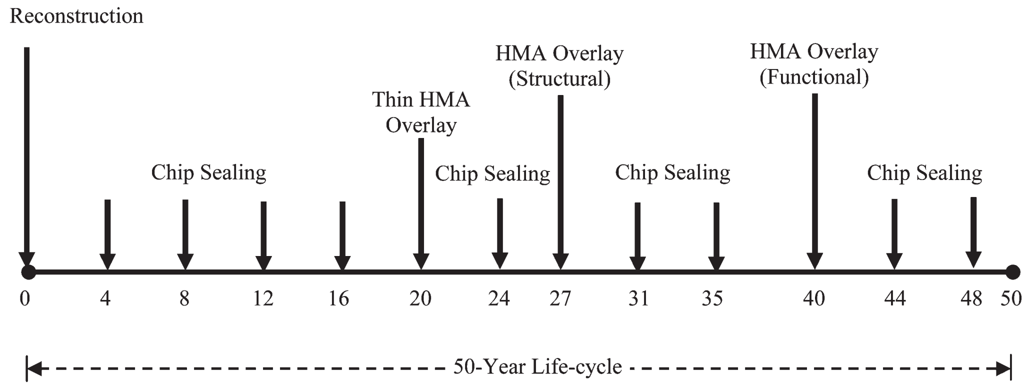


Figure II.G.36 M&R Profile for Flexible Pavement (NHS (NIS)) –16 (Low Traffic).

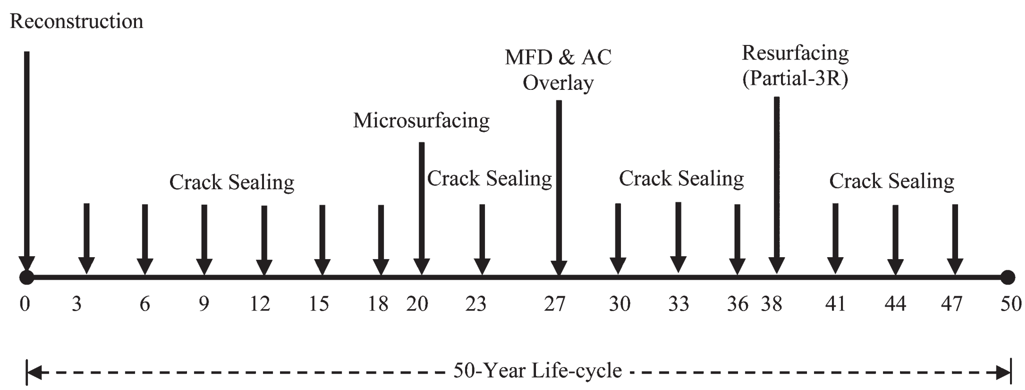


Figure II.G.37 M&R Profile for Flexible Pavement (NHS (NIS)) –17 (Low Traffic).

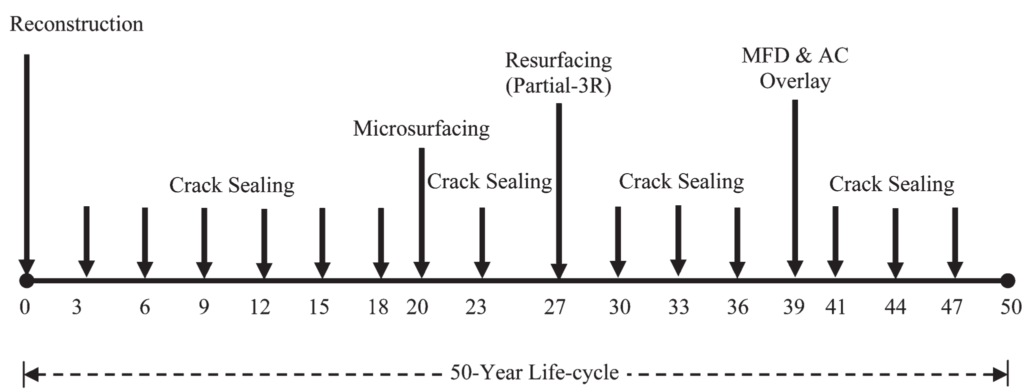


Figure II.G.38 M&R Profile for Flexible Pavement (NHS (NIS)) –18 (Low Traffic).

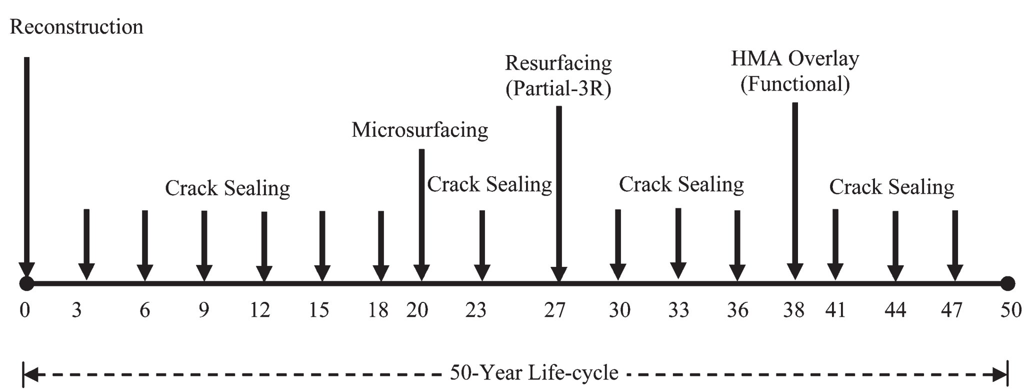


Figure II.G.39 M&R Profile for Flexible Pavement (NHS (NIS)) –19 (Low Traffic).

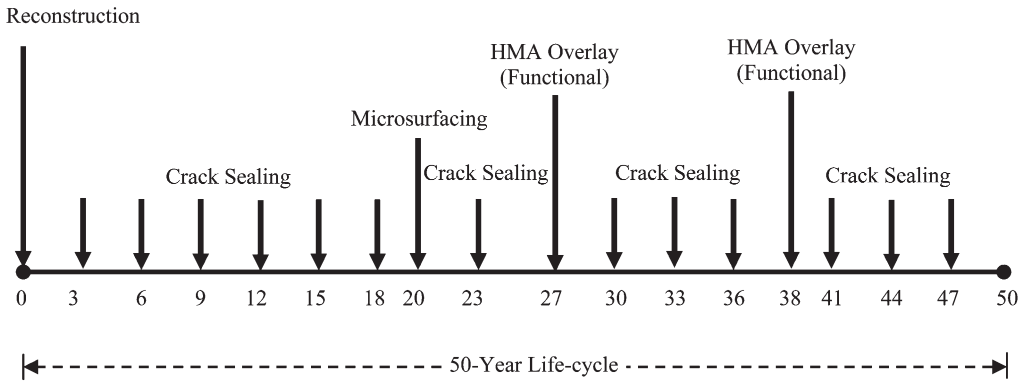


Figure II.G.40 M&R Profile for Flexible Pavement (NHS (NIS)) –20 (Low Traffic).

Life-cycle M&R Profiles – Flexible Pavements (NNHS)

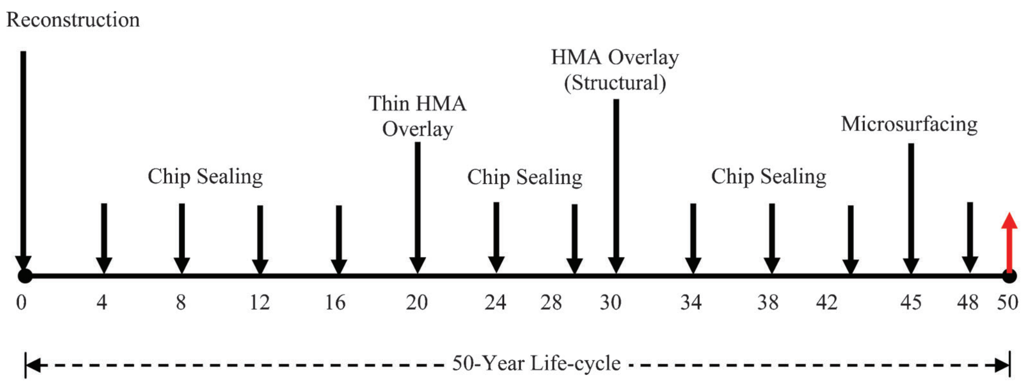


Figure II.G.41 M&R Profile for Flexible Pavement (NNHS) –1 (Very High Traffic).

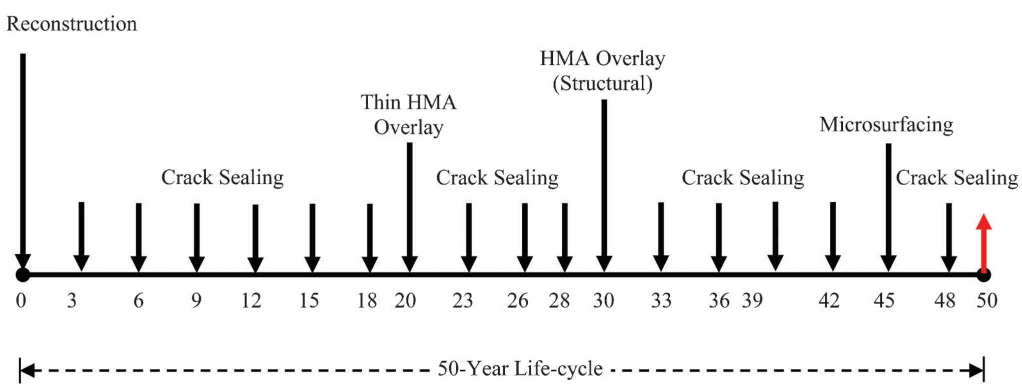


Figure II.G.42 M&R Profile for Flexible Pavement (NNHS) –2 (Very High Traffic).

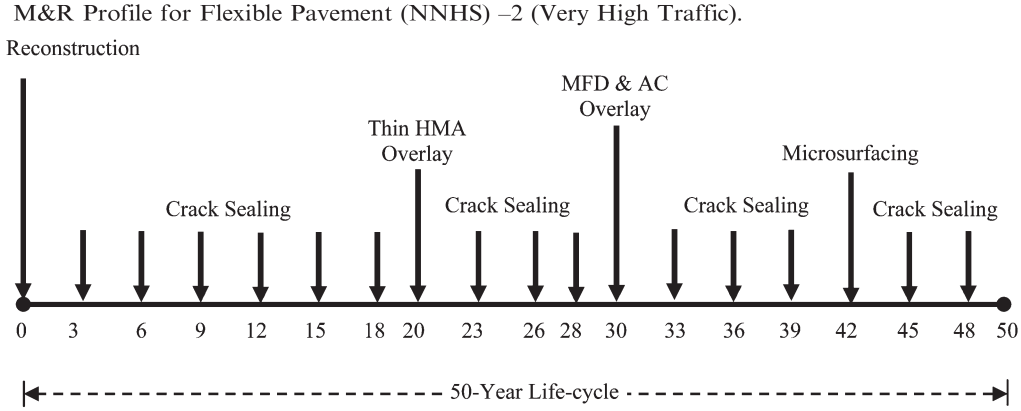


Figure II.G.43 M&R Profile for Flexible Pavement (NNHS) –3 (Very High Traffic).

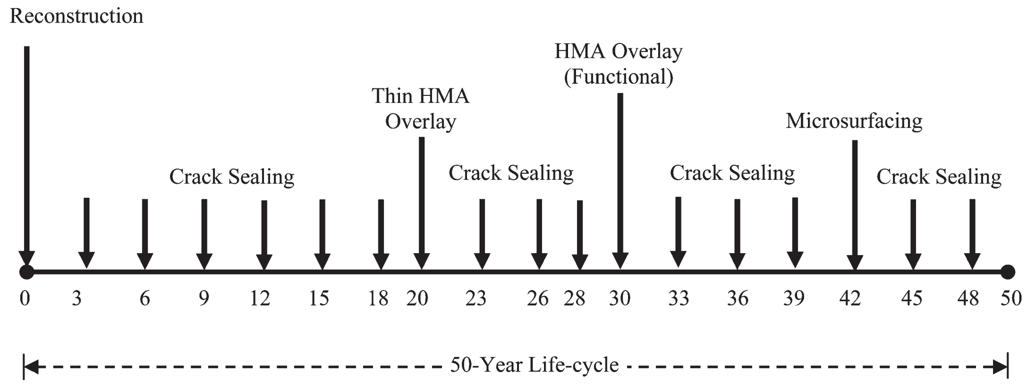


Figure II.G.44 M&R Profile for Flexible Pavement (NNHS) –4 (Very High Traffic).

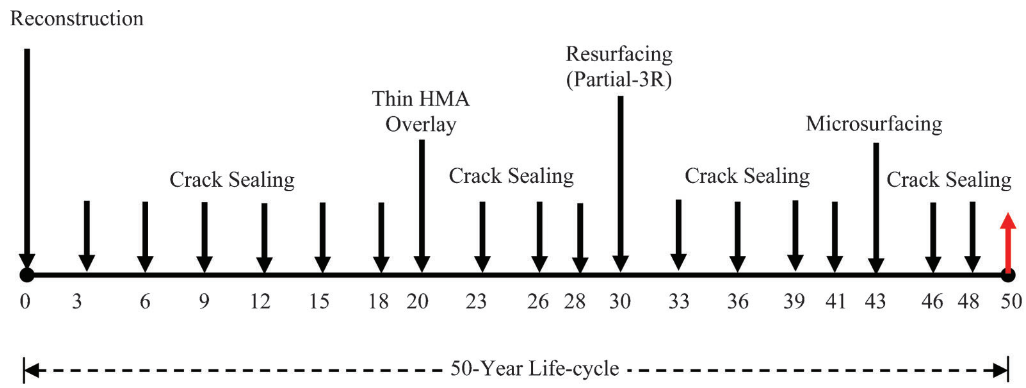


Figure II.G.45 M&R Profile for Flexible Pavement (NNHS) –5 (Very High Traffic).

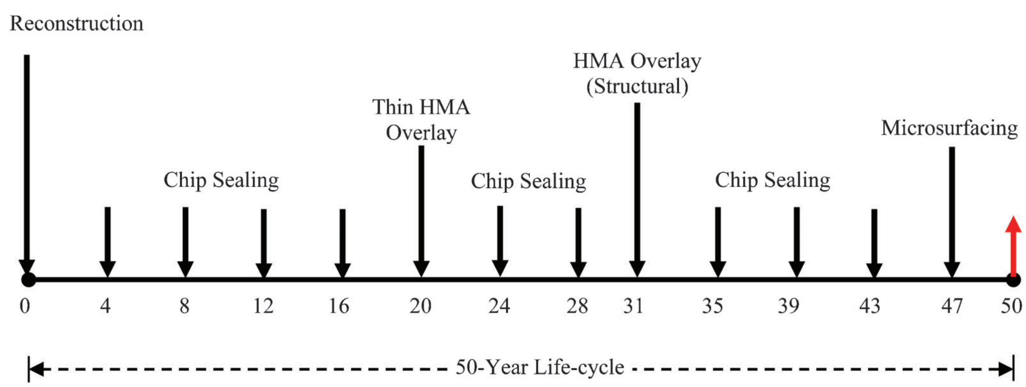


Figure II.G.46 M&R Profile for Flexible Pavement (NNHS) –6 (High Traffic).

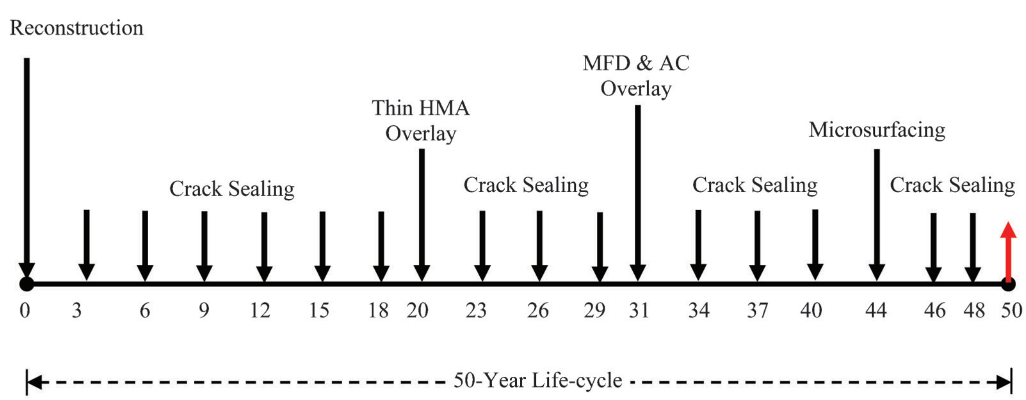


Figure II.G.47 M&R Profile for Flexible Pavement (NNHS) –7 (High Traffic).

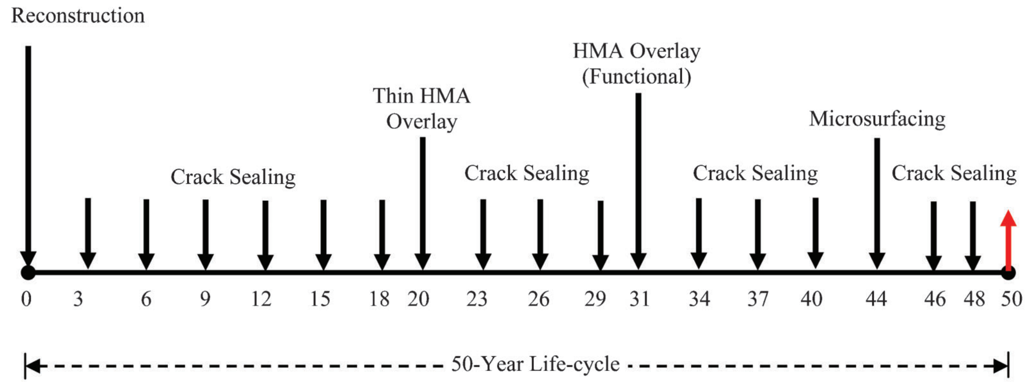


Figure II.G.48 M&R Profile for Flexible Pavement (NNHS) –8 (High Traffic).

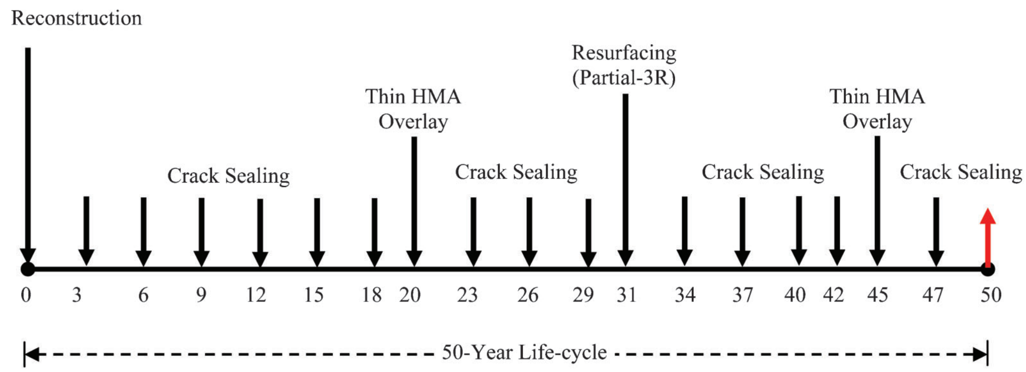


Figure II.G.49 M&R Profile for Flexible Pavement (NNHS) –9 (High Traffic).

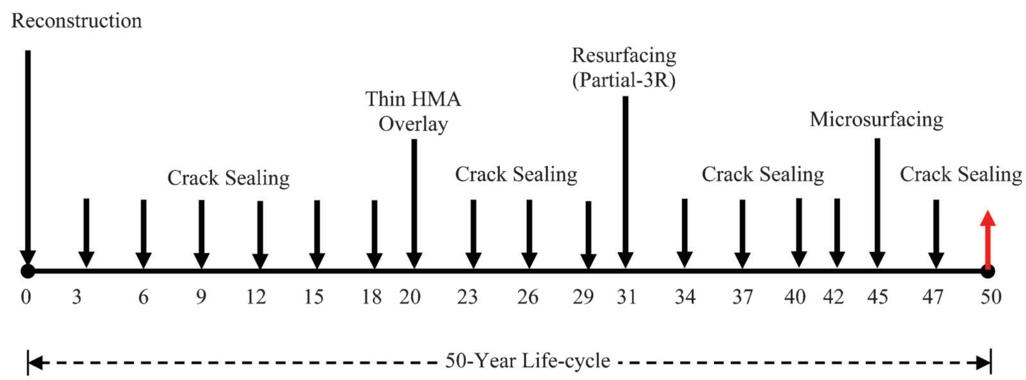


Figure II.G.50 M&R Profile for Flexible Pavement (NNHS) –10 (High Traffic).

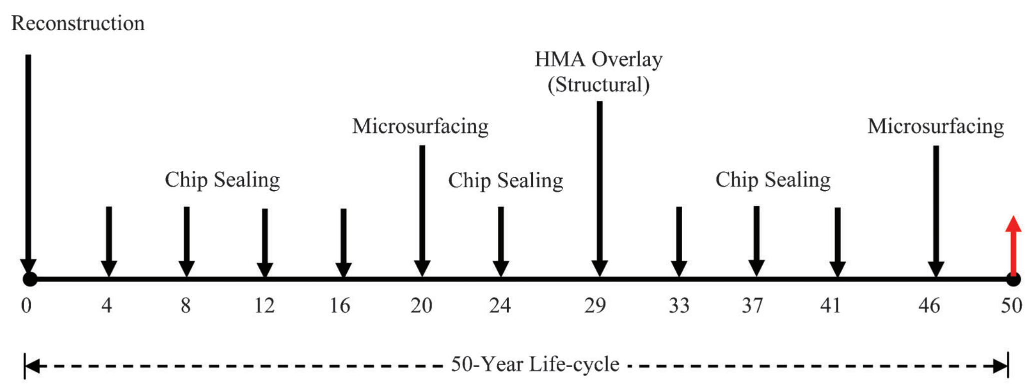


Figure II.G.51 M&R Profile for Flexible Pavement (NNHS) –11 (Medium Traffic).

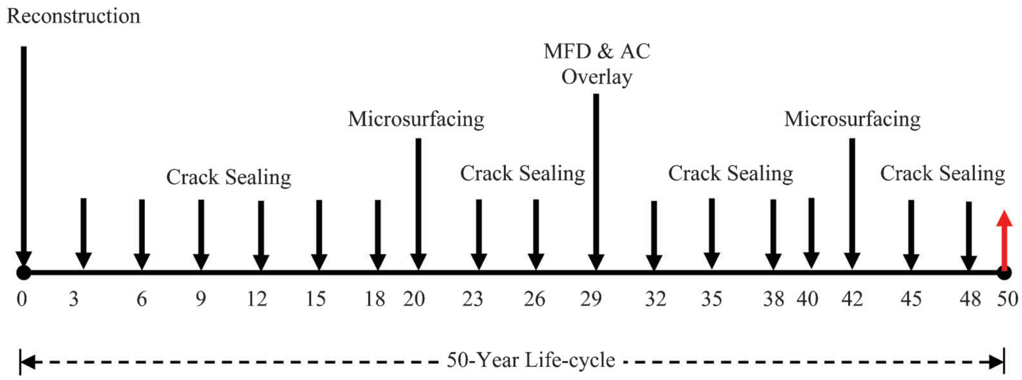


Figure II.G.52 M&R Profile for Flexible Pavement (NNHS) –12 (Medium Traffic).

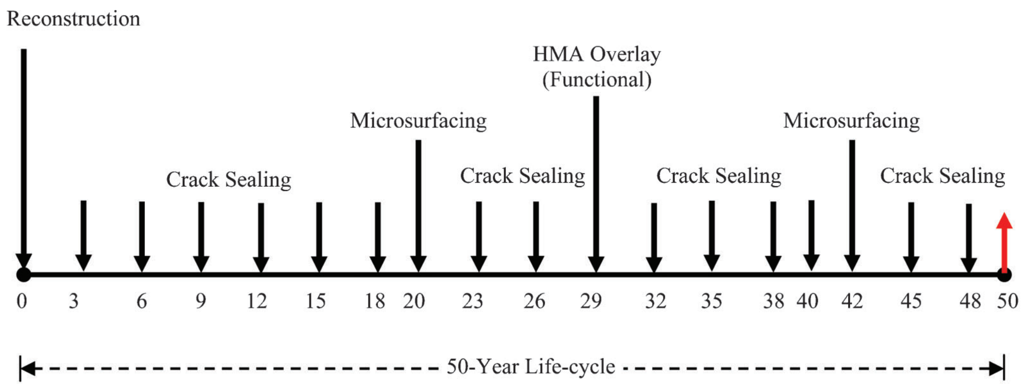


Figure II.G.53 M&R Profile for Flexible Pavement (NNHS) –13 (Medium Traffic).

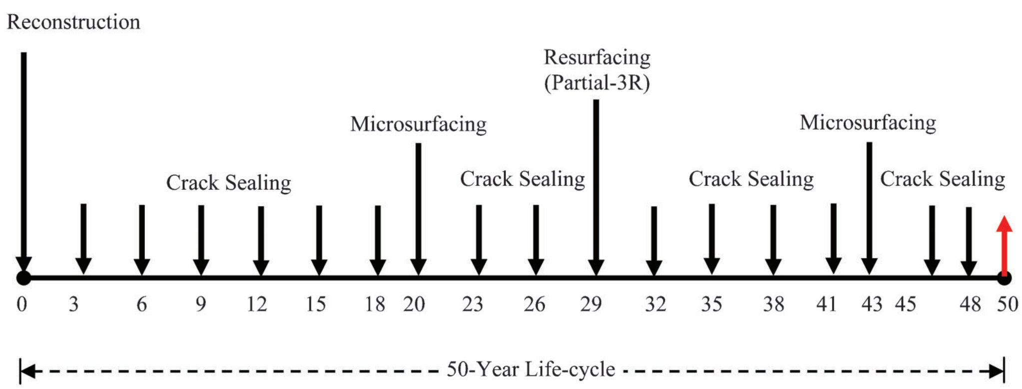


Figure II.G.54 M&R Profile for Flexible Pavement (NNHS) –14 (Medium Traffic).

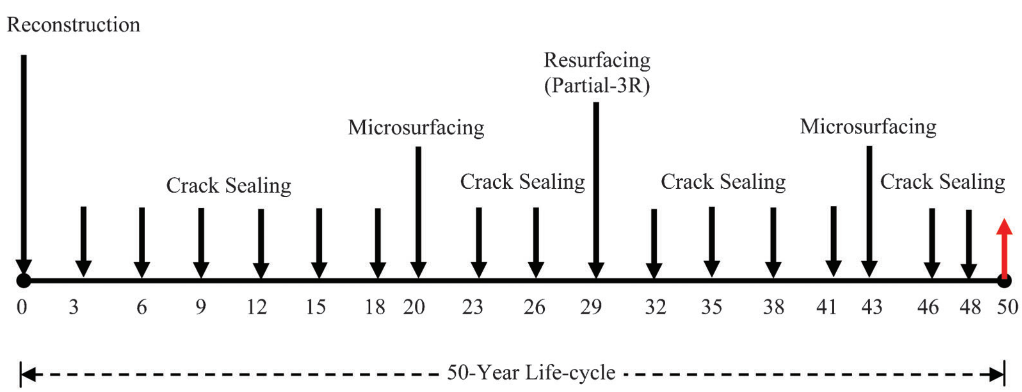


Figure II.G.55 M&R Profile for Flexible Pavement (NNHS) –15 (Medium Traffic).

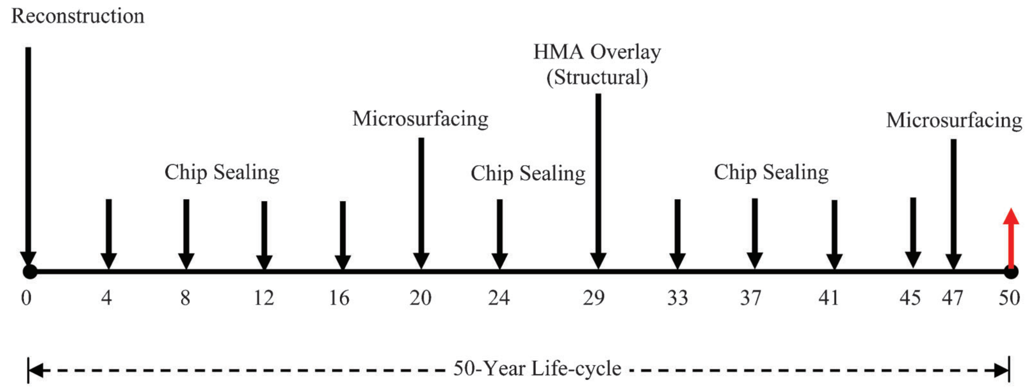


Figure II.G.56 M&R Profile for Flexible Pavement (NNHS) –16 (Low Traffic).

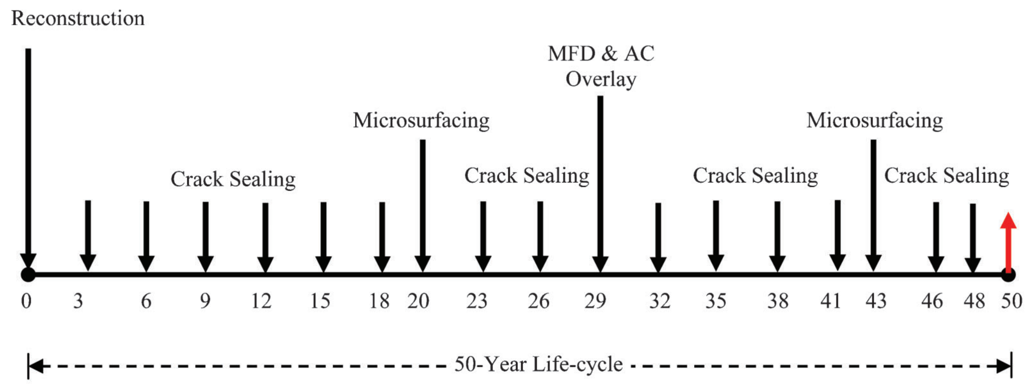


Figure II.G.57 M&R Profile for Flexible Pavement (NNHS) –17 (Low Traffic).

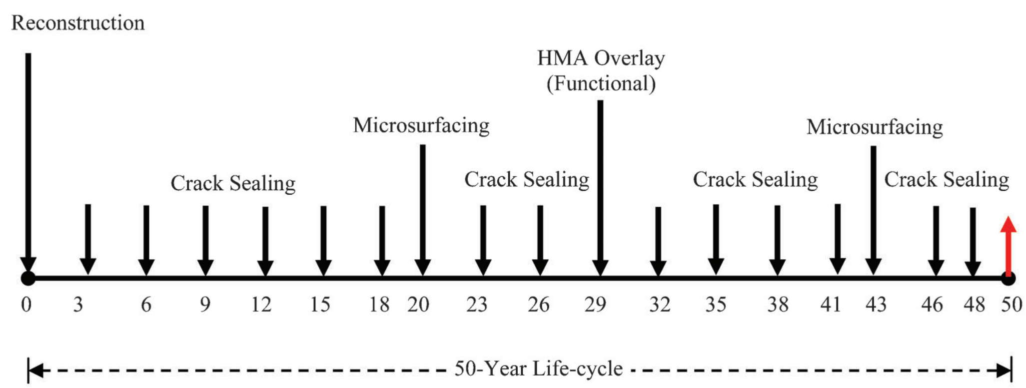


Figure II.G.58 M&R Profile for Flexible Pavement (NNHS) –18 (Low Traffic).

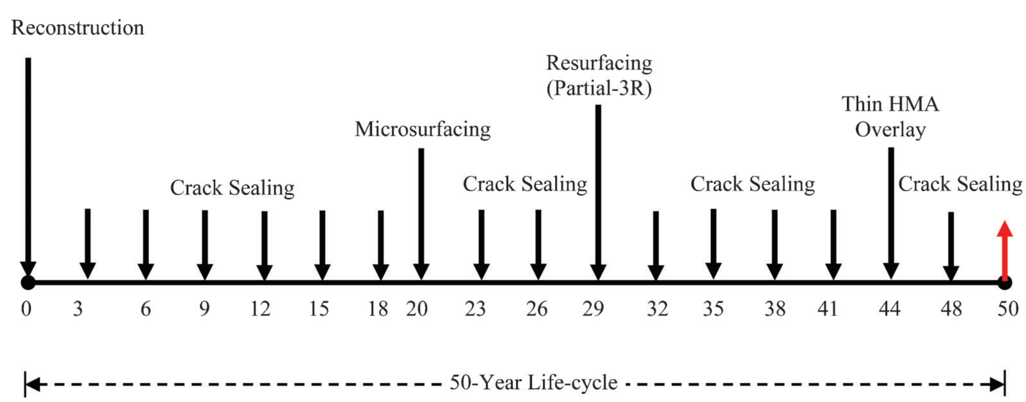


Figure II.G.59 M&R Profile for Flexible Pavement (NNHS) –19 (Low Traffic).

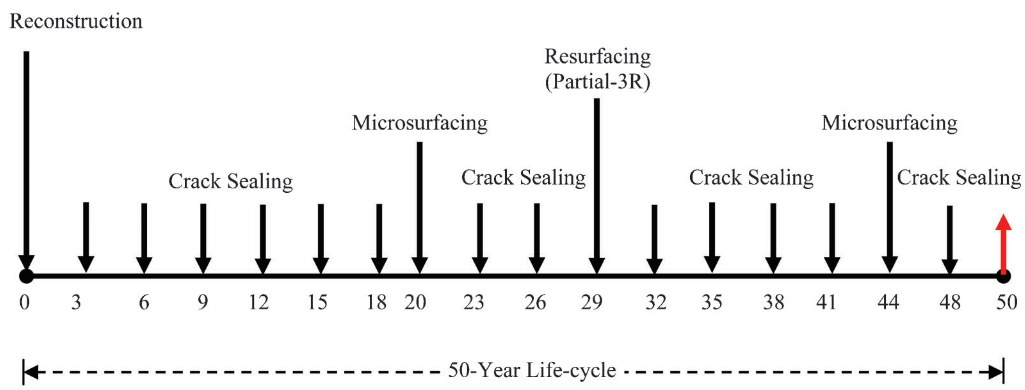


Figure II.G.60 M&R Profile for Flexible Pavement (NNHS) –20 (Low Traffic).

Life-cycle M&R Profiles – Rigid Pavements (Interstate)

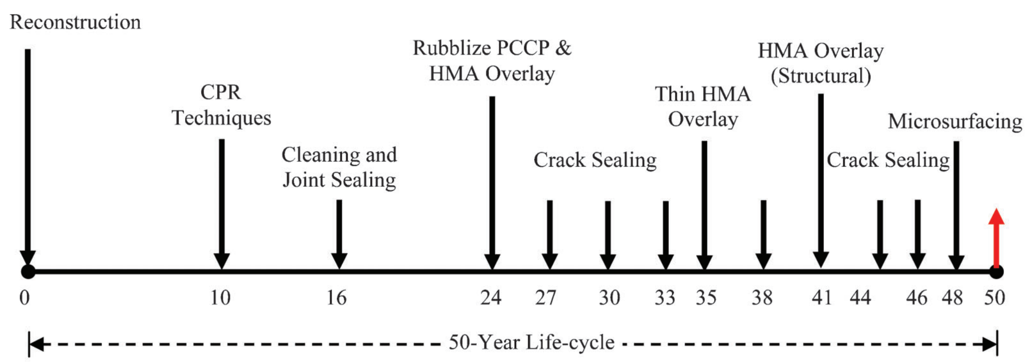


Figure II.G.61 M&R Profile for Rigid Pavement (Interstate) –1 (Very High Traffic).

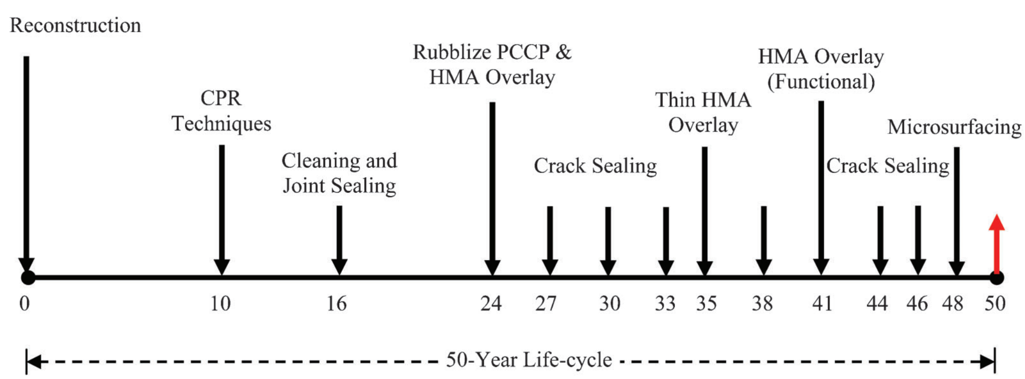
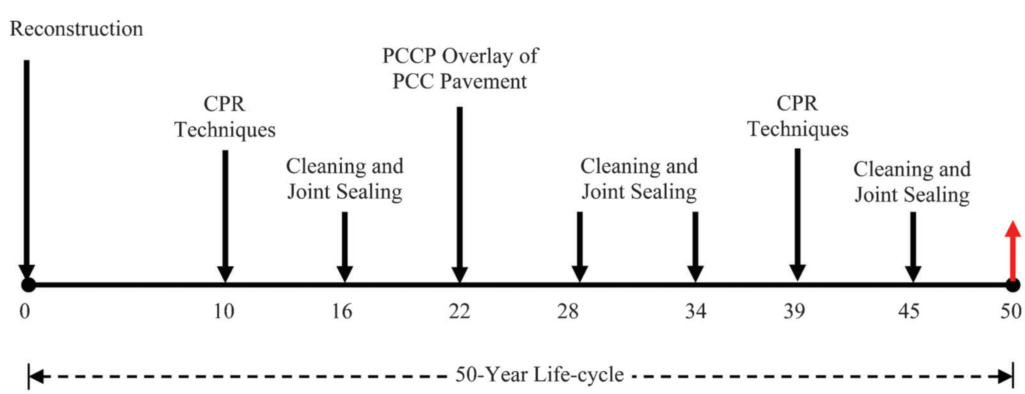


Figure II.G.62 M&R Profile for Rigid Pavement (Interstate) –2 (Very High Traffic).



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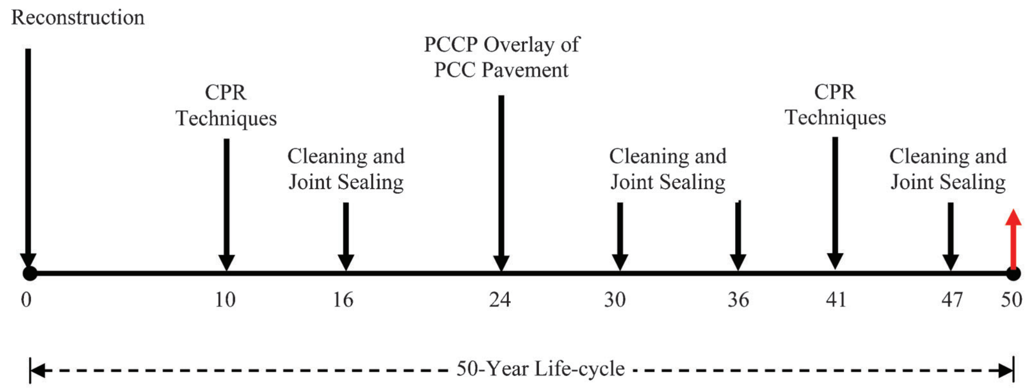
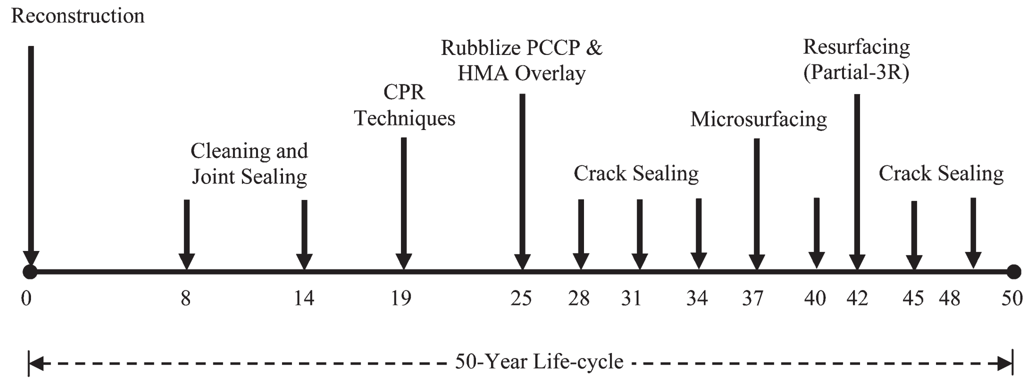


Figure II.G.64 M&R Profile for Rigid Pavement (Interstate) –4 (Very High Traffic).



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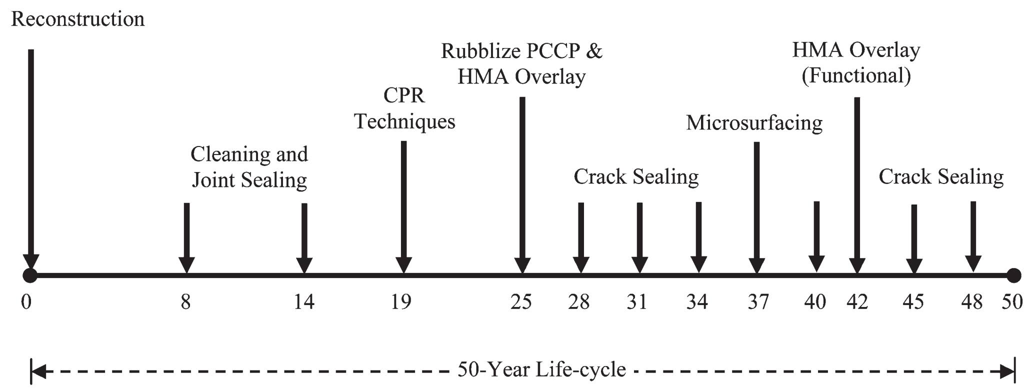


Figure II.G.66 M&R Profile for Rigid Pavement (Interstate) –6 (High Traffic).

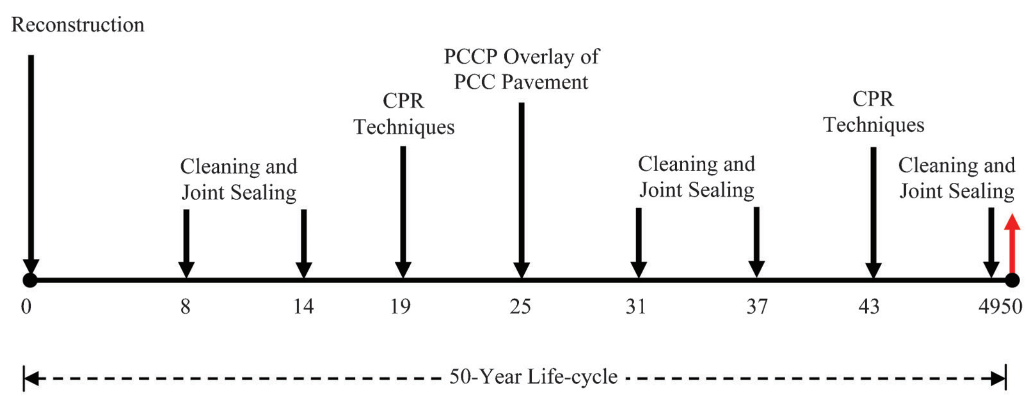


Figure II.G.67 M&R Profile for Rigid Pavement (Interstate) –7 (High Traffic).

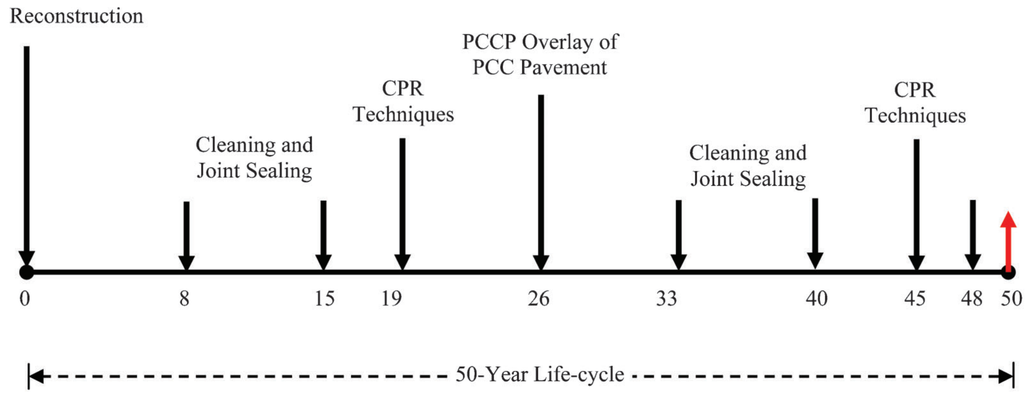


Figure II.G.68 M&R Profile for Rigid Pavement (Interstate) –8 (High Traffic).

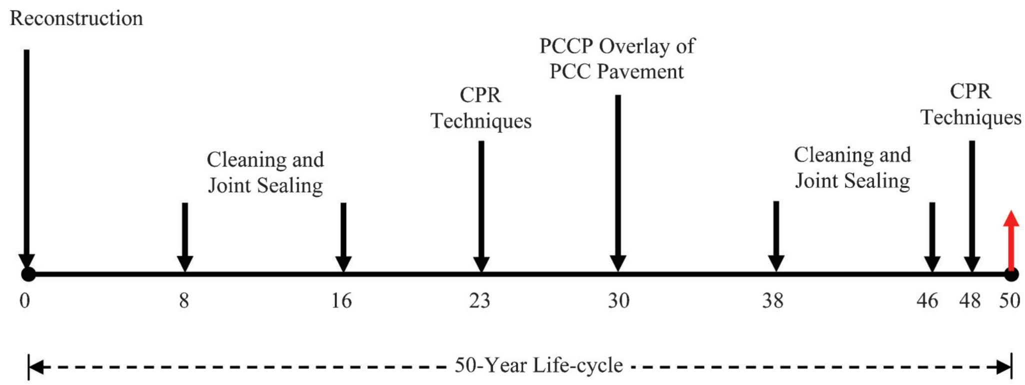


Figure II.G.69 M&R Profile for Rigid Pavement (Interstate) –9 (Medium Traffic).

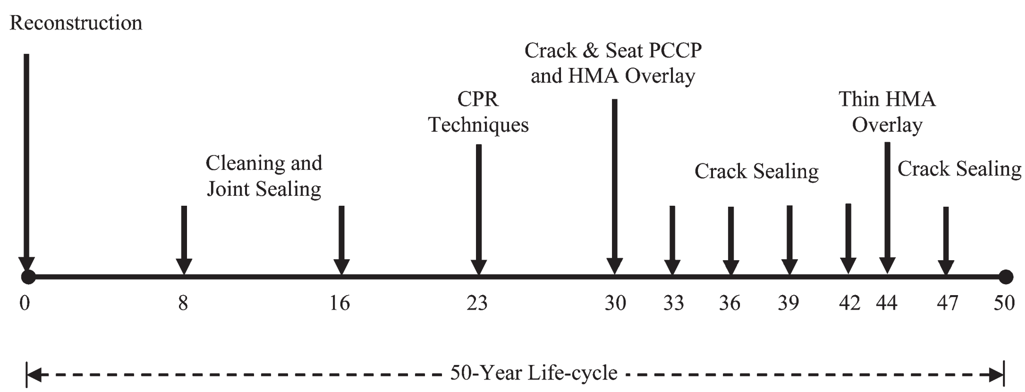


Figure II.G.70 M&R Profile for Rigid Pavement (Interstate) –10 (Medium Traffic).

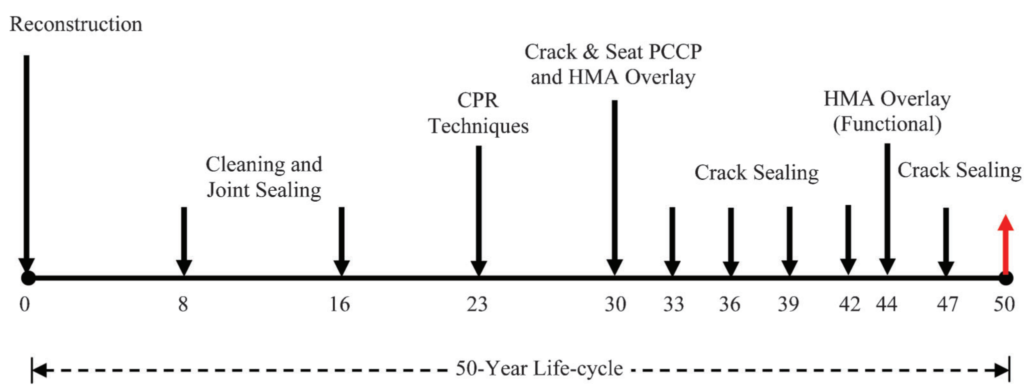


Figure II.G.71 M&R Profile for Rigid Pavement (Interstate) –11 (Medium Traffic).

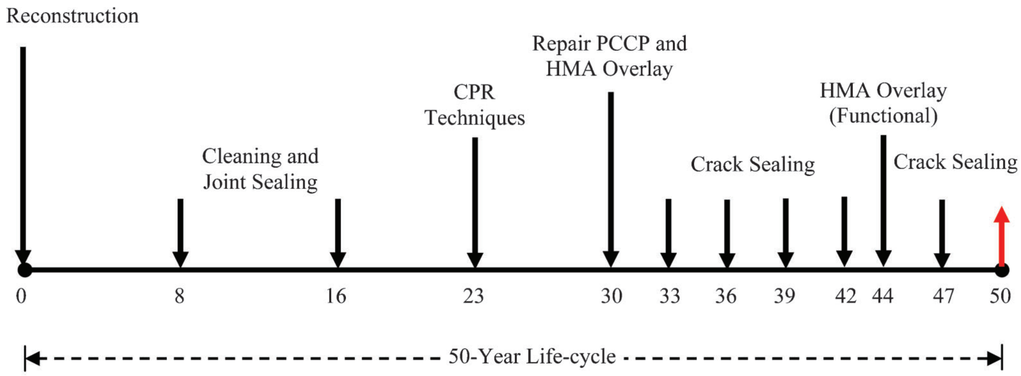


Figure II.G.72 M&R Profile for Rigid Pavement (Interstate) –12 (Medium Traffic).

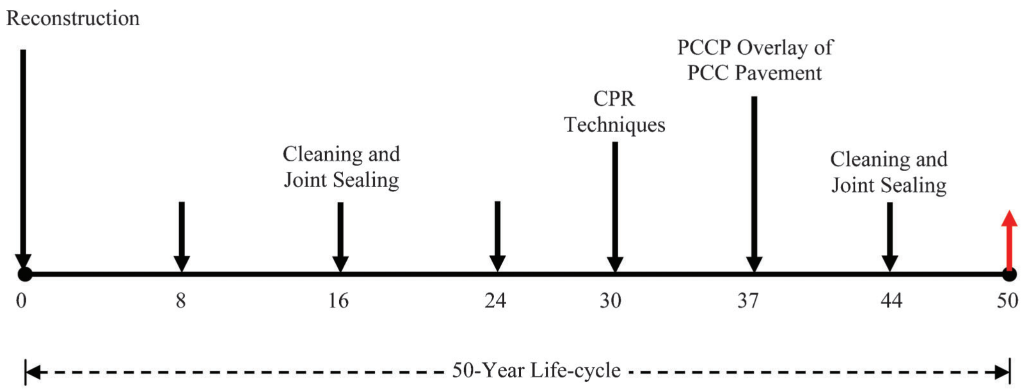


Figure II.G.73 M&R Profile for Rigid Pavement (Interstate) –13 (Low Traffic).

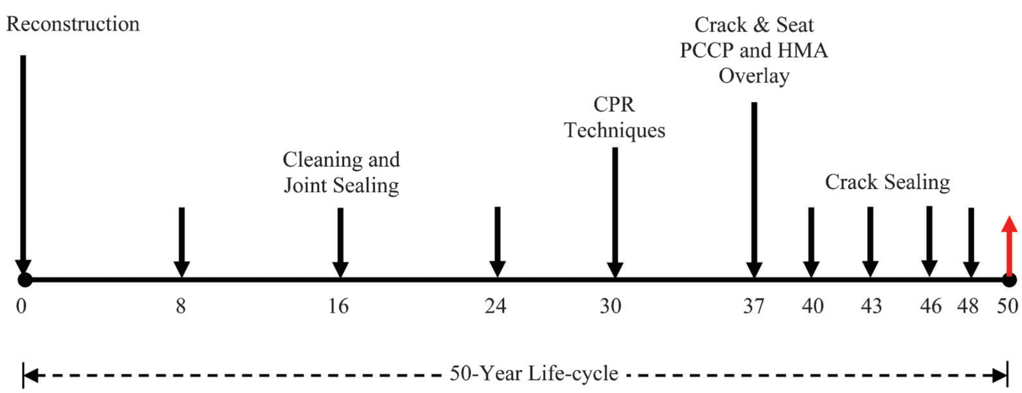


Figure II.G.74 M&R Profile for Rigid Pavement (Interstate) –14 (Low Traffic).

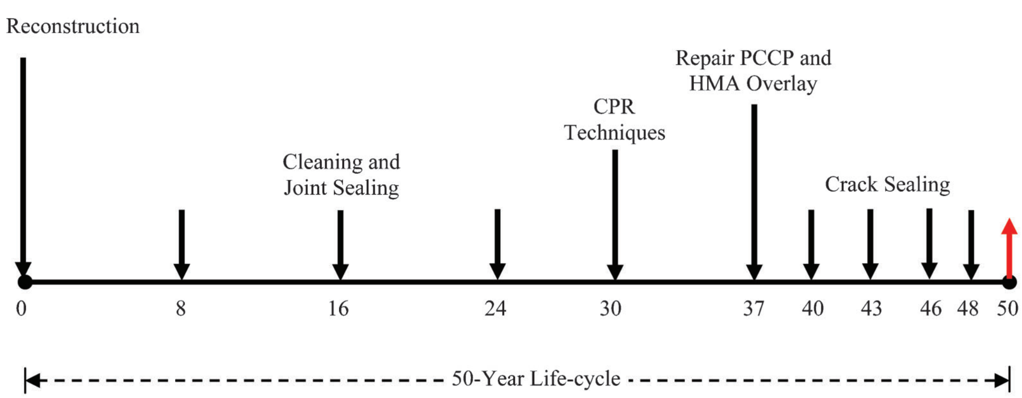


Figure II.G.75 M&R Profile for Rigid Pavement (Interstate) –15 (Low Traffic).

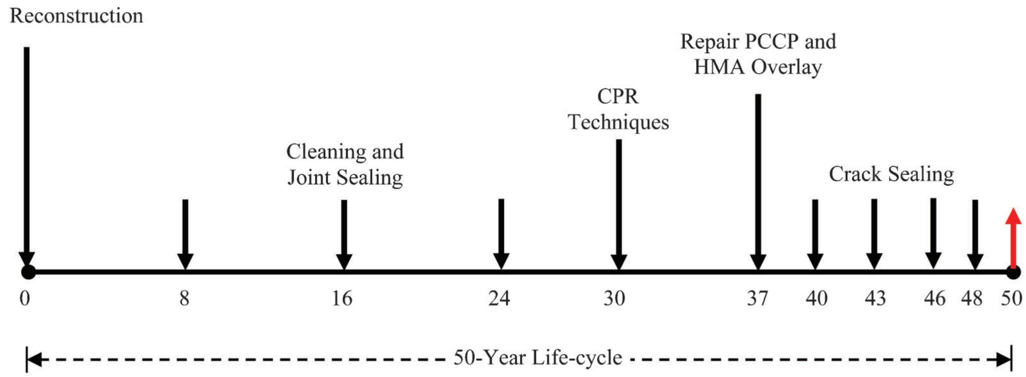


Figure II.G.76 M&R Profile for Rigid Pavement (Interstate) –16 (Low Traffic).

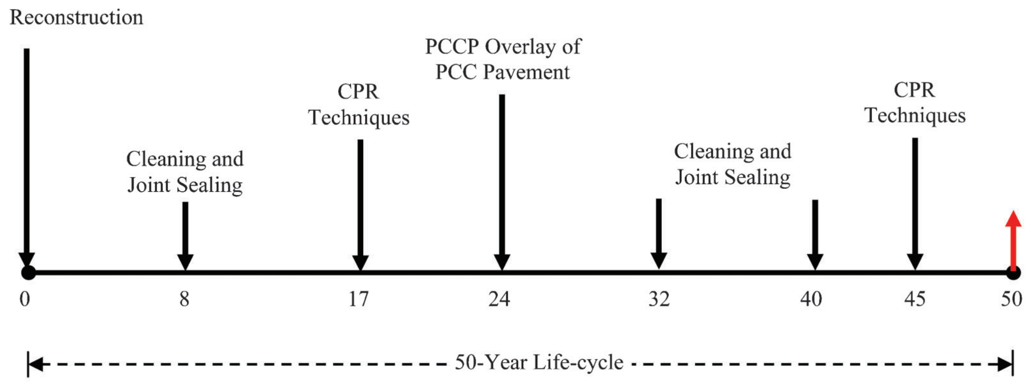


Figure II.G.77 M&R Profile for Rigid Pavement (Non-Interstate) –1 (Very High Traffic).

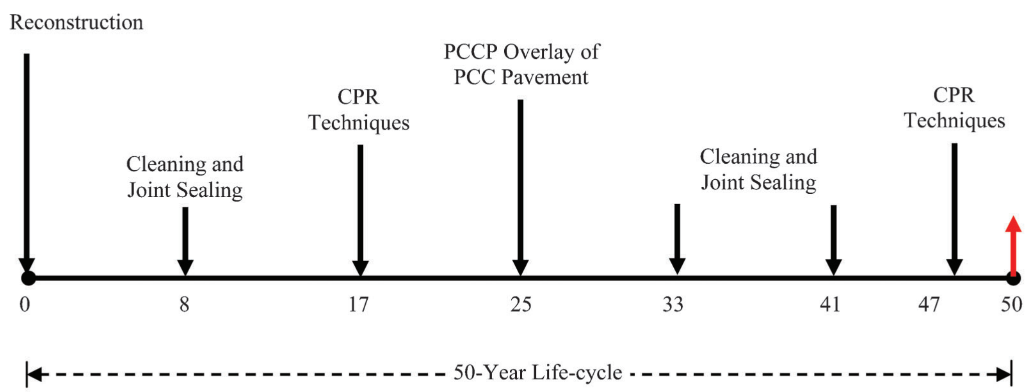


Figure II.G.78 M&R Profile for Rigid Pavement (Non-Interstate) –2 (Very High Traffic).

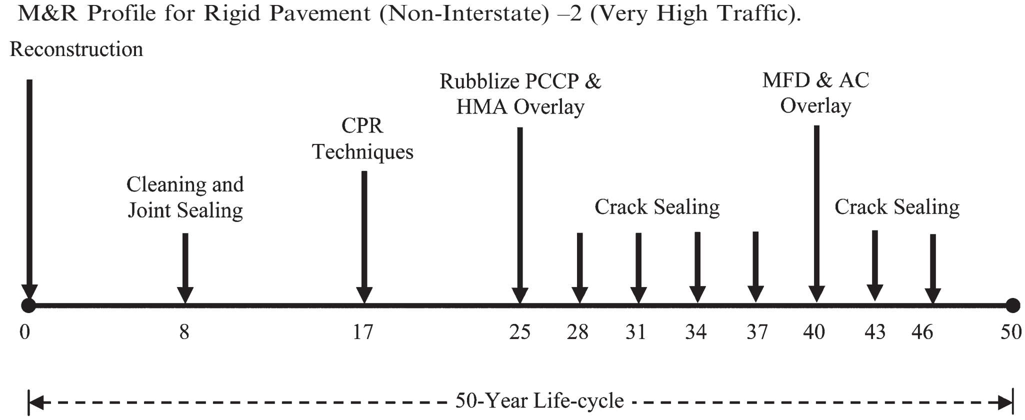


Figure II.G.79 M&R Profile for Rigid Pavement (Non-Interstate) –3 (Very High Traffic).

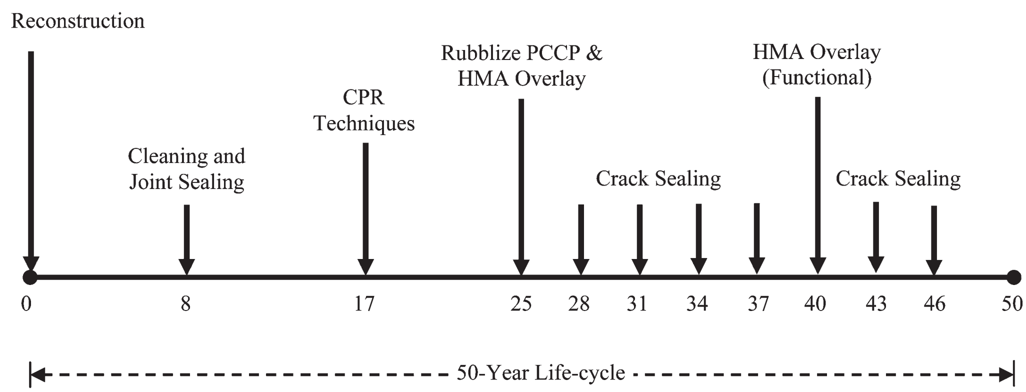


Figure II.G.80 M&R Profile for Rigid Pavement (Non-Interstate) –4 (Very High Traffic).

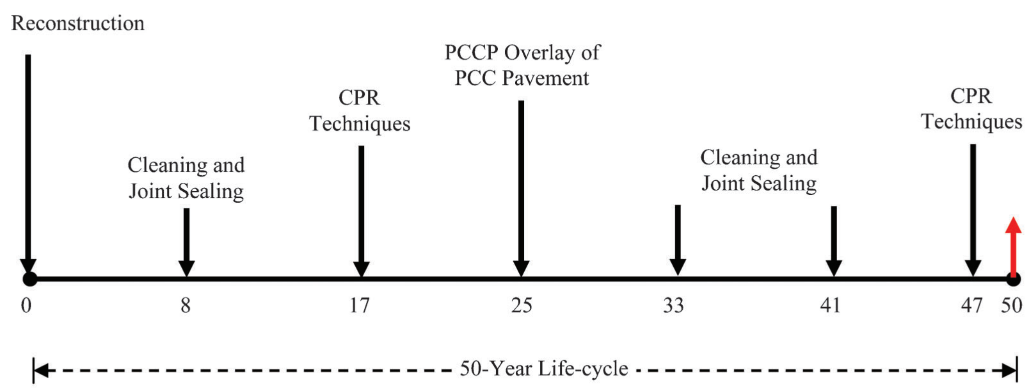


Figure II.G.81 M&R Profile for Rigid Pavement (Non-Interstate) –5 (High Traffic).

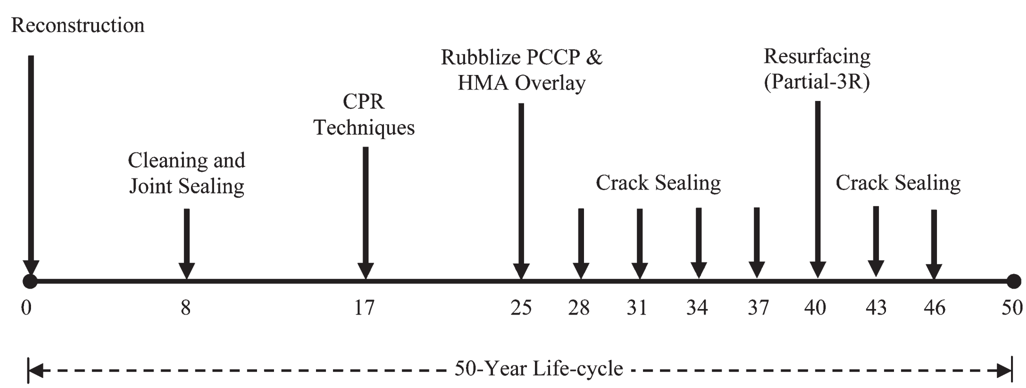


Figure II.G.82 M&R Profile for Rigid Pavement (Non-Interstate) –6 (High Traffic).

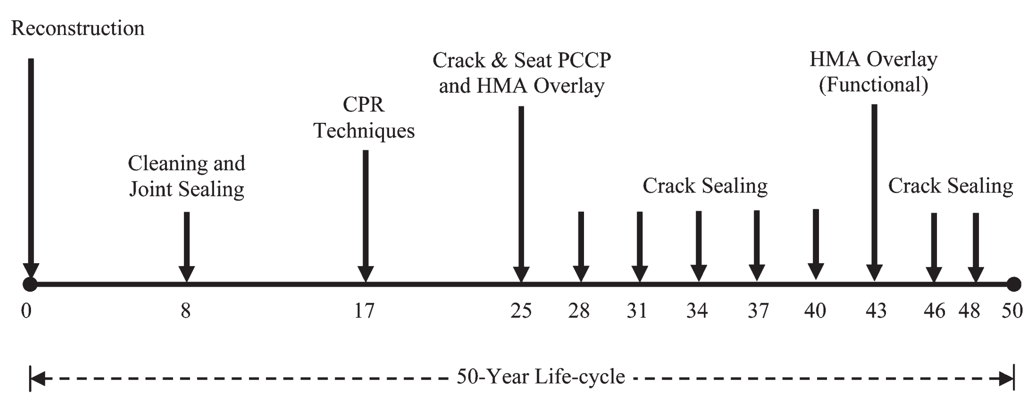


Figure II.G.83 M&R Profile for Rigid Pavement (Non-Interstate) –7 (High Traffic).

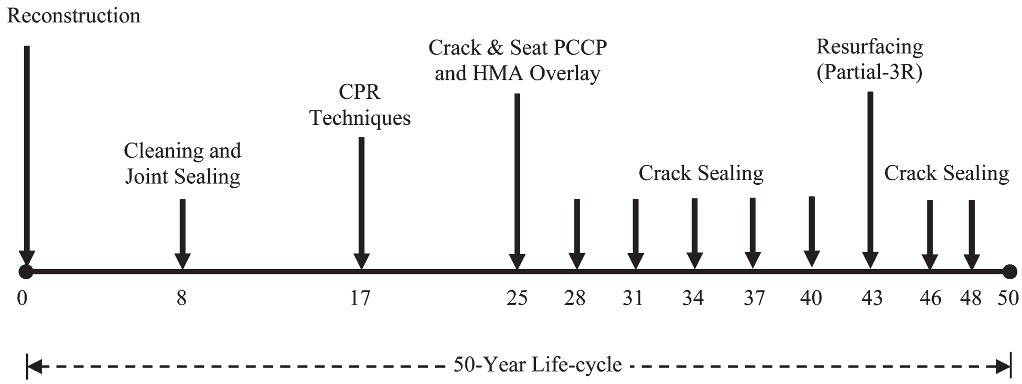


Figure II.G.84 M&R Profile for Rigid Pavement (Non-Interstate) –8 (High Traffic).

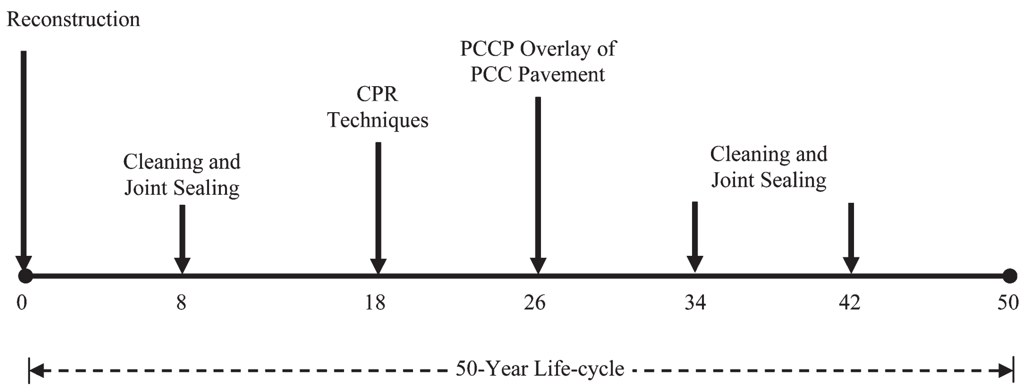


Figure II.G.85 M&R Profile for Rigid Pavement (Non-Interstate) –9 (Medium Traffic).

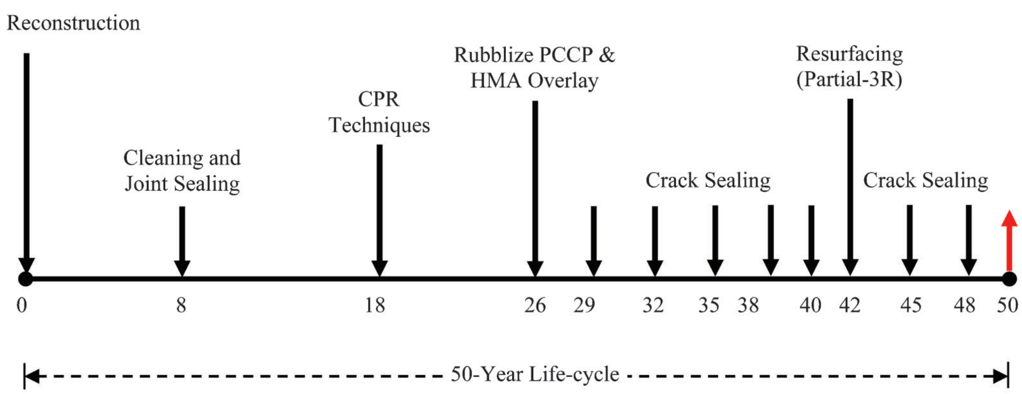


Figure II.G.86 M&R Profile for Rigid Pavement (Non-Interstate) –10 (Medium Traffic).

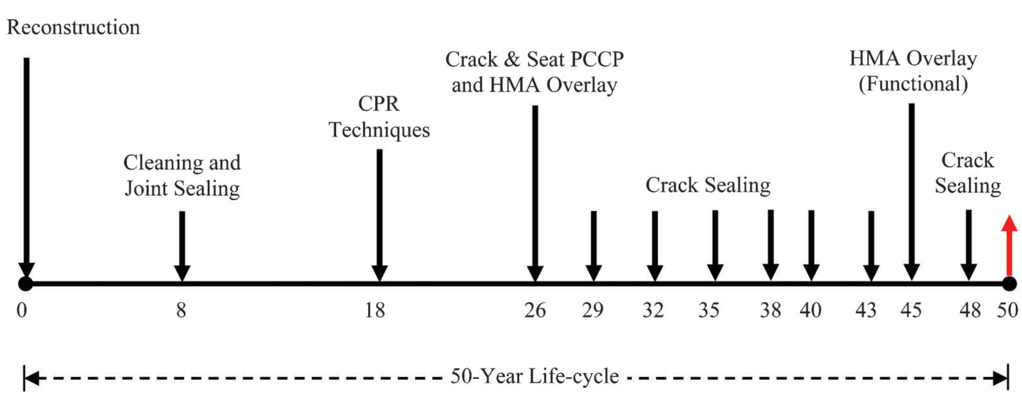


Figure II.G.87 M&R Profile for Rigid Pavement (Non-Interstate) –11 (Medium Traffic).

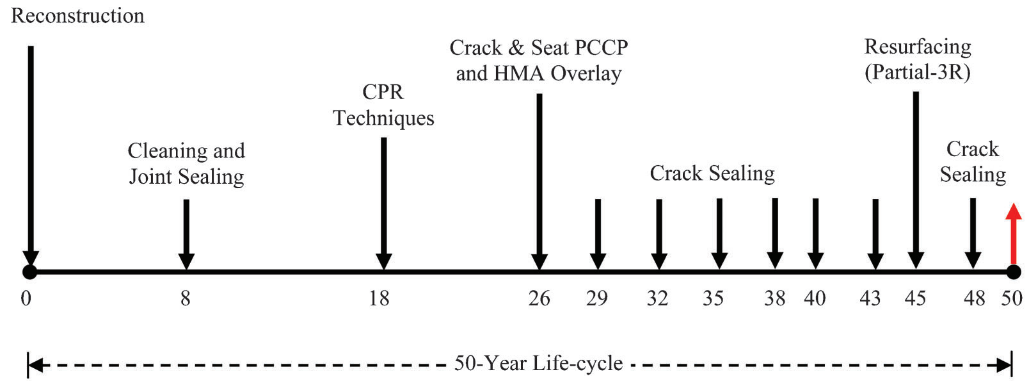


Figure II.G.88 M&R Profile for Rigid Pavement (Non-Interstate) –12 (Medium Traffic).

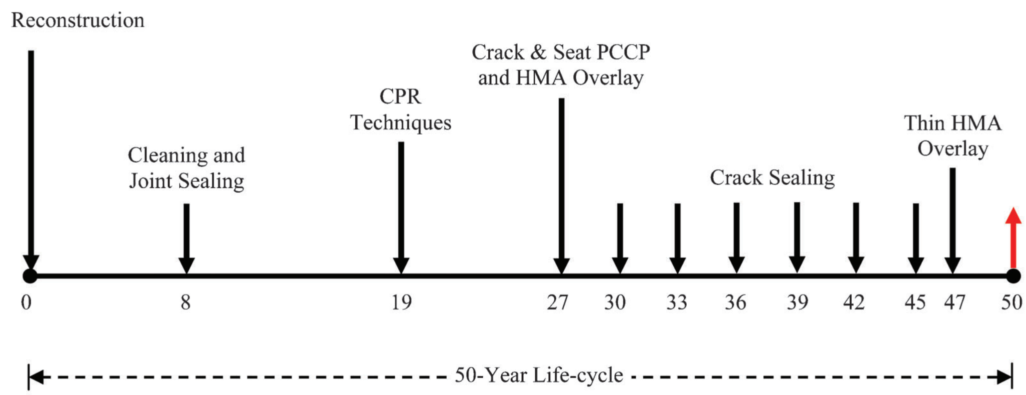


Figure II.G.89 M&R Profile for Rigid Pavement (Non-Interstate) –13 (Low Traffic).

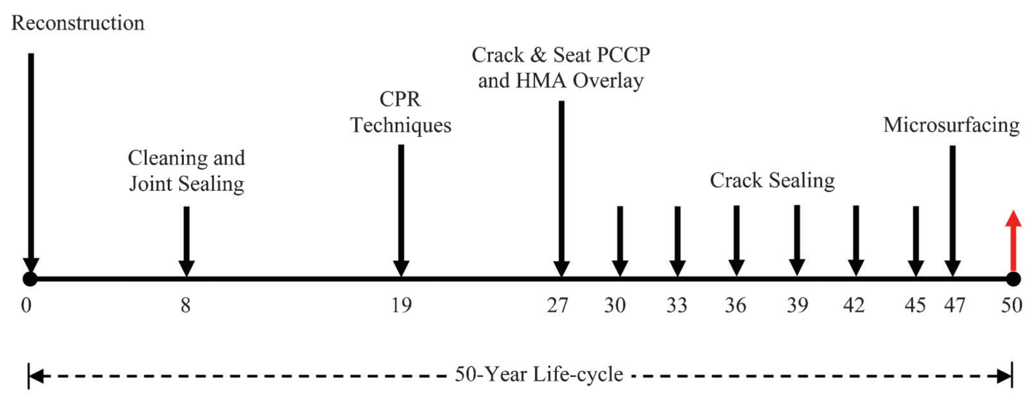


Figure II.G.90 M&R Profile for Rigid Pavement (Non-Interstate) –14 (Low Traffic).

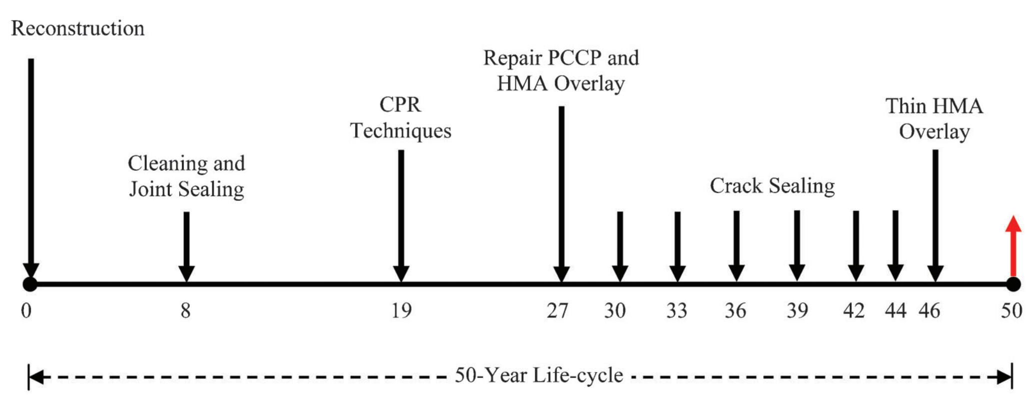


Figure II.G.91 M&R Profile for Rigid Pavement (Non-Interstate) –15 (Low Traffic).

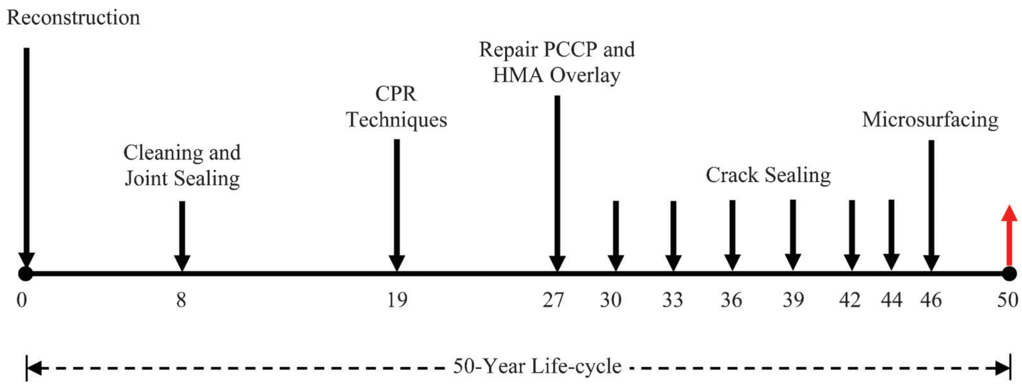


Figure II.G.92 M&R Profile for Rigid Pavement (Non-Interstate) –16 (Low Traffic).

PART III. BRIDGE DAMAGE COST ESTIMATION

8. INTRODUCTION

8.1 Background and Problem Statement

The Indiana Department of Transportation (INDOT), tasked with the stewardship of billions of dollars' worth of publicly-invested highway bridge infrastructure, continually seeks policies that prevent accelerated deterioration of its bridges through excessive loading and other factors. Consistent with this objective, INDOT wishes to determine the infrastructure damage caused by overweight vehicles, to serve as a basis for updating the existing structure for bridge use by overweight trucks. This knowledge would enable the agency to ascertain the true costs of overweight vehicle operations in terms of bridge damage repair.

In 1984, INDOT commissioned a cost allocation study to restructure the user charges that existed at the time (*150*). Then in 1988, the 1984 study was updated to provide information for an intended change in the fuel tax rate. From a general perspective, highway cost allocation and the concomitant analysis of revenue contribution for heavy truck permitting are recognized as a part of a continuous process of pricing and financing highway service delivery.

The need for a cost allocation study in Indiana for purposes of updating the state's heavy truck permitting fee structures for the state's bridges and pavements was further accentuated in a recent INDOT study that synthesized overweight vehicle permitting practices, including permit fee schedules and amounts, across the Midwest states in relation to the practice in Indiana (*151*).

8.2 Objective of the Study

The primary objective of the bridge aspect of the research is to estimate the bridge damage cost caused by overweight vehicles and relate it to truck operations in Indiana. It is expected that the investigation would yield an updated and more detailed methodology for attributing the costs of bridge repair. Pursuant to this overall objective, other objectives were:

- Identify the costs and revenues related to overweight vehicle operations at the state highway bridges in Indiana.
- Compare costs by vehicle weight class.

8.3 Study Scope

The study was carried out for bridges on the state highway system only. This means that the relevant route types were: Interstates, US Highways, and State Roads. For purposes of the study, bridges on these three route types were classified as follows: Interstate, NHS non-Interstate, and non-NHS. Bridges on county and local roads were excluded. From the perspective of bridge material type, the study scope covered the following: steel, prestressed concrete, reinforced concrete. Also, recognizing that the damage costs can vary by bridge condition or age, the bridges were placed into groups of 15–20 age (years). With respect to the source of damage inflicted to the bridge structure, the scope covered the standard AASHTO vehicle types, namely, HS-20 to H-41.

8.4 Organization of Part III the Report

This part of the report has six chapters. Chapter 9 reviews the existing literature and the study methodology related to the concepts of incremental cost analysis used for bridge cost allocation studies. Chapter 10 discusses the cost allocation methodology and its developmental components and addresses the question of what constitutes an overweight truck and how overweight truck traffic volumes are estimated. Chapter 10 also presents the developed statistical model that correlates AASHTO vehicles to FHWA vehicles and the incremental bridge cost allocation methodology that was developed in this research to allocate bridge damage cost to each vehicle class, including overweight trucks. Chapter 11 shows how the bridge life-cycle costs were estimated and Chapter 12 applies the methodology discussed in Chapter 10 to allocate the life-cycle costs that were estimated in Chapter 11. Chapter 13 presents the report summary and conclusions.

9. ESTIMATION OF BRIDGE DAMAGE COSTS

9.1 Introduction

This chapter presents a literature review on bridge damage cost estimation. The Chapter also discusses the incremental cost analysis methodology which is scientifically-proven and accepted for bridge cost allocation (*152–155*). The chapter also presents the types of costs used in the analysis and argues for the use of a full life-cycle cost analysis instead of the cost per activity, for the purposes of the costing aspect of the analysis. Finally, case studies related to the estimation of bridge damage costs for purposes of highway cost allocation, at the state and federal levels, are discussed.

As evidenced in the literature, there are various methods for estimating the costs of bridge damage. Often, this has been done as part of cost allocation studies (*150*). The most commonly-used approach is the cost-occasioned approach where each user is designated to pay an amount that is commensurate with the damage that the user causes or "occasions" by using the bridge. This approach was used in the last two highway cost allocation studies at the federal level (*153,156*). Also, a majority of the states have used this approach to allocate bridge costs (*157*).

An important issue that often arises with infrastructure damage cost estimation and cost allocation is equity. Critics contend, for example, that different vehicles within the same class can have varying impacts of damage on a bridge structure, and thus should pay different amounts for the use of the bridge. This contrasts with current policy at several states where all vehicles in a single class are charged the same amount for the use of the bridge. Equity, in the context of damage cost estimation and cost allocation, can be defined as payment of charges by each vehicle class in a manner that is proportionate to the true share of that vehicle class of the agency cost of the infrastructure provision and upkeep.

9.2 Incremental Cost Analysis

Incremental cost analysis, a technique based on the cost-occasioned approach, is widely used by highway agencies to estimate the cost of bridge damage by vehicle class because it has been found to be theoretically sound and widely acceptable. Incremental analysis involves repetitive designs of the bridge structure for different vehicle loadings (*150*). Then, for each loading-design configuration, the initial (construction) and life-cycle costs are estimated. For example, an automobile, compared to a heavy truck, requires a bridge structure of lower strength.

Thus, the incremental analysis estimates the cost of bridge damage on the basis of an incremental bridge design that indicates changes in bridge strength in order to accommodate increasingly higher classes (and weights) of vehicles. In most cases, any inaccuracies in bridge damage cost estimation and cost allocation using the incremental cost methodology are likely due to the use of a single bridge as a basis of the analysis (the bridge that is used may not be representative of the different types of bridges on the network); estimation of the damage costs and allocation of costs that are unrelated to bridge design; and the lack of detailed incremental analysis on the basis of the full range of vehicle classes. Notwithstanding these limitations, the classic incremental method is generally considered to be fundamentally sound and is used widely by most state agencies. Also, the FHWA used the incremental method for highway damage cost estimation and cost allocation until 1997 when it was modified (*153*).

The incremental approach is based fundamentally on a set of bridge structural designs for a standard set of vehicle loadings as defined by AASHTO (*158*). In the AASHTO bridge specifications, traffic-related loadings are represented by standard trucks or equivalent lane loads. The trucks are designated with an HS (tractor-trailer combinations) or H (two-axle truck) prefix followed by a number indicating the gross weight of the truck in tons.

The AASHTO bridge specifications provide four vehicle classes of highway design (HS20, HS15, H20 and H15). From AASHTO specifications, H15 is 75% of H20 (*158*). On the basis of the above designated loadings, other loadings can be determined by proportionally changing the standard weights. It may be noted that the design vehicle classes or loads are different from the gross vehicle weights (GVW). In order to reliably estimate the loading, the GVW must be correlated to the design vehicle or load classes. The incremental cost analysis is illustrated in Figure 9.1. In the incremental approach to bridge design, bridges are typically first placed into families based on their design, material type, size, and other characteristics.

9.2.1 Establishing a Vehicle Class

The vehicle classes used in the study were established on the basis of FHWA vehicle classes. In this study, only FHWA vehicle classes 7 to 13, that is, vehicles that could possibly exceed the legal load limit, were considered.

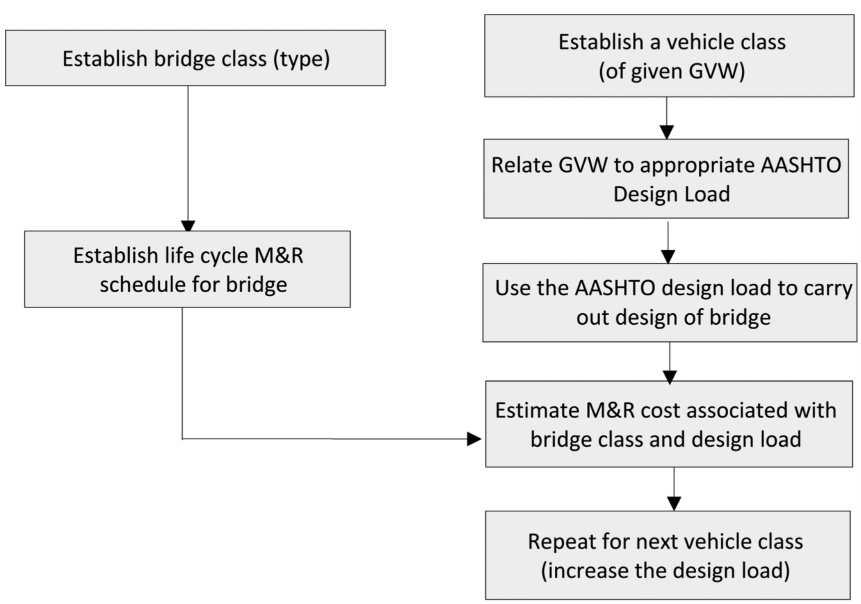


Figure 9.1 Steps in the incremental approach to bridge damage cost estimation.

9.2.2 Establishing Bridge Classes

As stated in the Introduction, the study was carried out for bridges on the state highway system only. For the purpose of this study three bridge classes were used (steel, prestressed and concrete) because they constitute the majority of the types of bridges along the state highway system.

9.2.3 Establishing Life-Cycle M&R Schedule and Estimating Cost

In order to establish the cost for each bridge type, the life-cycle maintenance and rehabilitation schedules were established. A detailed discussion of the life-cycle maintenance and rehabilitation schedules and cost estimation is presented in Chapter 11.

9.2.4 Relating GVW to Vehicle Design Loads

At this step, a quantitative correlation needs to be established between the weights of vehicles operating on the highways and AASHTO's design index loads. The vehicle live load for highway bridges is typically specified using design vehicles or lane loads. Each lane load is represented by a standard truck with a trailer or as a uniform load superimposed by concentrated loads. These loads are typically designated as H or HS loads in the AASHTO specifications. The design vehicles range from H20–HS20. For example, an H20 load simulates a two-axle single truck with a 14-foot wheel base and a total weight of 20 tons (40,000 lbs) while an HS-20 load is a three-axle tractor trailer combination with variable wheel spacing and a total weight of 36 tons (72,000 lbs). In order to yield the maximum stress for continuous spans bridges, a lane load or a truck load can be used. A lane load consist of a uniform load per linear foot of traffic loading combined with a single concentrated load (for a simple span bridge) or two concentrated loads for a continuous span bridge (*158*).

The basic AASHTO design loads are not the same as the loads of trucks operating on the highways. Rather, they are index loadings used to specify the design criteria, and their configurations are designed to simulate the maximum or severe live loads that operate on bridges. A number of past studies (*153,155*) have sought to correlate gross vehicle weights to the AASHTO design loads (Tables 9.1 and 9.2).

TABLE 9.1
Correlation of AASHTO Vehicles and Gross Vehicle Weights (*155*)

Gross Vehicle Weights (kips)	AASHTO Design Loads
0–10	H5
11–20	H10
21–40	H15
41–52	H20
Over 52	H20

TABLE 9.2
Structure Design Increments (*153*)

Design Load (lbs)	Design Increment
5,000	H2.5
10,000	H5
20,000	H10
30,000	H15
40,000	H20
54,000	HS15
63,000	HS17.5
72,000	HS20

Clearly, using this rather simple correlation approach precludes the incorporation of the effect of two remaining variables: axle load distributions and axle spacing. In a bid to refine the process to capture axle spacing and axle loading, Schelling and Saklas (*154*), in a Maryland study, developed a new methodology that established a relationship between the maximum moments produced on a bridge based on the FHWA vehicles and AASHTO design vehicles. Each vehicle group was identified by its design axle loading and axle spacing. In order to establish the correspondence, each weight class in the basic truck group was represented by loads acting on a simple bridge with alternate span lengths of 42 ft. to 400 ft. The analytical relationship was established using linear least squares techniques to fit the data. Although this approach seems to be useful, it was limited to only simply-supported single-span bridge structures. Therefore, extending the model to continuous spans can yield biased estimates.

To overcome this challenge, Tee et al. (*159*) introduced the equivalent load approach that used not the load but loading outcome (amount of deflection or moment) produced by the AASHTO design vehicle. Then the relationship was found between the loading outcome and FHWA classes (not GVW). It can be noted that the loading outcome, in terms of moment or deflection, is influenced by axle spacing, the axle-load distribution of the vehicles, and the bridge span type (simple or continuous). Because it used the loading outcome instead of the loads, the Tee methodology was found to be more robust than the WisDOT (*155*), FHWA (*153*), or Schelling and Saklas (*154*) methodologies. Although the Tee methodology is useful and relevant, it requires a longer computation time and some expertise in bridge design. In order to remove the above barriers, modifications were made to the Tee approach (also referred to as the equivalent load approach), for the present study. These modifications are discussed in Chapter 10.

9.2.5 Incremental Bridge Design

For a representative bridge representing each bridge family, a basic structure is designed with the minimum design load. The basic structure represents the minimum dimensions for the structural components. The minimum design depends largely on the engineer's judgment and varies with the bridge type, span, length, and crossing type. In the Wisconsin study (*155*), for example, a 24-ft roadway and one layer of steel bar reinforcement for 5-in concrete slabs were considered to constitute the minimum requirement. The structural types and span lengths were selected as representative structures based on 150 bridges constructed in the State of Wisconsin during the base period (1977–1980), which represent 96 percent of the bridges constructed in that period. For each bridge type and span length, a "basic" bridge was designed in the Wisconsin study for the minimum vehicle load. Also, different minimum designs carried out for highway systems of different functional classes. Then, for each additional increments of the design load up to the load for which the bridge was originally designed, the bridge is designed. The increments are established on the basis of vehicle classification.

9.2.6 Estimation of Incremental Cost

After the incremental bridge design, the next stage of analysis is the evaluation of the cost associated with each increment of design using cost data often obtained from contract documents. In order to determine the number of bridges to use in the analysis, any one of the four sampling approaches (full design method, representative-bridge design method, semi-statistical method, or heuristic method) could be used. The full design method uses all of the bridges constructed in the base period to find their incremental designs and associated costs. This method is more costly in terms of data collection but more accurate compared to the other sampling methods. However, the standardization of design procedures and the required engineering judgment in the incremental designs makes the full design method more laborious in its implementation. This method was used in the Maryland study (*154*).

The representative bridge method considers a group of representative bridge types selected from the base period and their span lengths. The difference between the full design and representative methods is that in the latter, a detailed incremental design and a cost evaluation are performed only for a single representative bridge in each bridge family but not for the entire population of bridges. For example, the Wisconsin study (*155*) used only six bridges, each representing one of the six bridge families established in that study. This method is the most commonly used in the literature and was adopted in two of the recent past cost allocation studies at the federal level (*160*). This method may lead to large variability in costs unless a sufficient number of representative bridge types are included.

The semi-statistical method is very simple to use and has been shown to be useful and therefore is considered acceptable. It involves selecting two or more bridges to represent each bridge family. A basic structure is then designed for each bridge family based on the minimum vehicle load. The cost of the basic structure is calculated and expressed as a ratio or percentage of the total cost of the actual structure. This is repeated for each loading level (after each load increment). A plot of the ratios (i.e., cost factors and the load increments) is developed and a statistical relationship or model between these two parameters is established using regression. The cost factor for any loading level can then be determined using the regression model. This method requires considerably less design effort compared with the other methods and minimal loss of accuracy. The Maryland study (*154*) also used this method.

For the heuristic method, cost allocation is carried out using established relationships between bridge cost and standard structural performance. For example, in order to link bridge cost to maximum moment, the relationship between the cost factor (as defined above for the semi-statistical method) and the moment may be assumed to follow some mathematical relationship. Cost factors from other states may be used, because bridge designs are standardized and thus exhibit little or no variations in the overall bridge cost analysis across states for the same bridge size, material, type, dimensions and functionality.

9.3 Life-Cycle Cost Analysis

For costing of bridge construction, rehabilitation and maintenance, most state agencies prefer using the actual expenditures incurred instead of the needed or optimal expenditure (*150*). For example, the 1997 FHWA study (*153*) used past expenditures on bridge construction, replacement, and major and minor rehabilitation to allocate costs to highway users (vehicles). It can be argued that using actual expenditures for cost allocation yields underestimates of the true cost required to maintain the bridge infrastructure because, in practice, agencies make infrastructure decisions based on budgetary constraints and thus only invest in bridge projects that are identified as critical or high priority. This leads to the deferment of other bridge projects that are deserving of same action but do not make the priority list.

As such, for the present study, the costing was carried out on the basis of the funding needed to keep the bridges in acceptable condition rather than the past expenditures. This was done using life-cycle cost analysis (LCCA), a tool that facilitates bridge management decisions. The LCCA methodology is discussed in Chapter 10.

9.4 Past Studies Related to Bridge Damage Cost Estimation

9.4.1 The 1997 Federal Bridge Cost Allocation Study (153,160)

For the federal bridge cost allocation study, the costs were categorized as follows: new bridge, bridge replacement, and major and minor bridge rehabilitation. In each category, the costs were clustered into four work classes: preliminary engineering, right-of-way, construction, and other. Approximately 50% and 25% of all the bridge costs were for bridge replacement and major rehabilitation, respectively.

For new bridges, there was a substantial improvement in the cost allocation procedure compared to the 1982 federal HCA approach. The basic principles, however, remained the same. In the 1997 federal HCA study, bridge design procedures were used to develop the relationships between vehicle size and weight on one hand and the costs associated with ensuring that the bridge is competent enough to safely accommodate the vehicle fleet on the other hand. The improved approach addresses some of the major shortcomings of the 1982 federal HCA study, particularly, the simplifying assumptions underlying the approach. The major differences are summarized in Table 9.3. In the present study, bridge replacement, not new bridge construction, is of interest because the focus on cost of damage repair and not provision of capacity. For the same reason, bridge widening costs were excluded in the present study.

In the 1997 study, simple spans and continuously-supported spans were considered separately. Furthermore, live load moments were calculated for each vehicle class/weight group, each functional highway class (based on the mean length of the primary span), and each bridge support type (simple and continuous). In the 1982 federal HCA study, vehicles were aggregated into fewer groups; all bridges were assumed to be simply-supported; all single-unit trucks were assumed to be a simple point load; and all combination trucks were assumed to produce a moment that was a simple multiple of the moment produced by single-unit trucks. In the 1982 study, vehicles that produce moments similar to HS15 to HS20 design vehicles were placed into the same group. This resulted in the situation where several medium-weight vehicles along with the "heaviest" trucks were assigned responsibility for the highest design increment. In the 1997 study, the number of design/cost increments was increased from 8 to 10 (see Table 9.2).

The cost allocation procedure for new bridges follows the bridge design process. Bridges are designed

TABLE 9.3
Structures' Cost Allocation: Summary of Improvements (*153*)

Item		1982 Study	1997 Study	Comments
Number of cost categories		New construction Replacement Repair	New construction Replacement Major rehabilitation Other	1982: based on PR-37 1997: FHWA implemented a more detailed system (FMIS) that added the "other" bridge cost category
Number of design/cost increments (H5, H10, HS15, etc.)		8	10	The addition of a design/cost increment (HS 18), especially at the upper (HS 15 to HS 20) end, greatly increases the overestimation of cost responsibility for the heavier trucks
Inter-increment allocator		Relative crude approximations using GVW	Live-load moment	This is the most important improvement in the 1997 bridge cost allocation process
The inter-increment allocator (the assignment of vehicle groups to the different design/cost increments were a function of	Span length	No	Yes	Span length is the single most important bridge characteristic in determining live-load moment
	Functional class	No	Yes	This is important because bridge span lengths vary significantly for different functional classes
	Axle loads	Only when aggregated as GVW	Yes	Axle loads and spacings for all vehicle classes and weight groups were used to compute the live-load moments
	Axle spacings	No	Yes	
	Bridge type	No	Yes	Because of the impact of superstructure type on live load moments, live load moments for both simple and continuous bridge types were computed
Bridge replacement		National Bridge Inventory (NBI) sufficiency rating	Bridge needs and investment process (BNIP)	The BNIP determined which bridges required replacement and the extent to which the replacement was load related

to withstand the dead load (the bridge weight) and the live load of the "heaviest" trucks, plus a safety factor. It must be noted that the heaviest vehicles do not cause an immediate collapse of the bridge but reduces the service life of the bridge structure because of fatigue stresses (*159*). Although the high safety factors used in bridge designs compensates for fatigue impacts, it is critical to monitor these bridges periodically along routes designated for heavy trucks (*161*). Any increase in the size and load of the heaviest vehicle will require a corresponding increase in the bridge size or strength. The procedure relates the additional costs necessary to make the bridge incrementally stronger to the set of vehicles that occasion these higher costs.

The bridges in the 1997 FHWA study (*153*) were grouped by highway functional class. For each representative bridge, the allocation was carried out by comparing the live load moments of each vehicle class and weight group to the moment produced by the design vehicle. This comparison allows each vehicle class and weight group to be placed in a specific design increment category, on the basis of whether its live load moment is less than or equal to that of the design vehicle.

The allocation of bridge replacement costs uses the incremental methodology described earlier. The percentage of replacement costs assigned to the design increments was estimated using the bridge needs and investment process model (BNIP), the same model used in estimating bridge investment requirements for an agency's condition and performance report.

The process for allocating major rehabilitation costs was similar to that for replacement costs but more complex because each of thirteen (13) rehabilitation types were considered, these included rehabilitation of the bridge deck, superstructure, or substructure, or some combination of the three. With regard to bridge replacement, a certain percentage of the cost was assigned to different vehicle categories. For new bridge costs, vehicle miles traveled (VMT) was used as the basis for cost allocation.

Also in the FHWA study, minor bridge rehabilitation and repairs were generally not related to vehicle characteristics. All costs were assigned to the base increment using VMT as the allocator. Figure 9.2 summarizes the allocation of bridge costs to vehicle categories. It can been seen from Figure 9.2 that, over 59 percent of bridge costs were allocated to passenger vehicles, 9.5 percent to single unit trucks, and over 21 percent to combination trucks.

In the FHWA study (*153*), bridge cost responsibilities for the vehicle classes were determined on the basis of operating weights (Table 9.4) and expressed in cents per mile. The cost per mile seemed to be rather high

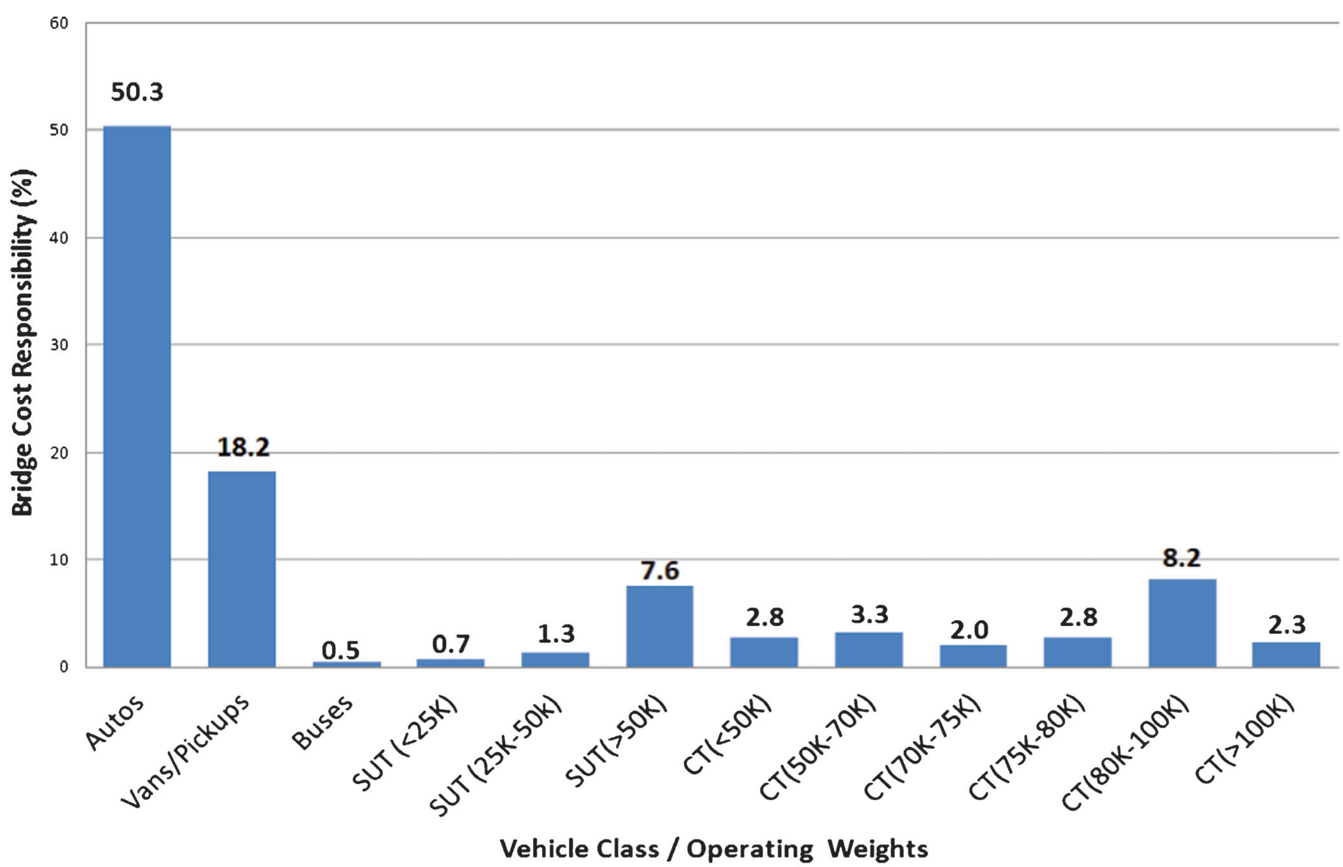


Figure 9.2 Federal bridge cost responsibility (%) by vehicle class (*153*).

TABLE 9.4
Bridge Cost Responsibilities (Cents Per Mile) Estimated by the 1997 FHWA Study (*153*)

Operating Weight (lbs)	SU2	SU3	CS5	CS6	DS5	DS8
0–10,000	0.1					
10,000–20,000	0.2	0.2	0.2	0.2	0.2	
20,000–30,000	0.2	0.2	0.2	0.2	0.2	0.2
30,000–40,000	0.7	0.6	0.2	0.2	0.3	0.2
40,000–50,000	2.4	1.7	0.3	0.3	0.3	0.2
50,000–60,000	4.5	4.3	0.4	0.3	0.3	0.3
60,000–70,000	—	19.1	0.6	0.6	0.4	0.3
70,000–80,000	—	23.9	1.2	0.9	0.7	0.4
80,000–90,000	—	—	2.1	2.4	1.4	0.8
90,000–100,000	—	—	4.4	5.5	2.3	1.3
100,000–110,000	—	—	12.1	13.1	—	1.8
110,000–120,000	—	—	—	21.9		3.1
120,000–130,000	—	—	—	—	—	7.7
130,000–140,000	—	—	—	—	—	8.1
140,000–150,000	—	—	—	—	—	16.5

NOTE: See Table 9.5 for vehicle class category definitions.

for heavy vehicles in each class due to the incremental nature of the cost allocation process. The incremental method assigns the cost of providing the last increments of bridge strength only to vehicles that produce the greatest moments; and heavy vehicles typically account for a relatively small amount of total miles of travel. For these two reasons, their cost responsibility per mile is relatively high. Vehicle class categories used for the federal HCA study are presented in Table 9.5.

9.4.2 Indiana Bridge Cost Allocation Study (162,163)

The modified incremental method was used in Indiana's 1986 HCAS and its 1988 update. The classic incremental methodology was modified at various stages of the allocation process prior to its use in that study. In the study, a group of bridges, representative of the majority of bridges in the state, were selected for the base period. A basic bridge structure was designed with minimum design load. The next step involved a set of designs. These designs were carried out for each bridge structure with additional loading increments up to the design load. The increments were established on the basis of the vehicle classifications which were correlated with the AASHTO design loadings. Such correlation was necessary because the vehicles on the road are different from the design vehicles whose loadings are used in bridge design specifications.

TABLE 9.5
Vehicle Class Categories in the 1997 FHWA Study (*153*)

Vehicle Class	Notation	Description
1	AUTO	Automobiles and motorcycles
2	LT4	Light trucks with 2 axles and 4 tires (pickup trucks, vans, minivans, etc.)
3	SU2	Single-unit, 2 axle, 6 tire trucks (includes SU2 pulling a utility trailer)
4	SU3	Single-unit, 3axle trucks (includes SU3 pulling a utility trailer)
5	SU4+	Single-unit trucks with 4 or more axles (includes SU4+ pulling a utility trailer)
6	CS3	Tractor-semitrailer combinations with 3 axles
7	CS4	Tractor-semitrailer combinations with 4 axles
8	CS5T	Tractor-semitrailer combinations with 5 axles, 2 rear tandem axles
9	CS5S	Tractor-semitrailer combinations with 5 axles, 2 split (>8) rear axles
10	CS6+	Tractor-semitrailer combinations with 6 or more axles
11	CS7+	Tractor-semitrailer combinations with 7 or more axles
12	CT34	Truck-trailers combinations with 3 or 4 axles
13	CT5	Truck-trailers combinations with 5 axles
14	CT6+	Truck-trailers combinations with 6 or more axles
15	DS5	Tractor-double semitrailer combinations with 5 axles
16	DS6	Tractor-double semitrailer combinations with 6 axles
17	DS7	Tractor-double semitrailer combinations with 7 axles
18	DS8+	Tractor-double semitrailer combinations with 8 or more axles
19	TRPL	Tractor-triple semitrailer or truck-double semitrailer combinations
20	BUS	Buses (all types)

The basic procedures developed by Sinha et al. (*162,163*) for the bridge cost allocation is as follows:

- The correspondence factors needed to correlate FHWA standard vehicle classifications to AASHTO design vehicle loads.
- A group of representative bridge structures were selected from the design records.
- For each bridge type, an incremental design of the bridge structure was carried out for each AASHTO vehicle design load. The design followed the relevant AASHTO specifications and the recommended bridge design practices of INDOT.
- The bridge cost data for the base period were established using historical records of bridge designs and bids.
- The unit cost of each major structural component was established using the contract bid records in the base period. The next step involved cost estimation for each incremental bridge design.
- The total cost responsibility of each vehicle class was then evaluated using individual cost factors.

9.4.3 Oregon Bridge Cost Allocation Study (152)

In Oregon, the incremental method was used directly in the allocation of bridge costs. The base design for a new bridge was one designed to support its own weight and to withstand non-load-related stresses and light traffic. Specifically, the factors influencing the design requirements, and therefore the bridge costs, were expressed in terms of the dead loads and live loads. The dead loads included the self-weight of the bridge and the other, non-load-related forces such as stream flow, wind, and seismic forces. The anticipated traffic loadings, on the other hand, were classified as live loads. The total design load is the sum of dead and live loads. Although the precise relationships differ by the type and location of the bridge under consideration, as a general rule, the longer the span length, the greater the relative importance of the non-load-related factors in determining the total cost of the bridge. The non-load cost is a common responsibility of all vehicles and was assigned to each class on the basis of the VMT share of the class.

The next step was an increment that identified the additional cost of constructing the bridge to accommodate heavy vehicles. This cost was assigned to all vehicles with gross weight exceeding 10,000 pounds on the basis of the relative VMT of each class of vehicles over 10,000 pounds. Similarly, the additional cost of the third increment was assigned to all vehicles with gross weight exceeding 50,000 pounds, and the cost of the fourth and final increment was assigned to vehicles having gross weights over 80,000 pounds.

The costs used in the allocation process could be expenditures from a past period, those anticipated for a future period, or a combination of past and future costs. The Oregon HCAS has traditionally used a prospective approach in which the expenditures allocated were those planned for a future period, specifically, the next fiscal biennium. The traffic data used in the study were projected for the future year.

The practice of using projected future expenditures has some drawbacks. First, it requires relying heavily on forecasts that are subject to large deviations from historical expenditures. Secondly, it does not address issues related to facilities with useful lives longer than the two-year study period. The Oregon study allocates expenditures rather than costs, which has its drawbacks as well. In the long run, expenditures may cover the full direct costs being imposed on the system or the system will deteriorate; but in the short run, however, expenditures may exceed or fall short of the costs imposed. The bridge cost responsibility by vehicle class presented in the Oregon study, is shown in Figure 9.3.

9.4.4 Nevada Highway Cost Allocation Study (164)

The bridge cost allocation procedure used in the 2009 Nevada HCAS was based on methods developed by FHWA for the 1982 and 1997 federal HCAS. For expenditures, three categories of bridge repair were considered: new bridge construction, bridge replacement, and bridge rehabilitation.

New bridge construction expenditures were allocated on the basis of an incremental analysis of the cost of construction using different design loadings. These loadings were based on hypothetical vehicles, and the resulting stresses in the load-bearing members of bridges were calculated and compared with permissible stress levels. As loadings were increased systematically the corresponding dimensions of the bridge members (and, consequently, the bridge construction costs) became larger. The base situation was associated with the lightest design loadings and all vehicles shared this cost. Thus, the determination of the vehicle classes that share the costs of each increment were established by comparing the stresses produced by the vehicles with the stresses imposed by the design loadings.

Bridge replacement expenditures in the Nevada study were allocated on the basis of the percentage of estimates of the expenditures that were incurred in a case where the load-bearing capacity of an existing bridge was deficient. These expenditures were allocated to vehicles that operated at weights that exceed the load-bearing capacities of the replaced bridges. The percentage of bridge replacement costs that were incurred as a result of deficient load-bearing capacities was estimated using FHWA's bridge sufficiency rating formula. Under the formula, bridges lose points for inadequate load-bearing capacity or for exhibiting signs of non-load-related distress such as pier scouring or narrow lanes.

Bridge rehabilitation expenditures were allocated on the basis of the estimates of the fraction of the costs of bridge rehabilitation types and the extent to which the expenditures of each type were load related. The allocation was based on information from FHWA's

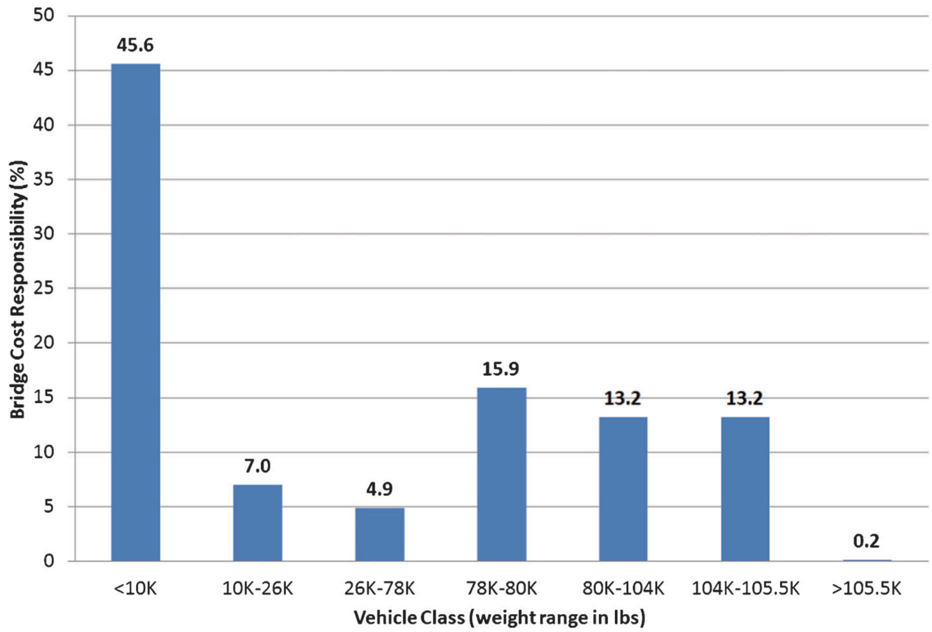


Figure 9.3 Oregon bridge cost responsibility (%) by vehicle class (*152*).

bridge needs and investment process. The primary input required was an analysis of a representative sample of bridge repair projects to determine the overall percentage of such projected costs that were expected to be load related and those expected to be non-load related. This split, broken down by road functional class, was then used to determine the split between (i) costs that should be allocated by the VMT broken down by the vehicle weight category and (ii) costs that should be allocated only by VMT for each vehicle class. The bridge cost responsibility by vehicle class is shown in Figure 9.4. As shown in the figure, the Nevada study suggested that approximately 40% of the bridge costs are attributable to passenger vehicles, approximately 6% to single-unit trucks, and approximately 52% to combination trucks.

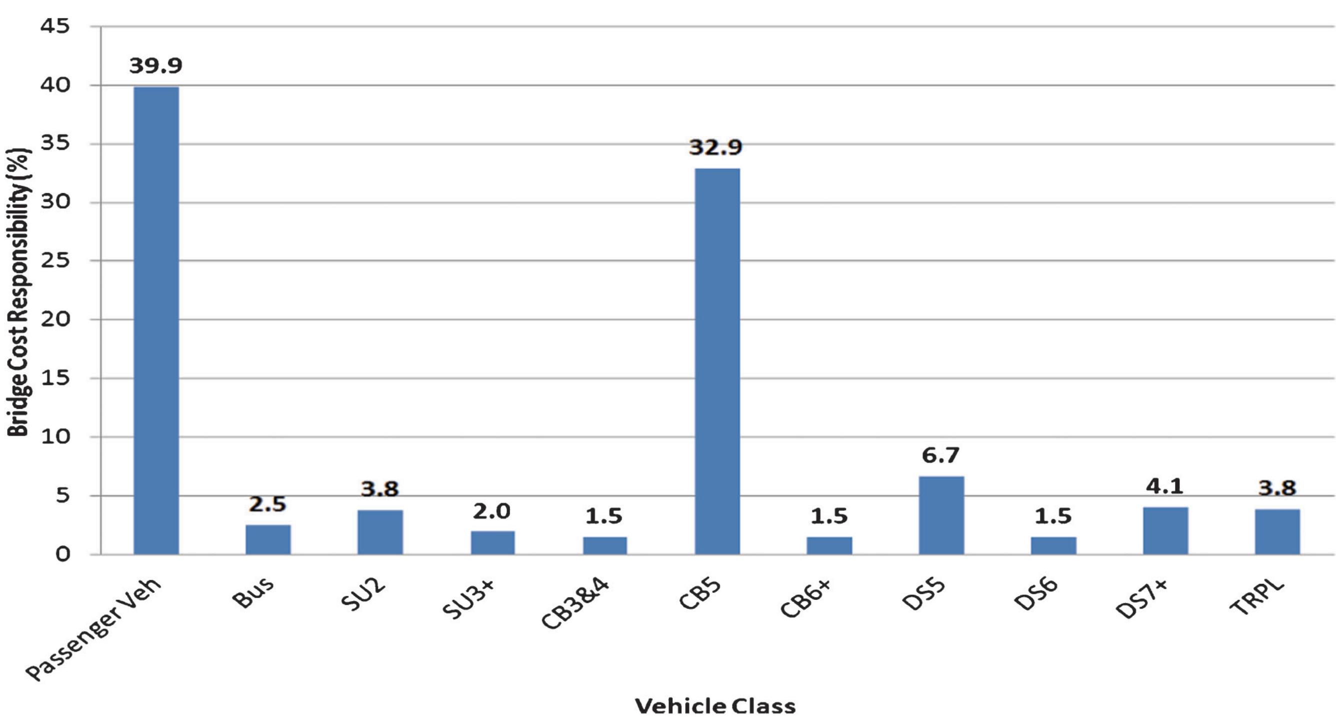


Figure 9.4 Bridge Cost Responsibility (%) by Vehicle Class in Nevada (*164*).

10. DEVELOPMENT OF METHODOLOGY FOR ESTIMATING BRIDGE DAMAGE COSTS

10.1 Introduction

This chapter discusses the elements of the methodology used to determine the bridge damage cost in this research. These include bridge classification by material highway class, material type and age, bridge activity profile, and selection of representative bridges. The definition of an overweight truck and how overweight truck traffic volume is estimated are then discussed. The chapter also includes the correlation of the AASHTO vehicle classification to the FHWA vehicle classification by weight and vehicle configuration, which is a critical part of methodology. In order to facilitate the correlation, a statistical model was developed, and a systematic approach for the incremental cost analysis, is discussed. The methodology is subsequently applied in Chapter 12 for allocating bridge cost to overweight trucks.

10.2 Highway Classification

Bridges on high-speed and high-volume roads such as Interstates have higher design standards compared to low-volume roads. In the present study, the selected bridges were located along "national truck routes." The bridges on routes designated as national truck networks were used because overweight trucks are allowed only on bridges designed for trucks. Therefore, the design live loads on these bridges did not differ significantly from each other. Specifically, all the bridges analyzed in the present study had a design live load of HS20 or above. In order to facilitate the estimation of bridge costs by highway type, the following highway bridge classifications were used: Interstate highway bridges, NHS non-Interstate highway bridges and non-NHS highway bridges.

10.3 Bridge Classification and Activity Profile

Bridges on routes often used by trucks are constructed predominantly using steel or concrete (*165,166*). The distribution of bridges by material type is discussed in the next section. The activity profiles for the bridge types do not differ significantly from each other. For example, using the Indiana bridge management software (*167*) developed for the state of Indiana, the life cycle are: steel bridges, 70–80 years; concrete bridges, 35–70 years; and prestressed bridges, 50–70 years. The life-cycle range depends on the superstructure design or construction which can be classified as slab; stringer/multi-beam or girder; girder and floor beam system; tee beam; box-beam or girders-multiple; box-beam or girders-single or spread; frame (except box culverts); truss deck; truss-thru; arch-deck; culvert (includes frame culverts); channel beam. For the purpose of the present study, the upper boundary of bridge life range was used for the analysis. The selected activity profiles for the different bridge types used in the study are shown in Figures 10.1 and 10.2. From the figures, it can be observed that the activity profiles do not vary significantly. Therefore, in the present study, all three bridge material types were considered as having the same activity profile. Bridges constructed using these materials constitute over 80% of all bridges (*165–167*). The life cycle adopted in the present study was bridge replacement in years 0 and 70, deck rehabilitation in years 20 and 55, and superstructure replacement in year 35 with annual routine maintenance.

10.4 Selection of Bridges

The bridges used for the present study were Indiana state highway bridges selected from the national bridge inventory (NBI) database (*165,166*). The bridges on routes designated as national truck networks were used because overweight trucks are allowed only on bridges designed for trucks. In order to establish the bridge cost due to overweight truck operations at any specific bridge, the bridges were clustered into groups with similar characteristics including highway class, bridge material type, and bridge age (Table 10.1).

The distribution of bridges by highway class (Figure 10.3) shows that out of 3,128 bridges on the national truck network in Indiana, approximately 45% are located on Interstates, approximately 29% on NHS-non-Interstates, and 25% on non-NHS highways.

In order to differentiate between bridges by material type for each highway class, the bridges were grouped as follows: steel, reinforced concrete, and prestressed concrete. Approximately 49% of bridges are steel, 31.7% are reinforced concrete, and 19.5% are prestressed concrete (Figure 10.4).

The age of a bridge influences the specific decision for bridge action (deck replacement or rehabilitation, superstructure replacement, or bridge replacement). To quantify the effect of bridge age on the total bridge cost associated with overweight truck operations, the bridges in this study were further clustered into four age groups based on the bridge life-cycle activity profile (Table 10.1). For each age group, the midpoint was used to represent that age group.

The distribution of bridges by age group (Figure 10.5) shows that approximately 56% of the bridges are 20 years or less in age and one percent are between 55 to 70 years in age.

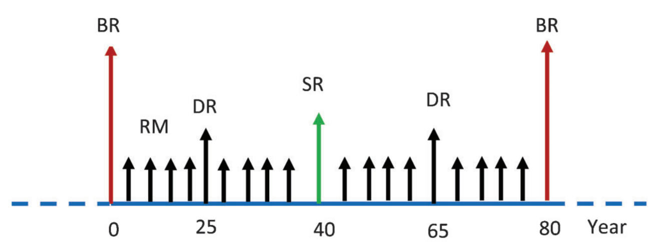


Figure 10.1 Activity profile for steel bridges (not to scale) (*167*).

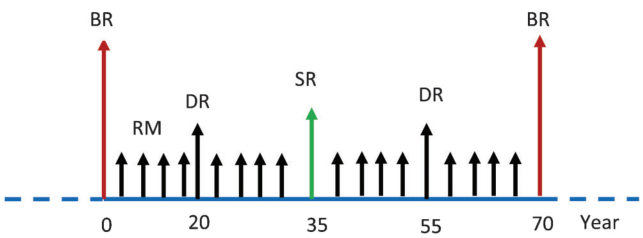


Figure 10.2 Concrete and prestressed concrete bridge activity profile (not to scale) (*167*). Where, BR: bridge replacement (reconstruction), RM: bridge routine maintenance, DR: deck replacement or rehabilitation; SR: superstructure replacement.

10.5 Overweight Truck Volume Estimation

In Indiana, the legal load limit is 80,000 lbs. Therefore, in the present study, an overweight vehicle is generally considered as any vehicle with an overall weight exceeding 80,000 lbs.

In incremental analysis, it is critical to estimate the expected number of overweight trucks. Data on overweight truck volumes across the highways in Indiana by vehicle weights were not available for this study. However, an overweight truck permit revenue database indicating the number of overweight trucks by axle spacing and axle load for the months of March and April 2011 was made available by INDOT for the present study. Using the permit revenue data, the overweight truck distribution by gross vehicle weight, axle spacing, and axle load were established (Figure 10.6 and Table 10.2). From the figure and table, it can be observed that overweight vehicles of weight 108,001–150,000 lbs represented approximately 47% of all overweight vehicles, and approximately 3% were overweight vehicles above 200,000 lbs. It should be noted that not all overweight vehicle operators perform their civic responsibilities to acquire a permit. Thus, the assumption here is that the distribution of all overweight vehicle weights (which is unknown) is similar to the weight distribution of overweight vehicles that acquire permits (which is known).

As stated in the previous paragraph, a projection of the two-month permit revenue count data over the entire year and also over the entire bridge life cycle will likely result in underestimating the volume of overweight trucks on the highways. This is because a significant number of overweight vehicles operate on the highways without prior acquisition of a permit (*168,169*). For example, the Bullock et al. study (*169*) verified the weights of trucks along urban Interstate I-65 at milepost 253.62 (Merrillville, Indiana) to enable effective police deployment towards overweight truck enforcement and concluded that the percentage of overweight trucks at that location ranged from 13.8% to 22.5%. The study did not indicate the percentage of these overweight trucks that were operating without permit. In order to estimate the approximate volume of overweight trucks in Indiana for the present study, combination truck data from FHWA (*170*) were used.

The combination truck data can be used to estimate the approximate volume of overweight trucks because all combination trucks are considered to be within FHWA's vehicle classes 8 to 13 which can be described as "operating as overweight trucks." This approach estimated the overweight truck volume based on the combination truck VMT in Indiana. The procedure used for estimating the overweight truck volume is presented below.

1. Determine the total vehicle miles of travel on all Interstates in Indiana, using recent published data for 2010 from FHWA (*170*).
2. Determine the Interstate miles available based on recent data from FHWA (*170*).
3. Compute the Interstate annual traffic volume by dividing Interstate VMT by Interstate miles.
4. Calculate the Interstate annual combination truck volume by multiplying Interstate annual traffic volume by the percentage of combination trucks on Interstates from Table 10.3.
5. Compute the annual overweight truck volume for year 2010 by multiplying the combination truck annual volume found in part (d) above by 13.8% as established by Bullock et al. (*169*) because using the average value can result in over-estimating the volume of overweight trucks as determined by those researchers.
6. Project the 2010 combination truck volume to 70 years (length of the bridge life cycle) with a growth factor of 1.5%. This growth factor was based on the average

TABLE 10.1
Placing the Bridges into Families

Highway Class	Bridge Material Type	Age Group (years)			
		0–20	20–35	35–55	55–70
Interstate	Steel	√	√	√	√
	Reinforced concrete	√	√	√	√
	Prestressed concrete	√	√	√	√
NHS non-Interstate	Steel	√	√	√	√
	Reinforced concrete	√	√	√	√
	Prestressed concrete	√	√	√	√
Non-NHS	Steel	√	√	√	√
	Reinforced concrete	√	√	√	√
	Prestressed concrete	√	√	√	√

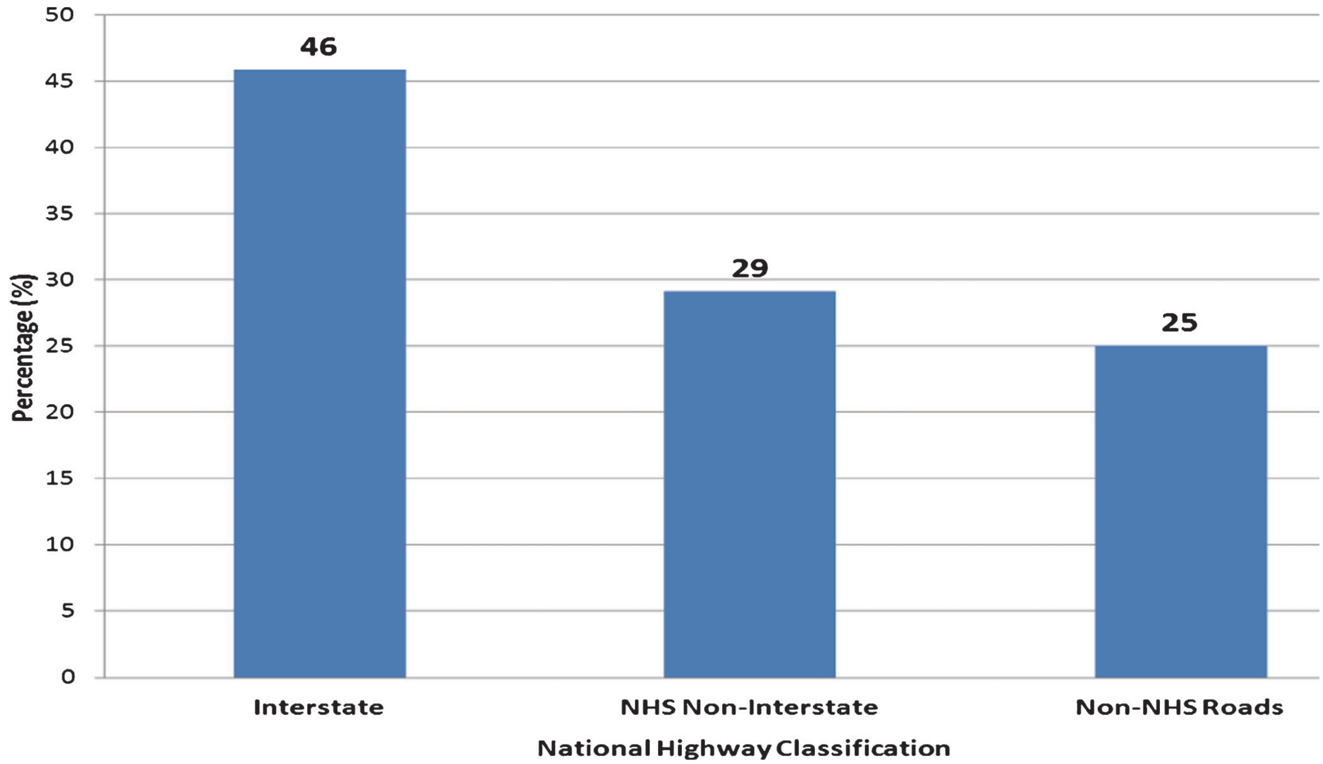


Figure 10.3 Distribution of bridges by highway class.

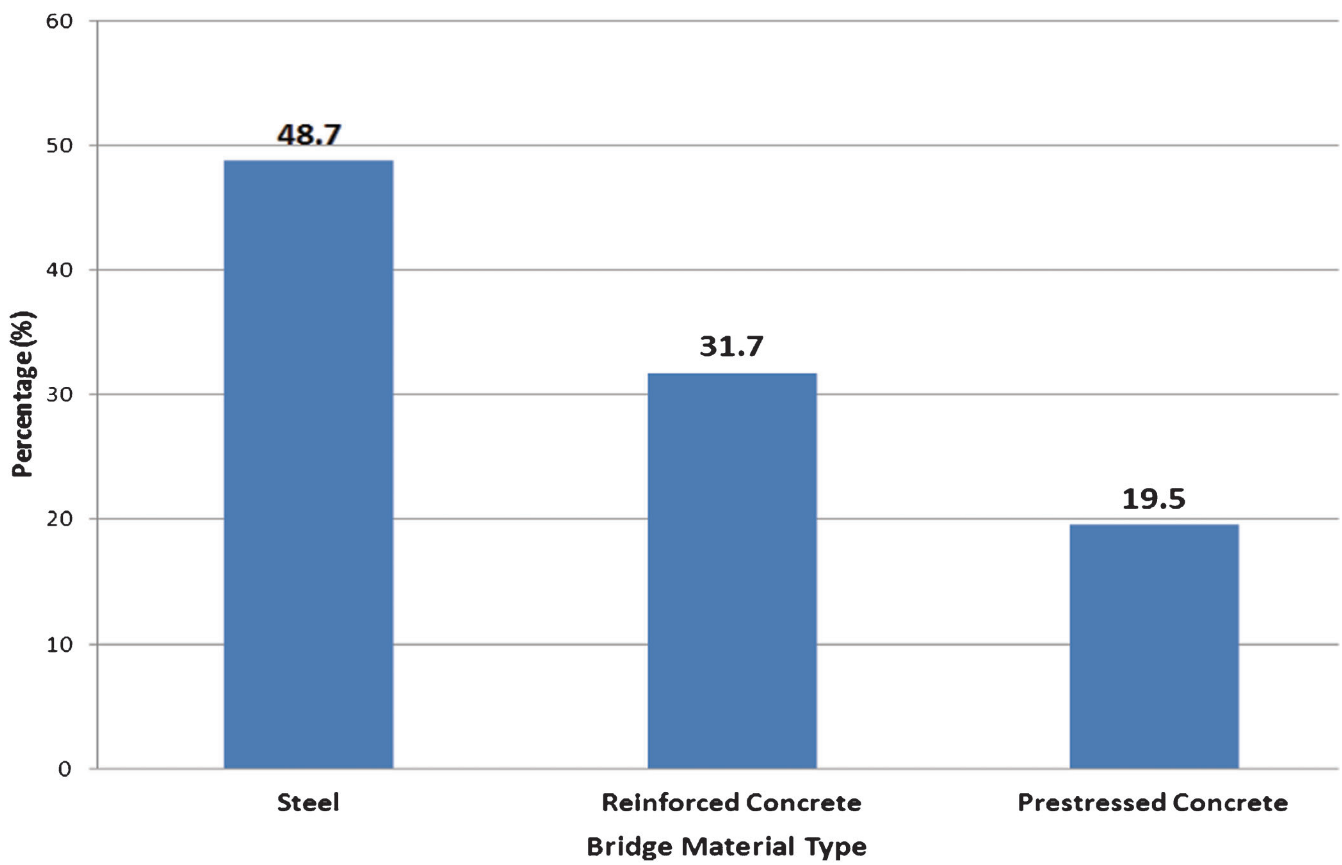


Figure 10.4 Distribution of bridges by bridge material type.

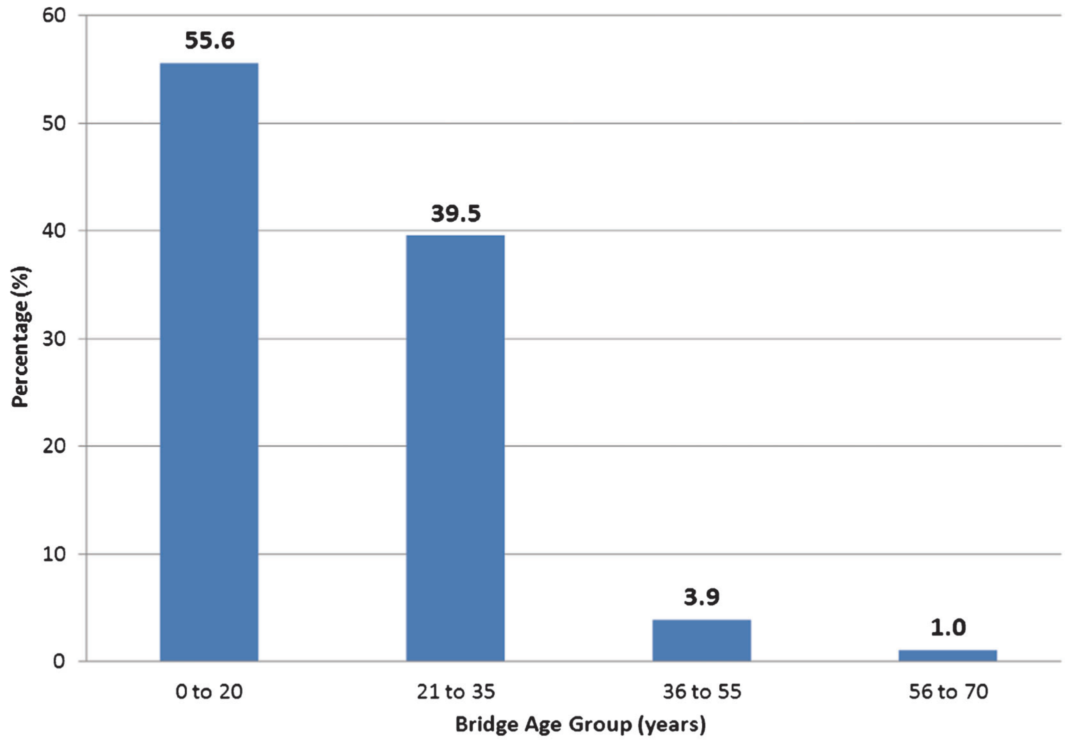


Figure 10.5 Distribution of bridges by age group.

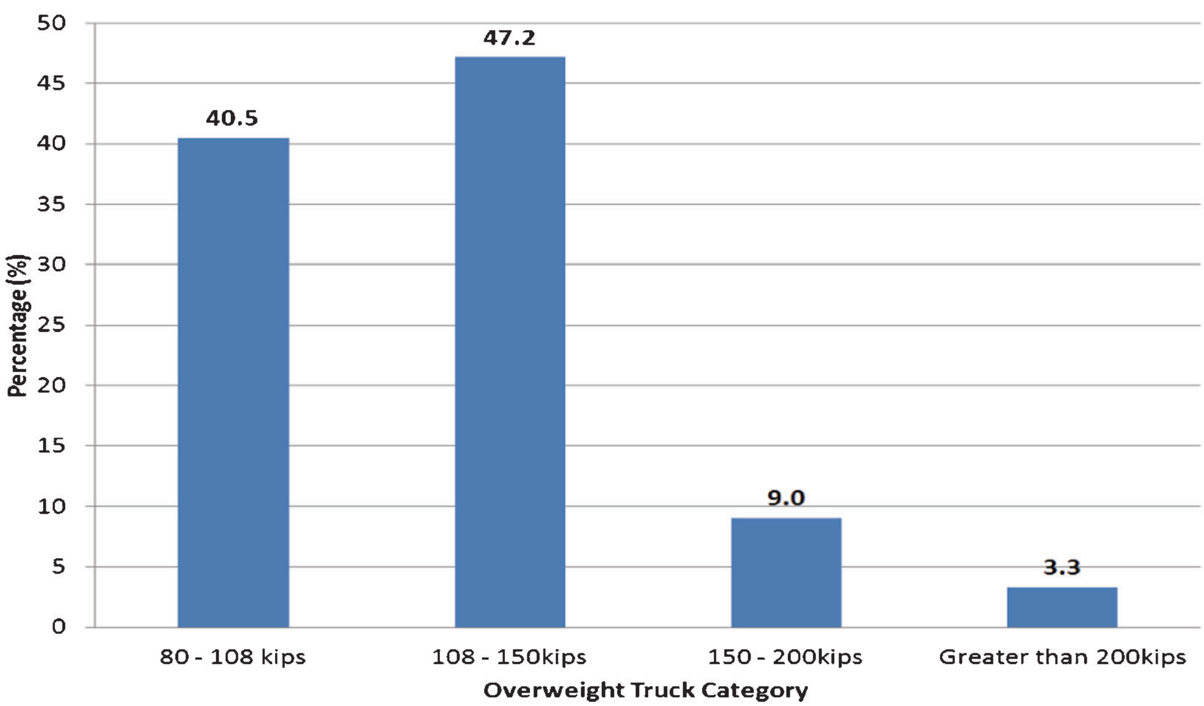


Figure 10.6 Distribution of overweight trucks.

TABLE 10.2
Distribution of Overweight Trucks

Weight Group	Truck Description	Percentage by Volume
80–108kips	4 axles	2.58
	5 axles	12.71
	6 axles	17.32
	7 or more axles	7.88
108–150kips	4 axles	0.40
	5 axles	0.62
	6 axles	18.83
	7 axles	17.87
	8 axles	3.72
	9 or more axles	5.71
150–200kips	7 axles	2.91
	8 axles	2.63
	9 axles	0.73
	10 axles	0.42
	11 axles	0.45
	12 or more axles	1.90
>200kips	11 axles	1.42
	12 axles	0.39
	13 axles	0.23
	14 axles	0.24
	15 or more axles	1.03

Source: INDOT (*221*).

growth of combination trucks in Indiana over the past five years.

7. Distribute the overweight trucks by type, using the information presented in Table 10.2.
8. Compute the overweight truck volumes for the remaining highway types (NHS non-Interstate, and non-NHS) based on the percentage distribution of combination trucks on each of the three highway classes (Table 3.3).

10.6 Linking AASHTO Design Vehicles to FHWA Vehicles

AASHTO design vehicles are used in bridge designs to simulate the most severe live loads on a given bridge. However, these vehicles are not those observed operating on the roads. In order to assign the cost increment to each vehicle weight group, a quantitative correlation between the AASHTO design vehicles and the FHWA vehicles operating on the highway must be established (*159*). Such correlation is critical in the allocation framework because inappropriate matching will result in significant errors in the allocation process. Specifically, the accuracy of the cost functions in terms of design loadings would not be reliable when converted into the FHWA vehicle classes. In the past, some studies (*153,155,160*) used gross vehicle weights (GVW) to establish the correlation between these two parameters. That approach assumes a very simple relationship between the observed FHWA vehicle weight groups and the design vehicle weight groups. This assumption is not compatible with bridge design because the analysis in the approach does not consider axle spacing and axle-load distribution which are important in bridge design.

In another study, conducted in Maryland (*154*) axle-load spacing and axle-load distribution were considered; however, that analysis was limited to simply-supported single-span bridges. The results from that analysis which used simply-supported single-span bridges can be expected to yield significant error when it is extended to bridges with continuous spans. To overcome this challenge, this study used the equivalent load approach proposed by Tee et al. (*159*). This approach relates the amount of moment produced by AASHTO design vehicles to that of FHWA vehicles. Tee et al. (*159*) found that Smoments produced depend on the axle spacing, the axle-load distribution of the vehicles, and the bridge span type (simple or continuous). Adopting the equivalent load approach will require significant computational time and specialized knowledge of bridge design.

In order to reduce computational time and also create a model that asset managers can easily use without having bridge design expertise, the modified equivalent vehicle model was developed for the present study. The flowchart for the model is shown in Figure 10.7. Seven key steps were used to develop the modified equivalent vehicle model approach.

The first step of the developed methodology involved the computation of the critical or maximum moments

TABLE 10.3
Percentages of Combination Trucks by Highway Type

Description	Highway Class	Combination Truck (%) in Year: 2009	2010	2-Year Average
Rural	Interstate	30.6	30.40	30.5
	NHS-NI	12.3	12.5	12.4
	N-NHS	3.8	4.50	4.15
Urban	Interstate	22.5	22.50	22.5
	NHS-NI	7.4	7.40	7.4
	N-NHS	1.3	1.70	1.5
Average (rural & urban)	Interstate	26.55	26.45	26.5
	NHS-NI	9.85	9.95	9.9
	N-NHS	2.55	3.10	2.83

Source: Developed using data from FHWA (*170*).

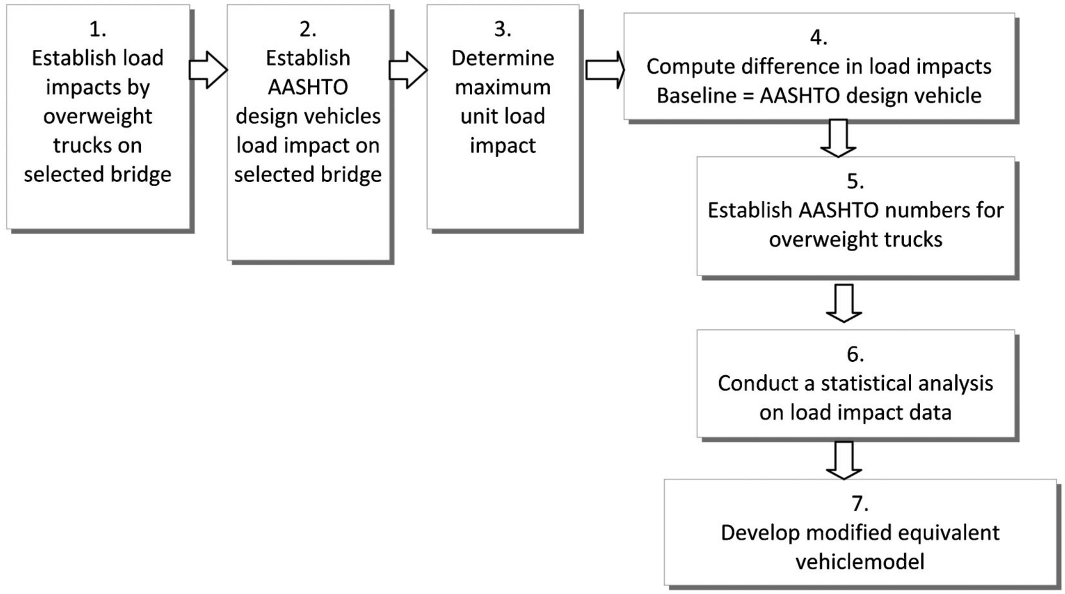


Figure 10.7 The modified equivalent-vehicle (MEV) methodology developed in this study.

produced by overweight trucks by using the bridge. This is based on the gross vehicle weight, axle loading, and axle spacing of the truck. INDOT's overweight truck permit database was used to select overweight trucks for the structural analysis. The second step is to correlate the moment generated by the FHWA weight group vehicles with AASHTO standard vehicles. For doing this, the critical moments produced by AASHTO standard vehicles HS15 and HS20 were determined. It may be noted that HS20 is the design vehicle for the bridges on the national truck network in Indiana. The AASHTO standard vehicle configuration for HS trucks is shown in Figure 10.8. The computed critical moments for overweight trucks within each load interval are shown in the Part III Appendix, Figure III.A.1.

In order to relate the AASHTO vehicle classification to FHWA vehicle classification, it was needed to establish the unit design critical moment. This is the focus of the third step. The unit design (HS1) critical moment was calculated from the critical moments produced by AASHTO standard vehicles HS15 and HS20 on the selected bridge as shown in Equation 10.1.

$$\mathrm{UDM_{HS1}} = \frac{CM_{HS20} - CM_{HS15}}{L_{HS20} - L_{HS15}} \qquad (10.1)$$

Where:

$\mathrm{UDM_{HS1}}$: unit design critical moment (ft.),

CM_{HS20}: computed critical moment produced by load HS20,

CM_{HS15}: computed critical moment produced by load HS15, and

$L_{HS20} - L_{HS15}$: is 5, that is the numerical difference between 20 and 15.

Step four establishes the difference between critical moment of an FHWA vehicle and that of an HS20. The critical moment produced by HS20 was used as the baseline in the difference computation. In Step five, each AASHTO code HSXY was correlated to each FHWA weight group class. In Step six, a multivariate non-linear regression was conducted using the generated data (38 observations) from steps one to five. For the statistical analysis, an initial set of independent variables were explored, including the minimum axle load, maximum axle load, average axle load, gross vehicle weight, bridge material type, and minimum axle spacing and maximum axle spacing. However, only three independent variables were found to be statistically significant in estimating the modified equivalent vehicle model (AASHTO design vehicle) as shown in Table 10.4: the gross vehicle weight (GVW) in pounds, the average axle spacing (AAS) in inches, and the average axle load (AAL) in pounds. The three variables were found to be statistically significant at the 99% confidence level.

From the results in Table 10.4, it can be seen that an increase in the GVW increased the equivalent vehicle load. Secondly, an increase in the axle spacing decreased the imposed load on the bridge structure, hence decreasing the equivalent vehicle load. This result is intuitive because from a general standpoint, the wider the spacing between axles, the lower the bridge damage. Finally, an increase in average axle loading per axle increased the AASHTO design vehicle class, which means that increasing the load on each axle increased the damage caused by that vehicle, thereby increasing the equivalent vehicle load. The final step presents the modified equivalent vehicle model (Equation 10.2).

$$\mathrm{MEV} = \alpha \left(\frac{GVW}{AAS} \right)^{\beta} \times AAL^{\gamma} \qquad (10.2)$$

Where: MEV: modified equivalent-vehicle (AASHTO loading in HS),

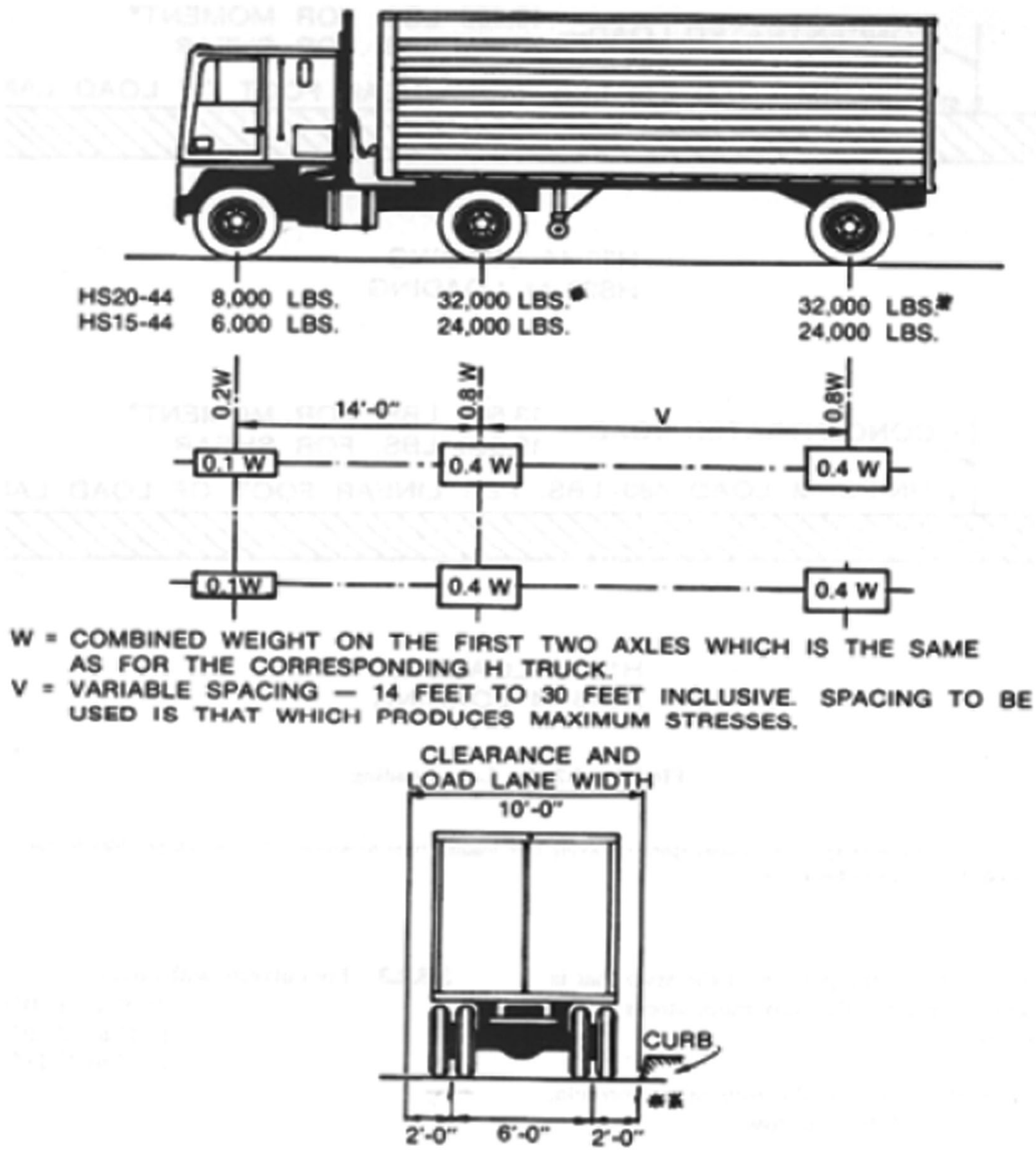


Figure 10.8 The AASHTO HS standard truck (*158*).

GVW: gross vehicle weight (lbs), AAS: average axle spacing (in), and

AAL: average axle load (lbs).

For example, an overweight truck with a GVW of 120,000 lbs, average axle spacing of 112 inches, and average axle load of 23,000 lbs was classified as HS 31 based on the model,

$$MEV = 0.0057\left(\frac{120000}{112}\right)^{0.313} \times 23000^{0.64} = 31.3.$$

Thus, the truck falls in the HS31 group (see Figure III.A.7 in the Part III Appendix).

TABLE 10.4
Statistical Results for Modified Equivalent Vehicle Model

Parameter	Coefficient	t-Statistic	Adjusted R^2
α	0.0057	2.121	
β	0.3130	6.804	0.923
γ	0.6400	4.211	

Where, α,β,γ are estimated parameters.

10.7 Methodology for Bridge Damage Repair Cost Estimation

The input variables for estimating the bridge repair cost include highway type, bridge material type, bridge length, bridge deck width, bridge age group, equivalent uniform average annual traffic volumes, and bridge life-cycle cost per unit of bridge length. The methodology used in the present study is summarized in Figure 10.9 and the detailed computational steps are outlined below:

1. Select a highway class (Interstate, NHS non-Interstate, NNHS).
2. Select a bridge by material type (steel, pre-stressed concrete, concrete).
3. Select the bridge age group (0–20; 21–35; 36–55; 55–70).
4. Establish the unit cost for each bridge element (superstructure, substructure, approach, and other relevant elements). Note that unit cost is in 2010 constant dollars to facilitate adjustments due to inflation.
5. Compute the partial life-cycle cost for all relevant activities scheduled for the bridge over its remaining life, based on the unit cost established in step (d). Note that the partial life-cycle cost is the present worth cost of the relevant activities for a bridge due to its age. For example, the partial life-cycle cost of a bridge in the age group 21-35 will include superstructure replacement cost, deck rehabilitation cost, and bridge replacement cost. Using a numerical example for the above illustration, if the present worth costs for superstructure replacement, deck rehabilitation and bridge replacement are $750,250; $85,620; and $1,304,767 respectively, then the partial cost will be the summation of the present worth costs ($2,140,637).
6. Compute bridge full life-cycle cost. This can be calculated as the present worth cost of all the different activities expected on the bridge during its complete life cycle. The formulation is discussed later in Chapter 11 (equation 11.1). For illustrative purposes, consider a bridge with the following costs (constant dollar): bridge reconstruction = $2,671,912 ($r$%, 0 yrs); deck rehabilitation in year 20 is $316,211 ($r$%, 20 yrs), deck replacement in year 35 is $225,015 ($r$%, 35 yrs), deck rehabilitation in year 55 is $112,376 ($r$%, 55 yrs). Therefore, the present worth of the bridge full life-cycle cost is $3,325,516.
7. Compute the bridge life-cycle cost in perpetuity. This is the sum of the partial life-cycle cost and cost of all full life cycles to perpetuity. Convert the life-cycle cost into the equivalent annualized uniform cost (EUAC). The formulation is discussed later in Chapter 11 (equation 11.4). Using the partial present worth of all life-cycle cost (partial and full) is $5,803,608,000 then the EUAC over the 70-year cycle is $199,276 as computed below:

$$EUAC = 5{,}803{,}608{,}000\left[\frac{0.03(1+0.03)^{70}}{(1+0.03)^{70}-1}\right]$$
$$= \$199{,}276{,}000$$

8. Convert the EUAC life-cycle cost into the EUAC per bridge length. In order to use representative bridge dimensions, the weighted average length and deck width of the bridges were computed. The weight for each bridge type was based on the number of bridges in that category. This was done in cognizance of the variation in bridge lengths and widths in the database. Note that the costs computed from steps (f) to (g) were based on a weighted bridge length (224 ft.) and a weighted deck width (53 ft.). The weighted bridge length and deck width were computed as shown in Equations 10.3 and 10.4:

$$\overline{\mathrm{BL}}_w = \frac{\sum_{\delta,\mu=1}^{n} w_{\delta\mu} BL_{\delta\mu}}{\sum_{\delta,\mu=1}^{n} w_{\delta\mu}} \quad (10.3)$$

$$\overline{\mathrm{DW}}_w = \frac{\sum_{\delta,\mu=1}^{n} w_{\delta\mu} DW_{\delta\mu}}{\sum_{\delta,\mu=1}^{n} w_{\delta\mu}} \quad (10.4)$$

Where, $\overline{\mathrm{BL}}_w$: weighted average bridge length (ft.), $\overline{\mathrm{DW}}_w$: weighted average bridge width (ft.),

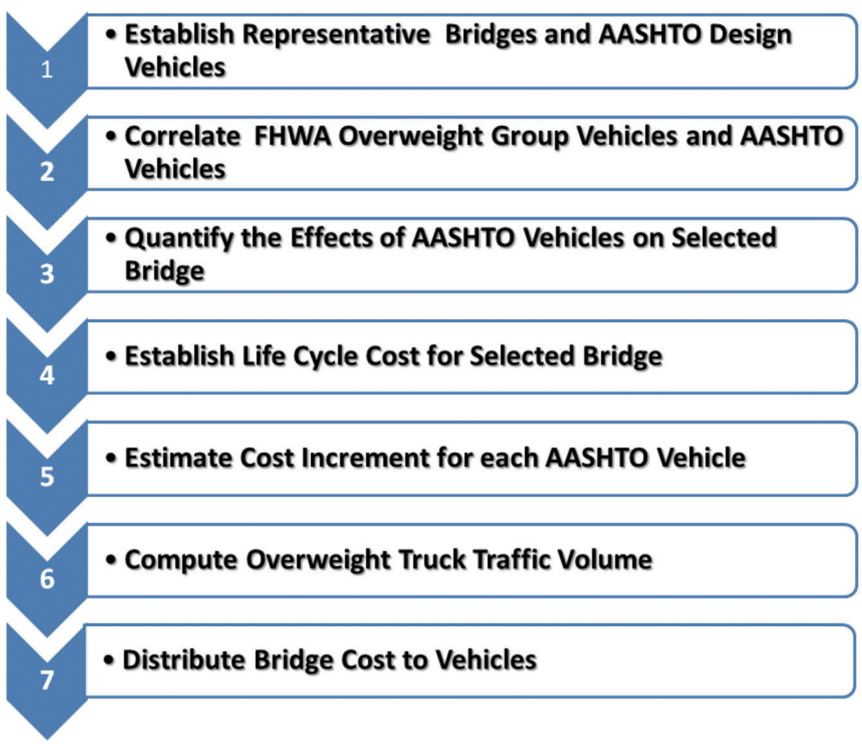


Figure 10.9 Developed methodology for bridge cost allocation.

$BL_{\delta\mu}$: length of bridge by bridge age δ and material type μ (ft.),

$DW_{\delta\mu}$: bridge deck width by bridge age δ and material type μ (ft.),

n: total number of bridges, and

$w_{\delta\mu}$: weight of bridge by bridge age δ and material type μ.

For illustrative purposes, assuming the annual maintenance cost of ten percent of estimated EUAC value in step (g), then the total EUAC will be $219,204,000 and the weighted bridge length from step (h) is 224ft, then EUAC per bridge length is approximately $979, 200 per ft. of bridge length.

9. Determine the percentage of bridge cost for each AASHTO vehicle class using Table 10.5.
10. Compute the cost increment for each loading increment using Equation 10.5.

$$CI_{\mathrm{p},\mu} = TC_{\mu} \times \left(CF_{p,\mu} - CF_{p-1,\mu}\right) \qquad (10.5)$$

Where,

$CI_{\mathrm{p},\mu}$: cost increment of AASHTO vehicle class ρ and bridge material type μ

TC_{μ}: total cost of bridge material type μ and

$CF_{p,\mu}$: cost factor of AASHTO design vehicle ρ and bridge material type μ

The cost factor of the AASHTO design vehicle (with MEV 35) p is (116.05) (calculated from Table 10.6) and the cost factor of the AASHTO design vehicle $(p-1)$ (with MEV 34) is 114.99 (calculated from Table 10.6). Thus, the cost increment is:

$$CI_{\mathrm{p},\mu} = 979{,}200 \times (116.05\% - 114.99\%) = \$10{,}400$$

11. Compute overweight truck equivalent uniform annual volume as described in Section 10.5. For numerical illustration let us assume a total of 25,000 overweight trucks.
12. Compute proportion of overweight truck type using Equation 10.6.

$$PATV_{\mathrm{p}} = \frac{ATV_p}{\sum_{p=1}^{n} ATV_p} \qquad (10.6)$$

Where,

$PATV_{\mathrm{p}}$: proportion of annual truck volume for AASHTO vehicle class p,

ATV_p: annual truck volume for AASHTO vehicle class p, and

n: number of overweight truck types.

For numerical illustration, let the number of AASHTO vehicle class p be 993 in the total population of 55,174 OW trucks (see step (k)), then $\mathrm{PATV_p} = \frac{993}{55174} = 0.018 = 1.8\%$.

13. Compute the incremental cost responsibility for each AASHTO vehicle class using Equation 10.7.

$$CR_{\mathrm{p}} = \mathrm{CI}_p \frac{PATV_p}{\sum_{p=1}^{n} PATV_p - \sum_{p=0}^{p-1} PATV_p} \qquad (10.7)$$

Where,

CR_{p}: cost responsibility of AASHTO design vehicle p, and

n: number of cost increments.

For illustrative purposes, the inputs and outputs from previous steps served as inputs for step (m). In this example, 87.63% of the volumes of OW are lighter in weight as compared to truck HS35.

Therefore, the cost responsibility of HS35 is $CR_{\mathrm{HS35}} = 10{,}400 \times \frac{1.8}{100-87.63} = \$1{,}513$.

14. Compute the total cost for each AASHTO design vehicle by summing up the cost at each incremental level using Equation 10.8:

$$TC_{\mathrm{p}} = \sum_{p=1}^{n} CR_p \qquad (10.8)$$

Where,

TC_{p}: total cost responsibility of AASHTO design vehicle p, and

n: number of cost increments.

The total cost for each AASHTO vehicle class will be the summation of the repeated cost increments (step m). For this example, 20 increments were carried out. The summation of the other nineteen increments was $7.907, then adding the increment in step m, the total cost for AASHTO vehicle class p is $TC_{\mathrm{p}} = 7{,}907 + 1{,}513 = \$9{,}421$.

15. Compute cost per AASHTO vehicle class by using Equation 10.9.

$$C_{\mathrm{p}} = \frac{TC_p}{PATV_p \times \sum_{p=1}^{n} ATV_p} \qquad (10.9)$$

Using inputs from the previous steps, $C_{\mathrm{HS35}} = \frac{9{,}421}{0.018 \times 55174} = \$9.49$. This corresponds to disaggregate cost (option 1) for AASHTO design vehicle HS35 as can be seen in Figure III.A.4 (last row) in the Part III Appendix.

16. Convert AASHTO vehicle class to FHWA vehicle class using Equation 10.10 to establish the cost per overweight truck, using FHWA vehicle classification.

TABLE 10.5
Estimation of Percentage of Bridge Cost for AASHTO Vehicle

Road Type	% of Total Bridge Cost Model
Interstate	$42.16 + 12.49\sqrt{MEV}$
NHS non-Interstate	$40.72 + 12.87\sqrt{MEV}$
NNHS	$49.20 + 11.61\sqrt{MEV}$

Source: Revised from (*159*).

$$\text{MEV} = 0.0057\left(\frac{GVW}{AAS}\right)^{0.313} \times AAL^{0.64} \qquad (10.10)$$

Assuming overweight truck has the following characteristics: GVW = 95,650 lbs, AAS =71 in, AAL = 23,940 lbs and computing the expected MEV, the cost responsibility can be assigned. On the basis of the truck configuration the computed MEV will be

$\text{MEV} = 0.0057\left(\frac{95650}{71}\right)^{0.313} \times 23940^{0.64} = 34.5 \approx 35$.This corresponds to AASHTO design vehicle class of HS 35.

10.8 Chapter Summary

This chapter discussed the components of the cost allocation methodology used in this research. Furthermore, the chapter presented the modified equivalent vehicle (MEV) model used to correlate the AASHTO vehicle classification to the FHWA vehicle classification on the basis of the weight and vehicle configuration. A methodology was developed in this chapter to estimate bridge damage cost. Using this result, the actual life-cycle cost estimation is carried out in the next chapter (Chapter 11).

11. ESTIMATION OF BRIDGE LIFE-CYCLE COST

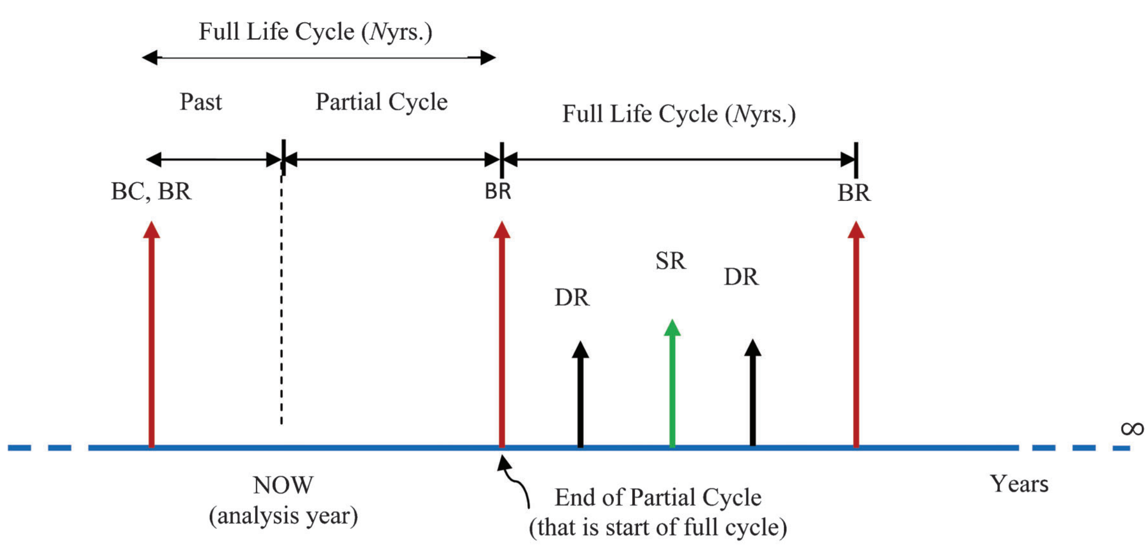
11.1 Introduction

The previous chapter presented an overall methodology for bridge damage cost estimation. The present chapter focuses on a key aspect of that methodology: bridge life-cycle cost estimation. The life-cycle cost approach was used in the present study in order to estimate the relevant agency costs that the agency incurs during the bridge life cycle. Specifically, the estimation of the life-cycle cost of a bridge is a critical input in bridge damage cost estimation because it specifies the schedule of activities needed to keep the bridge at a minimum level of performance over its life cycle. This chapter discusses the procedure used to estimate bridge life-cycle cost and how it was applied in the present study.

11.2 Estimation of Bridge Life-Cycle Cost

The bridge life-cycle cost for this study included the relevant agency costs that are expected to occur throughout the life of the bridge asset. The bridge life cycle is considered as the time interval between two consecutive bridge replacement activities (Figure 11.1). The focus of the present study is on the cost incurred in providing the bridge and the cost of repairing damage due to traffic loading. For the purposes of the study, bridge construction cost (new bridge where none existed hitherto) was excluded but reconstruction (replacement) cost of an existing bridge was included.

In order to recognize the fact that not all bridges in the network are new, study considered the remaining bridge life (referred to as a partial cycle in Figure 11.1). The partial cycle time is the time interval between the current year and the year of bridge replacement. Thus two bridges of the same material type and same design type are assumed herein to have the same full life-cycle cost. However, if one of these bridges is new and the other has existed for some years, then the former will have no partial life-cycle cost while the latter will have a partial cycle cost.



Where,
BC: bridge construction,
BR: bridge reconstruction,
DR: deck rehabilitation, and
SR: superstructure replacement.

Figure 11.1 Illustration of partial and full cycles for a bridge.

11.3 Selection of Cost Models and Average Unit Cost

The total cost associated with bridge provision and upkeep over partial or full cycle is the sum of the individual constituent costs of the MR&R schedule over the full or partial cycle. These costs include (re)construction cost, deck and superstructure rehabilitation costs, deck replacement costs, and maintenance costs. For estimating these costs, data from Rodriguez (*171*) were adjusted to 2010 dollars (Table 11.1) and used.

11.4 Life-Cycle Bridge Cost Analysis

In order to estimate the life-cycle cost, the schedule of treatments for each bridge family was established. Then, using the unit costs of the bridge treatments established in Section 11.3, the total cost for each life-cycle scenario, repeated until perpetuity was determined. The cost at each year was converted into present worth as shown in Equations 11.1 to 11.3 and total cost was determined as the sum of the full cycle present worth and the partial cycle present worth. The EUAC was then calculated by annualizing the "present worth of the total costs" in perpetuity.

In the present study, steel, prestressed concrete and concrete bridges were each assigned a 70-year life cycle. The choice of 70 years was based on the average life expectancies of these bridge types as indicated by Sinha et al. (*167*).

$$PW_{FC,\mu} = PW_{BR,\mu} + D_{rehab1,\mu}\left[\frac{1}{(1+r)^{20}}\right] + D_{replace,\mu}\left[\frac{1}{(1+r)^{35}}\right] + D_{rehab2,\mu}\left[\frac{1}{(1+r)^{55}}\right] + BR_{replace,\mu}\left[\frac{1}{(1+r)^{70}}\right] \quad (11.1)$$

$$PW_{PC,\mu} = D_{rehab1,\mu} = \left[\frac{1}{(1+r)^{20-\theta}}\right] + D_{replace,\mu}\left[\frac{1}{(1+r)^{35-\theta}}\right] + D_{rehab2,\mu}\left[\frac{1}{(1+r)^{55-\theta}}\right] + BR_{replace,\mu}\left[\frac{1}{(1+r)^{70-\theta}}\right] \quad (11.2)$$

$$PW_{TC,\mu} = PW_{PC,\mu} + PW_{FC,\mu} \quad (11.3)$$

$$EUAC_{\mu} = PW_{TC,\mu}\left[\frac{r(1+r)^n}{(1+r)^n - 1}\right] \quad (11.4)$$

Where,

TABLE 11.1
Average Unit Cost and Cost Model Used in Bridge Expenditure Analysis

Superstructure Type	Cost Component	Unit Cost ($/ft^2)	Cost Model
Steel bridges	SUPRC	70.26	N/A
	SUBRC	21.23	N/A
	APPRC	69.87	N/A
	OTHC	55.95	N/A
	DERC	N/A	$0.167 \times BL^{0.662} \times TDW^{0.949} + 16.752 \times SKEW + 1.24 \times DA^{0.525}$
Prestressed concrete bridges	SUPRC	57.47	N/A
	SUBRC	20.56	N/A
	APPRC	87.89	N/A
	OTHC	68.30	N/A
	DERC	N/A	$0.167 \times BL^{0.662} \times TDW^{0.949} + 16.752 \times SKEW + 1.24 \times DA^{0.525}$
Reinforced concrete bridges	SUPRC	53.33	N/A
	SUBRC	20.16	N/A
	APPRC	90.66	N/A
	OTHC	60.91	N/A
	DERC	N/A	$0.167 \times BL^{0.662} \times TDW^{0.949} + 16.752 \times SKEW + 1.24 \times DA^{0.525}$

Source: (*171*).
SUPRC: superstructure replacement cost, in 1,000s of year 2010 constant dollars.
SUBRC: substructure replacement cost, in 1,000s of year 2010 constant dollars.
APPRC: approach replacement cost, in 1,000s of year 2010 constant dollars.
OTHRC: other replacement cost, in 1,000s of year 2010 constant dollars.
DERC: deck rehabilitation cost, in 1,000s of year 2010 constant dollars.
BL: bridge length (in ft.).
TDW: total deck width (in ft.).
SKEW: bridge skewness (degrees).
N/A: not applicable.

$PW_{FC,\mu}$: present worth of all treatment costs over full cycle for bridge family μ,

$PW_{PC,\mu}$: present worth of all treatment costs over partial cycle for bridge family μ,

$PW_{TC,\mu}$: present worth of all life-cycle costs for bridge family μ,

$PW_{BR,\mu}$: present worth cost of bridge (re) construction for bridge family μ,

$D_{rehab1,\mu}$: cost of first deck rehabilitation for bridge familyμ,

$D_{replace,\mu}$: deck replacement cost for bridge family μ,

$D_{rehab2,\mu}$: cost of second deck rehabilitation for bridge family μ,

$BR_{replace,\mu}$: bridge replacement cost for bridge family μ,

$EUAC_{\mu}$: bridge equivalent uniform annual cost for bridge family μ,

r: discount rate, and

θ: age of bridge.

11.5 Estimate Life-Cycle Costs of Bridges in the Study

Using the analysis presented in Section 11.4, the life-cycle cost for each bridge family was calculated on the basis of representative bridges within each of the groups discussed in Chapter 10. The life-cycle cost for each bridge family was calculated using the bridge component cost models presented in Table 11.1. The EUAC for each bridge family, bridge age and highway functional class is presented in Table 11.2. The results presented in Table 11.2 are the costs per unit bridge length. It is worth iterating that the lifecycle activity profile being used in these calculations is that for concrete and prestressed concrete bridges, since these

TABLE 11.2
Computed Equivalent Uniform Annual Costs (EUAC)

Highway Type	Bridge Type	Bridge Age Group (yrs.)	EUAC/Bridge Length ($1,000s per ft.) (for all Vehicles)	EUAC/Bridge Length ($1,000s per ft.) (for Overweight Trucks)
Interstate	Steel	0–20	850.8	193.5*
		21–35	892.0	202.8
		36–55	892.2	202.9
		56–70	961.3	218.6
	Prestressed concrete	0–20	873.4	198.6
		21–35	910.2	206.9
		36–55	937.4	213.2
		56–70	1,017.5	231.4
	Reinforced concrete	0–20	842.7	191.6
		21–35	874.7	198.9
		36–55	905.0	205.8
		56–70	979.2	222.6
NHS non-Interstate	Steel	0–20	850.8	193.5
		21–35	892.0	202.8
		36–55	892.2	202.9
		56–70	961.3	218.6
	Prestressed concrete	0–20	873.4	198.6
		21–35	910.2	206.9
		36–55	937.4	213.2
		56–70	1,017.5	231.4
	Reinforced concrete	0–20	842.7	191.6
		21–35	874.7	198.9
		36–55	905.0	205.8
		56–70	979.2	222.6
Non-NHS	Steel	0–20	850.8	193.5
		21–35	892.0	202.8
		36–55	892.2	202.9
		56–70	961.3	218.6
	Prestressed concrete	0–20	873.4	198.6
		21–35	910.2	206.9
		36–55	937.4	213.2
		56–70	1,017.5	231.4
	Reinforced concrete	0–20	842.7	191.6
		21–35	874.7	198.9
		36–55	905.0	205.8
		56–70	979.2	222.6

NOTE: Amounts shown are in year 2010 constant dollar.
*The percentage of OW truck EUAC with respect to total EUAC is approximately 22.7% (193.5/850.8)

materials comprise the majority of Indiana bridge construction, and because the profiles do not vary significantly from those for steel bridges. The lifecycle activities can thus be described as follows: bridge replacement in years 0 and 70, deck rehabilitation in year 20 and 55, and superstructure replacement in year 35 with annual routine maintenance.

The results show that the EUAC increases as the bridge age increases. For example, the EUAC for an Interstate steel bridge (0–20 years) is approximately $850,000 (2010 constant dollars). However, for the same material type (steel) and functional class in an older age group (56–70 years), the EUAC is approximately $960,000 (2010 constant dollars). This variation in the EUAC values is consistent with expectation because for an older bridge, the planned reconstruction is closer to implementation and thus the time value of money has a greater effect compared to a younger bridge. The computed EUACs are presented in Table 11.2 and are used in Chapter 12 for the incremental cost analysis.

11.6 Chapter Summary

This chapter presented the systematic estimation of bridge life-cycle cost for the present study. The chapter presented the procedure used in the selection of cost models and units cost as inputs into the life-cycle cost analysis and the estimated bridge life-cycle cost values were presented. In the next chapter (Chapter 12), the estimated bridge life-cycle costs are assigned to overweight vehicles.

12. ALLOCATION OF BRIDGE COST RESPONSIBILITIES

12.1 Introduction

In the previous chapter, bridge life-cycle cost was estimated. In this chapter, the estimated life-cycle costs are allocated to overweight trucks using three approaches: disaggregate, semi-disaggregate and aggregate. In each approach, the cost responsibilities for each overweight truck were estimated on the basis of the attributes of the overweight truck, the bridge over which it passes, and the highway. The chapter investigates the feasibility and benefits of establishing overweight truck permit fees on the basis of their gross vehicle weights, axle loadings, and axle spacings. In doing so, the chapter examines the impacts of the common practice of aggregating all overweight vehicles into one category and charging them the same permit fee, in terms of efficiency and equity.

12.2 Cost Responsibilities of Overweight Trucks

The cost responsibility due to overweight trucks was found to be approximately 22.7% of the total bridge life-cycle cost that was presented in Table 11.2. Considering the fact that overweight trucks span a wide range of vehicle classes, it is important that this cost is allocated to each overweight truck class as discussed in Chapter 10. In order to do this, an incremental cost analysis for overweight trucks only, was carried out. An illustrative example is herein presented.

TABLE 12.1
Example Data on Cost Increment and Traffic Volume by Vehicle Class at a Bridge

AASHTO Vehicle Class	Damage Cost Increment (2010$ $\times 10^6$)	Traffic Volume ($\times 10^6$)
HS 20	25	55
HS 21	8	20
HS 22	7	25
Total	40	100

Table 12.1 presents a hypothetical example data on cost responsibilities and Table 12.2 presents example data on unit damage cost computation. In Table 12.1, 25 million dollars of the damage cost was allocated to the base overweight truck, HS20. The other heavier trucks, HS21 and HS22, had damage cost increments of 8 and 7 million dollars, respectively. The traffic volumes for the trucks, HS20, HS21, and HS22 were 55 million, 20 million and 25 million, respectively. In Table 12.2, the first increment share was distributed across each overweight truck on the basis of traffic volume. For example, HS20 truck was allocated $13.75 in the first increment, while HS21 and HS22 were allocated $5 and $6.25, respectively. In the second increment, only the next heavier vehicles (HS21 and HS22) are considered. This approach continues until the heaviest vehicle class is considered. The bridge unit damage cost is computed by dividing the allocated cost by the truck's traffic volume. For example, HS20 was allocated a unit bridge damage cost of $0.25. The results from the example show that overweight vehicles with weights far exceeding the legal limit inflict greater cost and hence are expected to pay more compared to overweight vehicles with weights not far above the legal limit. It is seen that the accumulated total damage cost for HS22 vehicles is $17.69 million (in 2010 constant dollars) and this cost is borne by 25 million vehicles translating to $0.71 per vehicle. However, for HS21 vehicles, the accumulated total damage cost is $8.56 million and this cost is borne by 20 million vehicles (translating to $0.428 per vehicle).

The illustration shows how incremental cost analysis is used to equitably allocate the damage cost incurred due to each vehicle class. This means that it is now possible to estimate the cost responsibility of each overweight truck on the basis of the relative damage it imposes on the bridge structure.

12.3 A Disaggregate Approach for Estimating the Cost of Bridge Damage Repair

Three approaches (disaggregate, semi-disaggregate and aggregate) were used separately in this chapter to estimate the cost responsibilities for each overweight truck. Under the disaggregate approach, the cost for each overweight truck was computed on the basis of

TABLE 12.2
Example Estimation of Bridge Damage Cost Responsibilities by Vehicle Class

Description	AASHTO Vehicle Class			Cost Increment Total
	HS 20	HS 21	HS 22	(2010$ $\times$ 10^6)
Share of first increment of damage due to load	$25 \times \frac{55}{100} = 13.75$	$25 \times \frac{20}{100} = 5.00$	$25 \times \frac{25}{100} = 6.25$	25
Share of second increment of damage due to load	—	$8 \times \frac{20}{45} = 3.5$	$8 \times \frac{25}{45} = 4.44$	8
Share of third increment of damage due to load	—	—	$7 \times \frac{25}{25} = 7.00$	7
Cost responsibility	**$13.75**	**$8.56**	**$17.69**	**$40**
Bridge unit damage cost				—

specific attributes of the bridge, including the highway class of the bridge, material type, age and on specific attributes of the overweight truck (GVW, axle loading, and axle spacing). In the semi-disaggregate approach, cost responsibilities were computed on the basis of information on highway functional class of the bridge, axle configurations and the GVW of the overweight truck in order to estimate cost of bridge damage for each vehicle class. Under the aggregate approach, overweight vehicles are clustered into easy-to-manage categories (80,000–108,000 lbs, 108,000–150,000 lbs and above 150,000 lbs) on the basis on GVW without due consideration of axle configurations.

The disaggregate costs of bridge damage for the bridge material types (steel, prestressed concrete, and concrete) are presented in Tables 12.3 to 12.8 and for bridge age group 0 to 20 years (the costs for the other bridge age groups are presented in Figures III.A.3 and III.A.4 in the Part III Appendix). The cost values presented in Tables III.A.3 and III.A.4 are indicated for AASHTO design vehicles. In order convert the cost to FHWA vehicle class, the user will require the variables discussed in Chapter 10 and conversion from AASHTO to FHWA vehicle class can be carried out using the modified equivalent vehicle model developed and discussed in Chapter 10.

Also, the bridge damage cost was computed under two options. Option 1 is defined as the costs on the basis of gross vehicle weight irrespective of the federal legal weight limit. For example, an overweight truck of 90,000 lbs would be assigned a cost consistent with the entire gross vehicle weight of 90,000 lbs. This option was developed in order to assign a cost to overweight trucks for the total damage they cause to the bridge. Option 2 refers to the costs due to the difference in the damage triggered by the excess weight beyond the legal vehicle weight limit of 80,000 lbs. For example, a truck of 90,000 lbs would be responsible for the damage caused by the extra 10,000 lbs only. The second option was developed to accommodate the assumption that vehicles weighing up to 80,000 lbs do not incur any cost associated with overweight operations.

In order to comprehend and adopt an acceptable permit fee on the basis of these damage costs, consideration must be given to the three vehicle variables used in the numerical computation of bridge damage. For example, Tables 12.3 to 12.8 show that a bridge damage cost analysis based on the GVW would be inappropriate, inadequate, and inefficient because a vehicle with a known GVW weight and a higher number of axles would be expected to pay a lower portion of bridge cost compared to another vehicle with the same GVW but with a lower number of axles.

From Figure 12.1 and Table 12.3, on the basis of option 1, a class 7 truck with the following configuration: GVW of 95,650 lbs, four axles, average axle spacing of 71 inches, and average axle load of 23,940 lbs would be incurring a unit cost of 87.9 cents (2010 constant dollars) per bridge length per pass, for example $87.90 for a one-time use of a bridge of 100 ft. span. A class 12 truck with a configuration of GVW of 100,845 lbs, six axles, 132-inch average axle spacing, and average axle loading of 16,808 lbs would pay 4.7 cents (2010 constant dollars) per bridge length per pass, for example $4.7 for a one-time use of a bridge of 100 ft. span.

Using the second option, truck 1 would be seen to be incurring a lower amount of 86.4 cents per bridge length per pass while truck 2 would be seen to be incurring a lower amount of 3.2 cents per bridge length per pass as illustrated in Figure 12.1.

It may be observed that from the above analysis (Figure 12.1), there are three factors that significantly influence the final cost of bridge damage: gross weight, axle spacing and number of axles. It can be seen that truck 2 has a higher GVW compared to truck 1. Secondly, truck 1's axle spacing is less than that of truck 2. Thirdly, truck 1's average axle load is higher than that of truck 2. On the basis of these three factors, truck 1 produces a higher moment (higher bridge damage) compared to truck 2. Therefore using, the modified equivalent vehicle model, truck 1 is classified as HS 35 while truck 2 is classified as HS 23.

Bridge damage cost computations were also carried out for different attributes of the bridge such as the bridge functional class and age. Quite expectedly, the results showed that for a vehicle of a given weight, number of axles and axle configuration, the unit damage cost, is higher for lower highway classes (such as state roads) compared to higher highway classes (such as Interstates). This difference could attributed to

TABLE 12.3
Cost of Steel Bridge Damage due to Overweight Trucks, Disaggregate Approach, 100% Load Share, 0–20 Years Age Group, Option 1*

Truck Description	Average GVW (lbs)	Average Spacing (in)	Average Axle Load (lbs)	Equivalent Load (HS)	Interstate Bridge Damage Cost (2010$/ft./pass)	NHS-NI Bridge Damage Cost (2010$/ft./pass)	NNHS Bridge Damage Cost (2010$/ft./pass)
80–108kips							
4 axles	95,650	71	23,940	35	0.879	2.354	8.250
5 axles	92,651	162	18,530	22	0.022	0.059	0.208
6 axles	100,845	132	16,808	23	0.047	0.127	0.445
7 or more axles	99,948	128	15,739	22	0.022	0.059	0.208
Weighted average					0.088	0.234	0.821
108–150kips							
4 axles	117,556	61	26,239	41	5.397	14.446	50.626
5 axles	118,893	93	23,779	34	0.738	1.976	6.925
6 axles	120,672	128	20,110	28	0.213	0.569	1.994
7 axles	128,996	116	18,428	27	0.170	0.455	1.595
8 axles	139,692	112	17,461	28	0.213	0.569	1.994
9 or more axles	130,472	120	18,206	27	0.170	0.455	1.595
Weighted average					0.242	0.649	2.274
150–200kips							
7 axles	154,627	111	22,086	33	0.619	1.656	5.803
8 axles	161,226	105	20,132	32	0.517	1.383	4.846
9 axles	172,992	122	19,221	30	0.348	0.932	3.267
10 axles	188,433	126	18,843	31	0.430	1.152	4.036
11 axles	189,618	128	17,238	29	0.276	0.739	2.591
12 or more axles	193,318	120	14,425	26	0.138	0.370	1.295
Weighted average					0.440	1.178	4.129
>200kips							
11 axles	216,333	127	19,667	33	0.619	1.656	5.803
12 axles	238,000	113	19,833	35	0.879	2.354	8.250
13 axles	241,986	127	18,616	33	0.619	1.656	5.803
14 axles	290,800	106	20,771	39	2.345	6.278	22.001
15 or more axles	417,174	106	23,122	47	8.960	26.880	89.600
Weighted average					3.365	9.907	33.290

*Option 1 is for the damage caused by the entire load of an overweight vehicle (>80,000 lbs).

TABLE 12.4
Cost of Steel Bridge Damage due to Overweight Trucks, Disaggregate Approach, 100% Load Share, 0–20 Years Age Group, Option 2*

Truck Description	Average GVW (lbs)	Average Spacing (in)	Average Axle Load (lbs)	Equivalent Load (HS)	Interstate Bridge Damage Cost (2010$/ft./pass)	NHS-NI Bridge Damage Cost (2010$/ft./pass)	NNHS Bridge Damage Cost (2010$/ft./pass)
80–108kips							
4 axles	95,650	71	23,940	35	0.864	2.308	8.097
5 axles	92,651	162	18,530	22	0.007	0.013	0.055
6 axles	100,845	132	16,808	23	0.032	0.081	0.292
7 or more axles	99,948	128	15,739	22	0.007	0.013	0.055
Weighted average					0.072	0.189	0.669
108–150kips							
4 axles	117,556	61	26,239	41	5.382	14.401	50.473
5 axles	118,893	93	23,779	34	0.723	1.930	6.772
6 axles	120,672	128	20,110	28	0.197	0.523	1.842
7 axles	128,996	116	18,428	27	0.155	0.409	1.442
8 axles	139,692	112	17,461	28	0.197	0.523	1.842
9 or more axles	130,472	120	18,206	27	0.155	0.409	1.442
Weighted average					0.227	0.603	2.122
150–200kips							
7 axles	154,627	111	22,086	33	0.603	1.610	5.650
8 axles	161,226	105	20,132	32	0.501	1.337	4.693
9 axles	172,992	122	19,221	30	0.333	0.887	3.115
10 axles	188,433	126	18,843	31	0.415	1.106	3.883
11 axles	189,618	128	17,238	29	0.261	0.694	2.438
12 or more axles	193,318	120	14,425	26	0.123	0.324	1.142
Weighted average					0.425	1.132	3.976
>200kips							
11 axles	216,333	127	19,667	33	0.603	1.610	5.650
12 axles	238,000	113	19,833	35	0.864	2.308	8.097
13 axles	241,986	127	18,616	33	0.603	1.610	5.650
14 axles	290,800	106	20,771	39	2.330	6.232	21.848
15 or more axles	417,174	106	23,122	47	8.945	26.834	89.447
Weighted average					3.350	9.861	33.137

*Option 2 is for the damage caused by the overweight portion only of an overweight vehicle.

TABLE 12.5
Cost of Prestressed Concrete Bridge Damage due to Overweight Trucks, Disaggregate Approach, 100% Load Share, 0–20 Years Age Group, Option 1*

Truck Description	Average GVW (lbs)	Average Spacing (in)	Average Axle Load (lbs)	Equivalent Load (HS)	Interstate Bridge Damage Cost (2010$/ft./pass)	NHS-NI Bridge Damage Cost (2010$/ft./pass)	NNHS Bridge Damage Cost (2010$/ft./pass)
			80–108kips				
4 axles	95,650	71	23,940	35	0.903	2.417	8.469
5 axles	92,651	162	18,530	22	0.023	0.061	0.213
6 axles	100,845	132	16,808	23	0.049	0.130	0.457
7 or more axles	99,948	128	15,739	22	0.023	0.061	0.213
Weighted average					0.090	0.241	0.843
			108–150kips				
4 axles	117,556	61	26,239	41	5.540	14.830	51.969
5 axles	118,893	93	23,779	34	0.758	2.028	7.109
6 axles	120,672	128	20,110	28	0.218	0.584	2.047
7 axles	128,996	116	18,428	27	0.175	0.467	1.637
8 axles	139,692	112	17,461	28	0.218	0.584	2.047
9 or more axles	130,472	120	18,206	27	0.175	0.467	1.637
Weighted average					0.249	0.666	2.335
			150–200kips				
7 axles	154,627	111	22,086	33	0.635	1.700	5.957
8 axles	161,226	105	20,132	32	0.530	1.420	4.975
9 axles	172,992	122	19,221	30	0.358	0.957	3.354
10 axles	188,433	126	18,843	31	0.442	1.182	4.143
11 axles	189,618	128	17,238	29	0.284	0.759	2.660
12 or more axles	193,318	120	14,425	26	0.142	0.379	1.329
Weighted average					0.452	1.209	4.238
			>200kips				
11 axles	216,333	127	19,667	33	0.635	1.700	5.957
12 axles	238,000	113	19,833	35	0.903	2.417	8.469
13 axles	241,986	127	18,616	33	0.635	1.700	5.957
14 axles	290,800	106	20,771	39	2.408	6.445	22.585
15 or more axles	417,174	106	23,122	47	8.965	26.892	89.643
Weighted average					3.382	9.952	33.448

*Option 1 is for the damage caused by the entire load of an overweight vehicle (>80,000 lbs).

TABLE 12.6
Cost of Prestressed Concrete Bridge Damage due to Overweight Trucks, Disaggregate Approach, 100% Load Share, 0–20 Years Age Group, Option 2*

Truck Description	Average GVW (lbs)	Average Spacing (in)	Average Axle Load (lbs)	Equivalent Load (HS)	Interstate Bridge Damage Cost (2010$/ft./pass)	NHS-NI Bridge Damage Cost (2010$/ft./pass)	NNHS Bridge Damage Cost (2010$/ft./pass)
80–108kips							
4 axles	95,650	71	23,940	35	0.887	2.369	8.311
5 axles	92,651	162	18,530	22	0.007	0.013	0.055
6 axles	100,845	132	16,808	23	0.033	0.083	0.298
7 or more axles	99,948	128	15,739	22	0.007	0.013	0.055
Weighted average					0.074	0.193	0.685
108–150kips							
4 axles	117,556	61	26,239	41	5.524	14.782	51.811
5 axles	118,893	93	23,779	34	0.742	1.981	6.950
6 axles	120,672	128	20,110	28	0.202	0.537	1.889
7 axles	128,996	116	18,428	27	0.159	0.420	1.479
8 axles	139,692	112	17,461	28	0.202	0.537	1.889
9 or more axles	130,472	120	18,206	27	0.159	0.420	1.479
Weighted average					0.233	0.619	2.176
150–200kips							
7 axles	154,627	111	22,086	33	0.619	1.653	5.650
8 axles	161,226	105	20,132	32	0.514	1.372	4.693
9 axles	172,992	122	19,221	30	0.342	0.910	3.115
10 axles	188,433	126	18,843	31	0.426	1.135	3.883
11 axles	189,618	128	17,238	29	0.268	0.712	2.438
12 or more axles	193,318	120	14,425	26	0.126	0.332	1.142
Weighted average					0.436	1.162	3.976
>200kips							
11 axles	216,333	127	19,667	33	0.619	1.653	5.650
12 axles	238,000	113	19,833	35	0.887	2.369	8.097
13 axles	241,986	127	18,616	33	0.619	1.653	5.650
14 axles	290,800	106	20,771	39	2.392	6.397	21.848
15 or more axles	417,174	106	23,122	47	8.949	26.845	89.447
Weighted average					3.366	9.905	33.137

*Option 2 is for the damage caused by the overweight portion only of an overweight vehicle.

TABLE 12.7
Cost of Concrete Bridge Damage due to Overweight Trucks, Disaggregate Approach, 100% Load Share, 0–20 Years Age Group, Option 1*

Truck Description	Average GVW (lbs)	Average Spacing (in)	Average Axle Load (lbs)	Equivalent Load (HS)	Interstate Bridge Damage Cost (2010$/ft./pass)	NHS-NI Bridge Damage Cost (2010$/ft./pass)	NNHS Bridge Damage Cost (2010$/ft./pass)
80–108kips							
4 axles	95,650	71	23,940	35	0.871	2.332	8.171
5 axles	92,651	162	18,530	22	0.022	0.059	0.206
6 axles	100,845	132	16,808	23	0.047	0.126	0.441
7 or more axles	99,948	128	15,739	22	0.022	0.059	0.206
Weighted average					0.087	0.232	0.814
108–150kips							
4 axles	117,556	61	26,239	41	5.345	14.308	50.143
5 axles	118,893	93	23,779	34	0.731	1.957	6.859
6 axles	120,672	128	20,110	28	0.211	0.564	1.975
7 axles	128,996	116	18,428	27	0.168	0.451	1.580
8 axles	139,692	112	17,461	28	0.211	0.564	1.975
9 or more axles	130,472	120	18,206	27	0.168	0.451	1.580
Weighted average					0.240	0.643	2.253
150–200kips							
7 axles	154,627	111	22,086	33	0.613	1.640	5.748
8 axles	161,226	105	20,132	32	0.512	1.370	4.800
9 axles	172,992	122	19,221	30	0.345	0.923	3.236
10 axles	188,433	126	18,843	31	0.426	1.141	3.997
11 axles	189,618	128	17,238	29	0.274	0.732	2.566
12 or more axles	193,318	120	14,425	26	0.137	0.366	1.283
Weighted average					0.436	1.167	4.089
>200kips							
11 axles	216,333	127	19,667	33	0.613	1.640	5.748
12 axles	238,000	113	19,833	35	0.871	2.332	8.171
13 axles	241,986	127	18,616	33	0.613	1.640	5.748
14 axles	290,800	106	20,771	39	2.323	6.218	21.791
15 or more axles	417,174	106	23,122	47	8.963	26.888	89.627
Weighted average					3.360	9.894	33.246

*Option 1 is for the damage caused by the entire load of an overweight vehicle (>80,000 lbs).

TABLE 12.8
Cost of Concrete Bridge Damage due to Overweight Trucks, Disaggregate Approach, 100% Load Share, 0–20 Years Age Group, Option 2*

Truck Description	Average GVW (lbs)	Average Spacing (in)	Average Axle Load (lbs)	Equivalent Load (HS)	Interstate Bridge Damage Cost (2010$/ft./pass)	NHS-NI Bridge Damage Cost (2010$/ft./pass)	NNHS Bridge Damage Cost (2010$/ ft./pass)
80–108kips							
4 axles	95,650	71	23,940	35	0.856	2.286	8.021
5 axles	92,651	162	18,530	22	0.007	0.013	0.055
6 axles	100,845	132	16,808	23	0.032	0.080	0.290
7 or more axles	99,948	128	15,739	22	0.007	0.013	0.055
Weighted average					0.072	0.187	0.663
108–150kips							
4 axles	117,556	61	26,239	41	5.330	14.263	49.992
5 axles	118,893	93	23,779	34	0.716	1.912	6.708
6 axles	120,672	128	20,110	28	0.196	0.518	1.825
7 axles	128,996	116	18,428	27	0.153	0.405	1.429
8 axles	139,692	112	17,461	28	0.196	0.518	1.825
9 or more axles	130,472	120	18,206	27	0.153	0.405	1.429
Weighted average					0.225	0.598	2.102
150–200kips							
7 axles	154,627	111	22,086	33	0.598	1.595	5.597
8 axles	161,226	105	20,132	32	0.497	1.324	4.649
9 axles	172,992	122	19,221	30	0.330	0.878	3.086
10 axles	188,433	126	18,843	31	0.411	1.095	3.847
11 axles	189,618	128	17,238	29	0.259	0.687	2.416
12 or more axles	193,318	120	14,425	26	0.122	0.321	1.132
Weighted average					0.421	1.122	3.939
>200kips							
11 axles	216,333	127	19,667	33	0.598	1.595	5.597
12 axles	238,000	113	19,833	35	0.856	2.286	8.021
13 axles	241,986	127	18,616	33	0.598	1.595	5.597
14 axles	290,800	106	20,771	39	2.308	6.173	21.640
15 or more axles	417,174	106	23,122	47	8.948	8.975	89.477
Weighted average					3.345	4.303	33.095

*Option 2 is for the damage caused by the overweight portion only of an overweight vehicle.

(i) differences in the life-cycle costs of reconstruction and rehabilitation across the highway functional class that are, in turn due to these different design standards of different highway classes, and (ii) the differences in truck traffic volumes across the highway classes (higher volumes on Interstates means more users share the cost).

Using the two truck configurations discussed earlier in this section (Figure 12.1), we estimated and compared the expected bridge damage cost for each highway class as shown in Table 5.3. For example, using a steel bridge length of 100 feet under option 1, truck 1 would be expected to incur a bridge damage cost (in 2010 constant dollars) of $88 (0.871 × 100), $235 (2.354 × 100), and $825 (8.25 × 100) per pass for Interstate, NHS-non-Interstate, and NNHS steel bridges, respectively under option 1. Truck 2's expected bridge damage cost are $5 (0.047 × 100), $13 (0.126 × 100) and $45 (0.445 × 100) per pass for a 100 ft. steel bridge of Interstate, NHS-non-Interstate and NNHS functional classes, respectively (Figure 12.2). The bridge damage costs for the two trucks, under option 2, are also presented in Figure 12.2.

The above analysis carried out for steel bridges is repeated for prestressed concrete bridges and concrete cast-in-situ bridges and the results are presented in Tables 12.5, 12.6, 12.7 and 12.8.

12.4 A Semi-aggregate Approach for Estimating the Cost of Bridge Damage Repair

In the previous section, the bridge damage cost was derived on the basis of the assumption that the agency possesses detailed disaggregate information on the highway bridge as well as the trucks using the bridge. It can be considered efficient to charge overweight

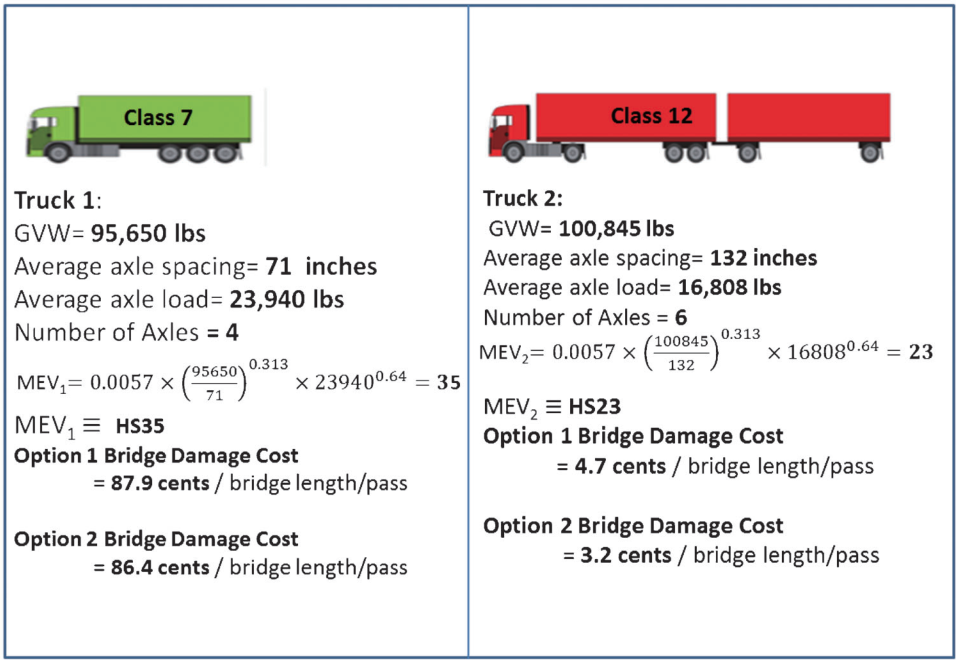


Figure 12.1 Illustration of bridge damage cost computation under the different options.

trucks at the disaggregate level because the bridge damage cost is determined using full information on the bridges and the overweight trucks.

However, where information on the individual bridges and vehicles is not available, the agency can cluster the bridges into an appropriate number of highways classes and then estimate the damage costs for overweight trucks based on their GVW, axle configurations and highway class. This is referred to as the semi-disaggregate approach. In this study, the semi-disaggregate costs of bridge damage were computed for each highway class by taking a weighted average of the bridge damage costs that were determined at the disaggregate level in Section 12.3. The results are presented in Tables 12.9 and 12.10.

From Table 12.9, using a bridge length of 100 feet under option 1, truck 1 was expected to incur a bridge damage cost (in 2010 constant dollars) of \$9 (0.895×100), \$242 (2.418×100) and \$849 (8.493×100) per pass at Interstate, NHS-non-Interstate, and NNHS steel bridges, respectively. Truck 2's expected bridge damage costs are \$5 (0.048×100),

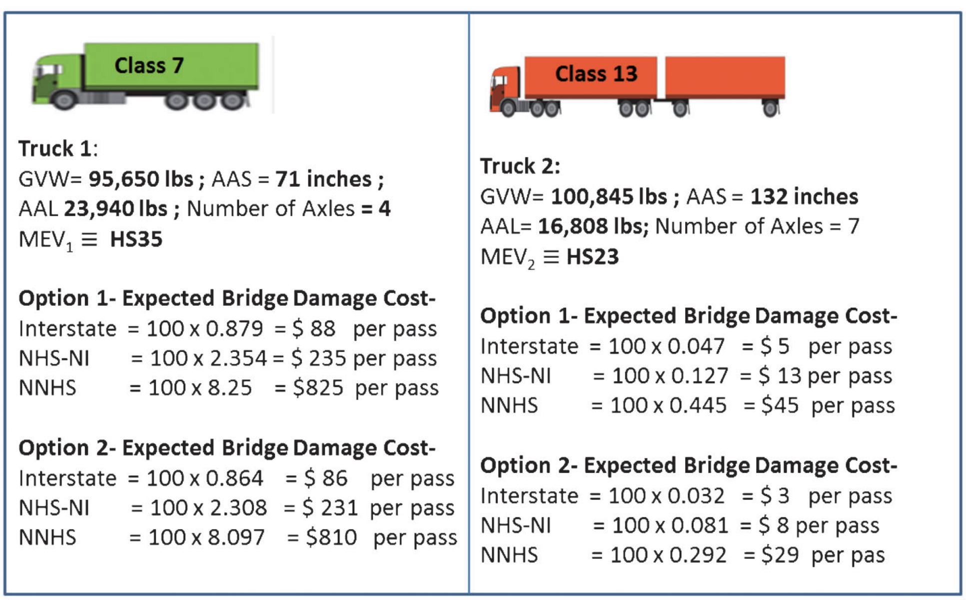


Figure 12.2 Overweight truck damage costs based on a 100-ft. steel bridge, using the disaggregate approach.

TABLE 12.9
Cost of Bridge Damage due to Overweight Trucks, Semi-disaggregate Approach, 100% Load Share, Option 1

Truck Description	Average GVW (lbs)	Average Spacing (in)	Average Axle Load (lbs)	Equivalent Load (HS)	Interstate Bridge Damage Cost (2010$/ft./pass)	NHS-NI Bridge Damage Cost (2010$/ft./pass)	NNHS Bridge Damage Cost (2010$/ft./pass)
80–108kips							
4 axles	95,650	71	23,940	35	0.895	2.418	8.493
5 axles	92,651	162	18,530	22	0.023	0.061	0.214
6 axles	100,845	132	16,808	23	0.048	0.130	0.458
7 or more axles	99,948	128	15,739	22	0.023	0.061	0.214
Weighted average					0.089	0.241	0.846
108–150kips							
4 axles	117,556	61	26,239	41	5.490	14.840	52.117
5 axles	118,893	93	23,779	34	0.751	2.030	7.129
6 axles	120,672	128	20,110	28	0.216	0.585	2.053
7 axles	128,996	116	18,428	27	0.173	0.467	1.642
8 axles	139,692	112	17,461	28	0.216	0.585	2.053
9 or more axles	130,472	120	18,206	27	0.173	0.467	1.642
Weighted average					0.247	0.667	2.341
150–200kips							
7 axles	154,627	111	22,086	33	0.629	1.701	5.974
8 axles	161,226	105	20,132	32	0.526	1.421	4.989
9 axles	172,992	122	19,221	30	0.354	0.958	3.364
10 axles	188,433	126	18,843	31	0.438	1.183	4.155
11 axles	189,618	128	17,238	29	0.281	0.760	2.667
12 or more axles	193,318	120	14,425	26	0.140	0.380	1.333
Weighted average					0.448	1.210	4.250
>200kips							
11 axles	216,333	127	19,667	33	0.629	1.701	5.974
12 axles	238,000	113	19,833	35	0.895	2.418	8.493
13 axles	241,986	127	18,616	33	0.629	1.701	5.974
14 axles	290,800	106	20,771	39	2.386	6.449	22.649
15 or more axles	417,174	106	23,122	47	34.388	26.896	89.667
Weighted average					11.268	9.954	33.472

$13 (0.130 × 100) and $46 (0.458 × 100) per pass for Interstate, NHS-non-Interstate, and NNHS steel bridges, respectively, as presented in Figure 12.3. The semi-disaggregate bridge damage costs for the two trucks, under option 2, are presented in Table 12.10 and shown in Figure 12.3.

12.5 An Aggregate Approach for Estimating the Cost of Bridge Damage

In the previous section, the semi-disaggregate approach was used for estimating the cost of bridge damage repair. Implementation of the semi-disaggregate approach would require the following information: the highway functional class, axle configurations and the GVW of the overweight truck. In the absence of an available database system that connects the above information, most agencies cluster overweight trucks into easy-to-manage categories in order to facilitate the permit fee issuing process. This appears to the case in Indiana, where INDOR issues permits of three categories corresponding to three overweight truck categories (80,000–108,000 lbs, 108,001–150,000 lbs and above 150,000 lbs) on the basis of GVWs without consideration of axle configurations for some categories. These three categories are considered when pavement permits are issued; however, for bridges, only overweight trucks above 200,000 lbs are issued bridge permits.

In the absence of available database systems needed to implement the disaggregate approach or the semi-disaggregate approach, the state of Indiana could adopt an aggregate level approach based on GVWs and axle configurations. However, if the state of Indiana seeks to continue using the existing overweight truck categories without incorporating the axle configurations, the weighted bridge damage cost for each truck category (Table 5.11) could potentially be used. It may be noted that the bridge damage cost established under the aggregate approach is a weighted average of the costs computed at the semi-aggregate level. The aggregate

TABLE 12.10
Cost of Bridge Damage due to Overweight Trucks, Semi-disaggregate Approach, 100% Load Share, Option 2

Truck Description	Average GVW (lbs)	Average Spacing (in)	Average Axle Load (lbs)	Equivalent Load (HS)	Interstate Bridge Damage Cost (2010$/ ft./pass)	NHS-NI Bridge Damage Cost (2010$/ft./pass)	NNHS Bridge Damage Cost (2010$/ft./pass)
80–108kips							
4 axles	95,650	71	23,940	35	0.882	2.366	8.366
5 axles	92,651	162	18,530	22	0.007	0.013	0.055
6 axles	100,845	132	16,808	23	0.033	0.083	0.300
7 or more axles	99,948	128	15,739	22	0.007	0.013	0.055
Weighted average					0.074	0.193	0.689
108–150kips							
4 axles	117,556	61	26,239	41	5.491	14.760	52.159
5 axles	118,893	93	23,779	34	0.737	1.978	6.997
6 axles	120,672	128	20,110	28	0.201	0.536	1.901
7 axles	128,996	116	18,428	27	0.158	0.419	1.488
8 axles	139,692	112	17,461	28	0.201	0.536	1.901
9 or more axles	130,472	120	18,206	27	0.158	0.419	1.488
Weighted average					0.232	0.618	2.191
150–200kips							
7 axles	154,627	111	22,086	33	0.615	1.650	5.837
8 axles	161,226	105	20,132	32	0.511	1.370	4.849
9 axles	172,992	122	19,221	30	0.340	0.908	3.217
10 axles	188,433	126	18,843	31	0.423	1.133	4.011
11 axles	189,618	128	17,238	29	0.266	0.711	2.518
12 or more axles	193,318	120	14,425	26	0.125	0.331	1.179
Weighted average					0.433	1.160	4.107
>200kips							
11 axles	216,333	127	19,667	33	0.615	1.650	5.837
12 axles	238,000	113	19,833	35	0.882	2.366	8.366
13 axles	241,986	127	18,616	33	0.615	1.650	5.837
14 axles	290,800	106	20,771	39	2.377	6.388	22.577
15 or more axles	417,174	106	23,122	47	8.948	26.847	89.508
Weighted average					3.362	9.903	33.334

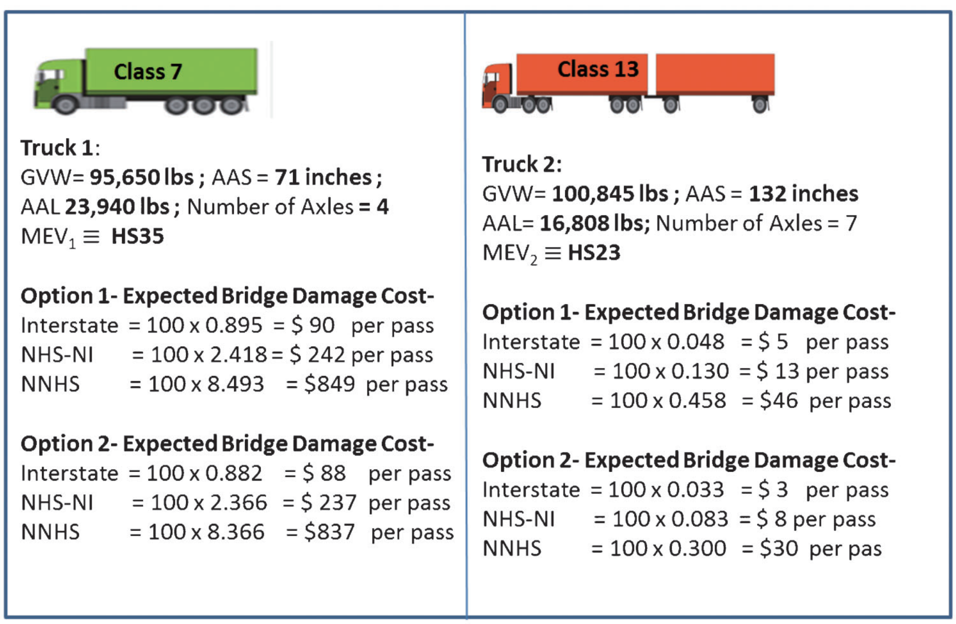


Figure 12.3 Bridge/overweight truck damage costs based on a 100-ft. steel bridge, using the semi-disaggregate approach.

TABLE 12.11
Cost of Bridge Damage due to OW Trucks, Aggregate Approach, 100% Load Share

Truck Description	% of Volume	Average GVW (lbs)	Average Spacing (in)	Average Axle Load (lbs)	Equivalent Load (HS)	Option 1: Total Truck Weight Bridge Damage Cost (2010$/mi)	Option 2: Excess Truck Weight Bridge Damage Cost (2010$/mi)
				80–108kips			
4 axles	2.58	95,650	71	23,940	35	369.486	363.437
5 axles	12.71	92,651	162	18,530	22	9.302	2.376
6 axles	17.32	100,845	132	16,808	23	19.920	13.020
7 or more axles	7.88	99,948	128	15,739	22	9.302	2.376
Weighted average						36.786	29.927
				108–150kips			
4 axles	0.40	117,556	61	26,239	41	2267.324	2265.892
5 axles	0.62	118,893	93	23,779	34	310.137	303.943
6 axles	18.83	120,672	128	20,110	28	89.321	82.589
7 axles	17.87	128,996	116	18,428	27	71.423	64.648
8 axles	3.72	139,692	112	17,461	28	89.321	82.589
9 and more axles	5.71	130,472	120	18,206	27	71.423	64.648
Weighted average						101.858	95.157
				150–200kips			
7 axles	2.91	154,627	111	22,086	33	259.898	253.581
8 axles	1.71	161,226	105	20,132	32	217.039	210.618
9 axles	0.48	172,992	122	19,221	30	146.336	139.743
10 axles	0.27	188,433	126	18,843	31	180.747	174.238
11 axles	0.29	189,618	128	17,238	29	116.047	109.380
12 and more axles	1.24	193,318	120	14,425	26	57.994	51.186
Weighted average						195.982	189.510
				>200kips			
11 axles	0.92	216,333	127	19,667	33	259.898	253.581
12 axles	0.26	238,000	113	19,833	35	369.486	363.437
13 axles	0.15	241,986	127	18,616	33	259.898	253.581
14 axles	0.16	290,800	106	20,771	39	985.325	980.773
15 and more axles	0.67	417,174	106	23,122	47	3,921.048	3,914.012
Weighted average						1462.428	1456.049

cost responsibilities were converted into a mileage-based cost using Equation 12.1. It must be noted that the number of bridges available on the national truck route is 3,128 (*165*) and the length of Indiana national truck network size is 6,145 miles (*166*).

For example, the aggregate cost responsibility for truck 1 (see Figure 12.1 for definition), per foot is $3.24, computed as the weighted average of the bridge damage cost across the three road classes. For truck 1 (HS-35), the damage cost for Interstate is $0.895 (see Table 5.9) and there are 1,434 Interstate bridges; for NHS-non-Interstate, the damage cost is $2.418 (Table 5.9) and there are 911 bridges; for non-NHS, damage cost was $8.493 (Table 5.9) and there 783 bridges. Therefore, taking a weighted average of these costs yields:

$$= \frac{(0.895 \times 1434) + (2.418 \times 911) + (8.493 \times 783)}{1434 + 911 + 783} = \$3.24/ft.$$

In order to convert the cost per foot to cost per mile, the $3.24 per foot will yield: $\frac{\$3.24}{ft} \times \frac{224\text{ft}}{bridge} \times \frac{3128\ bridge}{6145 mile} =$ $369.435 *per mile*.

This same approach was used for truck 2. Therefore, the aggregate cost for truck 2 is:

$$\frac{\$0.175}{\text{ft}} \times \frac{224\text{ft}}{\text{bridge}} \times \frac{3128\text{ bridge}}{6145\text{mile}} = \$19.92 \text{ per mile.}$$

In some states, such as New York, overweight trucks are required to pay as much as $25 per pass for certain bridges. However, because the above mentioned trucks are classified under category 1 overweight trucks (80,000–108,000 lbs), the weighted aggregate cost responsibility will be $36.79 per mile (under option 1) or $29.93 per mile (under option 2), all in 2010 constant dollars. The results for the three overweight truck categories are presented in Table 12.11.

Adopting an aggregate approach will result in lower estimates of the costs relative to their current fees for bridge damage costs. For example, using the aggregate approach, truck 1 (see Figure 12.1) incurs by 90% (under option 1) and over 92% (under option 2). On the other hand, a 7 or more axle overweight truck in category 1 (80,000–108,000 lbs) will be seen to incur costs that exceed their current fees by 395% and 1260% under options 1 and 2, respectively.

12.6 Scenarios for Load and Non-Load Shares of Bridge Damage Cost

The estimated bridge damage cost discussed up to this section of the report was carried out on the assumption that only load affects maintenance and rehabilitation expenditures. Thus, Tables 12.3 to 12.11 assume 100% load share and 0% non-load share of bridge damage cost. In reality, non-load factors can and do account for a significant share of bridge damage, as evidenced by the damaging effects of environmental factors including freeze and thaw cycles on the concrete, the corrosive effects of deicing salts on rebars, and oxidation of joint sealants, and other deleterious effects of the environment. However, due to the lack of any empirical study that establishes the load and non-load shares of bridge cost, the present study considers two scenarios for the load and non-load shares. The scenarios were determined on the basis of load and no-load shares that were established in pavement management by (*172*) as follows: 25% to 85% load and non-load shares of pavement maintenance and rehabilitation expenditures depending on factors including the pavement type and pavement improvement type. Thus, the two scenarios for load and non-load shares used in the present study are: Scenario 1: 25%–75%; and Scenario 2: 85%–15%.

For Scenario 1 that assumes 25% load share of bridge damage, this section presents the cost of bridge damage for the disaggregate approach (Tables 12.12 to 12.17), the semi-disaggregate approach (Tables 12.18 and 12.19), and the aggregate approach (Table 12.20). For each scenario and approach, the bridge damage costs are presented for each of the three types of bridge material (steel, prestressed concrete and concrete). Similarly, for Scenario 2 that assumes 85% of load share of bridge damage, the bridge damage cost for the disaggregate, semi-disaggregate and aggregate approaches are presented in Tables 12.21 to 12.29.

12.7 Comparison of Indiana's Bridge Damage Costs with Those of Other States

All states charge a form of fee for use of bridges by overweight trucks to cover bridge damage. In most states, it is implicit in the permit fee while in other states, it is explicit in the permit fee. However, the cost for bridge damage for each overweight truck type varies across the states. In some states, operators of a certain category of highly overweight trucks often considered as superloads (the weight threshold for a superload varies across states) are expected to pay permit fees after structural engineers have analyze the damage occasioned by the truck on the basis of its load and axle configurations. For example, in Indiana, overweight trucks above 200,000 lbs (classified as super loads (*173*), are required to pay the following fees (Figure III.A.2 in the Part III Appendix):

- $20 overweight fee
- $1 per mile fee
- $10 executive fee
- $25 design review fee and
- Bridge fee of $10 per bridge ($100 minimum if fewer than 10 bridges) (*173*)

The bridge fee is determined after the structural analysis was completed (some states charge extra for the structural analysis). In New Hampshire, for example, a design review fee of $40 is charged before the structural analysis is conducted. Other states charge a flat fee for all overweight trucks. For example, in New York, overweight trucks are charged $25 for a particular bridge crossing. The crossing of the same bridge in the opposite direction is not charged. Although the annual overweight permit is $1,000, it is limited to the crossing of 40 bridges by the truck receiving the permit. Beginning with the 41st bridge crossing, the overweight truck is invoiced an additional $25 for each crossing (*174*).

Charging all overweight vehicles regardless of weight and axle configuration, as practiced in the New York bridge, can result in undercharging overweight trucks of excessive overweight levels and overcharging overweight trucks of slightly overweight levels as discussed in previous sections in this chapter. Therefore, aggregating all overweight vehicles into one category and charging them the same permit fee will result in inefficiency and inequity.

It can be argued therefore, that overweight truck permit fees should be based on their GVW, axle loading, and axle spacing. This is feasible, as demonstrated by the results presented in Tables 12.3 to 12.5 and in the Part III Appendix (Figures III.A.3 and III.A.4). These results could be used to estimate the permit fee for any class of overweight trucks.

12.8 Chapter Summary

This chapter presented a numerical example for allocating bridge damage cost (incurred over a typical life cycle), to overweight trucks. Furthermore, this chapter presented three approaches, disaggregate, semi-disaggregate and aggregate, that can be used to estimate the cost responsibilities for each overweight truck on the basis of available bridge, highway and overweight truck information. In this chapter, bridge damage costs (and hence overweight truck permit fees) were established on the basis of GVW, axle loading, and axle spacing. It can be seen from the results that aggregating all overweight vehicles into one category and charging them the same permit fee will result in inefficiency and inequity. The chapter also recognized that not all bridge damage cost is due to load. However,

TABLE 12.12
Cost of Steel Bridge Damage due to Overweight Trucks, Disaggregate Approach, 25% Load Share, 0–20 Years Age Group, Option 1

Truck Description	Average GVW (lbs)	Average Spacing (in)	Average Axle Load (lbs)	Equivalent Load (HS)	Interstate Bridge Damage Cost (2010$/ft./pass)	NHS-NI Bridge Damage Cost (2010$/ft./pass)	NNHS Bridge Damage Cost (2010$/ft./pass)
80–108kips							
4 axles	95,650	71	23,940	35	0.220	0.589	2.063
5 axles	92,651	162	18,530	22	0.006	0.015	0.052
6 axles	100,845	132	16,808	23	0.012	0.032	0.111
7 or more axles	99,948	128	15,739	22	0.006	0.015	0.052
Weighted average					0.022	0.059	0.205
108–150kips							
4 axles	117,556	61	26,239	41	1.349	3.612	12.657
5 axles	118,893	93	23,779	34	0.185	0.494	1.731
6 axles	120,672	128	20,110	28	0.053	0.142	0.499
7 axles	128,996	116	18,428	27	0.043	0.114	0.399
8 axles	139,692	112	17,461	28	0.053	0.142	0.499
9 and more axles	130,472	120	18,206	27	0.043	0.114	0.399
Weighted average					0.061	0.162	0.569
150–200kips							
7 axles	154,627	111	22,086	33	0.155	0.414	1.451
8 axles	161,226	105	20,132	32	0.129	0.346	1.212
9 axles	172,992	122	19,221	30	0.087	0.233	0.817
10 axles	188,433	126	18,843	31	0.108	0.288	1.009
11 axles	189,618	128	17,238	29	0.069	0.185	0.648
12 and more axles	193,318	120	14,425	26	0.035	0.092	0.324
Weighted average					0.110	0.295	1.032
>200kips							
11 axles	216,333	127	19,667	33	0.155	0.414	1.451
12 axles	238,000	113	19,833	35	0.220	0.589	2.063
13 axles	241,986	127	18,616	33	0.155	0.414	1.451
14 axles	290,800	106	20,771	39	0.586	1.570	5.500
15 and more axles	417,174	106	23,122	47	2.240	6.720	22.400
Weighted average					0.841	2.477	8.322

TABLE 12.13
Cost of Steel Bridge Damage due to Overweight Trucks, Disaggregate Approach, 25% Load Share, 0–20 Years Age Group, Option 2

Truck Description	Average GVW (lbs)	Average Spacing (in)	Average Axle Load (lbs)	Equivalent Load (HS)	Interstate Bridge Damage Cost (2010$/ft./pass)	NHS-NI Bridge Damage Cost (2010$/ft./pass)	NNHS Bridge Damage Cost (2010$/ft./pass)
			80–108kips				
4 axles	95,650	71	23,940	35	0.216	0.577	2.024
5 axles	92,651	162	18,530	22	0.002	0.003	0.014
6 axles	100,845	132	16,808	23	0.008	0.020	0.073
7 or more axles	99,948	128	15,739	22	0.002	0.003	0.014
Weighted average					0.018	0.047	0.167
			108–150kips				
4 axles	117,556	61	26,239	41	1.345	3.600	12.618
5 axles	118,893	93	23,779	34	0.181	0.483	1.693
6 axles	120,672	128	20,110	28	0.049	0.131	0.460
7 axles	128,996	116	18,428	27	0.039	0.102	0.361
8 axles	139,692	112	17,461	28	0.049	0.131	0.460
9 and more axles	130,472	120	18,206	27	0.039	0.102	0.361
Weighted average					0.057	0.151	0.530
			150–200kips				
7 axles	154,627	111	22,086	33	0.151	0.403	1.413
8 axles	161,226	105	20,132	32	0.125	0.334	1.173
9 axles	172,992	122	19,221	30	0.083	0.222	0.779
10 axles	188,433	126	18,843	31	0.104	0.276	0.971
11 axles	189,618	128	17,238	29	0.065	0.173	0.610
12 and more axles	193,318	120	14,425	26	0.031	0.081	0.286
Weighted average					0.106	0.283	0.994
			>200kips				
11 axles	216,333	127	19,667	33	0.151	0.403	1.413
12 axles	238,000	113	19,833	35	0.216	0.577	2.024
13 axles	241,986	127	18,616	33	0.151	0.403	1.413
14 axles	290,800	106	20,771	39	0.583	1.558	5.462
15 and more axles	417,174	106	23,122	47	2.236	6.709	22.362
Weighted average					0.837	2.465	8.284

TABLE 12.14
Cost of Prestressed Concrete Bridge Damage due to Overweight Trucks, Disaggregate Approach, 25% Load Share, 0–20 Years Age Group, Option 1

Truck Description	Average GVW (lbs)	Average Spacing (in)	Average Axle Load (lbs)	Equivalent Load (HS)	Interstate Bridge Damage Cost (2010$/ft./pass)	NHS-NI Bridge Damage Cost (2010$/ft./pass)	NNHS Bridge Damage Cost (2010$/ft./pass)
				80–108kips			
4 axles	95,650	71	23,940	35	0.226	0.604	2.117
5 axles	92,651	162	18,530	22	0.006	0.015	0.053
6 axles	100,845	132	16,808	23	0.012	0.033	0.114
7 or more axles	99,948	128	15,739	22	0.006	0.015	0.053
Weighted average					0.022	0.060	0.211
				108–150kips			
4 axles	117,556	61	26,239	41	1.385	3.707	12.992
5 axles	118,893	93	23,779	34	0.189	0.507	1.777
6 axles	120,672	128	20,110	28	0.055	0.146	0.512
7 axles	128,996	116	18,428	27	0.044	0.117	0.409
8 axles	139,692	112	17,461	28	0.055	0.146	0.512
9 and more axles	130,472	120	18,206	27	0.044	0.117	0.409
Weighted average					0.062	0.167	0.584
				150–200kips			
7 axles	154,627	111	22,086	33	0.159	0.425	1.489
8 axles	161,226	105	20,132	32	0.133	0.355	1.244
9 axles	172,992	122	19,221	30	0.089	0.239	0.839
10 axles	188,433	126	18,843	31	0.110	0.296	1.036
11 axles	189,618	128	17,238	29	0.071	0.190	0.665
12 and more axles	193,318	120	14,425	26	0.035	0.095	0.332
Weighted average					0.113	0.302	1.060
				>200kips			
11 axles	216,333	127	19,667	33	0.159	0.425	1.489
12 axles	238,000	113	19,833	35	0.226	0.604	2.117
13 axles	241,986	127	18,616	33	0.159	0.425	1.489
14 axles	290,800	106	20,771	39	0.602	1.611	5.646
15 and more axles	417,174	106	23,122	47	2.241	6.723	22.411
Weighted average					0.846	2.488	8.362

TABLE 12.15
Cost of Prestressed Concrete Bridge Damage due to Overweight Trucks, Disaggregate Approach, 25% Load Share, 0–20 Years Age Group, Option 2

Truck Description	Average GVW (lbs)	Average Spacing (in)	Average Axle Load (lbs)	Equivalent Load (HS)	Interstate Bridge Damage Cost (2010$/ft./pass)	NHS-NI Bridge Damage Cost (2010$/ft./pass)	NNHS Bridge Damage Cost (2010$/ft./pass)
80–108kips							
4 axles	95,650	71	23,940	35	0.222	0.592	2.078
5 axles	92,651	162	18,530	22	0.002	0.003	0.014
6 axles	100,845	132	16,808	23	0.008	0.021	0.075
7 or more axles	99,948	128	15,739	22	0.002	0.003	0.014
Weighted average					0.019	0.048	0.171
108–150kips							
4 axles	117,556	61	26,239	41	1.381	3.696	12.953
5 axles	118,893	93	23,779	34	0.185	0.495	1.738
6 axles	120,672	128	20,110	28	0.051	0.134	0.472
7 axles	128,996	116	18,428	27	0.040	0.105	0.370
8 axles	139,692	112	17,461	28	0.051	0.134	0.472
9 and more axles	130,472	120	18,206	27	0.040	0.105	0.370
Weighted average					0.058	0.155	0.544
150–200kips							
7 axles	154,627	111	22,086	33	0.155	0.413	1.413
8 axles	161,226	105	20,132	32	0.129	0.343	1.173
9 axles	172,992	122	19,221	30	0.085	0.227	0.779
10 axles	188,433	126	18,843	31	0.106	0.284	0.971
11 axles	189,618	128	17,238	29	0.067	0.178	0.610
12 and more axles	193,318	120	14,425	26	0.031	0.083	0.286
Weighted average					0.109	0.291	0.994
>200kips							
11 axles	216,333	127	19,667	33	0.155	0.413	1.413
12 axles	238,000	113	19,833	35	0.222	0.592	2.024
13 axles	241,986	127	18,616	33	0.155	0.413	1.413
14 axles	290,800	106	20,771	39	0.598	1.599	5.462
15 and more axles	417,174	106	23,122	47	2.237	6.711	22.362
Weighted average					0.842	2.476	8.284

TABLE 12.16
Cost of Concrete Bridge Damage due to Overweight Trucks, Disaggregate Approach, 25% Load Share, 0–20 Years Age Group, Option 1

Truck Description	Average GVW (lbs)	Average Spacing (in)	Average Axle Load (lbs)	Equivalent Load (HS)	Interstate Bridge Damage Cost (2010$/ft./pass)	NHS-NI Bridge Damage Cost (2010$/ft./pass)	NNHS Bridge Damage Cost (2010$/ft./pass)
80–108kips							
4 axles	95,650	71	23,940	35	0.218	0.583	2.043
5 axles	92,651	162	18,530	22	0.005	0.015	0.051
6 axles	100,845	132	16,808	23	0.012	0.031	0.110
7 or more axles	99,948	128	15,739	22	0.005	0.015	0.051
Weighted average					0.022	0.058	0.203
108–150kips							
4 axles	117,556	61	26,239	41	1.336	3.577	12.536
5 axles	118,893	93	23,779	34	0.183	0.489	1.715
6 axles	120,672	128	20,110	28	0.053	0.141	0.494
7 axles	128,996	116	18,428	27	0.042	0.113	0.395
8 axles	139,692	112	17,461	28	0.053	0.141	0.494
9 and more axles	130,472	120	18,206	27	0.042	0.113	0.395
Weighted average					0.060	0.161	0.563
150–200kips							
7 axles	154,627	111	22,086	33	0.153	0.410	1.437
8 axles	161,226	105	20,132	32	0.128	0.342	1.200
9 axles	172,992	122	19,221	30	0.086	0.231	0.809
10 axles	188,433	126	18,843	31	0.107	0.285	0.999
11 axles	189,618	128	17,238	29	0.068	0.183	0.642
12 and more axles	193,318	120	14,425	26	0.034	0.091	0.321
Weighted average					0.109	0.292	1.022
>200kips							
11 axles	216,333	127	19,667	33	0.153	0.410	1.437
12 axles	238,000	113	19,833	35	0.218	0.583	2.043
13 axles	241,986	127	18,616	33	0.153	0.410	1.437
14 axles	290,800	106	20,771	39	0.581	1.555	5.448
15 and more axles	417,174	106	23,122	47	2.241	6.722	22.407
Weighted average					0.840	2.474	8.311

TABLE 12.17
Cost of Concrete Bridge Damage due to Overweight Trucks, Disaggregate Approach, 25% Load Share, 0–20 Years Age Group, Option 2

Truck Description	Average GVW (lbs)	Average Spacing (in)	Average Axle Load (lbs)	Equivalent Load (HS)	Interstate Bridge Damage Cost (2010$/ft./pass)	NHS-NI Bridge Damage Cost (2010$/ft./pass)	NNHS Bridge Damage Cost (2010$/ft./pass)
80–108kips							
4 axles	95,650	71	23,940	35	0.214	0.572	2.005
5 axles	92,651	162	18,530	22	0.002	0.003	0.014
6 axles	100,845	132	16,808	23	0.008	0.020	0.072
7 or more axles	99,948	128	15,739	22	0.002	0.003	0.014
Weighted average					0.018	0.047	0.166
108–150kips							
4 axles	117,556	61	26,239	41	1.333	3.566	12.498
5 axles	118,893	93	23,779	34	0.179	0.478	1.677
6 axles	120,672	128	20,110	28	0.049	0.130	0.456
7 axles	128,996	116	18,428	27	0.038	0.101	0.357
8 axles	139,692	112	17,461	28	0.049	0.130	0.456
9 and more axles	130,472	120	18,206	27	0.038	0.101	0.357
Weighted average					0.056	0.149	0.525
150–200kips							
7 axles	154,627	111	22,086	33	0.149	0.399	1.399
8 axles	161,226	105	20,132	32	0.124	0.331	1.162
9 axles	172,992	122	19,221	30	0.082	0.220	0.771
10 axles	188,433	126	18,843	31	0.103	0.274	0.962
11 axles	189,618	128	17,238	29	0.065	0.172	0.604
12 and more axles	193,318	120	14,425	26	0.030	0.080	0.283
Weighted average					0.105	0.280	0.985
>200kips							
11 axles	216,333	127	19,667	33	0.149	0.399	1.399
12 axles	238,000	113	19,833	35	0.214	0.572	2.005
13 axles	241,986	127	18,616	33	0.149	0.399	1.399
14 axles	290,800	106	20,771	39	0.577	1.543	5.410
15 and more axles	417,174	106	23,122	47	2.237	2.244	22.369
Weighted average					0.836	1.076	8.274

TABLE 12.18
Cost of Bridge Damage due to Overweight Trucks, Semi-disaggregate Approach, 25% Load Share, Option 1

Truck Description	Average GVW (lbs)	Average Spacing (in)	Average Axle Load (lbs)	Equivalent Load (HS)	Interstate Bridge Damage Cost (2010$/ft./pass)	NHS-NI Bridge Damage Cost (2010$/ft./pass)	NNHS Bridge Damage Cost (2010$/ ft./pass)
80–108kips							
4 axles	95,650	71	23,940	35	0.224	0.605	2.123
5 axles	92,651	162	18,530	22	0.006	0.015	0.053
6 axles	100,845	132	16,808	23	0.012	0.033	0.114
7 or more axles	99,948	128	15,739	22	0.224	0.605	2.123
Weighted average					0.065	0.175	0.614
108–150kips							
4 axles	117,556	61	26,239	41	1.373	3.710	13.029
5 axles	118,893	93	23,779	34	0.188	0.507	1.782
6 axles	120,672	128	20,110	28	0.054	0.146	0.513
7 axles	128,996	116	18,428	27	0.043	0.117	0.410
8 axles	139,692	112	17,461	28	0.054	0.146	0.513
9 and more axles	130,472	120	18,206	27	0.043	0.117	0.410
Weighted average					0.062	0.167	0.585
150–200kips							
7 axles	154,627	111	22,086	33	0.157	0.425	1.494
8 axles	161,226	105	20,132	32	0.131	0.355	1.247
9 axles	172,992	122	19,221	30	0.089	0.239	0.841
10 axles	188,433	126	18,843	31	0.109	0.296	1.039
11 axles	189,618	128	17,238	29	0.070	0.190	0.667
12 and more axles	193,318	120	14,425	26	0.035	0.095	0.333
Weighted average					0.112	0.303	1.063
>200kips							
11 axles	216,333	127	19,667	33	0.157	0.425	1.494
12 axles	238,000	113	19,833	35	0.224	0.605	2.123
13 axles	241,986	127	18,616	33	0.157	0.425	1.494
14 axles	290,800	106	20,771	39	0.596	1.612	5.662
15 and more axles	417,174	106	23,122	47	2.241	6.724	22.417
Weighted average					0.844	2.489	8.368

TABLE 12.19
Cost of Bridge Damage due to Overweight Trucks, Semi-disaggregate Approach, 25% Load Share, Option 2

Truck Description	Average GVW (lbs)	Average Spacing (in)	Average Axle Load (lbs)	Equivalent Load (HS)	Interstate Bridge Damage Cost (2010$/ft./pass)	NHS-NI Bridge Damage Cost (2010$/ft./pass)	NNHS Bridge Damage Cost (2010$/ft./pass)
			80–108kips				
4 axles	95,650	71	23,940	35	0.220	0.591	2.092
5 axles	92,651	162	18,530	22	0.002	0.003	0.014
6 axles	100,845	132	16,808	23	0.008	0.021	0.075
7 or more axles	99,948	128	15,739	22	0.220	0.591	2.092
Weighted average					0.061	0.163	0.577
			108–150kips				
4 axles	117,556	61	26,239	41	1.373	3.690	13.040
5 axles	118,893	93	23,779	34	0.184	0.495	1.749
6 axles	120,672	128	20,110	28	0.050	0.134	0.475
7 axles	128,996	116	18,428	27	0.039	0.105	0.372
8 axles	139,692	112	17,461	28	0.050	0.134	0.475
9 and more axles	130,472	120	18,206	27	0.039	0.105	0.372
Weighted average					0.058	0.154	0.548
			150–200kips				
7 axles	154,627	111	22,086	33	0.154	0.413	1.459
8 axles	161,226	105	20,132	32	0.128	0.343	1.212
9 axles	172,992	122	19,221	30	0.085	0.227	0.804
10 axles	188,433	126	18,843	31	0.106	0.283	1.003
11 axles	189,618	128	17,238	29	0.067	0.178	0.630
12 and more axles	193,318	120	14,425	26	0.031	0.083	0.295
Weighted average					0.108	0.290	1.027
			>200kips				
11 axles	216,333	127	19,667	33	0.154	0.413	1.459
12 axles	238,000	113	19,833	35	0.220	0.591	2.092
13 axles	241,986	127	18,616	33	0.154	0.413	1.459
14 axles	290,800	106	20,771	39	0.594	1.597	5.644
15 and more axles	417,174	106	23,122	47	2.237	6.712	22.377
Weighted average					0.841	2.476	8.334

TABLE 12.20
Cost of Bridge Damage due to Overweight Trucks, Aggregate Approach, 25% Load Share, Option 1

Truck Description	% of Volume	Average GVW (lbs)	Average Spacing (in)	Average Axle Load (lbs)	Equivalent Load (HS)	Option 1: Total Truck Weight Bridge Damage Cost (2010$/mi)	Option 2: Excess Truck Weight Bridge Damage Cost (2010$/mi)
				80–108kips			
4 axles	2.58	95,650	71	23,940	35	92.372	90.859
5 axles	12.71	92,651	162	18,530	22	2.326	0.594
6 axles	17.32	100,845	132	16,808	23	4.980	3.255
7 or more axles	7.88	99,948	128	15,739	22	2.326	0.594
Weighted average						9.196	7.482
				108–150kips			
4 axles	0.40	117,556	61	26,239	41	566.831	566.473
5 axles	0.62	118,893	93	23,779	34	77.534	75.986
6 axles	18.83	120,672	128	20,110	28	22.330	20.647
7 axles	17.87	128,996	116	18,428	27	17.856	16.162
8 axles	3.72	139,692	112	17,461	28	22.330	20.647
9 and more axles	5.71	130,472	120	18,206	27	17.856	16.162
Weighted average						25.464	23.789
				150–200kips			
7 axles	2.91	154,627	111	22,086	33	64.974	63.395
8 axles	1.71	161,226	105	20,132	32	54.260	52.655
9 axles	0.48	172,992	122	19,221	30	36.584	34.936
10 axles	0.27	188,433	126	18,843	31	45.187	43.559
11 axles	0.29	189,618	128	17,238	29	29.012	27.345
12 and more axles	1.24	193,318	120	14,425	26	14.498	12.797
Weighted average						48.995	47.377
				>200kips			
11 axles	0.92	216,333	127	19,667	33	64.974	63.395
12 axles	0.26	238,000	113	19,833	35	92.372	90.859
13 axles	0.15	241,986	127	18,616	33	64.974	63.395
14 axles	0.16	290,800	106	20,771	39	246.331	245.193
15 and more axles	0.67	417,174	106	23,122	47	980.262	978.503
Weighted average						365.607	364.012

TABLE 12.21
Cost of Steel Bridge Damage due to Overweight Trucks, Disaggregate Approach, 85% Load Share, Option 1

Truck Description	Average GVW (lbs)	Average Spacing (in)	Average Axle Load (lbs)	Equivalent Load (HS)	Interstate Bridge Damage Cost (2010$/ft./pass)	NHS-NI Bridge Damage Cost (2010$/ft./pass)	NNHS Bridge Damage Cost (2010$/ft./pass)
				80–108kips			
4 axles	95,650	71	23,940	35	0.748	2.001	7.013
5 axles	92,651	162	18,530	22	0.019	0.050	0.177
6 axles	100,845	132	16,808	23	0.040	0.108	0.378
7 or more axles	99,948	128	15,739	22	0.019	0.050	0.177
Weighted average					0.074	0.199	0.698
				108–150kips			
4 axles	117,556	61	26,239	41	4.587	12.279	43.032
5 axles	118,893	93	23,779	34	0.627	1.680	5.886
6 axles	120,672	128	20,110	28	0.181	0.484	1.695
7 axles	128,996	116	18,428	27	0.145	0.387	1.356
8 axles	139,692	112	17,461	28	0.181	0.484	1.695
9 and more axles	130,472	120	18,206	27	0.145	0.387	1.356
Weighted average					0.206	0.552	1.933
				150–200kips			
7 axles	154,627	111	22,086	33	0.526	1.408	4.933
8 axles	161,226	105	20,132	32	0.439	1.175	4.119
9 axles	172,992	122	19,221	30	0.296	0.793	2.777
10 axles	188,433	126	18,843	31	0.366	0.979	3.430
11 axles	189,618	128	17,238	29	0.235	0.628	2.202
12 and more axles	193,318	120	14,425	26	0.117	0.314	1.101
Weighted average					0.374	1.001	3.509
				>200kips			
11 axles	216,333	127	19,667	33	0.526	1.408	4.933
12 axles	238,000	113	19,833	35	0.748	2.001	7.013
13 axles	241,986	127	18,616	33	0.526	1.408	4.933
14 axles	290,800	106	20,771	39	1.994	5.336	18.701
15 and more axles	417,174	106	23,122	47	7.616	22.848	76.160
Weighted average					2.860	8.421	28.296

TABLE 12.22
Cost of Steel Bridge Damage due to Overweight Trucks, Disaggregate Approach, 85% Load Share, 0–20 Years Age Group, Option 2

Truck Description	Average GVW (lbs)	Average Spacing (in)	Average Axle Load (lbs)	Equivalent Load (HS)	Interstate Bridge Damage Cost (2010$/ft./pass)	NHS-NI Bridge Damage Cost (2010$/ft./pass)	NNHS Bridge Damage Cost (2010$/ft./pass)
80–108kips							
4 axles	95,650	71	23,940	35	0.735	1.962	6.883
5 axles	92,651	162	18,530	22	0.006	0.011	0.047
6 axles	100,845	132	16,808	23	0.027	0.069	0.248
7 or more axles	99,948	128	15,739	22	0.006	0.011	0.047
Weighted average					0.061	0.160	0.568
108–150kips							
4 axles	117,556	61	26,239	41	4.574	12.240	42.902
5 axles	118,893	93	23,779	34	0.615	1.641	5.756
6 axles	120,672	128	20,110	28	0.168	0.445	1.565
7 axles	128,996	116	18,428	27	0.132	0.348	1.226
8 axles	139,692	112	17,461	28	0.168	0.445	1.565
9 and more axles	130,472	120	18,206	27	0.132	0.348	1.226
Weighted average					0.193	0.513	1.803
150–200kips							
7 axles	154,627	111	22,086	33	0.513	1.369	4.803
8 axles	161,226	105	20,132	32	0.426	1.137	3.989
9 axles	172,992	122	19,221	30	0.283	0.754	2.648
10 axles	188,433	126	18,843	31	0.353	0.940	3.301
11 axles	189,618	128	17,238	29	0.222	0.590	2.073
12 and more axles	193,318	120	14,425	26	0.104	0.275	0.971
Weighted average					0.361	0.963	3.380
>200kips							
11 axles	216,333	127	19,667	33	0.513	1.369	4.803
12 axles	238,000	113	19,833	35	0.735	1.962	6.883
13 axles	241,986	127	18,616	33	0.513	1.369	4.803
14 axles	290,800	106	20,771	39	1.981	5.297	18.571
15 and more axles	417,174	106	23,122	47	7.603	22.809	76.030
Weighted average					2.847	8.382	28.167

TABLE 12.23
Cost of Prestressed Concrete Bridge Damage due to Overweight Trucks, Disaggregate Approach, 85% Load Share, 0–20 Years Age Group, Option 1

Truck Description	Average GVW (lbs)	Average Spacing (in)	Average Axle Load (lbs)	Equivalent Load (HS)	Interstate Bridge Damage Cost (2010$/ft./pass)	NHS-NI Bridge Damage Cost (2010$/ft./pass)	NNHS Bridge Damage Cost (2010$/ ft./pass)
			80–108kips				
4 axles	95,650	71	23,940	35	0.767	2.054	7.199
5 axles	92,651	162	18,530	22	0.019	0.052	0.181
6 axles	100,845	132	16,808	23	0.041	0.111	0.388
7 or more axles	99,948	128	15,739	22	0.019	0.052	0.181
Weighted average					0.076	0.205	0.717
			108–150kips				
4 axles	117,556	61	26,239	41	4.709	12.605	44.174
5 axles	118,893	93	23,779	34	0.644	1.724	6.042
6 axles	120,672	128	20,110	28	0.186	0.497	1.740
7 axles	128,996	116	18,428	27	0.148	0.397	1.392
8 axles	139,692	112	17,461	28	0.186	0.497	1.740
9 and more axles	130,472	120	18,206	27	0.148	0.397	1.392
Weighted average					0.212	0.566	1.984
			150–200kips				
7 axles	154,627	111	22,086	33	0.540	1.445	5.064
8 axles	161,226	105	20,132	32	0.451	1.207	4.229
9 axles	172,992	122	19,221	30	0.304	0.814	2.851
10 axles	188,433	126	18,843	31	0.375	1.005	3.521
11 axles	189,618	128	17,238	29	0.241	0.645	2.261
12 and more axles	193,318	120	14,425	26	0.120	0.322	1.130
Weighted average					0.384	1.028	3.603
			>200kips				
11 axles	216,333	127	19,667	33	0.540	1.445	5.064
12 axles	238,000	113	19,833	35	0.767	2.054	7.199
13 axles	241,986	127	18,616	33	0.540	1.445	5.064
14 axles	290,800	106	20,771	39	2.046	5.478	19.197
15 and more axles	417,174	106	23,122	47	7.620	22.858	76.196
Weighted average					2.875	8.459	28.431

TABLE 12.24
Cost of Prestressed Concrete Bridge Damage due to Overweight Trucks, Disaggregate Approach, 85% Load Share, 0–20 Years Age Group, Option 2

Truck Description	Average GVW (lbs)	Average Spacing (in)	Average Axle Load (lbs)	Equivalent Load (HS)	Interstate Bridge Damage Cost (2010$/ft./pass)	NHS-NI Bridge Damage Cost (2010$/ft./pass)	NNHS Bridge Damage Cost (2010$/ft./pass)
			80–108kips				
4 axles	95,650	71	23,940	35	0.754	2.014	7.064
5 axles	92,651	162	18,530	22	0.006	0.011	0.047
6 axles	100,845	132	16,808	23	0.028	0.070	0.254
7 or more axles	99,948	128	15,739	22	0.006	0.011	0.047
Weighted average					0.063	0.164	0.582
			108–150kips				
4 axles	117,556	61	26,239	41	4.696	12.565	44.040
5 axles	118,893	93	23,779	34	0.631	1.684	5.908
6 axles	120,672	128	20,110	28	0.172	0.456	1.606
7 axles	128,996	116	18,428	27	0.135	0.357	1.257
8 axles	139,692	112	17,461	28	0.172	0.456	1.606
9 and more axles	130,472	120	18,206	27	0.135	0.357	1.257
Weighted average					0.198	0.526	1.850
			150–200kips				
7 axles	154,627	111	22,086	33	0.526	1.405	4.803
8 axles	161,226	105	20,132	32	0.437	1.166	3.989
9 axles	172,992	122	19,221	30	0.290	0.773	2.648
10 axles	188,433	126	18,843	31	0.362	0.965	3.301
11 axles	189,618	128	17,238	29	0.228	0.605	2.073
12 and more axles	193,318	120	14,425	26	0.107	0.282	0.971
Weighted average					0.371	0.988	3.380
			>200kips				
11 axles	216,333	127	19,667	33	0.526	1.405	4.803
12 axles	238,000	113	19,833	35	0.754	2.014	6.883
13 axles	241,986	127	18,616	33	0.526	1.405	4.803
14 axles	290,800	106	20,771	39	2.033	5.438	18.571
15 and more axles	417,174	106	23,122	47	7.606	22.818	76.030
Weighted average					**2.861**	**8.419**	**28.167**

TABLE 12.25
Cost of Concrete Bridge Damage due to Overweight Trucks, Disaggregate Approach, 85% Load Share, 0–20 Years Age Group, Option 1

Truck Description	Average GVW (lbs)	Average Spacing (in)	Average Axle Load (lbs)	Equivalent Load (HS)	Interstate Bridge Damage Cost (2010$/ft./pass)	NHS-NI Bridge Damage Cost (2010$/ft./pass)	NNHS Bridge Damage Cost (2010$/ft./pass)
				80–108kips			
4 axles	95,650	71	23,940	35	0.740	1.982	6.946
5 axles	92,651	162	18,530	22	0.019	0.050	0.175
6 axles	100,845	132	16,808	23	0.040	0.107	0.374
7 or more axles	99,948	128	15,739	22	0.019	0.050	0.175
Weighted average					0.074	0.197	0.692
				108–150kips			
4 axles	117,556	61	26,239	41	4.544	12.162	42.621
5 axles	118,893	93	23,779	34	0.621	1.664	5.830
6 axles	120,672	128	20,110	28	0.179	0.479	1.679
7 axles	128,996	116	18,428	27	0.143	0.383	1.343
8 axles	139,692	112	17,461	28	0.179	0.479	1.679
9 and more axles	130,472	120	18,206	27	0.143	0.383	1.343
Weighted average					0.204	0.546	1.915
				150–200kips			
7 axles	154,627	111	22,086	33	0.521	1.394	4.886
8 axles	161,226	105	20,132	32	0.435	1.164	4.080
9 axles	172,992	122	19,221	30	0.293	0.785	2.751
10 axles	188,433	126	18,843	31	0.362	0.970	3.398
11 axles	189,618	128	17,238	29	0.233	0.622	2.181
12 and more axles	193,318	120	14,425	26	0.116	0.311	1.090
Weighted average					0.371	0.992	3.476
				>200kips			
11 axles	216,333	127	19,667	33	0.521	1.394	4.886
12 axles	238,000	113	19,833	35	0.740	1.982	6.946
13 axles	241,986	127	18,616	33	0.521	1.394	4.886
14 axles	290,800	106	20,771	39	1.975	5.285	18.522
15 and more axles	417,174	106	23,122	47	7.618	22.855	76.183

TABLE 12.26
Cost of Concrete Bridge Damage due to Overweight Trucks, Disaggregate Approach, 85% Load Share, 0–20 Years Age Group, Option 2

Truck Description	Average GVW (lbs)	Average Spacing (in)	Average Axle Load (lbs)	Equivalent Load (HS)	Interstate Bridge Damage Cost (2010$/ft./pass)	NHS-NI Bridge Damage Cost (2010$/ft./pass)	NNHS Bridge Damage Cost (2010$/ ft./pass)
			80–108kips				
4 axles	95,650	71	23,940	35	0.728	1.944	6.818
5 axles	92,651	162	18,530	22	0.006	0.011	0.047
6 axles	100,845	132	16,808	23	0.027	0.068	0.246
7 or more axles	99,948	128	15,739	22	0.006	0.011	0.047
Weighted average					0.061	0.159	0.563
			108–150kips				
4 axles	117,556	61	26,239	41	4.531	12.124	42.493
5 axles	118,893	93	23,779	34	0.609	1.625	5.702
6 axles	120,672	128	20,110	28	0.166	0.441	1.551
7 axles	128,996	116	18,428	27	0.130	0.345	1.215
8 axles	139,692	112	17,461	28	0.166	0.441	1.551
9 and more axles	130,472	120	18,206	27	0.130	0.345	1.215
Weighted average					0.191	0.508	1.787
			150–200kips				
7 axles	154,627	111	22,086	33	0.508	1.356	4.757
8 axles	161,226	105	20,132	32	0.422	1.126	3.952
9 axles	172,992	122	19,221	30	0.280	0.747	2.623
10 axles	188,433	126	18,843	31	0.349	0.931	3.270
11 axles	189,618	128	17,238	29	0.220	0.584	2.053
12 and more axles	193,318	120	14,425	26	0.103	0.273	0.962
Weighted average					0.358	0.953	3.348
			>200kips				
11 axles	216,333	127	19,667	33	0.508	1.356	4.757
12 axles	238,000	113	19,833	35	0.728	1.944	6.818
13 axles	241,986	127	18,616	33	0.508	1.356	4.757
14 axles	290,800	106	20,771	39	1.962	5.247	18.394
15 and more axles	417,174	106	23,122	47	7.606	7.629	76.055
Weighted average					2.844	3.658	28.131

TABLE 12.27
Cost of Bridge Damage due to Overweight Trucks, Semi-aggregate Approach, 85% Load Share, Option 1

Truck Description	Average GVW (lbs)	Average Spacing (in)	Average Axle Load (lbs)	Equivalent Load (HS)	Interstate Bridge Damage Cost (2010$/ft./pass)	NHS-NI Bridge Damage Cost (2010$/ft./pass)	NNHS Bridge Damage Cost (2010$/ ft./pass)
80–108kips							
4 axles	95,650	71	23,940	35	0.760	2.056	7.219
5 axles	92,651	162	18,530	22	0.019	0.052	0.182
6 axles	100,845	132	16,808	23	0.041	0.111	0.389
7 or more axles	99,948	128	15,739	22	0.760	2.056	7.219
Weighted average					0.220	0.595	2.089
108–150kips							
4 axles	117,556	61	26,239	41	4.667	12.614	44.299
5 axles	118,893	93	23,779	34	0.638	1.725	6.060
6 axles	120,672	128	20,110	28	0.184	0.497	1.745
7 axles	128,996	116	18,428	27	0.147	0.397	1.395
8 axles	139,692	112	17,461	28	0.184	0.497	1.745
9 and more axles	130,472	120	18,206	27	0.147	0.397	1.395
Weighted average					0.210	0.567	1.990
150–200kips							
7 axles	154,627	111	22,086	33	0.535	1.446	5.078
8 axles	161,226	105	20,132	32	0.447	1.207	4.241
9 axles	172,992	122	19,221	30	0.301	0.814	2.859
10 axles	188,433	126	18,843	31	0.372	1.006	3.531
11 axles	189,618	128	17,238	29	0.239	0.646	2.267
12 and more axles	193,318	120	14,425	26	0.119	0.323	1.133
Weighted average					0.381	1.029	3.613
>200kips							
11 axles	216,333	127	19,667	33	0.535	1.446	5.078
12 axles	238,000	113	19,833	35	0.760	2.056	7.219
13 axles	241,986	127	18,616	33	0.535	1.446	5.078
14 axles	290,800	106	20,771	39	2.028	5.482	19.251
15 and more axles	417,174	106	23,122	47	7.619	22.862	76.217
Weighted average					2.870	8.461	28.451

TABLE 12.28
Cost of Bridge Damage due to OW Trucks, Semi-aggregate Approach, 85% Load Share, Option 2

Truck Description	Average GVW (lbs)	Average Spacing (in)	Average Axle Load (lbs)	Equivalent Load (HS)	Interstate Bridge Damage Cost (2010$/ft./pass)	NHS-NI Bridge Damage Cost (2010$/ft./pass)	NNHS Bridge Damage Cost (2010$/ ft./pass)
				80–108kips			
4 axles	95,650	71	23,940	35	0.749	2.011	7.111
5 axles	92,651	162	18,530	22	0.006	0.011	0.047
6 axles	100,845	132	16,808	23	0.028	0.070	0.255
7 or more axles	99,948	128	15,739	22	0.749	2.011	7.111
Weighted average					0.207	0.553	1.961
				108–150kips			
4 axles	117,556	61	26,239	41	4.667	12.546	44.335
5 axles	118,893	93	23,779	34	0.627	1.681	5.947
6 axles	120,672	128	20,110	28	0.171	0.456	1.616
7 axles	128,996	116	18,428	27	0.134	0.356	1.265
8 axles	139,692	112	17,461	28	0.171	0.456	1.616
9 and more axles	130,472	120	18,206	27	0.134	0.356	1.265
Weighted average					0.197	0.525	1.862
				150–200kips			
7 axles	154,627	111	22,086	33	0.523	1.403	4.962
8 axles	161,226	105	20,132	32	0.435	1.165	4.121
9 axles	172,992	122	19,221	30	0.289	0.772	2.734
10 axles	188,433	126	18,843	31	0.360	0.963	3.409
11 axles	189,618	128	17,238	29	0.226	0.604	2.140
12 and more axles	193,318	120	14,425	26	0.106	0.282	1.002
Weighted average					0.368	0.986	3.491
				>200kips			
11 axles	216,333	127	19,667	33	0.523	1.403	4.962
12 axles	238,000	113	19,833	35	0.749	2.011	7.111
13 axles	241,986	127	18,616	33	0.523	1.403	4.962
14 axles	290,800	106	20,771	39	2.021	5.429	19.190
15 and more axles	417,174	106	23,122	47	7.606	22.820	76.082
Weighted average					2.858	8.417	28.334

TABLE 12.29
Cost of Bridge Damage due to OW Trucks, Aggregate Approach, 85% Load Share

Truck Description	% of Volume	Average GVW (lbs)	Average Spacing (in)	Average Axle Load (lbs)	Equivalent Load (HS)	Option 1: Total Truck Weight Bridge Damage Cost (2010$/mi)	Option 2: Excess Truck Weight Bridge Damage Cost (2010$/mi)
80–108kips							
4 axles	2.58	95,650	71	23,940	35	314.063	308.921
5 axles	12.71	92,651	162	18,530	22	7.907	2.020
6 axles	17.32	100,845	132	16,808	23	16.932	11.067
7 or more axles	7.88	99,948	128	15,739	22	7.907	2.020
Weighted average						31.268	25.438
108–150kips							
4 axles	0.40	117,556	61	26,239	41	1927.226	1926.008
5 axles	0.62	118,893	93	23,779	34	263.617	258.351
6 axles	18.83	120,672	128	20,110	28	75.923	70.201
7 axles	17.87	128,996	116	18,428	27	60.709	54.951
8 axles	3.72	139,692	112	17,461	28	75.923	70.201
9 and more axles	5.71	130,472	120	18,206	27	60.709	54.951
Weighted average						86.579	80.883
150–200kips							
7 axles	2.91	154,627	111	22,086	33	220.913	215.544
8 axles	1.71	161,226	105	20,132	32	184.483	179.026
9 axles	0.48	172,992	122	19,221	30	124.385	118.782
10 axles	0.27	188,433	126	18,843	31	153.635	148.102
11 axles	0.29	189,618	128	17,238	29	98.640	92.973
12 and more axles	1.24	193,318	120	14,425	26	49.295	43.508
Weighted average						166.585	161.083
>200kips							
11 axles	0.92	216,333	127	19,667	33	220.913	215.544
12 axles	0.26	238,000	113	19,833	35	314.063	308.921
13 axles	0.15	241,986	127	18,616	33	220.913	215.544
14 axles	0.16	290,800	106	20,771	39	837.526	833.657
15 and more axles	0.67	417,174	106	23,122	47	3332.891	3326.910
Weighted average						1243.064	1237.642

given the paucity of past studies on the load and non-load split of bridge damage, no specific split was used; instead, the results were presented for each of three scenarios regarding the split: 100%–0%; 85%–15%; and 25%–75%. This was done for each of the three levels of analysis aggregation and each of the three bridge material types.

13. SUMMARY AND CONCLUSIONS

13.1 Summary

The present study investigated the costs of bridge damage due to overweight trucks. A truck is considered to be overweight when it has a GVW above the legal limit of 80,000 lbs. The damage it causes can be considered as a function of its axle spacing and number of axles. As such, the FHWA vehicle classes were correlated to AASHTO's vehicle classes (which are a better reflection of damage potential). This was done on the basis of the modified equivalent vehicle (MEV) model developed in this study. Then life-cycle cost analysis was used to estimate the bridge life-cycle cost for each bridge family. The bridge damage cost due to overweight trucks was estimated using the incremental cost approach that estimates the cost of bridge damage to vehicle classes based on their configurations and their average frequency of using the bridge. VMT was used as the cost allocator because it could represent the frequency of usage of the bridge, for each vehicle class.

For the damage cost estimation purposes, the bridges in this study were considered to be designed in a repetitive manner based on the highest vehicle load available. Incremental designs were performed and cost functions were developed based on the AASHTO design vehicles. Each FHWA vehicle weight group was classified into an equivalent AASHTO loading using the modified equivalent vehicle model, which is based on GVW, axle loading, and axle spacing. The results were used to incrementally assign bridge damage costs to each vehicle class.

The studied bridges were classified by material type: steel, prestressed concrete, or concrete. Each bridge material type was also sub-classified into four different age groups: 0 to 20 years, 21 to 35 years, 36 to 55 years, and 56 to 70 years.

Life-cycle cost analysis was used to estimate the full bridge cost. Allocating expenditures based on individual bridge projects activities (bridge replacement, deck rehabilitation, and deck replacement) was considered unsuitable for the present study because doing so fails to mimic the entire schedule of bridge maintenance, rehabilitation, and replacement strategies from a practical standpoint. Furthermore, bridges are designed for continual replacement/reconstruction after several decades, to perpetuity; hence, using individual activity expenditure could result in under estimating or overestimating the true cost of bridge activities over its life cycle.

The present study pertains to overweight trucks. Thus, the results presented do not pertain to truck weights 80,000 lbs or lower. The total cost allocated to a vehicle class was calculated as the sum of its cost responsibilities; and the bridge damage cost per overweight vehicle class was computed as the cost responsibility divided by the average truck volume that typically uses the bridge.

The bridge damage cost in the present study was estimated for two alternative permit fee options. Option 1 is for the damage caused by the entire load of an overweight vehicle; in other words, a vehicle with GVW exceeding 80,000 lbs. Option 2 is for the damage caused by the overweight portion only of an overweight vehicle.

In order to issue a permit that is efficient, effective, and equitable, considerations must be given to the full information on the bridges (material type, age, and dimensions) and overweight truck (GVW and axle configurations). Three approaches were considered: disaggregate, semi-disaggregate, and aggregate. The merits and demerits for each approach were also discussed. In the disaggregate approach, the bridge damage cost for each overweight truck was computed based on complete information available on the bridges and the overweight trucks. In the semi-disaggregate approach, the bridge damage cost was computed at the highway class level; and in the aggregate approach, the bridge damage cost was charged for every mile of highway driven by an overweight vehicle.

13.2 Conclusions

From the results of this study, approximately 22.7% of the total bridge cost was found to be attributable to overweight trucks. Furthermore, bridge damage cost was shown to be a function not only of GVW, but also of all three of the vehicle variables GVW, axle spacing, and axle loads. Adopting a permit structure based on GVW therefore would result in some vehicles significantly underpaying. It should be noted that on the basis of the results, all overweight trucks are currently underpaying their bridge damage cost.

Three approaches for determining the damage cost were developed in this study and any one of the three can be implemented where the requisite data are available. Of the three approaches, implementation of the disaggregate approach (for setting the permit fee) appears to be the most efficient, effective, and equitable. Adopting this approach will require the development of a software capable of incorporating the required information to facilitate the issuance of permits. Although the development of the software is the best way to implement the approach, it may take a number of years for that to be completed. In the short term (one to three years), the aggregate approach bridge damage cost can be considered and implemented based on the GVW and axle configurations. The bridge damage costs were estimated for two scenarios based on load and non-load share of bridge cost. The scenarios were considered due to the unavailability of load/non-load splits from past studies.

13.3 Future Work

This study provides a robust framework for estimating bridge damage cost due to overweight trucks. In the course of the study, an assumption regarding the load and non-load split was made. This could be verified or refined in future research. Such a study can illuminate further the issues regarding the nature of bridge deterioration in response to heavy traffic loads and the environment, as well as any interactions therein, and thus could introduce further equity in the bridge damage cost estimation process and permit fees for overweight trucks.

Description	Truck Weight (lbs)	Number of Axles	Maximum Moment (KNm)	Maximum Shear(KN)
Tractor-Trailer	90,000	6	714	239.17
Tractor-Trailer	100,000	10	690	214.00
Tractor-Trailer	110,000	13	707	188.24
Tractor-Trailer	120,000	13	787	228.49
Tractor-Trailer	123,000	9	947	284.10
Tractor-Trailer	140,000	9	1,106	290.00
Tractor-Trailer	150,000	7	1,215	396.90
Tractor-Trailer	160,000	8	1,296	362.42
Tractor-Trailer	170,000	8	1,379	413.17
Tractor-Trailer	180,000	10	973	324.65
Truck-Trailer	190,000	11	1,430	486.04
Tractor-Trailer	199,999	10	1,483	410.19
Tractor-Trailer	212,000	13	1,291	361.60
Tractor-Trailer	219,000	11	1,589	554.33
Tractor-Trailer	218,500	13	1,042	381.49
Tractor-Trailer	241,000	13	1,131	414.33
Tractor-Trailer	246,000	13	1,252	436.22
Tractor-Trailer	252,000	13	1,733	507.55
Tractor-Trailer	253,000	13	1,840	616.88
Tractor-Trailer	272,000	14	1,878	553.21
Tractor-Trailer	288,000	14	1,670	455.40
Tractor-Trailer	298,000	15	2,012	729.28
Truck	314,000	19	1,909	600.96
Tractor-Trailer	352,000	18	1,852	565.58
Tractor-Trailer	380,000	19	1,563	514.55
Tractor-Trailer	384,000	19	2,273	613.03
Tractor-Trailer	398,000	19	1,773	540.31
Tractor-Trailer	404,520	15	3,123	1042.04
Tractor-Trailer	416,000	19	1,732	577.66
Tractor-Trailer	425,520	15	2,882	743.39
Tractor-Trailer	422,700	19	1,887	586.82
Tractor-Trailer	470,000	16	2,033	731.35
Tractor-Trailer	476,100	19	2,071	725.27
Truck-Trailer	551,800	21	2,148	746.43
Self-Propelled Equipment	559,000	18	3,714	1195.88
Self-Propelled Equipment	636,000	18	4,226	1360.61
HS 20	**72,000**	**3**	**901**	**289**
HS15	**54,000**	**3**	**676**	**216**

Figure III.A.1 Computed critical moments of overweight trucks.

Category	Type	Forms	Single Trip Fee	90 Day Fee	Annual Fee
Oversize Permit	Single Trip 90 Day Annual	M-233, Permit M-233, Permit M-233, Permit	$20: up to 95' in length, 12'4" wide & legal height $30: between 96' and 110' in length, 12'5" and 16' wide or 13'7" and 15' tall $40: over 110' in length, 16' wide, 15' tall and 80,000 pounds	$100	$405
Overweight Permit	Single Trip (15 Days)	M-233, Permit	$20 + $.35 per mile for vehicles up to 108,000 lbs. *$20 + $.60 per mile for vehicles over 108,000 to 150,000 lbs. **$20 + $1.00 per mile for vehicles over 150,000 lbs.		
Oversize & Overweight Permit	Single Trip (15 Days)	M-233, Permit	Greater of the oversize or overweight fee calculated above		
Special Weight Permit	Multiple Trip (1 Day) Quarterly billing	M-233ST, Permit M-211, Registration M-219, Bond Form	$42.50		
12'4" Mobile Home Rig Permit	Single Trip (15 Days) Annual Quarterly Dealer's	M-233, Permit M-233DR, Permit	$10	$250	$1000 $40 for dealers.
14'4" Mobile Home Rig Permit	Single Trip (5) Days Quarterly Annual	M-233, Permit	$18	$500	$2000
Toll Road Gate Permit	Annual	M-233T, Permit			$20 per gate, per truck.

* Vehicles over 120,000 lbs charged $10 executive fee.
** Vehicles over 200,000 lbs charged $10 executive fee + $25 design and review fee + bridges fees.

Figure III.A.2 List of permits and fees for Indiana. (Source: (*173*).)

Highway Type	Bridge Type	Age Group (yrs)	Number	EUA Overweight Truck Volume	EUAC/Length (2010$ x 10^3/ft) for all Vehicles	EUAC/Length (2010$ x 10^3/ft) for Overweight Trucks	Cost per Length per pass for AASHTO Loadings (HS)(2010$ /ft)										
							20	21	22	23	24	25	26	27	28	29	30
Interstate	Steel	0 to 20	570	517,564	850.8	342.6	0.015	0.021	0.022	0.047	0.076	0.107	0.138	0.170	0.213	0.276	0.348
		21 to 35	374		892.0	359.2	0.016	0.022	0.023	0.050	0.080	0.112	0.145	0.178	0.223	0.290	0.365
		36 to 55	2		892.2	359.3	0.016	0.022	0.023	0.050	0.080	0.112	0.145	0.178	0.223	0.290	0.365
		56 to 70	0		961.3	387.1	0.018	0.024	0.025	0.054	0.086	0.121	0.156	0.192	0.240	0.312	0.394
	Prestressed Concrete	0 to 20	103		873.4	351.7	0.016	0.022	0.023	0.049	0.078	0.110	0.142	0.175	0.218	0.284	0.358
		21 to 35	53		910.2	366.5	0.017	0.023	0.024	0.051	0.082	0.114	0.148	0.182	0.227	0.295	0.373
		36 to 55	2		937.4	377.5	0.018	0.023	0.024	0.052	0.084	0.118	0.152	0.187	0.234	0.304	0.384
		56 to 70	0		1,017.5	409.7	0.020	0.025	0.026	0.057	0.091	0.128	0.165	0.203	0.254	0.330	0.417
	Reinforced Concrete	0 to 20	256		842.7	339.4	0.015	0.021	0.022	0.047	0.075	0.106	0.137	0.168	0.211	0.274	0.345
		21 to 35	65		874.7	352.2	0.016	0.022	0.023	0.049	0.078	0.110	0.142	0.175	0.219	0.284	0.358
		36 to 55	9		905.0	364.4	0.017	0.022	0.024	0.050	0.081	0.114	0.147	0.181	0.226	0.294	0.370
		56 to 70	0		979.2	394.3	0.019	0.024	0.025	0.055	0.088	0.123	0.159	0.196	0.245	0.318	0.401
NHS Non-Interstate	Steel	0 to 20	190	193,354	850.8	342.6	0.046	0.053	0.059	0.127	0.204	0.286	0.370	0.455	0.569	0.739	0.932
		21 to 35	175		892.0	359.2	0.049	0.055	0.062	0.133	0.214	0.300	0.387	0.477	0.597	0.775	0.977
		36 to 55	14		892.2	359.3	0.049	0.055	0.062	0.133	0.214	0.300	0.387	0.477	0.597	0.775	0.978
		56 to 70	0		961.3	387.1	0.054	0.060	0.067	0.143	0.230	0.323	0.417	0.514	0.643	0.835	1.053
	Prestressed Concrete	0 to 20	143		873.4	351.7	0.047	0.054	0.061	0.130	0.209	0.293	0.379	0.467	0.584	0.759	0.957
		21 to 35	84		910.2	366.5	0.050	0.057	0.063	0.136	0.218	0.306	0.395	0.487	0.609	0.791	0.997
		36 to 55	10		937.4	377.5	0.052	0.059	0.065	0.140	0.225	0.315	0.407	0.501	0.627	0.815	1.027
		56 to 70	0		1,017.5	409.7	0.057	0.064	0.071	0.152	0.244	0.342	0.442	0.544	0.681	0.884	1.115
	Reinforced Concrete	0 to 20	151		842.7	339.4	0.045	0.052	0.059	0.126	0.202	0.283	0.366	0.451	0.564	0.732	0.923
		21 to 35	108		874.7	352.2	0.047	0.054	0.061	0.130	0.210	0.294	0.380	0.468	0.585	0.760	0.959
		36 to 55	23		905.0	364.4	0.050	0.056	0.063	0.135	0.217	0.304	0.393	0.484	0.605	0.786	0.992
		56 to 70	13		979.2	394.3	0.055	0.061	0.068	0.146	0.235	0.329	0.425	0.524	0.655	0.851	1.073
Non-NHS Roads	Steel	0 to 20	80	55,174	850.8	342.6	0.153	0.18021	0.208	0.445	0.715	1.001	1.295	1.595	1.994	2.591	3.267
		21 to 35	107		892.0	359.2	0.163	0.190	0.218	0.466	0.749	1.050	1.358	1.672	2.091	2.716	3.425
		36 to 55	10		892.2	359.3	0.163	0.190	0.218	0.466	0.750	1.050	1.358	1.672	2.091	2.717	3.426
		56 to 70	2		961.3	387.1	0.180	0.207	0.235	0.503	0.808	1.131	1.463	1.802	2.253	2.928	3.692
	Prestressed Concrete	0 to 20	121		873.4	351.7	0.158	0.186	0.213	0.457	0.734	1.028	1.329	1.637	2.047	2.660	3.354
		21 to 35	89		910.2	366.5	0.167	0.195	0.222	0.476	0.765	1.071	1.385	1.706	2.133	2.772	3.495
		36 to 55	6		937.4	377.5	0.174	0.201	0.229	0.490	0.788	1.103	1.427	1.757	2.197	2.855	3.600
		56 to 70	0		1,017.5	409.7	0.193	0.221	0.248	0.532	0.855	1.198	1.549	1.907	2.385	3.099	3.907
	Reinforced Concrete	0 to 20	124		842.7	339.4	0.151	0.178	0.206	0.441	0.708	0.992	1.283	1.580	1.975	2.566	3.236
		21 to 35	182		874.7	352.2	0.159	0.186	0.214	0.457	0.735	1.029	1.331	1.639	2.050	2.664	3.359
		36 to 55	45		905.0	364.4	0.166	0.193	0.221	0.473	0.760	1.065	1.377	1.696	2.121	2.756	3.475
		56 to 70	17		979.2	394.3	0.184	0.212	0.239	0.512	0.823	1.152	1.490	1.835	2.295	2.982	3.760

Figure III.A.3 Bridge damage cost for HS20–HS30: option 1.

Highway Type	Bridge Type	Age Group (yrs)	Number	EUA Overweight Truck Volume	EUAC/Length (2010$ x 10^3/ft) for all Vehicles	EUAC/Length (2010$ x 10^3/ft) for Overweight Trucks	Cost per Length per pass for AASHTO Loadings (HS)(2010$ /ft)									
							31	32	33	34	35	36	37	38	39	40
Interstate	Steel	0 to 20	570	517,564	850.8	342.6	0.430	0.517	0.619	0.738	0.879	1.042	1.278	1.715	2.345	3.384
		21 to 35	374		892.0	359.2	0.451	0.542	0.649	0.774	0.922	1.093	1.340	1.798	2.459	3.548
		36 to 55	2		892.2	359.3	0.451	0.542	0.649	0.774	0.922	1.093	1.340	1.799	2.459	3.549
		56 to 70	0		961.3	387.1	0.486	0.584	0.699	0.834	0.994	1.178	1.444	1.938	2.650	3.824
	Prestressed Concrete	0 to 20	103		873.4	351.7	0.442	0.530	0.635	0.758	0.903	1.070	1.312	1.761	2.408	3.474
		21 to 35	53		910.2	366.5	0.460	0.553	0.662	0.790	0.941	1.115	1.367	1.835	2.509	3.620
		36 to 55	2		937.4	377.5	0.474	0.569	0.682	0.813	0.969	1.148	1.408	1.890	2.584	3.729
		56 to 70	0		1,017.5	409.7	0.515	0.618	0.740	0.883	1.052	1.247	1.529	2.051	2.805	4.047
	Reinforced Concrete	0 to 20	256		842.7	339.4	0.426	0.512	0.613	0.731	0.871	1.032	1.266	1.699	2.323	3.352
		21 to 35	65		874.7	352.2	0.442	0.531	0.636	0.759	0.904	1.072	1.314	1.764	2.411	3.479
		36 to 55	9		905.0	364.4	0.458	0.550	0.658	0.785	0.935	1.109	1.360	1.825	2.495	3.600
		56 to 70	0		979.2	394.3	0.495	0.595	0.712	0.850	1.012	1.200	1.471	1.974	2.699	3.895
NHS Non-Interstate	Steel	0 to 20	190	193,354	850.8	342.6	1.152	1.383	1.656	1.976	2.354	2.790	3.422	4.592	6.278	9.059
		21 to 35	175		892.0	359.2	1.207	1.450	1.736	2.072	2.468	2.925	3.587	4.814	6.582	9.497
		36 to 55	14		892.2	359.3	1.208	1.450	1.736	2.072	2.469	2.926	3.588	4.815	6.583	9.499
		56 to 70	0		961.3	387.1	1.301	1.562	1.871	2.233	2.660	3.153	3.866	5.188	7.093	10.235
	Prestressed Concrete	0 to 20	143		873.4	351.7	1.182	1.420	1.700	2.028	2.417	2.864	3.513	4.714	6.445	9.299
		21 to 35	84		910.2	366.5	1.232	1.479	1.771	2.114	2.518	2.985	3.660	4.912	6.716	9.691
		36 to 55	10		937.4	377.5	1.269	1.524	1.824	2.177	2.594	3.074	3.770	5.059	6.917	9.981
		56 to 70	0		1,017.5	409.7	1.377	1.654	1.980	2.363	2.815	3.337	4.092	5.491	7.508	10.833
	Reinforced Concrete	0 to 20	151		842.7	339.4	1.141	1.370	1.640	1.957	2.332	2.764	3.389	4.548	6.218	8.973
		21 to 35	108		874.7	352.2	1.184	1.422	1.702	2.031	2.420	2.869	3.518	4.721	6.454	9.313
		36 to 55	23		905.0	364.4	1.225	1.471	1.761	2.102	2.504	2.968	3.640	4.884	6.678	9.636
		56 to 70	13		979.2	394.3	1.325	1.591	1.906	2.274	2.709	3.211	3.938	5.284	7.225	10.425
Non-NHS Roads	Steel	0 to 20	80	55,174	850.8	342.6	4.036	4.846	5.803	6.925	8.250	9.779	11.991	16.092	22.001	31.747
		21 to 35	107		892.0	359.2	4.231	5.081	6.084	7.260	8.649	10.252	12.571	16.870	23.065	33.282
		36 to 55	10		892.2	359.3	4.232	5.081	6.085	7.261	8.651	10.254	12.573	16.873	23.069	33.288
		56 to 70	2		961.3	387.1	4.560	5.475	6.556	7.824	9.321	11.048	13.548	18.181	24.857	35.868
	Prestressed Concrete	0 to 20	121		873.4	351.7	4.143	4.975	5.957	7.109	8.469	10.038	12.309	16.519	22.585	32.589
		21 to 35	89		910.2	366.5	4.317	5.184	6.208	7.408	8.825	10.461	12.827	17.214	23.535	33.961
		36 to 55	6		937.4	377.5	4.446	5.339	6.393	7.629	9.089	10.773	13.211	17.729	24.239	34.976
		56 to 70	0		1,017.5	409.7	4.826	5.795	6.940	8.281	9.866	11.694	14.340	19.244	26.310	37.965
	Reinforced Concrete	0 to 20	124		842.7	339.4	3.997	4.800	5.748	6.859	8.171	9.685	11.877	15.938	21.791	31.444
		21 to 35	182		874.7	352.2	4.149	4.982	5.966	7.119	8.481	10.053	12.327	16.543	22.617	32.636
		36 to 55	45		905.0	364.4	4.293	5.155	6.173	7.366	8.775	10.401	12.755	17.116	23.401	33.768
		56 to 70	17		979.2	394.3	4.645	5.577	6.678	7.969	9.494	11.253	13.800	18.519	25.319	36.535

Figure III.A.4 Bridge damage cost for HS31–HS40: option 1.

Highway Type	Bridge Type	Age Group (yrs)	Number	EUA Overweight Truck Volume	EUAC/Length (2010$ x 10^3/ft) for all Vehicles	EUAC/Length (2010$ x 10^3/ft) for Overweight Trucks	Cost	Cost per Length per pass for AASHTO Loadings (HS)(2010$ /ft)								
							41	42	43	44	45	46	47	48	49	50
Interstate	Steel	0 to 20	570	517,564	850.8	342.6	5.397	5.667	5.937	6.207	6.478	7.632	8.960	10.484	12.227	14.217
		21 to 35	374		892.0	359.2	5.658	5.864	6.070	6.277	6.483	7.638	8.968	10.494	12.241	14.233
		36 to 55	2		892.2	359.3	5.659	5.865	6.071	6.277	6.483	7.638	8.968	10.494	12.241	14.234
		56 to 70	0		961.3	387.1	6.098	6.196	6.294	6.393	6.491	7.650	8.982	10.512	12.263	14.262
	Prestressed Concrete	0 to 20	103		873.4	351.7	5.540	5.775	6.010	6.245	6.480	7.635	8.965	10.490	12.235	14.226
		21 to 35	53		910.2	366.5	5.773	5.951	6.129	6.307	6.485	7.641	8.972	10.499	12.247	14.241
		36 to 55	2		937.4	377.5	5.946	6.082	6.217	6.353	6.488	7.646	8.977	10.506	12.256	14.252
		56 to 70	0		1,017.5	409.7	6.454	6.465	6.476	6.487	6.498	7.659	8.993	10.526	12.282	14.285
	Reinforced Concrete	0 to 20	256		842.7	339.4	5.345	5.629	5.912	6.196	6.479	7.634	8.963	10.488	12.232	14.223
		21 to 35	65		874.7	352.2	5.548	5.782	6.016	6.250	6.483	7.639	8.969	10.496	12.243	14.236
		36 to 55	9		905.0	364.4	5.741	5.927	6.114	6.300	6.487	7.644	8.975	10.503	12.252	14.248
		56 to 70	0		979.2	394.3	6.211	6.282	6.354	6.425	6.496	7.656	8.990	10.522	12.276	14.278
NHS Non-Interstate	Steel	0 to 20	190	193,354	850.8	342.6	14.446	15.693	16.939	18.186	19.433	22.895	26.880	31.452	36.682	42.650
		21 to 35	175		892.0	359.2	15.145	16.220	17.296	18.371	19.446	22.913	26.902	31.479	36.718	42.695
		36 to 55	14		892.2	359.3	15.148	16.222	17.297	18.372	19.446	22.913	26.902	31.480	36.718	42.695
		56 to 70	0		961.3	387.1	16.322	17.109	17.896	18.683	19.470	22.943	26.939	31.526	36.778	42.771
	Prestressed Concrete	0 to 20	143		873.4	351.7	14.830	15.982	17.135	18.288	19.440	22.905	26.892	31.467	36.702	42.675
		21 to 35	84		910.2	366.5	15.454	16.453	17.453	18.453	19.453	22.921	26.912	31.492	36.734	42.715
		36 to 55	10		937.4	377.5	15.916	16.802	17.689	18.575	19.462	22.933	26.926	31.510	36.758	42.745
		56 to 70	0		1,017.5	409.7	17.276	17.829	18.382	18.935	19.489	22.968	26.969	31.563	36.827	42.833
	Reinforced Concrete	0 to 20	151		842.7	339.4	14.308	15.591	16.873	18.155	19.437	22.902	26.888	31.462	36.695	42.666
		21 to 35	108		874.7	352.2	14.851	16.000	17.150	18.299	19.448	22.915	26.905	31.483	36.723	42.701
		36 to 55	23		905.0	364.4	15.366	16.389	17.412	18.435	19.458	22.929	26.921	31.503	36.749	42.734
		56 to 70	13		979.2	394.3	16.625	17.340	18.054	18.769	19.483	22.961	26.961	31.553	36.814	42.815
Non-NHS Roads	Steel	0 to 20	80	55,174	850.8	342.6	50.626	54.163	57.701	61.238	64.775	76.318	89.600	104.840	122.275	142.166
		21 to 35	107		892.0	359.2	53.074	56.012	58.949	61.886	64.824	76.380	89.677	104.936	122.400	142.324
		36 to 55	10		892.2	359.3	53.084	56.019	58.954	61.889	64.824	76.381	89.678	104.937	122.400	142.325
		56 to 70	2		961.3	387.1	57.198	59.125	61.052	62.979	64.905	76.486	89.807	105.099	122.611	142.590
	Prestressed Concrete	0 to 20	121		873.4	351.7	51.969	55.178	58.386	61.594	64.802	76.352	89.643	104.893	122.343	142.253
		21 to 35	89		910.2	366.5	54.157	56.829	59.501	62.173	64.845	76.408	89.711	104.979	122.455	142.394
		36 to 55	6		937.4	377.5	55.776	58.051	60.327	62.602	64.877	76.449	89.762	105.043	122.538	142.499
		56 to 70	0		1,017.5	409.7	60.542	61.649	62.757	63.864	64.971	76.571	89.913	105.230	122.782	142.806
	Reinforced Concrete	0 to 20	124		842.7	339.4	50.143	53.805	57.468	61.130	64.792	76.340	89.627	104.874	122.319	142.222
		21 to 35	182		874.7	352.2	52.045	55.241	58.437	61.634	64.830	76.388	89.687	104.949	122.416	142.345
		36 to 55	45		905.0	364.4	53.849	56.603	59.357	62.111	64.866	76.434	89.744	105.020	122.508	142.461
		56 to 70	17		979.2	394.3	58.262	59.934	61.607	63.280	64.953	76.547	89.883	105.193	122.734	142.746

Figure III.A.5 Bridge damage cost for HS41–HS50: option 1.

Highway Type	Bridge Type	Age Group (yrs)	Number	EUA Overweight Truck Volume	EUAC/Length (2010$ x 10^3/ft) for all Vehicles	EUAC/Length (2010$ x 10^3/ft) for Overweight Trucks	Cost per Length per pass for AASHTO Loadings (HS||2010$ /ft)											
							20	21	22	23	24	25	26	27	28	29	30	31
Interstate	Steel	0 to 20	569	517,564	850.8	342.6	0.000	0.006	0.007	0.032	0.061	0.091	0.123	0.155	0.197	0.261	0.333	0.415
		21 to 35	374		892.0	359.2	0.000	0.006	0.007	0.033	0.064	0.096	0.128	0.162	0.207	0.273	0.349	0.435
		36 to 55	2		892.2	359.3	0.000	0.006	0.007	0.033	0.064	0.096	0.128	0.162	0.207	0.273	0.349	0.435
		56 to 70	0		961.3	387.1	0.000	0.006	0.007	0.035	0.068	0.102	0.138	0.174	0.222	0.294	0.375	0.468
	Prestressed Concrete	0 to 20	102		873.4	351.7	0.000	0.006	0.007	0.033	0.062	0.094	0.126	0.159	0.202	0.268	0.342	0.426
		21 to 35	53		910.2	366.5	0.000	0.006	0.007	0.034	0.065	0.097	0.131	0.165	0.211	0.279	0.356	0.443
		36 to 55	2		937.4	377.5	0.000	0.006	0.007	0.035	0.066	0.100	0.135	0.170	0.217	0.287	0.366	0.456
		56 to 70	0		1,017.5	409.7	0.000	0.006	0.007	0.037	0.072	0.108	0.145	0.184	0.235	0.311	0.397	0.495
	Reinforced Concrete	0 to 20	255		842.7	339.4	0.000	0.006	0.007	0.032	0.060	0.091	0.122	0.153	0.196	0.259	0.330	0.411
		21 to 35	65		874.7	352.2	0.000	0.006	0.007	0.033	0.062	0.094	0.126	0.159	0.203	0.268	0.342	0.426
		36 to 55	9		905.0	364.4	0.000	0.006	0.007	0.034	0.064	0.097	0.130	0.164	0.209	0.277	0.354	0.441
		56 to 70	0		979.2	394.3	0.000	0.006	0.007	0.036	0.069	0.104	0.140	0.177	0.226	0.299	0.382	0.477
NHS Non-Interstate	Steel	0 to 20	188	193,354	850.8	342.6	0.000	0.007	0.013	0.081	0.158	0.240	0.324	0.409	0.523	0.694	0.887	1.106
		21 to 35	175		892.0	359.2	0.000	0.007	0.013	0.084	0.165	0.251	0.339	0.428	0.548	0.726	0.929	1.159
		36 to 55	14		892.2	359.3	0.000	0.007	0.013	0.084	0.165	0.251	0.339	0.428	0.548	0.727	0.929	1.159
		56 to 70	0		961.3	387.1	0.000	0.007	0.013	0.090	0.177	0.269	0.364	0.461	0.589	0.782	1.000	1.248
	Prestressed Concrete	0 to 20	129		873.4	351.7	0.000	0.007	0.013	0.083	0.162	0.246	0.332	0.420	0.537	0.712	0.910	1.135
		21 to 35	84		910.2	366.5	0.000	0.007	0.013	0.086	0.168	0.256	0.345	0.437	0.559	0.741	0.947	1.182
		36 to 55	10		937.4	377.5	0.000	0.007	0.013	0.088	0.173	0.263	0.355	0.450	0.575	0.763	0.975	1.217
		56 to 70	0		1,017.5	409.7	0.000	0.007	0.013	0.094	0.187	0.284	0.384	0.487	0.623	0.827	1.058	1.320
	Reinforced Concrete	0 to 20	151		842.7	339.4	0.000	0.007	0.013	0.080	0.157	0.238	0.321	0.405	0.518	0.687	0.878	1.095
		21 to 35	108		874.7	352.2	0.000	0.007	0.013	0.083	0.162	0.246	0.332	0.420	0.538	0.713	0.911	1.136
		36 to 55	23		905.0	364.4	0.000	0.007	0.013	0.085	0.167	0.254	0.343	0.434	0.556	0.737	0.942	1.175
		56 to 70	13		979.2	394.3	0.000	0.007	0.013	0.091	0.180	0.274	0.370	0.469	0.600	0.796	1.018	1.271
Non-NHS Roads	Steel	0 to 20	72	55,174	850.8	342.6	0.000	0.028	0.055	0.292	0.562	0.849	1.142	1.442	1.842	2.438	3.115	3.883
		21 to 35	107		892.0	359.2	0.000	0.028	0.055	0.304	0.587	0.887	1.195	1.509	1.928	2.554	3.263	4.068
		36 to 55	10		892.2	359.3	0.000	0.028	0.055	0.304	0.587	0.887	1.195	1.509	1.928	2.554	3.263	4.069
		56 to 70	2		961.3	387.1	0.000	0.028	0.055	0.323	0.628	0.952	1.283	1.622	2.074	2.748	3.512	4.380
	Prestressed Concrete	0 to 20	111		873.4	351.7	0.000	0.028	0.055	0.298	0.576	0.870	1.171	1.479	1.889	2.502	3.196	3.985
		21 to 35	89		910.2	366.5	0.000	0.028	0.055	0.309	0.598	0.904	1.218	1.539	1.966	2.605	3.328	4.150
		36 to 55	6		937.4	377.5	0.000	0.028	0.055	0.316	0.614	0.929	1.253	1.583	2.023	2.681	3.426	4.273
		56 to 70	0		1,017.5	409.7	0.000	0.028	0.055	0.339	0.661	1.004	1.355	1.714	2.192	2.905	3.714	4.633
	Reinforced Concrete	0 to 20	118		842.7	339.4	0.000	0.028	0.055	0.290	0.557	0.841	1.132	1.429	1.825	2.416	3.086	3.847
		21 to 35	182		874.7	352.2	0.000	0.028	0.055	0.299	0.576	0.871	1.173	1.481	1.892	2.505	3.201	3.990
		36 to 55	45		905.0	364.4	0.000	0.028	0.055	0.307	0.594	0.899	1.211	1.530	1.955	2.590	3.310	4.127
		56 to 70	17		979.2	394.3	0.000	0.028	0.055	0.328	0.639	0.968	1.306	1.651	2.111	2.798	3.576	4.460

Figure III.A.6 Bridge damage cost for HS20–HS30: option 2.

Highway Type	Bridge Type	Age Group (yrs)	Number	EUA Overweight Truck Volume	EUAC/Length (2010$ x 10^3/ft) for all Vehicles	EUAC/Length (2010$ x 10^3/ft) for Overweight Trucks	Cost per Length per pass for AASHTO Loadings (HS)(2010$ /ft)									
							31	32	33	34	35	36	37	38	39	40
Interstate	Steel	0 to 20	569	517,564	850.8	342.6	0.415	0.501	0.603	0.723	0.864	1.027	1.263	1.700	2.330	3.369
		21 to 35	374		892.0	359.2	0.435	0.525	0.632	0.758	0.906	1.077	1.324	1.782	2.442	3.532
		36 to 55	2		892.2	359.3	0.435	0.525	0.632	0.758	0.906	1.077	1.324	1.782	2.443	3.532
		56 to 70	0		961.3	387.1	0.468	0.566	0.681	0.816	0.976	1.160	1.426	1.920	2.632	3.806
	Prestressed Concrete	0 to 20	102		873.4	351.7	0.426	0.514	0.619	0.742	0.887	1.054	1.296	1.745	2.392	3.458
		21 to 35	53		910.2	366.5	0.443	0.536	0.645	0.773	0.924	1.098	1.351	1.818	2.492	3.604
		36 to 55	2		937.4	377.5	0.456	0.552	0.664	0.796	0.951	1.131	1.391	1.872	2.566	3.711
		56 to 70	0		1,017.5	409.7	0.495	0.598	0.720	0.863	1.032	1.227	1.509	2.032	2.785	4.028
	Reinforced Concrete	0 to 20	255		842.7	339.4	0.411	0.497	0.598	0.716	0.856	1.017	1.251	1.684	2.308	3.337
		21 to 35	65		874.7	352.2	0.426	0.515	0.620	0.743	0.888	1.056	1.298	1.748	2.395	3.463
		36 to 55	9		905.0	364.4	0.441	0.533	0.641	0.769	0.919	1.092	1.343	1.808	2.478	3.583
		56 to 70	0		979.2	394.3	0.477	0.576	0.693	0.831	0.994	1.181	1.452	1.956	2.681	3.876
NHS Non-Interstate	Steel	0 to 20	188	193,354	850.8	342.6	1.106	1.337	1.610	1.930	2.308	2.745	3.376	4.546	6.232	9.013
		21 to 35	175		892.0	359.2	1.159	1.401	1.687	2.023	2.419	2.877	3.539	4.765	6.533	9.448
		36 to 55	14		892.2	359.3	1.159	1.401	1.688	2.023	2.420	2.877	3.539	4.766	6.534	9.450
		56 to 70	0		961.3	387.1	1.248	1.509	1.817	2.179	2.606	3.099	3.812	5.134	7.040	10.182
	Prestressed Concrete	0 to 20	129		873.4	351.7	1.135	1.372	1.653	1.981	2.369	2.817	3.465	4.666	6.397	9.252
		21 to 35	84		910.2	366.5	1.182	1.429	1.721	2.064	2.468	2.935	3.610	4.862	6.666	9.641
		36 to 55	10		937.4	377.5	1.217	1.472	1.773	2.125	2.542	3.022	3.718	5.007	6.865	9.929
		56 to 70	0		1,017.5	409.7	1.320	1.596	1.923	2.306	2.758	3.279	4.035	5.434	7.450	10.776
	Reinforced Concrete	0 to 20	151		842.7	339.4	1.095	1.324	1.595	1.912	2.286	2.718	3.344	4.503	6.173	8.927
		21 to 35	108		874.7	352.2	1.136	1.374	1.655	1.984	2.373	2.821	3.470	4.673	6.406	9.265
		36 to 55	23		905.0	364.4	1.175	1.421	1.712	2.052	2.454	2.918	3.590	4.835	6.628	9.586
		56 to 70	13		979.2	394.3	1.271	1.537	1.851	2.219	2.655	3.156	3.883	5.230	7.170	10.371
Non-NHS Roads	Steel	0 to 20	72	55,174	850.8	342.6	3.883	4.693	5.650	6.772	8.097	9.626	11.838	15.939	21.848	31.594
		21 to 35	107		892.0	359.2	4.068	4.918	5.921	7.097	8.486	10.089	12.408	16.707	22.902	33.119
		36 to 55	10		892.2	359.3	4.069	4.919	5.922	7.098	8.488	10.091	12.411	16.710	22.906	33.126
		56 to 70	2		961.3	387.1	4.380	5.296	6.377	7.644	9.141	10.868	13.368	18.001	24.677	35.688
	Prestressed Concrete	0 to 20	111		873.4	351.7	3.985	4.817	5.799	6.950	8.311	9.880	12.151	16.361	22.426	32.431
		21 to 35	89		910.2	366.5	4.150	5.017	6.041	7.241	8.658	10.293	12.660	17.047	23.368	33.793
		36 to 55	6		937.4	377.5	4.273	5.165	6.220	7.456	8.916	10.600	13.037	17.555	24.065	34.802
		56 to 70	0		1,017.5	409.7	4.633	5.602	6.746	8.088	9.673	11.501	14.146	19.050	26.117	37.772
	Reinforced Concrete	0 to 20	118		842.7	339.4	3.847	4.649	5.597	6.708	8.021	9.535	11.726	15.787	21.640	31.293
		21 to 35	182		874.7	352.2	3.990	4.823	5.807	6.960	8.323	9.894	12.169	16.384	22.459	32.478
		36 to 55	45		905.0	364.4	4.127	4.989	6.007	7.200	8.609	10.235	12.589	16.950	23.236	33.602
		56 to 70	17		979.2	394.3	4.460	5.393	6.494	7.785	9.310	11.069	13.616	18.335	25.135	36.351

Figure III.A.7 Bridge damage cost for HS31–HS40: option 2.

Highway Type	Bridge Type	Age Group (yrs)	Number	EUA Overweight Truck Volume	EUAC/Length (2010$ x 10^3/ft) for all Vehicles	EUAC/Length (2010$ x 10^3/ft) for Overweight Trucks	Cost	Cost per Length per pass for AASHTO Loadings (HS)(2010$ /ft)								
							41	42	43	44	45	46	47	48	49	50
Interstate	Steel	0 to 20	569	517,564	850.8	342.6	5.382	5.652	5.922	6.192	6.462	7.616	8.945	10.469	12.212	14.201
		21 to 35	374		892.0	359.2	5.642	5.848	6.054	6.260	6.466	7.622	8.952	10.478	12.224	14.217
		36 to 55	2		892.2	359.3	5.643	5.849	6.055	6.260	6.466	7.622	8.952	10.478	12.225	14.217
		56 to 70	0		961.3	387.1	6.079	6.178	6.276	6.375	6.473	7.632	8.964	10.493	12.245	14.244
	Prestressed Concrete	0 to 20	102		873.4	351.7	5.524	5.759	5.994	6.229	6.465	7.620	8.949	10.474	12.219	14.210
		21 to 35	53		910.2	366.5	5.756	5.934	6.112	6.290	6.468	7.625	8.955	10.482	12.230	14.224
		36 to 55	2		937.4	377.5	5.928	6.064	6.200	6.335	6.471	7.628	8.960	10.488	12.238	14.235
		56 to 70	0		1,017.5	409.7	6.434	6.446	6.457	6.468	6.479	7.639	8.974	10.506	12.262	14.265
	Reinforced Concrete	0 to 20	255		842.7	339.4	5.330	5.614	5.897	6.181	6.464	7.619	8.948	10.473	12.217	14.207
		21 to 35	65		874.7	352.2	5.532	5.766	6.000	6.234	6.467	7.623	8.953	10.480	12.227	14.220
		36 to 55	9		905.0	364.4	5.724	5.910	6.097	6.284	6.470	7.628	8.959	10.486	12.236	14.231
		56 to 70	0		979.2	394.3	6.192	6.264	6.335	6.406	6.478	7.638	8.972	10.503	12.258	14.260
NHS Non-Interstate	Steel	0 to 20	188	193,354	850.8	342.6	14.401	15.647	16.894	18.140	19.387	22.849	26.834	31.406	36.637	42.604
		21 to 35	175		892.0	359.2	15.096	16.172	17.247	18.322	19.398	22.864	26.853	31.431	36.669	42.646
		36 to 55	14		892.2	359.3	15.099	16.174	17.248	18.323	19.398	22.865	26.853	31.431	36.670	42.646
		56 to 70	0		961.3	387.1	16.268	17.055	17.842	18.629	19.416	22.890	26.886	31.472	36.725	42.717
	Prestressed Concrete	0 to 20	129		873.4	351.7	14.782	15.935	17.088	18.240	19.393	22.858	26.845	31.420	36.655	42.627
		21 to 35	84		910.2	366.5	15.404	16.404	17.403	18.403	19.403	22.871	26.862	31.442	36.684	42.665
		36 to 55	10		937.4	377.5	15.864	16.750	17.637	18.523	19.410	22.881	26.875	31.458	36.706	42.693
		56 to 70	0		1,017.5	409.7	17.218	17.772	18.325	18.878	19.431	22.910	26.912	31.506	36.770	42.775
	Reinforced Concrete	0 to 20	151		842.7	339.4	14.263	15.545	16.828	18.110	19.392	22.856	26.843	31.416	36.650	42.620
		21 to 35	108		874.7	352.2	14.804	15.953	17.102	18.251	19.401	22.868	26.857	31.435	36.675	42.653
		36 to 55	23		905.0	364.4	15.316	16.340	17.363	18.386	19.409	22.879	26.872	31.454	36.699	42.684
		56 to 70	13		979.2	394.3	16.570	17.285	17.999	18.714	19.429	22.906	26.906	31.498	36.759	42.761
Non-NHS Roads	Steel	0 to 20	72	55,174	850.8	342.6	50.473	54.011	57.548	61.085	64.623	76.165	89.447	104.687	122.122	142.014
		21 to 35	107		892.0	359.2	52.912	55.849	58.786	61.724	64.661	76.218	89.515	104.773	122.237	142.162
		36 to 55	10		892.2	359.3	52.922	55.857	58.791	61.726	64.661	76.218	89.515	104.774	122.238	142.162
		56 to 70	2		961.3	387.1	57.019	58.945	60.872	62.799	64.726	76.306	89.628	104.919	122.431	142.411
	Prestressed Concrete	0 to 20	111		873.4	351.7	51.811	55.019	58.227	61.436	64.644	76.194	89.484	104.734	122.185	142.095
		21 to 35	89		910.2	366.5	53.989	56.662	59.334	62.006	64.678	76.241	89.544	104.812	122.288	142.227
		36 to 55	6		937.4	377.5	55.602	57.878	60.153	62.428	64.703	76.276	89.589	104.869	122.364	142.325
		56 to 70	0		1,017.5	409.7	60.349	61.456	62.563	63.671	64.778	76.378	89.719	105.037	122.589	142.613
	Reinforced Concrete	0 to 20	118		842.7	339.4	49.992	53.654	57.317	60.979	64.642	76.189	89.477	104.723	122.168	142.071
		21 to 35	182		874.7	352.2	51.886	55.082	58.279	61.475	64.671	76.230	89.529	104.790	122.257	142.186
		36 to 55	45		905.0	364.4	53.683	56.437	59.191	61.946	64.700	76.269	89.578	104.854	122.342	142.295
		56 to 70	17		979.2	394.3	58.078	59.750	61.423	63.096	64.769	76.363	89.699	105.009	122.550	142.562

Figure III.A.8 Bridge damage cost for HS41–HS50: option 2.

1	Classification	Latitude	Longitude	Year Built	Skew	Bridge Type	Structure Length (ft)	Deck Width (ft)	Highway System of Inventory Route(NHS)	Designated National Network	Year After Bridge Replacement
2	State Roads	40071341	87270607	1979	8	STEEL	345	55	1	1	3
3	State Roads	40154309	86391943	1969	33	STEEL	253	63	0	1	3
4	US Roads	39522400	84531800	2008	8	STEEL	182	124	1	1	4
5	State Roads	39014200	86554200	1982	27	STEEL	162	47	0	1	4
6	State Roads	40151173	87250283	1976	0	Prestressed concrete	211	43	1	1	4
7	State Roads	40151216	87250328	1976	0	Prestressed concrete	211	43	1	1	4
8	State Roads	40024927	86484336	1964	43	STEEL	279	48	0	1	4
9	US Roads	39453600	87050000	1959	20	STEEL	240	36	0	1	4
10	State Roads	40061200	85391200	1948	20	STEEL	440	80	0	1	4
11	State Roads	40200000	85471200	1939	0	Prestressed concrete	33	47	0	1	4
12	State Roads	40303215	86520713	1930	0	Concrete	68	27	0	1	4
13	Interstate	39524800	86161200	2007	28	Concrete	42	38	1	1	5
14	US Roads	39042758	85161459	2007	0	Concrete	105	50	0	1	5
15	State Roads	40031015	87280793	2007	0	Prestressed concrete	112	35	0	1	5
16	State Roads	38284200	86054200	2007	15	Prestressed concrete	176	44	0	1	5
17	US Roads	39531800	84533000	2007	0	Prestressed concrete	192	87	1	1	5
18	US Roads	37553200	87022600	2007	34	Prestressed concrete	223	46	1	1	5
19	State Roads	38014200	87241200	2007	29	Prestressed concrete	150	57	0	1	5
20	State Roads	38014200	87241200	2007	29	Prestressed concrete	140	45	0	1	5
21	Interstate	39520900	86161200	2007	99	Prestressed concrete	186	49	1	1	5
22	US Roads	38294800	86544700	2007	0	Prestressed concrete	700	48	1	1	5
23	US Roads	37565100	87021000	2007	22	Prestressed concrete	252	43	1	1	5
24	State Roads	38020600	87231800	2007	25	Prestressed concrete	86	44	0	1	5
25	State Roads	38020600	87231800	2007	25	Prestressed concrete	86	44	0	1	5
26	State Roads	38274200	86050000	2007	5	Prestressed concrete	122	45	0	1	5
27	State Roads	41435400	85583000	1991	5	STEEL	246	29	0	1	5
28	State Roads	39423600	86223000	1968	30	Concrete	96	43	0	1	5
29	State Roads	39423600	86223000	1968	30	Concrete	96	43	0	1	5
30	Interstate	39534800	86033000	1968	18	STEEL	144	42	1	1	5
31	US Roads	40074200	87143600	1965	0	Prestressed concrete	210	36	1	1	5
32	US Roads	40074200	87143600	1965	0	Prestressed concrete	210	36	1	1	5
33	State Roads	40024800	86300000	2006	30	Concrete	87	71	0	1	6
34	US Roads	41365400	87285400	2006	0	Prestressed concrete	170	80	1	1	6
35	US Roads	37553200	87022600	2006	34	Prestressed concrete	223	46	1	1	6
36	US Roads	37565100	87021000	2006	22	Prestressed concrete	253	43	1	1	6
37	State Roads	38301800	86433600	2006	0	Prestressed concrete	51	47	0	1	6
38	State Roads	38552400	86340000	2006	40	Prestressed concrete	71	43	0	1	6
39	US Roads	39584800	86541200	2006	21	Prestressed concrete	98	48	1	1	6
40	State Roads	38493600	85383000	2006	0	STEEL	265	38	0	1	6
41	State Roads	40024800	86292400	2006	31	STEEL	198	89	0	1	6
42	State Roads	41273600	85503600	1982	30	Concrete	80	47	0	1	6
43	State Roads	41352400	87024200	1969	11	Prestressed concrete	132	43	1	1	6
44	State Roads	41352400	87024200	1969	11	Prestressed concrete	132	43	1	1	6
45	State Roads	38001200	87351800	1961	27	Prestressed concrete	123	88	0	1	6
46	State Roads	38001200	87351800	1961	26	STEEL	162	88	0	1	6
47	State Roads	38001200	87353000	1960	14	Prestressed concrete	154	88	0	1	6
48	State Roads	37600000	87340000	1960	0	STEEL	360	88	0	1	6
49	State Roads	38034200	87040000	1955	30	Concrete	31	41	0	1	6
50	Interstate	39410000	86200000	2005	10	Prestressed concrete	112	45	1	1	7
51	Interstate	39410000	86200000	2005	11	Prestressed concrete	152	35	1	1	7
52	US Roads	38345400	86360000	2005	25	Prestressed concrete	213	48	0	1	7
53	Interstate	39412400	86191800	2005	99	Prestressed concrete	347	37	1	1	7
54	Interstate	39412400	86190600	2005	99	Prestressed concrete	1,354	53	1	1	7
55	Interstate	39413000	86185400	2005	99	Prestressed concrete	821	53	1	1	7
56	US Roads	39515400	85581200	2005	20	Prestressed concrete	133	87	0	1	7
57	Interstate	39410600	86200000	2005	40	Prestressed concrete	275	37	1	1	7
58	Interstate	39544200	86161200	2005	2	Prestressed concrete	173	79	1	1	7
59	Interstate	39544200	86161200	2005	2	Prestressed concrete	173	78	1	1	7

Figure III.A.9 Selected study bridges: 1–59.

1	Classification	Latitude	Longitude	Year Built	Skew	Bridge Type	Structure Length (ft)	Deck Width (ft)	Highway System of Inventory Route(NHS)	Designated National Network	Year After Bridge Replacement
60	Interstate	39544200	86161200	2005	2	Prestressed concrete	173	47	1	1	7
61	Interstate	39525400	86161200	2005	1	Prestressed concrete	174	79	1	1	7
62	Interstate	39525400	86161200	2005	1	Prestressed concrete	174	124	1	1	7
63	State Roads	39233600	86273600	1972	0	STEEL	228	43	1	1	7
64	Interstate	39480600	86100000	1969	0	Concrete	52	145	1	1	7
65	Interstate	39474200	86095400	1968	9	STEEL	171	133	1	1	7
66	Interstate	39475400	86100000	1968	99	STEEL	546	133	1	1	7
67	Interstate	39475400	86095400	1968	99	STEEL	571	29	1	1	7
68	Interstate	39481800	86100000	1968	2	STEEL	119	155	1	1	7
69	Interstate	39483000	86100000	1968	6	STEEL	144	130	1	1	7
70	Interstate	39483600	86100600	1968	33	STEEL	187	130	1	1	7
71	State Roads	38320600	86364200	1967	0	Concrete	99	45	0	1	7
72	State Roads	38324200	86364200	1967	30	Prestressed concrete	149	46	0	1	7
73	Interstate	39410600	86200000	1966	10	Prestressed concrete	112	79	1	1	7
74	Interstate	39410600	86200000	1966	10	Prestressed concrete	112	135	1	1	7
75	State Roads	41383000	86175400	1964	11	Prestressed concrete	202	86	1	1	7
76	Interstate	41074800	85103000	1960	0	STEEL	141	44	1	1	7
77	Interstate	41440600	85470600	1956	19	STEEL	120	49	1	1	7
78	Interstate	41440600	85470600	1956	19	STEEL	120	49	1	1	7
79	Interstate	41435400	85464200	1956	22	STEEL	159	49	1	1	7
80	Interstate	41435400	85464200	1956	22	STEEL	159	49	1	1	7
81	Interstate	41441200	84594200	1956	0	STEEL	158	49	1	1	7
82	Interstate	41441200	84594200	1956	0	STEEL	158	74	1	1	7
83	Interstate	41435400	84581800	1956	31	STEEL	158	49	1	1	7
84	Interstate	41435400	84581800	1956	31	STEEL	158	49	1	1	7
85	State Roads	39233600	86273600	1938	0	STEEL	228	42	1	1	7
86	State Roads	39204575	86545066	1934	45	Concrete	32	27	0	1	7
87	State Roads	40443600	85101800	1934	15	Concrete	343	57	0	1	7
88	State Roads	39172400	86464800	1934	0	Concrete	32	35	1	1	7
89	US Roads	39153600	86481800	1934	0	Concrete	107	35	1	1	7
90	State Roads	39285400	86025400	2004	32	Concrete	46	54	0	1	8
91	US Roads	40123000	86220600	2004	15	Prestressed concrete	212	44	0	1	8
92	State Roads	38004800	87540000	2004	15	Prestressed concrete	179	48	1	1	8
93	State Roads	38010600	87540000	2004	0	Prestressed concrete	203	48	1	1	8
94	State Roads	38323600	86054200	2004	15	Prestressed concrete	186	44	0	1	8
95	State Roads	38342400	86055400	2004	0	Prestressed concrete	188	44	0	1	8
96	US Roads	40110000	84581200	2004	15	Prestressed concrete	182	48	1	1	8
97	US Roads	38393600	86470600	2004	0	Prestressed concrete	269	34	0	1	8
98	County Roads	37550600	86432400	2004	99	Prestressed concrete	204	31	0	1	8
99	State Roads	37583600	87293600	2004	99	Prestressed concrete	317	56	1	1	8
100	State Roads	37583600	87293600	2004	99	Prestressed concrete	317	56	1	1	8
101	US Roads	41401800	86370000	2004	35	Prestressed concrete	110	75	1	1	8
102	Interstate	41355400	87182400	2004	99	STEEL	507	64	1	1	8
103	Interstate	41355400	87182400	2004	99	STEEL	516	73	1	1	8
104	others	38171800	85452400	2004	99	STEEL	694	40	0	1	8
105	State Roads	38221200	85452400	2004	19	STEEL	185	51	0	1	8
106	State Roads	38221200	85452400	2004	19	STEEL	185	51	0	1	8
107	Interstate	38170600	85451800	2004	33	STEEL	120	73	1	1	8
108	Interstate	38170600	85451800	2004	33	STEEL	120	73	1	1	8
109	Interstate	41352400	87164800	2004	9	STEEL	64	68	1	1	8
110	Interstate	41352400	87164800	2004	9	STEEL	64	68	1	1	8
111	Interstate	41080000	85085400	1992	60	Prestressed concrete	221	44	1	1	8
112	Interstate	41080000	85085400	1992	60	Prestressed concrete	221	44	1	1	8
113	State Roads	39171800	85374200	1984	25	STEEL	152	47	1	1	8
114	State Roads	38044200	87553600	1978	0	Concrete	112	47	1	1	8
115	State Roads	37563000	87445400	1976	0	Prestressed concrete	65	43	1	1	8
116	State Roads	37563600	87445400	1973	0	Prestressed concrete	64	47	1	1	8

Figure III.A.10 Selected study bridges: 60–116.

1	Classification	Latitude	Longitude	Year Built	Skew	Bridge Type	Structure Length (ft)	Deck Width (ft)	Highway System of Inventory Route(NHS)	Designated National Network	Year After Bridge Replacement
116	State Roads	37563600	87445400	1973	0	Prestressed concrete	64	47	1	1	8
117	Interstate	40222400	86470600	1968	14	STEEL	147	76	1	1	8
118	Interstate	40222400	86470600	1968	14	STEEL	147	76	1	1	8
119	Interstate	40223000	86470600	1968	10	STEEL	191	76	1	1	8
120	Interstate	40223000	86470600	1968	10	STEEL	191	76	1	1	8
121	Interstate	39553600	86150600	1967	0	STEEL	419	49	1	1	8
122	Interstate	39553600	86150600	1967	0	STEEL	419	49	1	1	8
123	Interstate	39554200	86152400	1967	38	STEEL	192	54	1	1	8
124	Interstate	39554200	86152400	1967	38	STEEL	192	57	1	1	8
125	Interstate	39554200	86153600	1967	18	STEEL	145	62	1	1	8
126	Interstate	39554200	86153600	1967	18	STEEL	145	82	1	1	8
127	Interstate	38104800	87454800	1966	20	Concrete	106	43	1	1	8
128	Interstate	38104800	87454800	1966	20	Concrete	106	43	1	1	8
129	Interstate	38095400	87430000	1966	4	Concrete	143	43	1	1	8
130	Interstate	38095400	87430000	1966	4	Concrete	143	43	1	1	8
131	Interstate	38100600	87394800	1966	27	Prestressed concrete	128	43	1	1	8
132	Interstate	38100600	87394800	1966	20	Prestressed concrete	138	43	1	1	8
133	Interstate	38105400	87455400	1966	18	STEEL	157	43	1	1	8
134	Interstate	38105400	87455400	1966	18	STEEL	157	43	1	1	8
135	Interstate	38095400	87401200	1966	17	STEEL	155	43	1	1	8
136	Interstate	38100000	87401200	1966	17	STEEL	155	43	1	1	8
137	State Roads	37541800	86443000	1966	0	STEEL	2,709	34	0	1	8
138	US Roads	40170600	84583600	1964	20	Concrete	144	36	1	1	8
139	US Roads	40165400	84583600	1964	10	STEEL	197	46	1	1	8
140	Interstate	41074800	85100000	1960	20	Prestressed concrete	109	56	1	1	8
141	Interstate	41050000	85133600	1960	19	STEEL	160	42	1	1	8
142	Interstate	41435400	85565400	1956	3	STEEL	112	49	1	1	8
143	Interstate	41435400	85565400	1956	3	STEEL	112	49	1	1	8
144	Interstate	41434800	85535400	1956	5	STEEL	112	49	1	1	8
145	Interstate	41434800	85535400	1956	5	STEEL	112	49	1	1	8
146	Interstate	41424800	84564200	1956	9	STEEL	159	49	1	1	8
147	Interstate	41424800	84564200	1956	9	STEEL	159	49	1	1	8
148	Interstate	41424200	84563000	1956	16	STEEL	136	49	1	1	8
149	Interstate	41424200	84563000	1956	16	STEEL	141	49	1	1	8
150	US Roads	40571800	87264200	1953	42	STEEL	231	43	1	1	8
151	US Roads	40571800	87264200	1953	42	STEEL	231	43	1	1	8
152	State Roads	41190600	87112400	1936	0	Prestressed concrete	35	47	0	1	8
153	US Roads	41315400	87281800	1935	19	Prestressed concrete	210	75	1	1	8
154	State Roads	39151200	85424800	1929	0	Concrete	197	48	1	1	8
155	State Roads	39134800	86370600	2003	45	Concrete	118	57	1	1	9
156	US Roads	40551200	86314200	2003	15	Concrete	87	38	0	1	9
157	US Roads	40011200	86541800	2003	40	Concrete	99	86	1	1	9
158	US Roads	38275400	86551800	2003	35	Concrete	90	48	1	1	9
159	US Roads	40455400	86523000	2003	45	Concrete	101	42	0	1	9
160	US Roads	40125091	86541516	2003	40	Concrete	23	47	1	1	9
161	State Roads	38050000	87461200	2003	0	Prestressed concrete	111	48	0	1	9
162	State Roads	39073000	85460000	2003	0	Prestressed concrete	122	44	0	1	9
163	Interstate	38210600	85451800	2003	35	Prestressed concrete	303	86	1	1	9
164	Interstate	38210600	85451800	2003	35	Prestressed concrete	303	89	1	1	9
165	others	38195400	85451800	2003	7	Prestressed concrete	184	95	1	1	9
166	US Roads	39453953	86465929	2003	15	Prestressed concrete	317	44	0	1	9
167	US Roads	41004200	86343600	2003	25	Prestressed concrete	80	38	0	1	9
168	US Roads	40004200	86541200	2003	0	Prestressed concrete	56	86	1	1	9
169	State Roads	39473000	85265400	2003	20	Prestressed concrete	78	40	1	1	9
170	State Roads	39091800	86234200	2003	15	Prestressed concrete	97	46	1	1	9
171	Interstate	38191200	85451200	2003	26	Prestressed concrete	124	85	1	1	9
172	Interstate	38191200	85451800	2003	26	Prestressed concrete	124	85	1	1	9

Figure III.A.11 Selected study bridges: 116–172.

1	Classification	Latitude	Longitude	Year Built	Skew	Bridge Type	Structure Length (ft)	Deck Width (ft)	Highway System of Inventory Route(NHS)	Designated National Network	Year After Bridge Replacement
173	Interstate	41352400	87181800	2003	0	STEEL	191	59	1	1	9
174	Interstate	38192400	85451200	2003	58	STEEL	170	35	1	1	9
175	Interstate	38193600	85452400	2003	64	STEEL	110	44	1	1	9
176	Interstate	41355400	87182400	2003	9	STEEL	135	59	1	1	9
177	Interstate	41354200	87182400	2003	39	STEEL	92	71	1	1	9
178	Interstate	41354200	87182400	2003	38	STEEL	90	82	1	1	9
179	US Roads	41384800	86183600	2003	12	STEEL	59	43	1	1	9
180	US Roads	41384800	86183600	2003	12	STEEL	59	43	1	1	9
181	State Roads	38444800	87254800	1983	0	Prestressed concrete	84	47	0	1	9
182	State Roads	40043600	85221800	1979	30	Concrete	86	43	1	1	9
183	State Roads	40073000	85221800	1978	45	Prestressed concrete	132	43	1	1	9
184	Interstate	39474824	86020384	1977	99	Prestressed concrete	779	44	1	1	9
185	Interstate	39460600	86083600	1974	99	Prestressed concrete	185	160	1	1	9
186	Interstate	39460600	86083600	1974	3	STEEL	180	171	1	1	9
187	Interstate	39461200	86083600	1974	32	STEEL	294	160	1	1	9
188	Interstate	39461800	86083600	1974	0	STEEL	140	185	1	1	9
189	Interstate	39462400	86083600	1974	0	STEEL	118	171	1	1	9
190	Interstate	39463000	86083600	1974	99	STEEL	134	67	1	1	9
191	Interstate	39463000	86083600	1974	0	STEEL	134	100	1	1	9
192	Interstate	39463000	86083600	1974	99	STEEL	176	67	1	1	9
193	Interstate	39464200	86083000	1974	13	STEEL	137	124	1	1	9
194	Interstate	39464200	86083000	1974	20	STEEL	146	116	1	1	9
195	Interstate	39465400	86083000	1974	99	STEEL	166	60	1	1	9
196	Interstate	39470600	86083600	1974	99	STEEL	149	43	1	1	9
197	Interstate	39470600	86083600	1974	12	STEEL	182	59	1	1	9
198	Interstate	39470000	86084200	1974	99	STEEL	168	43	1	1	9
199	Interstate	39470600	86084200	1974	99	STEEL	168	43	1	1	9
200	Interstate	39470600	86084200	1974	99	STEEL	220	43	1	1	9
201	Interstate	39465400	86083000	1974	1	STEEL	149	127	1	1	9
202	Interstate	39465400	86083000	1974	99	STEEL	199	100	1	1	9
203	Interstate	39470600	86082400	1974	99	STEEL	460	99	1	1	9
204	Interstate	39470600	86083600	1974	99	STEEL	240	65	1	1	9
205	Interstate	39471200	86083000	1974	99	STEEL	157	121	1	1	9
206	Interstate	39471200	86082400	1974	99	STEEL	327	120	1	1	9
207	State Roads	40083600	85223600	1973	0	Concrete	120	43	1	1	9
208	State Roads	40083600	85223600	1973	0	Concrete	120	43	1	1	9
209	State Roads	40094200	85211200	1973	0	STEEL	139	43	1	1	9
210	State Roads	40094200	85211800	1973	0	STEEL	139	43	1	1	9
211	State Roads	40084800	85220600	1973	33	STEEL	225	42	1	1	9
212	State Roads	40084800	85220600	1973	33	STEEL	225	42	1	1	9
213	US Roads	40100000	85210600	1973	26	STEEL	175	43	0	1	9
214	US Roads	40100000	85211200	1973	26	STEEL	175	43	0	1	9
215	US Roads	40102400	85203000	1973	15	STEEL	297	42	0	1	9
216	US Roads	40102400	85203000	1973	15	STEEL	297	42	0	1	9
217	US Roads	40104200	85201200	1973	1	STEEL	170	62	0	1	9
218	US Roads	40104200	85201200	1973	1	STEEL	170	52	0	1	9
219	US Roads	40144200	85220000	1973	52	STEEL	301	43	0	1	9
220	US Roads	40144200	85220000	1973	52	STEEL	301	43	0	1	9
221	Interstate	38115400	87530000	1967	2	Concrete	106	43	1	1	9
222	Interstate	38115400	87530000	1967	2	Concrete	106	43	1	1	9
223	Interstate	38110600	87473000	1967	11	Concrete	72	43	1	1	9
224	Interstate	38110600	87473000	1967	11	Concrete	72	43	1	1	9
225	Interstate	38123600	87565400	1967	38	STEEL	751	36	1	1	9
226	Interstate	38123600	87565400	1967	38	STEEL	751	36	1	1	9
227	Interstate	38115400	87550600	1967	25	STEEL	125	43	1	1	9
228	Interstate	38115400	87550600	1967	25	STEEL	125	43	1	1	9
229	Interstate	38114800	87520600	1967	9	STEEL	219	43	1	1	9
230	Interstate	38114800	87520600	1967	9	STEEL	219	43	1	1	9

Figure III.A.12 Selected study bridges: 173–230.

	F	V	W	AC	AK	AZ	BJ	BO	DG	DP	EE
1	Classification	Latitude	Longitude	Year Built	Skew	Bridge Type	Structure Length (ft)	Deck Width (ft)	Highway System of Inventory Route(NHS)	Designated National Network	Year After Bridge Replacement
231	Interstate	38115400	87535400	1966	0	STEEL	846	36	1	1	9
232	Interstate	38115400	87535400	1966	0	STEEL	846	36	1	1	9
233	Interstate	38115400	87533600	1966	15	STEEL	1,099	36	1	1	9
234	Interstate	38115400	87533600	1966	15	STEEL	1,099	36	1	1	9
235	US Roads	41390600	86190000	1964	13	STEEL	162	86	1	1	9
236	State Roads	40333600	85384800	1961	8	Prestressed concrete	369	48	0	1	9
237	US Roads	38414200	87294200	1961	15	STEEL	182	52	1	1	9
238	US Roads	38414200	87293600	1961	15	STEEL	182	52	1	1	9
239	Interstate	38590600	85503600	1960	30	Concrete	72	66	1	1	9
240	Interstate	38590600	85504200	1960	30	Concrete	72	43	1	1	9
241	Interstate	39061800	85565400	1960	20	Concrete	59	64	1	1	9
242	Interstate	39061800	85570000	1960	20	Concrete	59	43	1	1	9
243	State Roads	40043600	85221800	1960	30	Concrete	86	43	1	1	9
244	State Roads	40073000	85221800	1960	45	Prestressed concrete	130	43	1	1	9
245	US Roads	38423000	87311200	1960	0	STEEL	1,746	36	1	1	9
246	US Roads	38423000	87311200	1960	0	STEEL	1,743	36	1	1	9
247	Interstate	38581200	85503600	1959	16	STEEL	147	66	1	1	9
248	Interstate	38581200	85504200	1959	16	STEEL	147	43	1	1	9
249	Interstate	39405400	85581800	1958	40	Concrete	199	43	1	1	9
250	US Roads	40014800	84562400	1957	45	Prestressed concrete	133	47	1	1	9
251	State Roads	40334800	85424800	1956	0	STEEL	127	35	0	1	9
252	State Roads	40334800	85424200	1956	0	STEEL	156	35	0	1	9
253	US Roads	41353000	86535400	1956	16	STEEL	250	36	0	1	9
254	Interstate	39403600	85574800	1954	15	STEEL	163	43	1	1	9
255	Interstate	39385400	85550600	1954	0	STEEL	312	54	1	1	9
256	State Roads	38175400	87000000	1953	10	Concrete	25	41	0	1	9
257	State Roads	38331800	86370000	1952	20	Concrete	100	55	0	1	9
258	US Roads	41341800	87142400	1941	0	Concrete	289	47	1	1	9
259	US Roads	41342400	87142400	1941	0	STEEL	177	46	1	1	9
260	US Roads	39464200	87183000	2002	45	Concrete	112	55	0	1	10
261	State Roads	39114800	86342400	2002	35	Concrete	70	44	1	1	10
262	State Roads	39114800	86342400	2002	35	Concrete	70	44	1	1	10
263	State Roads	39111800	86340000	2002	37	Concrete	74	71	1	1	10
264	State Roads	39111800	86340000	2002	37	Concrete	75	44	1	1	10
265	State Roads	40181800	85140600	2002	20	Prestressed concrete	101	71	0	1	10
265	State Roads	40181800	85140600	2002	20	Prestressed concrete	101	71	0	1	10
266	US Roads	41371800	87303600	2002	30	Prestressed concrete	262	82	1	1	10
267	Interstate	39480000	86021800	2002	99	Prestressed concrete	273	50	1	1	10
268	Interstate	39480000	86020600	2002	15	Prestressed concrete	214	61	1	1	10
269	Interstate	39480000	86020000	2002	99	Prestressed concrete	171	61	1	1	10
270	Interstate	39475400	86020600	2002	22	Prestressed concrete	82	73	1	1	10
271	Interstate	39475400	86020600	2002	22	Prestressed concrete	83	63	1	1	10
272	Interstate	41354200	87182400	2002	7	STEEL	175	87	1	1	10
273	Interstate	41354200	87181800	2002	7	STEEL	175	80	1	1	10
274	Interstate	39440000	86024200	2002	99	STEEL	1,155	393	1	1	10
275	State Roads	41340000	87260000	2002	25	STEEL	260	124	1	1	10
276	Interstate	39483600	86015400	2002	99	STEEL	109	119	1	1	10
277	Interstate	39483600	86015400	2002	99	STEEL	80	96	1	1	10
278	US Roads	37541200	87021200	2002	0	STEEL	4,505	78	1	1	10
279	State Roads	41281200	87011800	1987	18	STEEL	210	44	1	1	10
280	State Roads	41281200	87012400	1987	18	STEEL	210	44	1	1	10
281	State Roads	41283600	87011800	1987	5	STEEL	153	44	1	1	10
282	State Roads	41283600	87011800	1987	5	STEEL	154	44	1	1	10
283	State Roads	41284200	87011800	1987	0	STEEL	157	44	1	1	10
284	State Roads	41284200	87011800	1987	0	STEEL	157	44	1	1	10
285	US Roads	41330600	87002400	1985	10	Concrete	85	47	1	1	10
286	US Roads	38493600	86304800	1984	0	STEEL	935	43	1	1	10
287	US Roads	39510600	86534800	1981	0	STEEL	398	47	1	1	10
288	State Roads	38554800	85334800	1976	10	Prestressed concrete	221	47	0	1	10
289	State Roads	39553000	87263600	1976	38	STEEL	226	42	1	1	10
290	Interstate	40070444	86305416	1970	35	Concrete	98	60	1	1	10

Figure III.A.13 Selected study bridges: 231–290.

PART IV. ENFORCEMENT

14. INTRODUCTION

The purpose of this part of the report is to examine the overweight enforcement issues in the state of Indiana. Ideally, the study should cover all enforcement efforts spanning the entire range of roadway functional classes in the state. However, due to data constraints, only the major roadways, particularly, the National Highway System (see Part IV Appendix B), were considered. The first chapter of this part of the report discusses the history and organization of traffic law enforcement in Indiana, and briefly presents a snapshot of traffic patterns in the state. The second chapter focuses on reviewing the overweight truck enforcement efforts of surrounding states. The third chapter addresses the enforcement activities specific to the state of Indiana, including a description of historical efforts, physical facilities, and mobile enforcement. Chapter 16 makes recommendations for enhancing the capability of the Indiana truck weight monitoring system, and thus identifies a numbers of locations for proposed new static weigh stations, virtual weigh stations, and weigh-in-motion (WIM) systems. This is accompanied by discussions on future truck inspections, inspection buildings, federal funding for inspections, and the correlation between safety and weight violations. This part of the report concludes with a discussion of possible future technology-driven directions in vehicle monitoring to reduce the cost, yet increase the effectiveness, of enforcing the overweight truck regulations.

14.1 General Background

The importance of establishing an effective system to enforce vehicle weights cannot be overemphasized. This is particularly the case for the state of Indiana, a logistics-oriented state that is centrally situated in the continental United States and thus experiences a significant amount of truck traffic on its highways. Appropriately nicknamed the "Crossroads of America," the state has a highway network that serves Interstate freight in both north-south and east-west directions and is a critical part of a wider multimodal system that also includes rail, air, and waterway modes thus enhancing the economy not only of the state but also of the Midwest region and the nation as a whole. Furthermore, the volume of truck traffic in Indiana continues to increase annually as the state's efficient roadway infrastructure is reputed, at least anecdotally, to provide carriers with a distinct competitive advantage over other modes. Of all the states in the union, Indiana ranks 2nd in through-truck ton-miles (*175*), 5th in trailer and semi-trailer registrations (*176*), 7th in trucking employment (*177*), 12th in Interstate miles (*178*), and 18th in highway bridges (*179*).

These statistics are not only a testament to the critical role played by the highway transportation infrastructure in the socio-economic development of the state of Indiana and the region but also underscore the need for continual attention to preserving the investments made by taxpayers in constructing, operating, and maintaining such infrastructure. Consistent with the need for preservation is the regulation, for purposes of safety and system preservation, trucking operational characteristics (speed, weights, widths, heights, etc.) using federal and state legislation and policies. The state duly realizes the need to monitor the use of its highways by overweight vehicles so that it can protect the highway infrastructure from premature and accelerated deterioration of such assets through excess loading or undue safety hazard through oversize loads. To do this, the state police, and the state departments of revenue and transportation, contiually monitor the operations of overweight commercial vehicles. However, the state finds itself in a Catch-22 situation: rigid enforcement of trucking operating regulations will discourage economic development and will thus defeat one of the key purposes for which the highways are provided. In striking a compromise, the state continues to maintain a flexible policy where special permits are granted by the state department of revenue to truck operators to allow the latter to exceed the specified operational restrictions albeit not to such extent that the highway infrastructure longevity is compromised. Such flexibility helps the state to retain and attract heavy industry including those that involve haulage of large loads.

14.2 History and Organization of Traffic Law Enforcement in Indiana

14.2.1 History

In July 1921, the Indiana state legislature commissioned a 16-man Motor Vehicle Police Force. This was the first law enforcement agency in the state to have statewide jurisdiction to enforce traffic laws; however, they had rather limited authority and were only authorized to enforce a non-standardized set of "rules of the road" and a handful of other motor vehicle laws. In 1933, this agency evolved into the Indiana State Police and in July 1935, the first formal academy was established to train state troopers (*180*). The Indiana State Police is also renowned for another first: it was the first law enforcement agency in North America to have authorized the use of the "Drunk-o-meter", a chemical test to determine levels of alcohol intoxication (this equipment was developed in 1938, towards the end of the prohibition era, by Dr. Rolla Harger, a professor at Indiana University). In 1954, Indiana State Police Captain Robert F. Borkenstein, in collaboration with Dr. Harger, improved the device and named it the Breathalyzer (*181*), which is still used today by police agencies worldwide to assess alcohol impairment in drunken driving offenses. This piece of traffic enforcement history is evidential of the fact that the state of Indiana has long been concerned with, and has had pioneering roles in, issues regarding traffic law enforcement in general.

The branch of the Indiana State Police tasked with overseeing commercial vehicle enforcement is aptly named the Commercial Vehicle Enforcement (CVE) division. The CVE division has a long and storied history of working on a number of unique projects, besides assisting new entrants to the commercial motor vehicle industry understand the complex laws and regulations by which they must abide. An example of such a project is assisting the United States Department of Agriculture in helping to halt the spread of the emerald ash borer, an insect which has devastated forests across the country, by scrutinizing trucks that haul lumber-related products. Because of their efforts, especially with respect to the enforcement of vehicle weight and safety regulations, the CVE division received the United States Department of Transportation's Motor Carrier Safety Assistance Program Leadership Award in 2008, 2009, and 2010 (*182*).

14.2.2 Organization

The Indiana State Police is currently led by a superintendent, whose command staff includes an assistant superintendent who holds the rank of colonel, and four deputy superintendents. Each member of the command staff holds the rank of at least lieutenant colonel, and manages four primary areas of responsibility:

- Financial Management, including the Fiscal and Logistics Divisions
- Support Services, including the Divisions of Criminal Justice Data, Laboratory, and Records, and Public Information Office
- Investigations which includes the Office of Professional Standards, Training Division, and Criminal Investigation Division;
- Enforcement, which includes the Commercial Vehicle Enforcement Division, Human Resources Division, and Operations Support Division.

Enforcement operations throughout the state are the responsibility of separate north zone and south zone commanders, which further oversee five separate areas, each commanded by a captain. These areas are divided into 14 districts, covering from four to 11 counties each, and are individually commanded by a lieutenant (*182*).

In terms of job-related duties, the CVE division is responsible for the following areas, several of which will be described in detail later in the report:

- Fixed Scale Facility Operations
- Field Enforcement
- School Bus Inspection
- Compliance Review Squad
- New Entrant Squad

In addition to these, the CVE division maintains the agency's Superload Escort program, the Motor Carrier Safety Assistance Program, SafetyNet, and the non-division Commercial Vehicle Inspection programs.

14.3 Overall Traffic Patterns in Indiana

Indiana has an extensive network of Interstate, U.S., and state routes which provide truck access to various commercial centers across the state. In 2009, Indiana had 95,680 miles of public highways; these include approximately 11,500 miles of state highways, of which 1,171 miles are Interstates (*183*). That year, a total of 76,628 million vehicle-miles were travelled on Indiana highways (*184*); of this, a weighted average of all highway vehicle-miles traveled (VMT) shows that approximately 5% of travel was by combination trucks (*185*). Indiana's Interstate highway system, on which approximately 30% of VMT is by combination trucks, serves as the backbone for heavy truck movement throughout the state. The Interstate system comprises six major routes: I-80/90, I-70, I-74, and I-64 (which run from east to west), and I-65 and I-69 (which run from south to north). Indianapolis serves as the hub of this network of highways: in addition to the I-465 beltway, four other Interstate routes pass through the city. Indiana also has a number of U.S. highways and state roads connecting its major population centers, roughly aligned in what can generally be described as an east-west and north-south grid of highways. Major U.S. highways (US) and state roads (SR) include US 27, US 31, US 41, US 231, US 421, SR 37, and SR 3, all of which generally run north-south, and US 24, US 25, US 30, US 50, and SR 46, which run east-west (*183*).

Figure 14.1 graphically compares the annual average daily traffic (AADT) and annual average daily truck traffic (AADTT) on Indiana's highway functional classes. The figure suggests that there is marked difference in the level of traffic loading across the major highway classes, as is to be expected. As was discussed briefly in Part II of this report (pavement damage cost estimation) there are a number of explanations for this trend; Interstates have superior

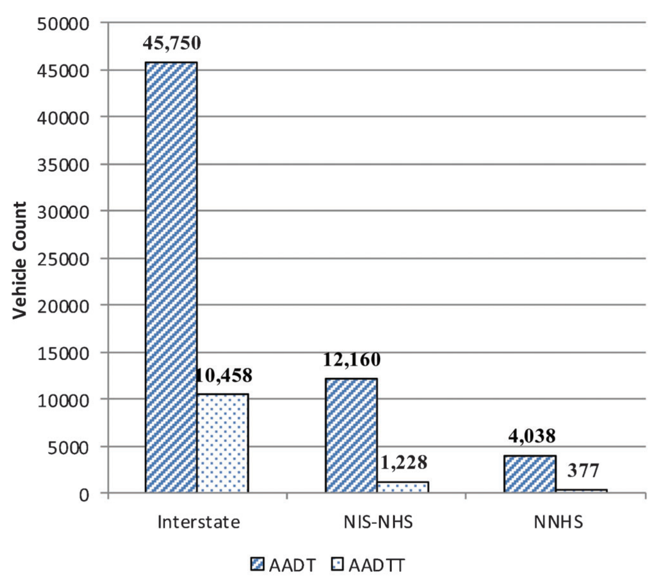


Figure 14.1 Traffic volume by functional class.

geometric standards to other highway classes, and their limited accessibility, higher mobility, and general safety are preferred by heavy vehicle operators, especially for long-distance travel.

An examination of the traffic volume across specific routes yields further interesting observations. In a similar pattern, certain Interstate segments have significantly higher truck traffic than others (Figure 14.2). Of these highways, Interstate 80/90 in the northern part of Indiana is clearly the most highly trafficked. Other Interstates with considerably high truck traffic (ADTT greater exceeding 10,000) are I-465, I-94, I-65, I-70, I-74, I-69, and I-64. For non-Interstate highway routes, shown in Figure 14.3, a comparable trend was observed: certain routes have high truck traffic and others have relatively low truck traffic. Of the non-Interstate highways, SR 912 had the heaviest truck traffic. These wide variations in pavement loading patterns demand that, for future effective studies related to highway investment, it may be prudent to classify pavement segments not only on the basis of surface type or functional class but also on the basis of traffic loading.

AADT and AADTT are the average daily number of total vehicles and trucks, respectively, passing a specific road segment, and are obtained by dividing the total yearly vehicle/truck traffic counts by 365 days (total number of days in a year). The Indiana Department of Transportation (INDOT) utilizes 114 continuous traffic counters (CTCs) across the state; these collect data on traffic speed and volume on a non-stop, year-round basis. Of the 114 CTC sites, 50 are also currently equipped with weigh-in-motion (WIM) technology to collect truck weight data–the concept of WIMS in improving CVE activities and efficiency will be discussed in a later section. Also, INDOT has a coverage count program that utilizes 30,000 temporary count locations on a three-year cycle. At coverage count locations, at least 48 hours of traffic data are collected and subsequently used to estimate AADT on the basis of adjustment factors (axle, weekday, and seasonal) developed from CTC-generated data. As part

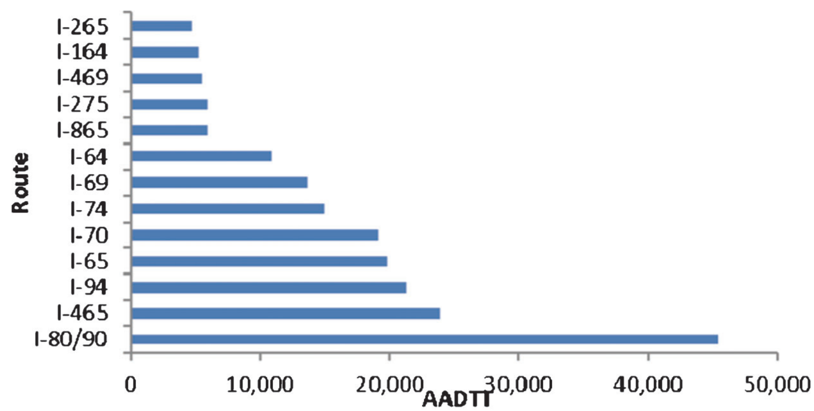


Figure 14.2 Annual average daily truck traffic (AADTT) on Indiana Interstate routes, 2010.

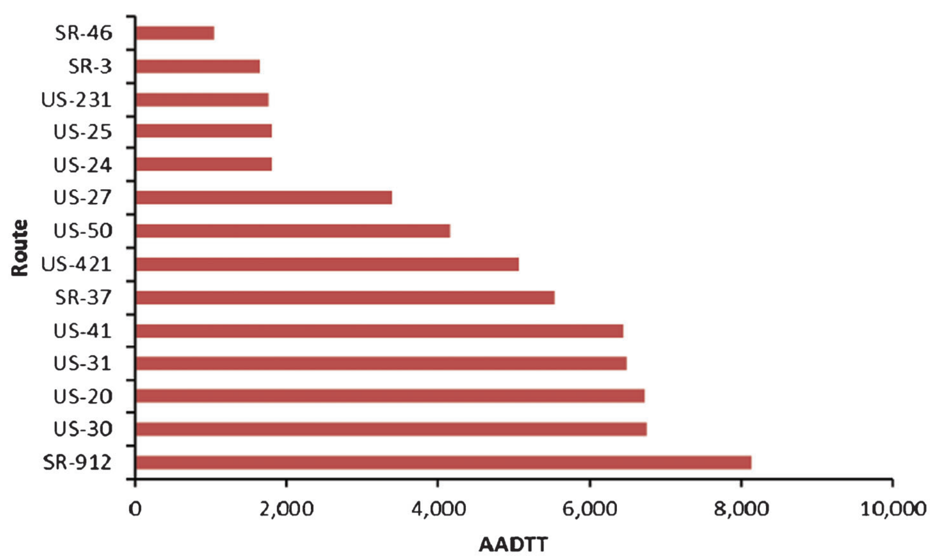


Figure 14.3 Annual average daily truck traffic at Indiana U.S. highway and state routes, 2010.

of this process, INDOT classifies all vehicles into 13 different categories, depending upon the axle spacing and number of axles; vehicles in Classes 4 through 13, as per the FHWA classification system (see Part IV Appendix A), are counted as commercial vehicles. For the purpose of developing schedules for long-term rehabilitation and maintenance, traffic loading is projected using the most recent AADT and AADTT.

15. THE STATE OF PRACTICE

15.1 Enforcement in Surrounding States

As part of the effort to assess the issues associated with overweight commercial vehicle enforcement in the state of Indiana, a brief survey was conducted of adjacent Midwestern states (i.e., Illinois, Kentucky, Michigan, and Ohio) in order to gage the level of their enforcement activities. This survey was primarily undertaken by examining the annual reports of the respective state police agencies for information relating to truck violations and patrol staffing, as well as by contacting individuals in FHWA's Freight Management & Operations office. In addition, review was made of a study conducted by Straus and Semmens (*186*) that supplied critical information otherwise not available to this research team at the time of the report preparation. The results are presented for each individual state in the paragraphs below.

One of the weight enforcement tools discussed across multiple states below is the PrePass inspection system. Utilized by a number of states in the Midwest and around the country, this technology, which was developed in the 1990s through the FHWA's Heavy Vehicle Electronic License Plate (HELP) program, allows trucks equipped with proprietary transponders to bypass specific weighing and inspection stations. The credentials and safety record of participating carriers are verified with state and federal agencies prior to enrollment. Also, tools including as WIM scales are increasingly being used, in conjunction with randomly-selected spot checks, to ensure that trucks remain in compliance. Carriers in the program are charged a fee for participation which helps to offset the cost of maintaining PrePass facilities. Currently, there are 31 states with at least one facility that participates in the PrePass program, and over 400,000 trucks nationwide have enrolled (*187,188*). Additional details relating to PrePass and its use in Indiana commercial motor vehicle enforcement will be discussed in the recommendations chapter of this report.

15.1.1 Illinois

The state of Illinois maintains an extensive network of static weigh stations in order to effectively enforce state and federal laws for overweight vehicles, with a total of 35 stations located on highways throughout the state. Of these thirty-five (35) stations, twenty-six (26) are located on Interstate highways, eight (8) are located on U.S. highways, and one (1) is located on an Illinois state route (*189*). This distribution of stations reflects the prevailing tendency in Illinois for overweight trucks to travel on a mix of Interstate and intrastate routes (*186*).

The spatial distribution of the static weigh station network in Illinois is such that a number of stations are located on major highways at the state borders (known as the "ports of entry"), as well as on various highway routes that traverse the interior parts of the state. Approximately 40% of all commercial trucks travelling on Illinois highways are weighed at these ports of entry, where Commercial Vehicle Enforcement Operators (CVEOs) typically staff the facilities for two 8-hour shifts daily. For those trucks that are not weighed at the ports of entry or other static weigh stations, a system of mobile enforcement is also implemented across the state. This mobile enforcement consists of patrol officers with portable scales working approximately 249,600 hours annually. In conjunction with the weigh stations, this force is responsible for the 45,000 trucks that are weighed on Illinois highways annually (*186,190*).

With respect to trucks that are found to be in violation of weight restrictions, data from the Illinois State Police suggest that the violation rate for overweight trucks is approximately 27.1% of all commercial vehicles weighed, or just over 12,000 trucks per year. Of these violators, the average excess weight over the 80,000 lb load limit has been found to be approximately 6,000 lbs, a level that is generally consistent with the situation at other states (*186*).

15.1.2 Kentucky

Information from the FHWA shows that as of 2011, the network of static enforcement facilities in Kentucky consists of 14 static weigh stations, 600 portable scales, 5 semi-portable scales, and 14 WIM facilities (*191*). The static weigh stations appear to be interspersed throughout the state rather than concentrated at the ports of entry, and 10 of them are compliant with PrePass infrastructure (*187*).

Available literature suggests that the Kentucky State Police has been particularly aggressive over the past several years in commercial vehicle enforcement, especially with respect to overweight vehicle violations. One measure of effectiveness, the percentage of weighed coal trucks that are overweight (coal trucks constitute a significant portion of commercial truck traffic in Kentucky), shows that the violation rate decreased from 77% in 2004 to just under 3% in 2006. However, one should note that this measure can only be compared across years within Kentucky; differences in the way that vehicles are weighed between different states make it difficult to draw meaningful conclusions from such statistics from one state to another, and may lead to erroneous inferences on the effectiveness of enforcement activities. As a case in point, it has been reported that the vehicle out-of-service rate for Kentucky, a measure by which the effectiveness of roadside inspections can be assessed, was 15.48% in

2006, somewhat below the national average of 22.89% (*192*).

Table 15.1 presents a selection of key inspection and weight enforcement statistics from the Kentucky State Police CVE division for the years 2006–2011. Additionally, it was found that the top reasons for commercial vehicles being removed from Kentucky highways include issues pertaining to medical certificate errors, drivers operating their vehicles beyond the maximum number of allowed operating hours, and errors with recording driving hours in the vehicle log (*193,194*).

15.1.3 Michigan

The Research Team for the present study contacted the Michigan DOT and the Michigan State Police office, and was directed to submit requests for information pertaining to commercial vehicle enforcement through the office's Freedom of Information Act website. As of the time of the report preparation, the Research Team had not received any responses. As such, detailed data pertaining to the state's commercial vehicle enforcement efforts were not available to document in the present report. The information presented below was obtained from online and other sources.

An online search for information on commercial vehicle enforcement in Michigan shows that the network of physical enforcement facilities around Michigan consists of 21 static weigh stations. Of these, 16 are located on Interstate highways, with the remainder on U.S. highway routes (*195*). The weigh stations seem to be well distributed throughout the state but only two of them are compliant with PrePass infrastructure (*187*).

15.1.4 Ohio

In Ohio, the physical enforcement system consists of 16 weigh stations. Thirteen (13) of these facilities are located on Interstate highways, and the remaining three are on U.S. routes (*196*). These stations are staffed by employees in 8-hour shifts, and are responsible for weighing approximately 3% of all commercial trucks at the state's ports of entry. According to the Ohio State Patrol, most overweight truck violations occur on intrastate routes, and the violations occur predominantly during the daytime, although this is likely correlated significantly with the hours during which the weigh stations are staffed (*186*). Ten (10) of the weigh station facilities in Ohio are compatible with PrePass infrastructure, including one WIM facility (*187*).

In 2011, Ohio State Patrol officers conducted nearly 80,000 inspections of commercial vehicles, resulting in approximately 20% of the inspected trucks being placed out of service. Table 15.1 presents current statistics for commercial vehicle weight enforcement in Ohio; in 2011, the weight violation rate at static scales (platforms) was approximately 0.2%, while the violation rate at portable scales was 80.4% (*197*). This appears to be logical, as those truck drivers who avoid the static scales are likely to do so on purpose due to weight violations, and will typically be apprehended by mobile enforcement officers instead.

15.2 Commercial Vehicle Enforcement in Indiana

15.2.1 Overview

Besides the previously discussed assignments, the principal directives of the Indiana State Police CVE division are to: (1) reduce the number of commercial vehicle-related crashes in the state of Indiana, and (2) reduce the pavement and bridge damage by heavy weight vehicles using Indiana's highways. In addition, the division maintains a host of other duties, including commercial driver's licensing, dyed fuel enforcement, hazardous materials inspection, and safety inspections of commercial vehicles. Because the CVE division is responsible for preventing damage from overweight vehicles on all of Indiana's highways, they must adapt their techniques to a variety of conditions; as such, this agency makes use of a number of tools, principally portable and static truck scales, in the course of their duties (*182*).

In order to maintain consistency of enforcement operations across the entire state, the CVE division abides by a stringent set of regulations when determining whether a commercial vehicle is oversize or overweight. In order to be considered legal, the truck dimensions and weight must not exceed the following criteria, adapted from the Federal Highway Administration (*198*):

TABLE 15.1
Kentucky Truck Weight Enforcement & Inspection Statistics. Courtesy of Kentucky State Highway Police (*194*).

Year	Oversize Violation (Current Year)	Overweight Violation (Current Year)	Vehicles Weighed (Fixed platform)	Vehicles Weighed (WIM)	Vehicles Weighed (Portable)	Vehicles Weighed (Semi-portable)
2006	447	4,945	71,686	7,543,389	3,534	8,583
2007	421	2,544	75,337	6,304,357	5,652	6,865
2008	465	2,957	96,228	5,758,643	5,029	3,364
2009	691	3,500	100,717	4,669,900	4,782	1,832
2010	588	3,354	119,421	4,620,598	4,286	455
2011	721	2,650	103,191	4,655,087	5,001	1,559

- 13 feet 6 inches in height; or
- 8 feet 6 inches in width; or
- 40 feet in length for a single vehicle; or
- 60 feet in length for a two-vehicle combination. *Note: If a two-vehicle combination is connected by a fifth wheel hook-up, there is not an overall length limit, but the trailer and load length must not exceed 53 ft.*
- 80,000 pounds gross vehicle weight (GVW); or
- 12,000 pounds on the steering axle; or
- 20,000 pounds on a single axle; or
- 34,000 pounds on a tandem axle; or
- 800 pounds per inch of rim width and subject to the above axle weights. *Note: Regardless of the individual axle weights, the GVW of the truck must not exceed 80,000 pounds.*

15.2.2 Historical Commercial Vehicle Enforcement Patterns

Historically, INDOT has always monitored both overweight and oversize trucks. The enforcement pattern over the last decade is presented in Table 15.2 and shown graphically in Figure 15.1. Note that the category of "measured trucks" includes those commercial vehicles which undergo a complete physical safety inspection, pursuant to Federal Motor Carrier Safety Administration (FMCSA) regulations; the measurement of the vehicle's physical dimensions is only one step in this process (*199*).

Overall, these patterns indicate that over the past decade, patrol hours have exhibited a trend of remaining steady to slightly increasing, while the total numbers of trucks weighed and measured (inspected) have decreased precipitously (with the exception of 2010—the reason for this increase is unclear). The reasons for these decreases are not definitively known, although it may be related to budget reductions in recent years, which have decreased the time that static weigh stations are staffed—if there is no paid staff present at the weigh station, commercial vehicles cannot be weighed or ticketed for overweight loads; this will be discussed further in a later section.

Additionally, the decrease in trucks weighed and measured may be due to the allocation of commercial vehicle enforcement resources on Indiana highways. A 2006 survey to INDOT indicated that the majority of overweight truck violations occur on the I-80/I-90/I-94 corridor in the northern part of the state; data on the allocation of enforcement resources by highway district and/or route was not available for this report, but if the Indiana State Police is focusing its commercial vehicle enforcement efforts on other routes throughout the state with greater numbers of officers, it is possible that the related enforcement statistics would see a subsequent decrease. This survey also indicated that 100% of commercial vehicles are weighed on WIM stations at the state's ports-of-entry, suggesting that the aforementioned numbers do not include these physical facilities (*186*). Also, in 2010, 4,508 citations were issued to commercial vehicles for weight violations, for a failure rate of approximately 0.9% (*182*).

Figure 15.2 presents a distribution of the gross vehicle weights for trucks that are ticketed or warned by commercial vehicle enforcement officers. While this figure only contains data for a single month, it suggests a distinct trend in which the vehicles that are ticketed are predominantly only a few thousand pounds over the legal weight limit of 80,000 pounds; this suggests that enforcement officers are less likely to allow for any flexibility in the GVW, and that many commercial carriers attempt to "sneak" a small amount of additional weight onto their vehicles.

15.2.3 Enforcement through Static Weighing

15.2.3.1 Physical facilities for static weighing. Indiana's Commercial Vehicle Enforcement Division makes use of 10 permanent scales, all of which are located on Interstate highway routes in various locations around the state. Of these static weigh stations, three are presently not operational. The detailed locations of these static weight enforcement facilities are listed in Table 15.3, and shown graphically in Figure 15.3. Scales 9 and 10 currently lack staffing, while the fixed scales at site 7 suffer from structural integrity problems. Figure 15.4 provides an example of a static weight enforcement facility in operation with a commercial vehicle.

In order to further effectively manage the high volume of commercial trucks on Indiana highways, the majority of the static weigh stations employ auxiliary WIM sorting scales. Using vehicle information such as axle spacing, axle weights and speed, any vehicle suspected of violating weight limitations through a WIM scale is sent to a certified static scale, while compliant vehicles are allowed to continue travel without stopping. Additionally, seven static weight enforcement facilities are currently equipped

TABLE 15.1
Ohio Truck Weight Enforcement Statistics. Courtesy of Ohio State Highway Police (*197*)

		Number			Change (+/−)	
		Current (2011)	Last (2010)	3-Year Avg (2008–10)	2010 to 2011	3-yr Avg to 2011
Platform weighing	Trucks weighed	2,950,368	3,058,932	3,792,553	−108,564 (−4%)	−842,185 (−22%)
	Trucks overweight	6,079	5,120	7,018	959 (+19%)	−939 (−13%)
Portable weighing	Trucks weighed	4,354	4,841	5,662	−487 (−10%)	−1,308 (−23%)
	Trucks overweight	3,501	3,781	4,539	−280 (−7%)	−1,038 (−23%)

TABLE 15.2
Historical Enforcement Patterns in Indiana. Data Courtesy of Indiana State Police (*182*).

Year	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
# of trucks measured	17,490	17,735	10,233	6,157	7,037	6,828	5,431	6,186	1,473	1,243	1,697
# of trucks weighed	463,150	488,350	797,319	770,998	423,080	377,184	374,156	271,906	226,701	203,939	480,080
Traffic patrol hours	335,585	332,140	325,896	293,275	271,324	285,705	282,032	321,257	431,692	457,950	424,908

with infrastructure for the PrePass system (*187*). Figures 15.5 and 15.6 demonstrate a sample placement of these WIM facilities with respect to the static weight enforcement stations.

Finally, as previously mentioned, although Indiana currently has 12 static weigh enforcement facilities, funding cuts over the past decade have severely limited, or even completely eliminated the staffing at several facilities, effectively removing them from the list of available stations. The I-74 eastbound station at Veedersburg, and the I-65 stations at Seymour are completely unused, essentially rendering a west-north/south corridor through the center of the state devoid of full-time commercial vehicle weight enforcement, with the exception of the limited number of trucks along this route that are inspected by state troopers with portable scales (Figure 15.7). Any recommendations for future weigh stations operations, to be discussed later in the report, must take cognizance of the potential of these existing stations to effectively serve their intended purpose.

In addition to weight enforcement, officers of the Commercial Vehicle Enforcement Division are tasked with inspecting vehicles for a number of safety and length violations that would pose a hazard to other vehicles on the highway. In order to conduct these inspections, officers typically use inspection buildings located on the premises of the static weight enforcement facilities. However, currently only six of the seven operational weigh stations have these buildings, meaning that officers at the other two locations are unable to conduct inspections during periods of inclement weather; depending on the time of year, this can greatly reduce the capacity of the enforcement officers in conducting their duties. Figure 15.8 provides an illustration of a typical inspection building located adjacent to the main scale house at a static weigh station.

15.2.3.2 Staffing for static weighing. Of the 93 employees that are presently employed with the Commercial Vehicle Enforcement Division, 49 are permanently stationed at static weight enforcement facilities, and are referred to as Motor Carrier Inspectors.

General responsibilities. In general, the responsibilities of Motor Carrier Inspectors are as follows:

- Check working order of scales prior to use
- Conduct inspections of applicable vehicles for safety registration, proper operator papers, permits, documentation and proper safety equipment
- Weigh trucks on permanent and/or portable scales
- Complete proper reports on each enforcement action taken
- Set up portable scales in order to weigh trucks
- Testify in court
- Perform duties in conjunction with troopers to detect motor carrier violations and/or to weigh trucks at random on portable scales
- Ensure violator vehicles are properly secured
- Inform county prosecutors on motor carrier violations and technicalities for preparation of trials
- Assist and inform trucking companies and motorist regarding motor carrier laws

Figure 15.1 Historical enforcement patterns in Indiana, 2001–2009. Data courtesy of INDOT (*200*).

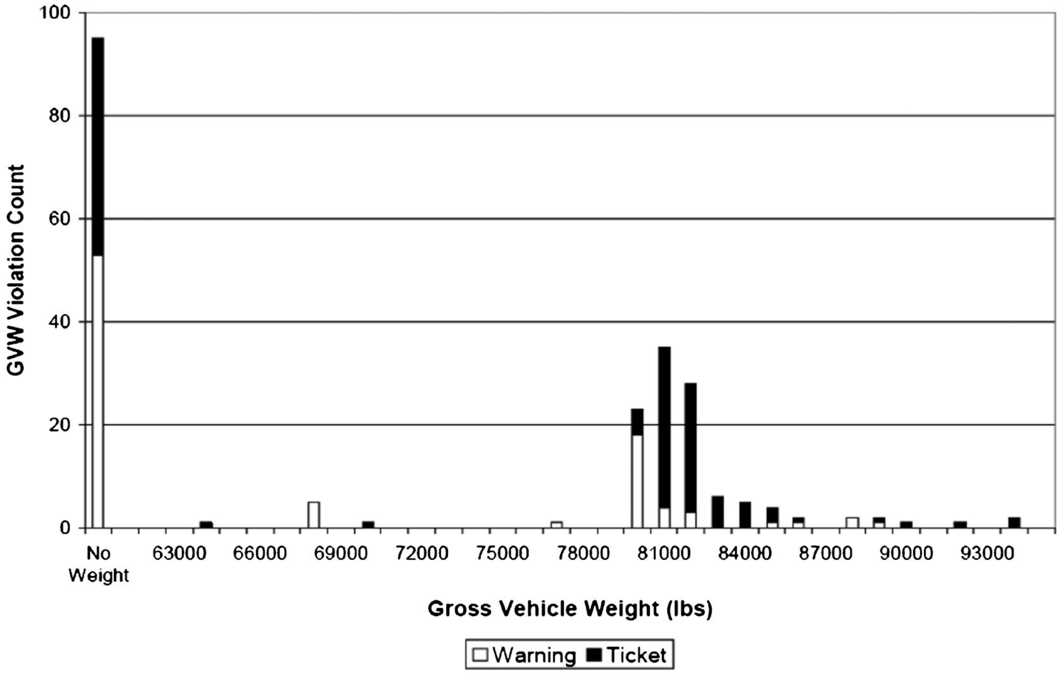


Figure 15.2 Gross vehicle weight violations at Indiana static weigh stations, August–September 2003.

- Assist troopers and other police agencies with truck enforcement problems
- Keep assigned equipment in condition pursuant to Standard Operating Procedure
- Perform school bus inspections
- Submit daily and monthly reports
- Train, assist and supervise Motor Carrier Inspector Trainees in performing the required tasks
- Participate in the Safety Audit Program as required

Staff daily schedules. A crucial factor in determining the effectiveness of the static weigh stations is the hours during which motor carrier inspectors are scheduled to be working. While the exact number of hours varies by weigh station, Indiana traditionally uses 16-hour schedules for many of the facilities; this typically consists of two 8-hour shifts (*187*). These shifts often begin at 6:00AM and end at 10:00PM, rendering the weigh station dormant at nighttime.

TABLE 15.3
Static Weight Enforcement Stations in Indiana. Data Courtesy of INDOT (*200*).

Scale	Location	Details
1	I-65 SB Lowell	
2	I-94 WB Chesterton	
3	I-94 EB Chesterton	
4	I-69 SB Fort Wayne	
5	I-70 WB Richmond	
6	I-74 WB W. Harrison	
7	I-65 NB Seymour	Not operational
8	I-70 EB Terre Haute	
9	I-65 SB Seymour	Not operational
10	I-74 EB Veedersburg	Not operational

While this is sufficient for apprehending many inadvertent offenders of weight regulations (that is, those trucks that unintentionally overload or accidentally set their axle spacing incorrectly), it is not sufficient to catch those carriers and drivers that deliberately violate weight regulations by overloading their vehicles. These drivers and carriers are typically informed about weigh station staffing hours and regulations and thus often modify their driving schedule such that they pass at the weigh stations only during the late evening or early morning hours when the stations are closed. As such, any recommendations for staffing changes are these facilities need to take due cognizance of such scheduling disparities.

Staffing costs. In computing the costs for employing motor carrier inspectors at weigh stations across the state, several criteria must be considered. These are listed below. The amount indicated with each item represents approximate costs that were made available directly from the Indiana State Police Pay Matrix Website (the specific values for different employee levels can be found in Part IV Appendix C. *Note that these costs are not adjusted for inflation, as the exact wage adjustment mechanism was unavailable from the Indiana State Police at the time of this report.*) (*201,202*):

- Annual salary = $46,768
- Cost of equipment necessary to perform duties = $47,876
- Cost of benefits = $15,901 (34% of annual salary)
- Cost of training necessary to perform duties = $65,000

Thus, based on these figures, the 49 motor carrier inspectors result in a total annual cost of approximately $8.6 million.

Figure 15.3 Location of static weight enforcement stations in Indiana as of December 2011.

15.2.4 Resources for Mobile Enforcement

Besides permanent scales, portable scales (shown in Figure 15.9) are used by commercial vehicle enforcement officers to weigh commercial trucks and supplement the permanent scales. In addition to being used for vehicles that are pulled over for compliance checks, portable scales are used to weigh overweight trucks involved in accidents. However, since each set of scales is actually multiple scales, they are more cumbersome and time-consuming to use, and there is a greater risk for inaccurate measurements compared with WIMs or static scales.

Figure 15.4 Static weight enforcement facility in operation.

Besides the motor carrier inspectors, the second major branch of employment within the Commercial Vehicle Enforcement Division is that of the state troopers that patrol the highways. The most significant difference between these commercial vehicle enforcement officers and motor carrier inspectors is that the former are allowed to carry firearms, in event that a violent confrontation with a truck driver occurs. These specialized officers, hired from the general pool of state police offers, perform a number of specialized duties, which are described below.

Note that portable scales are by far the slowest form of vehicle weight measurement, because of the fact that individual scales must be set up for each axle, and are typically done so in less-than-ideal environmental conditions (e.g., on the shoulder of a busy highway).

15.2.4.1 Physical facilities and staffing for mobile enforcement. While members of the mobile section of Indiana's CVE division are necessarily free to operate in any location around the state, a number of physical facilities are available to assist them in the performance of their duties. Similar to motor carrier inspectors, mobile enforcement officers are able to direct commercial vehicle operators to weigh at static weight facilities in order to obtain a more definitive answer to whether or not a truck is in violation of weight restrictions.

Additionally, mobile enforcement officers have access to the state's six inspection buildings, which are located at various static weight facilities. While vehicle inspections can take place on the side of the highway, oftentimes safety and weather conditions necessitate an inspection to occur in an enclosed facility. Finally, mobile enforcement officers are allocated office space at each district's headquarters in order to more efficiently perform various administrative functions.

Responsibilities. The Commercial Vehicle Enforcement Division employs a total of 44 state troopers. Although these officers undergo the same initial training and maintain the same general responsibilities as all Indiana State Police, they are additionally tasked with the following items pursuant to the enforcement of commercial vehicle laws and regulations:

- Weight enforcement
- Writing up crash reports at the crash scene
- Issuing warrants
- Conducting DUI patrols
- Working with the federal police force
- Answering phone calls at district offices
- Helping stranded motorists
- Making public appearances at schools, parades, etc.

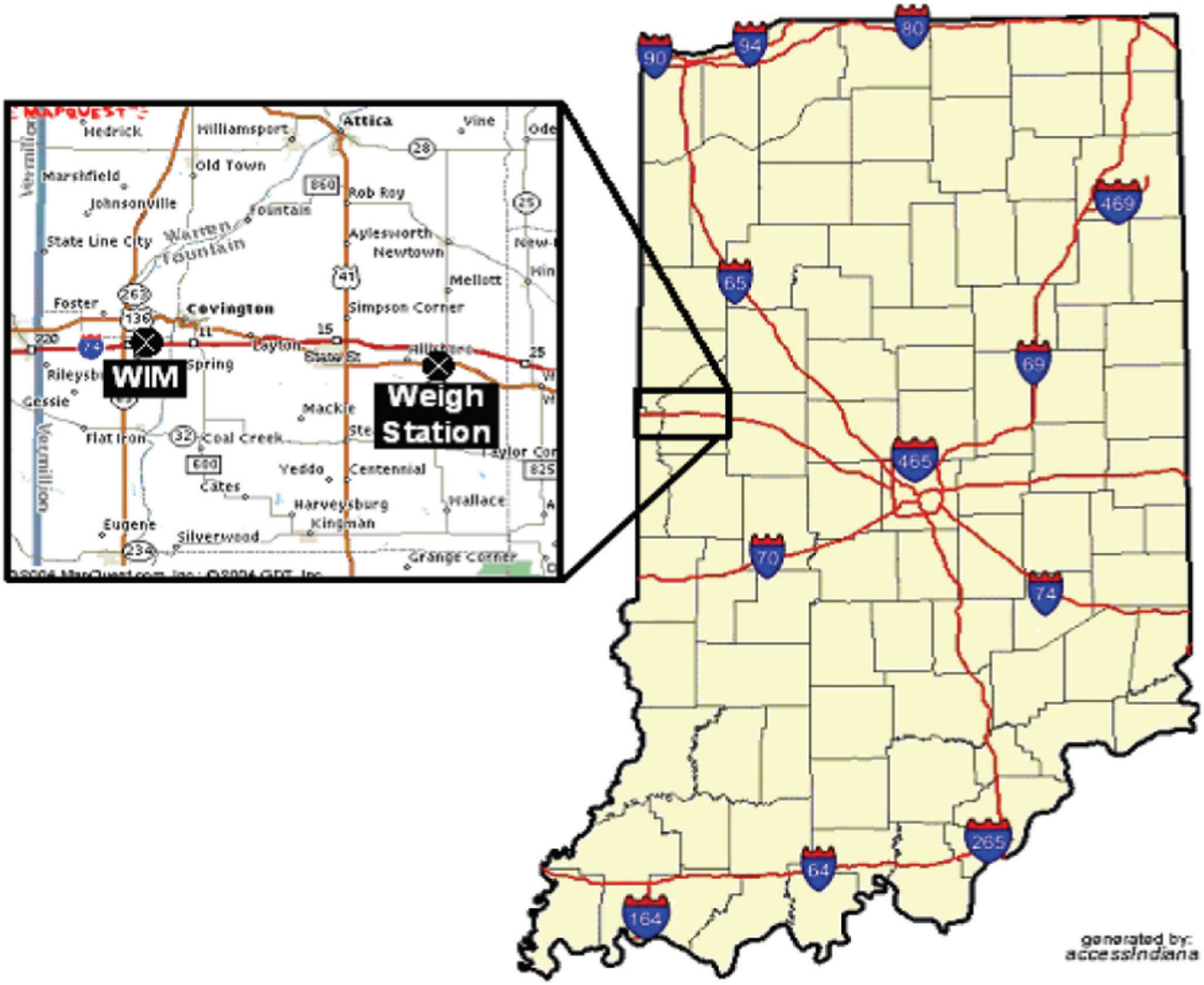


Figure 15.5 A typical example of sequentially locating WIM and static weigh stations.

The principal activity of these officers is weight enforcement. This consumes 80% of their time in an average work week. The remaining duties take up the other 20% of time, and are more in keeping with the general duties of all Indiana State Police officers. Instead of being assigned to a specific static weigh station, these officers spend their time driving and

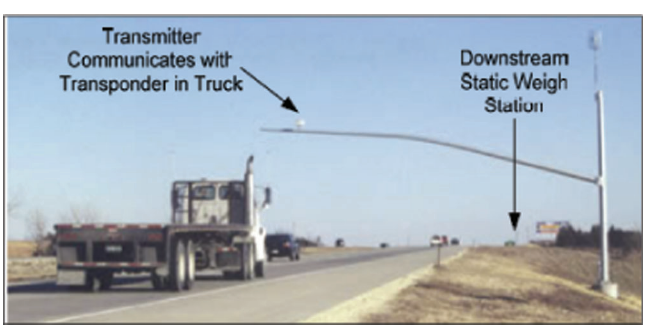


Figure 15.6 Typical WIM/PrePass transponder configuration.

Figure 15.7 Typical use of portable scales by commercial vehicle enforcement officer.

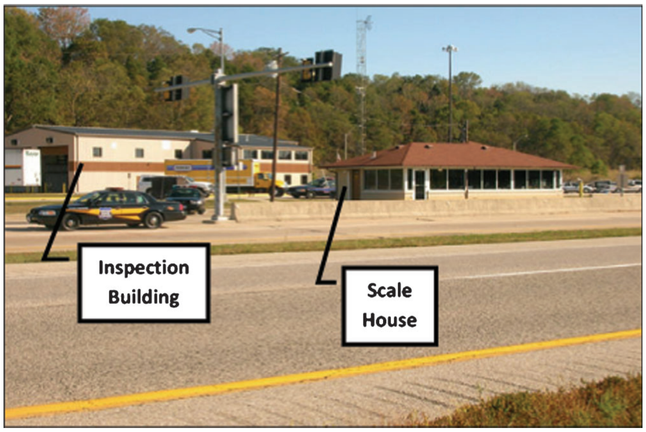


Figure 15.8 Typical inspection building at static weight enforcement facility.

carrying out mobile commercial vehicle enforcement with portable and semi-portable scales. If the troopers suspect that a commercial vehicle is in violation of safety, weight, or size regulations, they pull the truck over on the side of the road and perform a field inspection or weighing. As such, these officers carry four portable scales at all times in their vehicles. Once the scales are laid in position, each tire of the truck rolls onto the scales, one axle at a time. The resulting measurement could then serve as a basis for citing a vehicle that is over the 80,000-pound weight limit without a valid permit.

Coverage. The following calculations demonstrate the annual coverage, on average, of a single commercial vehicle enforcement state trooper:

- Indiana NHS Roadways = 2,897 miles (including 1,171 miles of Interstate highways)
- 44 state troopers = 188,642 miles/month provided by Indiana State Police (*203*)
- 44 state troopers = 2,263,704 miles/year (computed from previous figure)

Figure 15.9 Indiana State Trooper using a portable scale to weigh a truck.

Thus,

Number of times that all troopers cover all NHS roads in a year $= \frac{2,263,704}{2,897} = 781$

Number of times that one trooper covers all NHS roads in a year $= \frac{781}{44} = 18$

On average, number of NHS miles covered by 1 trooper in a year = one trooper covers miles per year$\frac{2,263,704}{44} = 51,448$

Costs. According to Captain Wayne Andrews, an assistant commander for the CVE division, the same salary information can be used to approximate the costs for commercial vehicle state troopers as for motor carrier inspectors (*203*). Thus, the figures for salary, benefits, equipment, and training from above still apply. Based on these numbers, and an estimated count of 44 troopers, the total annual cost for this segment of the division is approximately $7.7 million. This brings the total cost for staffing within the CVE division to $16.3 million.

16. RECOMMENDATIONS

This chapter details a set of recommendations pertaining to the static monitoring and mobile enforcement, and truck inspections which are part of the Indiana State Police CVE division. These recommendations will provide INDOT and the Indiana State Police with a broad-level roadmap for future commercial vehicle enforcement efforts, from which they can perform further studies to assess different strategies and impacts of implementing these recommendations.

16.1 Physical Facilities

16.1.1 Static Weigh Station Locations

Based on the earlier section of the report which detailed the locations and capabilities of existing static weight enforcement facilities, a number of additional stations have been recommended for implementation across the state. Although this report is meant to provide general guidance only for the locations of these stations (the final locations should be the subject of a separate detailed study), the following factors were considered in making the recommendations:

- Proximity to the Indiana state border.
- Truck traffic volumes.
- Ability to weigh incoming trucks before their detouring to avoid a weigh station.
- Proximity to regions/industries which produce a significant amount of truck traffic.
- Proximity to and capacity of nearby weigh stations.

On the basis of these factors, Table 16.1 lists the new recommended weigh stations, along with any notes that relate to the recommendation. A more detailed justification for each recommendation is provided below:

TABLE 16.1
Recommended New Locations for Static Weigh Stations

Station	Location	Notes
1	I-64 EB Elberville	New station construction
2	I-65 SB Remington	Complement existing station at Lowell
3	I-65 NB & SB Seymour	Reopen or replace existing unused facilities
4	I-69 NB Warren	Adjacent to current weigh station on SB lanes
5	I-69 NB Washington	New station construction on new I-69
6	I-74 EB Veedersburg	Reopen existing station

Detailed costs are not included in this report for all recommended stations—rather, these should be the subject of a separate, detailed engineering analysis for each proposed location. The last weigh station constructed in Indiana, at Terre Haute in the late 1990s, cost $13.5 million, and included the addition of a significant amount of concrete pavement. Some cost information will be provided on the location of the Seymour station, but similarly-constructed new facilities can easily approach the $15 to $20 million dollar range per direction (*204*).

Interstate 64. In addition to the weigh stations that are recommended for Interstate highways in the central and northern portions of Indiana, it is recommended that a permanent weigh station be constructed on a section of Interstate 64 in the southwest section of the state. The most significant reason for this recommendation is the anticipation of heavy truck movements related to the coal mining and processing industry that has developed in this region. Figure 16.1 shows the distribution of coal mining activity within Indiana, with an especially heavy concentration of surface mining activity located along

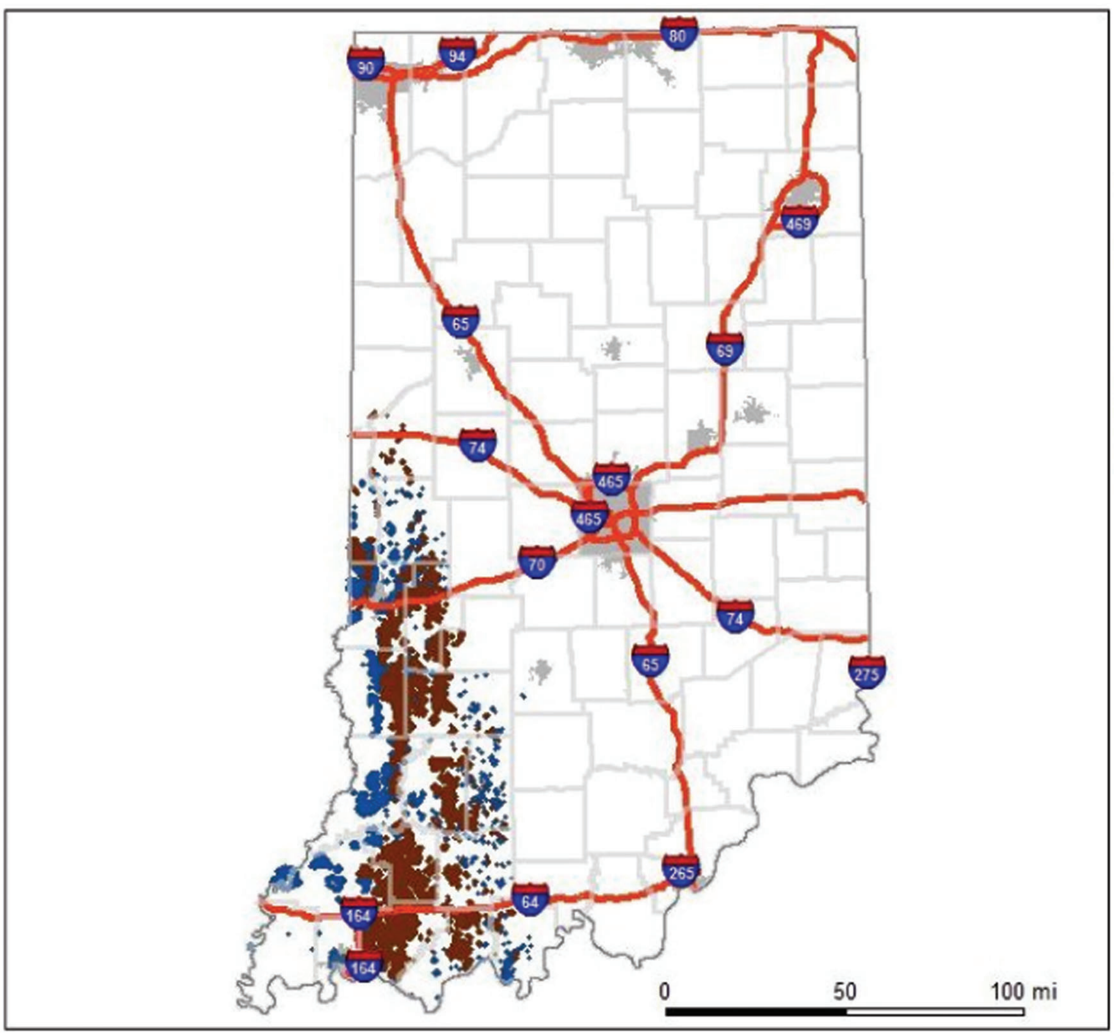


Figure 16.1 Coal mining activity in Indiana. (Adapted from (*205*).)

the I-64 corridor. Additional data from the Indiana Coal Council indicates that approximately 86% of the coal produced in Indiana is consumed within the state (*205*). This implies that the vast majority of these heavy coal trucks are traveling eastward on Indiana highways, in order to supply the energy and industrial needs for the rest of the state; as such, a static weigh station which captures this traffic would ideally be situated east of the coal producing region on a major transportation route, such as I-64.

In order to further narrow down the list of candidate locations at which a weigh station on I-64 should be located, truck traffic information from the Indiana DOT was analyzed for the corridor east of I-164. This information shows an appreciable decrease in the commercial vehicle traffic east of the I-64/US 231 interchange; this suggests that a significant amount of truck traffic is entering or exiting the I-64 corridor at this location. Thus, based on these findings, it is recommended that a static weigh station be located in the eastbound lanes of I-64, between the I-64/I-164 interchange and the I-64/US 231 interchange.

Interstate 65

Remington. This location should be considered for a weigh station in the southbound lanes in order to complement the existing facility further north near Lowell. This would help monitor the increasing amounts of truck traffic between the Chicago and Indianapolis metropolitan areas; current estimates place AADTT along this corridor at approximately 15,000, and the volume of traffic may be expected to increase significantly in the future. However, further studies with more refined truck traffic projections should be conducted before this recommendation is implemented.

Seymour. As discussed previously, the southbound lanes on I-65 near Seymour are the current site of a weigh station that has been unused for over a year, and the station on the northbound lanes. In both cases, the stations are unused and thus have fallen into disrepair; they will require significant rehabilitation, or even complete replacement, in order to restore them to operational capacity. The following is a detailed cost estimate for each side of I-65 at Seymour, based on a cursory review of the facility needs; the cost information comes primarily from direct interviews with INDOT employee and former state trooper Guy Boruff (*204*). The total estimated cost for each direction is approximately \$2.45 million, bringing the total cost for both weigh stations to \$4.9 million.

- **New Scale: \$500,000.** Install a new $80' \times 12'$ scale and new pit. The existing scale and pit will be demolished. New concrete walls will be placed to accommodate the new scale, and new conduit will run to the basement of the existing building for the electronics of the load cells.
- **Refurbished Scale House: \$100,000.** The scale house has been emptied and vacant for over a year. The scale house needs to be refurbished in place or demolished and moved to the east side of the ramp. It is desirable for Indiana State Police to face the mainline while operating the static scale. The current configuration does not allow that option.
- **Mainline Sorting System: \$750,000.** The mainline sorting system will include WIMs, loops, variable message signs, and will be tied to the scale house similar to the scale bypass lanes at other scales. These items will be on the highway mainline and will require additional signage for trucks and passenger vehicles.
- **Virtual Weigh Stations: \$250,000 each.** US50 west to SR11 N is the bypass route used by trucks that seek to avoid the existing weigh station. It is imperative to install Virtual Weigh Stations along the bypass route to discourage trucks from bypassing the weigh station.
- **Inspection Barn: \$500,000.** Indiana State Police perform inspections on trucks to ensure they meet minimum mechanical standards. A simple yet safe inspection barn will allow the performance of inspections year-round regardless of weather conditions.
- **Site Improvements: \$200,000.** As the new scales, loop system, building refurbishment and inspection barn are completed, site improvements such as new drainage structures, sidewalks and pavement sections may need to be addressed.
- **Engineering: \$150,000.** Engineering for the project by a consultant to provide engineering drawings for a proper weighing system.

While these costs have been deemed accurate for the Seymour location, they should not be considered typical for new station construction. The particular situation with Seymour is that a large amount of the existing facility will be reused and/or rehabilitated, including the installation of a mainline sorting system, which will negate the need to purchase additional ROW for the construction of a bypass lane. With a new pavement, a new scale house, a high-end inspection barn, and additional ROW purchases, construction costs for a brand new station would likely exceed \$15 million per direction (*206*).

Interstate 69

Warren. This location should be considered for a weigh station in the northbound lanes, in order to complement the existing weigh station on the southbound lanes. A review of AADTT on I-69 reveals that the majority of truck traffic travelling north towards Michigan and Ohio originates in the direction of Indianapolis, rather than Fort Wayne itself, or highways to the east of the city. By placing this weigh station south of Fort Wayne, Indiana State Police can avoid having to track vehicles which bypass the weigh station by detouring east into Ohio once they reach the I-469 beltway.

Evansville–Indianapolis extension. Plans are currently underway to extend Interstate 69 from its present southern terminus in Indianapolis, in order to connect with a short section of the highway to the southwest in Evansville. The first three sections of this highway, near Evansville, are expected to be functioning by October 2012 (*207*). Due to reduced pavement thickness as a cost-saving measure, a weigh station along this corridor would be useful in discouraging overweight truck travel and thus preserving the highway condition. It is recommended that a static weigh station and a WIM station be constructed along this section of highway on the northbound lanes, perhaps near Washington, in anticipation for large volumes of commercial truck traffic that will travel to the northern and eastern parts of the state. This highway route could also serve as an alternate path for heavy coal trucks originating in southwest Indiana; as such, a comprehensive engineering study should be conducted to ensure that the proposed I-64 weigh station is not rendered redundant or obsolete at a future date.

Interstate 74. It is recommended that the weigh station on eastbound I-74 near Veedersburg be evaluated for reopening. Currently, there is no station for weighing commercial vehicles which enter the state on I-74 from the west, resulting in a situation in which a truck could theoretically travel across the entire state without being weighed until it reaches the Indiana-Ohio border. Furthermore, with the I-65 stations in Seymour in disrepair, there is essentially no static station enforcement of commercial trucks that enter the state from Illinois on I-74 and exit to Kentucky on I-65, and vice-versa.

In light of these gaps in enforcement, the condition of the existing weigh station at Veedersburg should be assessed, and the necessary funding should be acquired to either refurbish and reopen the facility, or demolish it and construct a new weigh station nearby.

16.1.2 Weigh-in-Motion (WIM) Stations

In addition to the recommendations above for static weigh station construction, it is advised that a review be undertaken of the existing WIM stations around the state. For those static weigh stations that are not currently preceded spatially by a WIM station, it is recommended that WIM infrastructure (such as that shown in Figures 16.2 and 16.3) be incorporated into the mainline highway network in order to allow more commercial vehicles to bypass the static scales. This will reduce congestion at the static weigh stations and will achieve savings in time and fuel usage for commercial carriers and drivers.

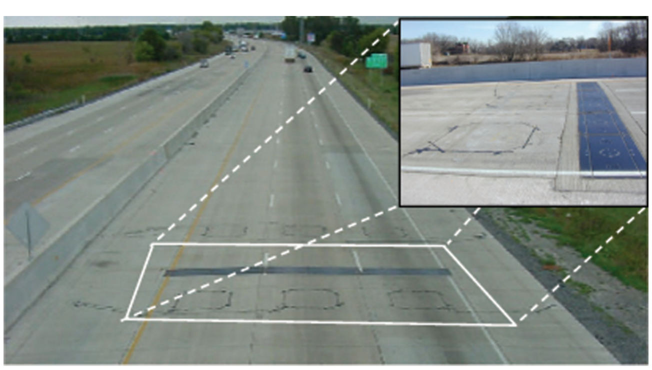


Figure 16.2 WIM scale (with side view) on I-65 at Merrillville.

An assessment of the effectiveness of WIMs to accurately weigh commercial trucks is presented in Figure 16.4. This comparison between the measures of WIM and static weigh stations for the same vehicles shows that the WIMS are suitable for an initial screening tool of general truck traffic. In the majority of cases, the WIMS measurement was equal to or greater than the corresponding static scale measurement; thus, a certain number of "false positives" for overweight vehicles might be generated based on the WIM scales, which could then be confirmed at the static weigh station. Perhaps more importantly, the number of instances in which the WIM measurement was less than that of the static scales is very infrequent, and it appears that several outlying data points visually skew the data; these could represent unique axle configurations or some other confounding factor. Furthermore, in instances where these weight differences occurred, there was only one case where it resulted in an overweight truck potentially being able to bypass the static scales.

16.1.3 Virtual Weigh Stations & Screening Technology

Besides operating as a pre-screening tool in conjunction with static weight facilities, WIM stations can also be combined with a host of software tools and other digital enforcement mechanisms to form what are known as "Virtual Weigh Stations." The premise of a virtual weigh station is that it is able to record information about commercial vehicles in the traffic stream in order to formulate an identification of the vehicle with state and federal motor carrier databases. Based on this data, the virtual weigh station can flag vehicles which represent a risk to other vehicles on the road, due to items such as hours of service violations, improper vehicle registration, etc. The virtual weigh station is also able to utilize WIM scales to capture weight information about vehicles on the mainline, and record the information of any vehicle in violation of weight restrictions for follow-up by proper authorities (*208*). While traditional static weight stations are able to accomplish most of these tasks, the automated nature of a Virtual Weigh Station and its reliance on WIM scales makes it significantly easier to deploy and results in substantially fewer staffing, maintenance, and equipment costs. Figure 16.5 shows an example of the automated data that is collected for each truck. In this example, the most recent weighed truck was reported to exceed the legal weight limit of 80,000 pounds by approximately 8,500 pounds.

Virtual weigh stations can be employed without fixed scale weight facilities, or can supplement these sites to increase their effectiveness. The flexibility of virtual weigh station placements and configurations makes them suitable for capturing commercial vehicle data, and for identifying violators, in areas where it is not feasible to construct static weight facilities, or provide continuous mobile enforcement. As such, it is recommended that the Indiana DOT conduct a comprehensive study to identify urban and secondary road sites

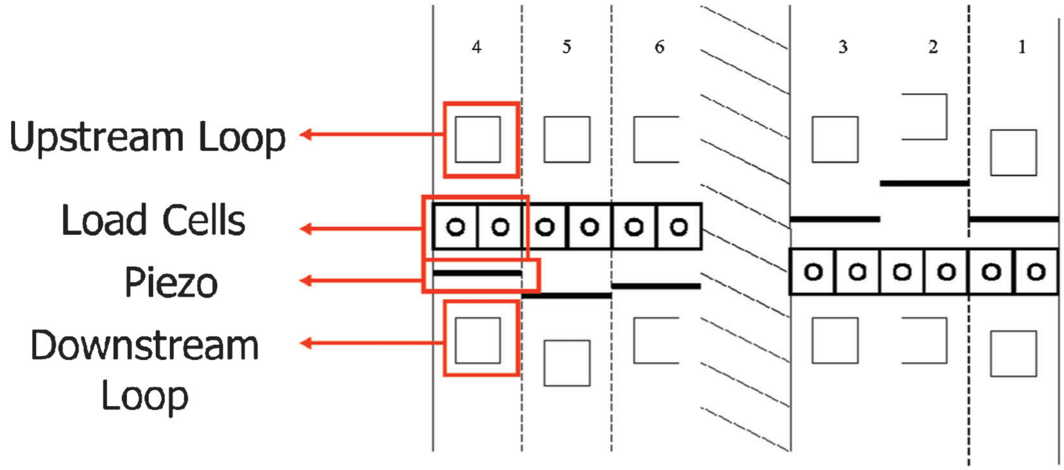


Figure 16.3 Overview of WIM scale scales and speed loops (I-65 @ Merrillville).

with high levels of motor carriers and/or high levels of pavement damage from commercial motor vehicles, and determine the suitability of incorporating virtual weigh stations at these locations. Finally, it is recommended that the same sites on Interstate routes which are recommended to install or continue the use of WIM scales also incorporate the use of virtual weigh station elements into their enforcement procedures.

A number of different protocols are currently in use for serving the software-side needs of WIM and virtual weigh stations. As previously discussed, PrePass technology can be used to ensure that "trusted" commercial vehicles are able to minimize the total delay spent at weight and inspection stations (*209*). PrePass motor carriers are registered with federal and individual state transportation agencies; each PrePass-equipped vehicle contains a transponder with auditory and visual components. When a truck approaches a PrePass-enabled station, the transponder transmits the vehicle information to an enforcement officer at the weigh station in order to conduct an automated check of the vehicle's credentials. A signal is then sent back to the vehicle transponder, authorizing the driver to bypass the station, or pull off the main line if problems are detected (*187*). PrePass is currently in use at all seven operational Indiana static weight facilities, and it is recommended that its use be continued and expanded as additional weigh stations are constructed.

It is currently estimated that, on average, approximately 30% of commercial vehicles that pass through PrePass-enabled weigh stations are equipped with PrePass transponders (*210*). Conversely, this means that 70% of commercial vehicles (or more, in the case of non-PrePass stations) must currently still be screened

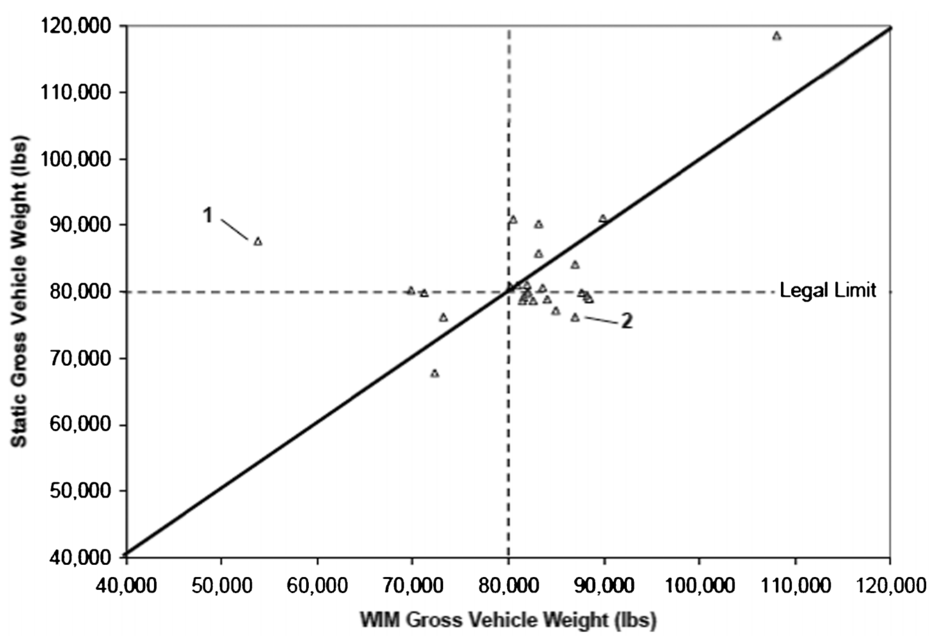


Figure 16.4 Comparison of WIM and static weigh station measurements. Data provided by INDOT (*200*).

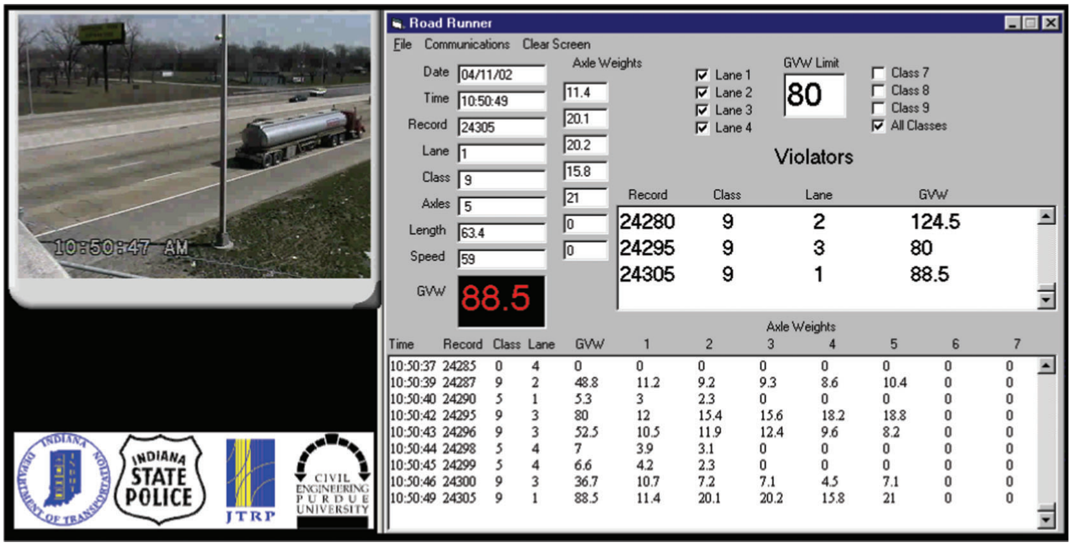


Figure 16.5 Example data collection at a virtual weigh station.

by enforcement officers with conventional methods. The implementation of virtual weigh stations and WIM scales can provide a great deal of information to enforcement officers regarding the characteristics of these non-equipped vehicles; however, in addition to the physical WIM, Virtual Weigh Station, and PrePass infrastructure, consideration must be given to the software components which reliably record, verify, and catalog commercial vehicle data. 360SmartView is an example of such a system that is currently being evaluated by INDOT (*209*). 360SmartView is essentially represents the backend component that takes information transmitted through WIMs, license plate readers, and other Virtual Weigh Station technology, and reconciles it with state and federal motor carrier databases to formulate a comprehensive identification of each vehicle, along with any safety and/or operation deficiencies that vehicle may possess. Using this comprehensive vehicle identification, motor carrier inspectors can decide whether or not to stop the vehicle for additional weighing and inspection, or whether it can return to the mainline. This results in a greater number of total vehicles able to be inspected, and will reduce the need for additional staffing in the future. It is recommended that 360SmartView, or a similarly-featured program, be implemented at all static weigh stations equipped with advanced WIM and virtual weigh station components on a trial period, and that an in-depth study be performed to assess its long-term cost effectiveness.

16.2 Staffing

Figure 16.6 presents a distribution of the overweight truck violations in Indiana, with the late night violations presumably being administered by mobile commercial vehicle enforcement troopers. Based on this figure, it is evident that a large number of overweight trucks travel during the late night and early morning hours, most likely in an effort to avoid the hours of weigh stations staffing in Indiana. To combat this problem, one of two different policies is recommended for implementation:

- Transition from 16-hour weigh station shifts to around-the-clock shifts at weigh stations. This would raise the annual cost for motor carrier inspectors to $12.9 million, although substantial cost savings could be realized if the current group of motor carrier inspectors is scheduled for longer or more frequent shifts instead, if hiring new inspectors.
- Maintain the current 16-hour shifts at weigh stations but implement a randomized scheduling process for the individual shifts. If truck drivers cannot accurately predict the times and locations when weigh stations will not be staffed, they will be unable to continue a systematic policy of moving overweight loads. While the logistics of this policy are unknown (e.g., a certain amount of confidentiality would be required amongst motor carrier inspectors and administrators to ensure that the scheduling process is not known to trucking operators), it is not expected to lead to a significant increase in staffing costs.

Note that these staffing recommendations are made on the basis of INDOT's current network of weight enforcement facilities only. It is entirely feasible that with the expanded use of WIMs and Virtual Weigh Stations, such drastic staffing changes need not be made, particularly if such automated facilities allows officials to develop a targeted plan for adjusting staffing hours at individual sites based on daily distributions of weight violators.

Figure 16.7 also shows a sampling of overweight commercial vehicles on the eastbound I-80/94 corridor in Indiana, from January to March of 2002. This data was collected by WIM scales along the corridor, and provides information which can be useful in further

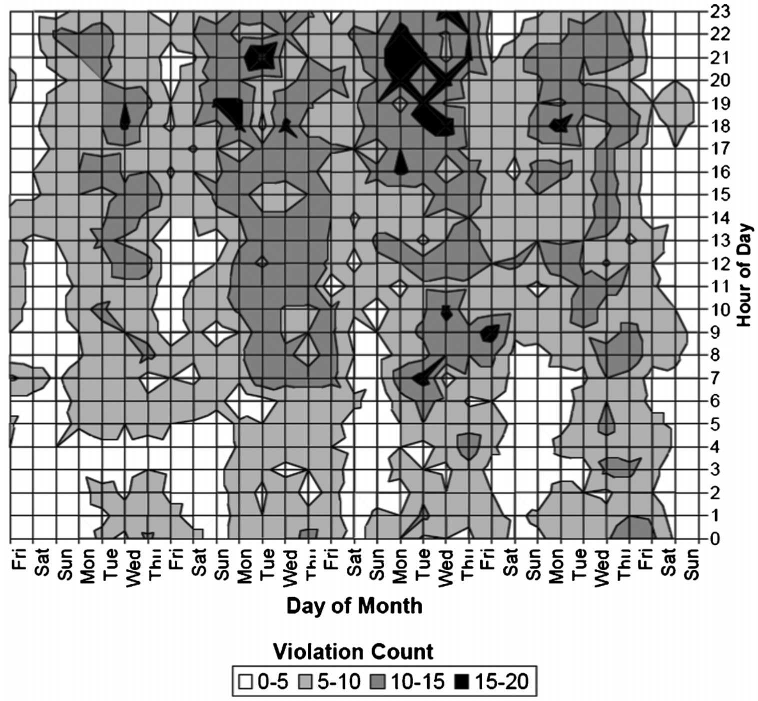


Figure 16.6 Distribution of overweight truck violations by time of day and day of the month in Indiana (*211*).

refining the staffing recommendations contained within this report. Regardless of the decisions made for virtual weigh station construction, it is recommended that similar WIM data be collected from existing scales for all routes in the state that contain static weigh facilities, and that this data be reviewed periodically to ensure that staffing patterns are optimally fulfilling the needs and travel patterns of overweight vehicles.

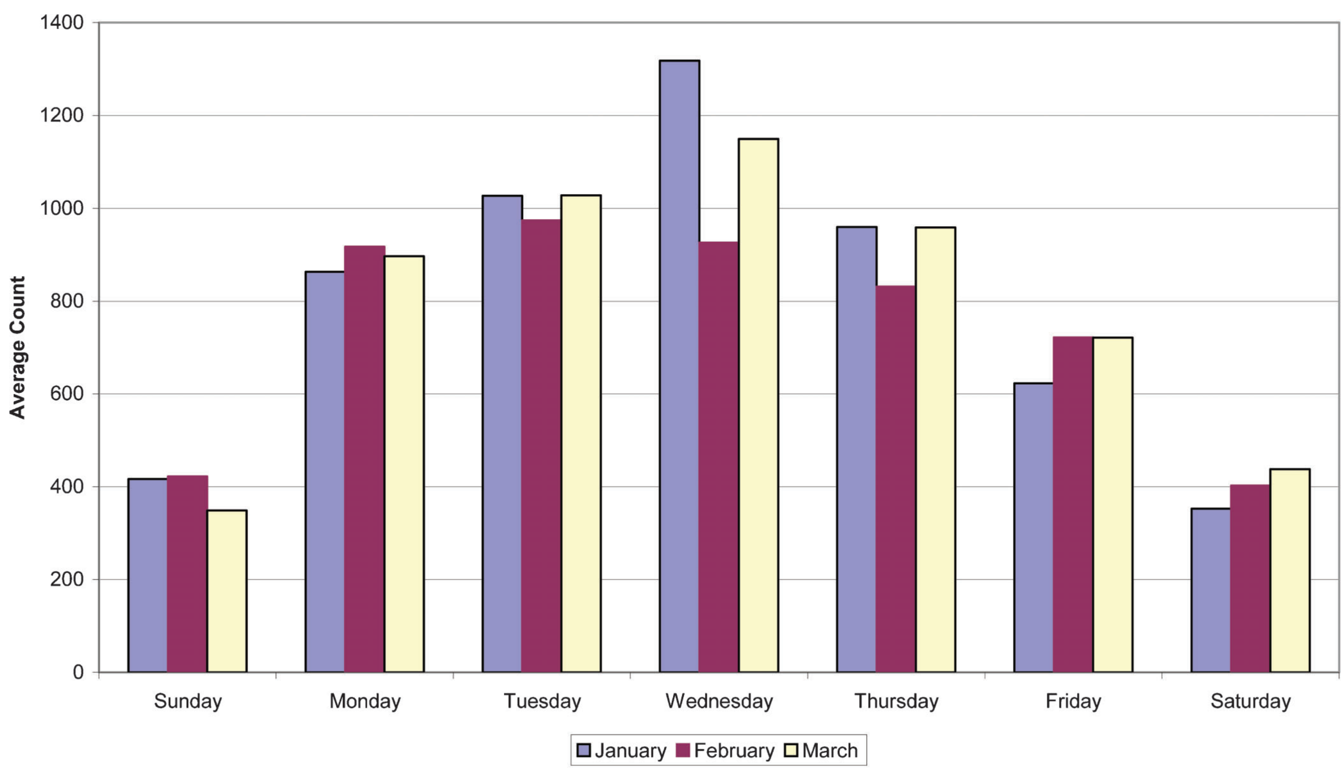


Figure 16.7 Overweight commercial vehicle counts from WIM scales, I-80/94 corridor, January–March 2002.

16.3 Mobile Enforcement

With respect to the deployment of commercial vehicle enforcement officers across the state, there are several recommendations that can be made to enhance their effectiveness. The first recommendation is to review the allocation of officers across the various districts, and assess whether there is an imbalance between manpower and need in any locations. In a previous section, it was discussed that over the past decade, the patrol hours for law enforcement have slightly increased while the number of trucks weighed and measured has substantially decreased. While this may be in large part due to staffing reductions at the static weigh stations, it is prudent to review the current efforts and placement of mobile law enforcement officers as well, and reallocate them to the highway corridors with the greatest volumes of truck traffic or highest historical rates of weight violation. Furthermore, a thorough audit should be conducted within the division to identify the various duties that these officers perform on a daily basis, in order to ensure that their time spent on patrol for weight, length, and safety violations is maximized.

A second recommendation relates to the construction of new static weigh stations around the state. Until these stations become usable, it is recommended that the commercial vehicle enforcement officer pool be temporarily increased, in order to accommodate the additional patrols that are needed to ensure thorough and complete enforcement of the state's commercial vehicle regulations. Once the new weigh stations are open, this force can be gradually reduced, although it should not be reverted exactly back to current levels, given the continued expectation of growth in commercial truck traffic on Indiana highways. A detailed forecasting study of these growth patterns, along with the most effective annual miles of coverage for individual officers, should supplement this report in order to provide a more precise estimate of mobile enforcement demand.

16.4 Discussions

16.4.1 Truck Inspections

As previously discussed, in addition to duties pertaining to weight enforcement, commercial vehicle enforcement officers and motor carrier inspectors are responsible for inspecting commercial vehicles for length and safety violations, in order to reduce the number of fatal and injury crashes on the highways (both those between commercial and passenger vehicles, and those involving commercial vehicles only). This section briefly discusses recommendations for a follow-up study of truck inspection process, and the possibility of incorporating weight enforcement with current inspection procedures.

16.4.2 Inspection Buildings

Currently, six of the seven functioning static weigh stations have an enclosed inspection building. These buildings, which are typically located immediately adjacent to static scales, provide a controlled environment in which safety and length inspections can be professionally and reliably conducted. Without these structures, motor carrier inspectors and commercial vehicle enforcement officers are at the mercy of the elements when conducting vehicle inspections; this could severely reduce their capacity to efficiently perform their duties. It is recommended that a review be carried out of all of the current inspection buildings around the state, and that new buildings should be constructed at the stations that lack such shelter, for an estimated cost of $300,000 each. Existing structures should be rehabilitated as needed.

16.4.3 Federal Funding

The Indiana Commercial Motor Vehicle Enforcement Division receives the majority of its funding for vehicle safety inspections from the Federal Motor Carrier Safety Administration (FMCSA), through its Motor Carrier Safety Assistance Program (MCSAP). The principal goal of MCSAP is to reduce crashes, fatalities, and injuries from commercial motor vehicles by consistently and effectively enforcing FMCSA-developed safety regulations. By investing money in various safety and inspection programs that are carried out by state police and transportation agencies, the FMCSA takes a proactive approach in reducing the number of dangerous drivers and commercial vehicles on the nation's highways (*213*). In 2008, the last year for which data is available, the state of Indiana received approximately $5.7 million from MCSAP in order to implement various safety and inspection programs, including the inspections carried out by the Commercial Vehicle Enforcement Division (*212*).

16.4.4 Tie-in with Overweight Trucks

Unfortunately, there are currently no federal programs which explicitly provide funding for implementing programs to enforce weight regulations at the state level. However, it is recommended that INDOT and the Indiana State Police investigate the feasibility of incorporating weight measurement into the safety inspection process prescribed by the FMCSA. Such a program would allow Indiana to achieve a substantially higher rate of compliance from overweight vehicles, not only because more trucks would be weighed, but also because more motor carrier inspectors and state troopers could be hired with the combined state and federal funding.

16.4.5 Correlation between Safety and Weight Violations

It is also recommended that INDOT investigate the feasibility of funding a study to explore the relationship between overweight commercial vehicles and safety violations. Anecdotal evidence seems to suggest that trucks found in violation of weight regulations at any given time, are more likely to have a history of prior weight violations, and more importantly, safety-related issues; however, little or no research has been done to verify and quantify this hypothesis at various areas of the country. Any evidence of a relationship between excess weight or weight violations and safety could be used to better identify specific groups of commercial vehicles for focus during compliance checking, and to petition the FMCSA for increased funding to implement the strategy.

This is an issue that the FMCSA is very interested in supporting, as evidenced by the recent announcement of a cooperative research opportunity as part of the Specialized Heavy Vehicle Initiative (SHVI) which aims to address this issue (*214*).

16.5 Possible Future Directions in Truck Monitoring/Inspections

The Federal Highway Administration (FHWA) and Federal Motor Carrier Safety Administration (FMCSA) have joined together in partnership to support the Smart Roadside Initiative (SRI) in a bid to help address the growing issues associated with truck weight and size enforcement. SRI was designed, in part, to extend truck inspection capabilities away from the traditional fixed site environment to the roadside. As stated in FHWA literature, the vision for SRI is one in which commercial vehicles, motor carriers, enforcement resources, highway facilities, intermodal facilities, and toll facilities collect data for their own purposes and share the data seamlessly in order to improve motor carrier safety, operational efficiency, and freight mobility. It is envisaged that this vision is achievable using interoperable technology and information sharing between in-vehicle, on-the-road, and freight facility systems (*215*).

In augmenting existing truck inspections with technology, it is expected that the following benefits will be realized: reduced infrastructure damage caused by overloading; increased safety in highway operations; reduced overall highway-based vehicle emissions; reduced transport costs and enhanced global competitiveness; and substantially decreased time between inspections.

The key elements of SRI include the development, testing, and deployment of advanced technologies that accurately measure commercial vehicles while they are in motion; determine a motor carrier's or commercial vehicle's compliance with Federal and State size and weight, safety, and credentialing regulations; and target enforcement at noncompliant/high-risk motor carriers and commercial vehicles. Two key components of these SRI elements are wireless roadside inspections and virtual weigh stations. The wireless roadside inspection increases the frequency of roadside safety inspections by using on-board systems and roadside and communication technologies, and virtual weigh stations increase the frequency of roadside size and weight measurements through the expanded monitoring of bypass, secondary, remote, and urban routes and targeting of enforcement action on high-risk carriers and vehicles. Depending on their configuration, virtual weigh stations also have the potential to increase the frequency with which a motor carrier's/commercial vehicle's compliance with Federal and State safety and credential regulations is verified (*191*).

FHWA and Cambridge Systematics interviewed stakeholders from nine states that are at the forefront of the deployment of roadside enforcement systems. Site visits were conducted in four of these states. During the course of these interviews and visits, several standard applications of roadside technologies were identified. These standard deployments include: Traffic monitoring WIM systems; Mobile screening at WIM sites; Virtual weigh stations; Fixed site-based mainline weight screening; and Ramp (not mainline) WIM systems.

Despite the potential of advanced technologies to dramatically improve the effectiveness and efficiency of roadside enforcement operations, a number of challenges commonly confront states that attempt to deploy these systems. These challenges include cost; manpower requirements; interagency cooperation; data issues; technology performance; funding; and lack of standards/architecture. A number of states have employed certain strategies to successfully overcome these challenges. Also, there exists program support that could potentially be offered by FHWA to help states overcome these challenges. These are all detailed in a recent report on a research carried out by Cambridge Systematics for the FHWA (*191*).

Also, the state of Indiana could sponsor, on a 3–4 year cycle, the relevant personnel at INDOT, INDOR, and/or the state police, to attend relevant FHWA-sponsored courses implemented by the National Highway Institute, such as "Principles of Effective Commercial Motor Vehicle (CMV) Size and Weight Enforcement." This 2-day course provides advanced, in-depth, understanding of federal motor vehicle size and weight regulations and the importance of vehicle size and weight enforcement programs at the state level. The course targets transportation professionals that oversee the preservation of federal and state highway assets through annual vehicle size and weight (VSW) enforcement planning and federal certification. The course provides techniques and strategies designed for those individuals working to implement VSW enforcement programs. The cost of the course is $400.

PART IV. APPENDIX A. FHWA VEHICLE CLASSES WITH DEFINITIONS

1. **Motorcycles (Optional):** All two or three-wheeled motorized vehicles. Typical vehicles in this category have saddle type seats and are steered by handlebars rather than steering wheels. This category includes motorcycles, motor scooters, mopeds, motor-powered bicycles, and three-wheel motorcycles. This vehicle type may be reported at the option of the State.
2. **Passenger Cars:** All sedans, coupes, and station wagons manufactured primarily for the purpose of carrying

passengers and including those passenger cars pulling recreational or other light trailers.

3. **Other Two-Axle, Four-Tire Single Unit Vehicles:** All two-axle, four-tire, vehicles, other than passenger cars. Included in this classification are pickups, panels, vans, and other vehicles such as campers, motor homes, ambulances, hearses, carryalls, and minibuses. Other two-axle, four-tire single-unit vehicles pulling recreational or other light trailers are included in this classification. *Because automatic vehicle classifiers have difficulty distinguishing class 3 from class 2, these two classes may be combined into class 2.*
4. **Buses:** All vehicles manufactured as traditional passenger-carrying buses with two axles and six tires or three or more axles. This category includes only traditional buses (including school buses) functioning as passenger-carrying vehicles. Modified buses should be considered to be a truck and should be appropriately classified. NOTE: In reporting information on trucks the following criteria should be used:

   a. Truck tractor units traveling without a trailer will be considered single-unit trucks.
   b. A truck tractor unit pulling other such units in a "saddle mount" configuration will be considered one single-unit truck and will be defined only by the axles on the pulling unit.
   c. Vehicles are defined by the number of axles in contact with the road. Therefore, "floating" axles are counted only when in the down position.
   d. The term "trailer" includes both semi- and full trailers.

5. **Two-Axle, Six-Tire, Single-Unit Trucks:** All vehicles on a single frame including trucks, camping and recreational vehicles, motor homes, etc., with two axles and dual rear wheels.
6. **Three-Axle Single-Unit Trucks:** All vehicles on a single frame including trucks, camping and recreational vehicles, motor homes, etc., with three axles.
7. **Four or More Axle Single-Unit Trucks:** All trucks on a single frame with four or more axles.
8. **Four or Fewer Axle Single-Trailer Trucks:** All vehicles with four or fewer axles consisting of two units, one of which is a tractor or straight truck power unit.
9. **Five-Axle Single-Trailer Trucks:** All five-axle vehicles consisting of two units, one of which is a tractor or straight truck power unit.
10. **Six or More Axle Single-Trailer Trucks:** All vehicles with six or more axles consisting of two units, one of which is a tractor or straight truck power unit.
11. **Five or fewer Axle Multi-Trailer Trucks:** All vehicles with five or fewer axles consisting of three or more units, one of which is a tractor or straight truck power unit.
12. **Six-Axle Multi-Trailer Trucks:** All six-axle vehicles consisting of three or more units, one of which is a tractor or straight truck power unit.
13. **Seven or More Axle Multi-Trailer Trucks:** All vehicles with seven or more axles consisting of three or more units, one of which is a tractor or straight truck power unit.

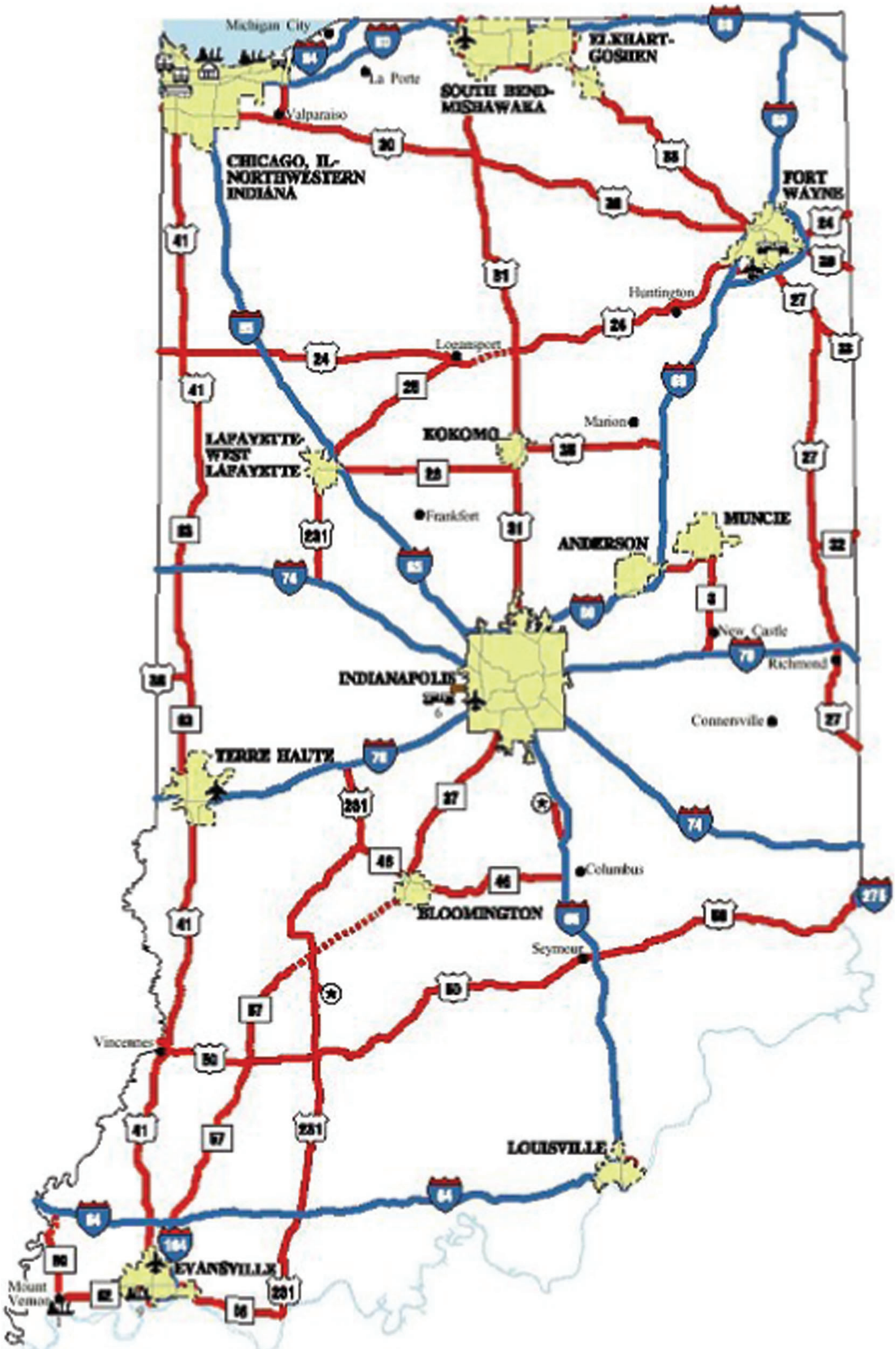


Figure IV.B.1 Indiana's National Highway System.

Indiana State Police Troopers

RANK	0	1	2	3	4	5	6	7	8	9
Trooper Trainee	$36,852									
(Biweekly)	*$1,417.40*									
Probationary Trooper	$38,444									
(Biweekly)	*$1,478.60*									
Trooper		$40,100	$41,132	$42,164	$43,199	$44,850	$4[illegible],848	$46,348	$47,[illegible]98	$48,448
(Biweekly)		*$1,542.30*	*$1,582.00*	*$1,621.70*	*$1,661.50*	*$1,725.00*	*$1,[illegible]3.40*	*$1,782.60*	*$1,8[illegible]3.00*	*$1,863.40*
Corporal			$42,999	$44,998	$46,998	$48,498	$49,499	$50,500	$51,498	$52,499
(Biweekly)			*$1,653.80*	*$1,730.70*	*$1,807.60*	*$1,865.30*	*$1,903.80*	*$1,942.30*	*$1,980.70*	*$2,019.20*
Sergeant		[illegible]	$49,000	$51,498	$53,999	$56,498	$58,500	$59,498	$60,499	$60,999
(Biweekly)		[illegible]	*$1,884.60*	*$1,980.70*	*$2,0[illegible]*	[illegible]	[illegible]	*$2,288.40*	*$2,326.90*	*$2,346.10*
First Sergeant		[illegible]	$52,000	$54,998	$57[illegible]	[illegible]	[illegible]	$62,000	$62,998	$63,500
(Biweekly)		[illegible]	*$2,000.00*	*$2,115.30*	*$2,1[illegible]*	[illegible]	[illegible]	*$2,384.60*	*$2,423.00*	*$2,442.30*
Lieutenant			$54,998	$57,499	$59[illegible]	[illegible]	[illegible]	$64,498	$65,499	$65,998
(Biweekly)			*$2,115.30*	*$2,211.50*	*$2,2[illegible]*	[illegible]	[illegible]	*$2,480.70*	*$2,519.20*	*$2,538.40*
Captain			$57,000	$59,498	$61,498	$63,500	$65,499	$66,498	$67,499	$67,998
(Biweekly)			*$2,192.30*	*$2,288.40*	*$2,365.30*	*$2,442.30*	*$2,519.20*	*$2,557.60*	*$2,596.10*	*$2,615.30*
Major			$59,998	$62,499	$64,498	$66,498	$68,500	$69,498	$70,499	$71,500
(Biweekly)			*$2,307.60*	*$2,403.80*	*$2,480.70*	*$2,557.60*	*$2,634.60*	*$2,673.00*	*$2,711.50*	*$2,750.00*
Lieutenant Colonel			$66,999	$70,000	$71,999	$75,598	$76,248	$77,350	$78,499	$79,300
(Biweekly)			*$2,576.90*	*$2,692.30*	*$2,769.20*	*$2,907.60*	*$2,932.60*	*$2,975.00*	*$3,019.20*	*$3,050.00*
Colonel			$73,999	$76,500	$78,499	$82,498	$83,148	$84,149	$85,150	$85,998
(Biweekly)			*$2,846.10*	*$2,942.30*	*$3,019.20*	*$3,173.00*	*$3,198.00*	*$3,236.50*	*$3,275.00*	*$3,307.60*

44 total employed

These two pay grades are averaged

Motor Carrier Inspectors

Rank	Trainee	1	2	3	4	5	6	7	8	9	10
MCI											
Annual	$27,4[illegible]	[illegible]	[illegible]7	$32,958	$35,220	$37,619	$38,165	$38,672	$38,867	$39,354	$41,421
Biweekly	$1,055.[illegible]	[illegible]	[illegible]0	$1,267.60	$1,354.60	$1,446.90	[illegible]	[illegible]	[illegible]	$1,513.60	$1,593.10
District Coordinator											
Annual		[illegible]	[illegible]7	$34,921	$37,034	$39,148	[illegible]	[illegible]	[illegible]	$47,60[illegible]	$49,712
Biweekly		[illegible]	[illegible]0	$1,343.10	$1,424.40	$1,505.70	[illegible]	[illegible]	[illegible]	$1,830.8[illegible]	$1,912.00
Zone Coordinator											
Annual		[illegible]	[illegible]6	$36,644	$39,060	$41,475	$43,893	$46,309	$48,724	$51,142	$53,557
Biweekly		[illegible]	[illegible]0	$1,409.40	$1,502.30	$1,595.20	$1,688.20	$1,781.10	$1,874.00	$1,967.00	$2,059.90
MCI Administrator											
Annual		[illegible]	[illegible]8	$39,268	$41,857	$44,450	$47,039	$49,629	$52,221	$54,811	$57,400
Biweekly		[illegible]	[illegible]0	$1,510.30	$1,609.90	$1,709.60	$1,809.20	$1,908.80	$2,008.50	$2,108.10	$2,207.70

42 total employed

3 total employed

4 total employed

These salaries are averaged

Figure IV.C.1 Indiana state employee pay matrices.

Enforcement	1,226
Civilian	562
TOTAL	1,788

Figure IV.D.1 Total civilian and enforcement employment. (Source: (*182*).)

Rank	Percent of Total	Total within Rank
Superintendent	.08	1
Colonel	.08	1
Lieutenant Colonel	.30	4
Major	1.10	14
Captain	1.50	18
Lieutenant	3.30	40
Sergeant Major	.08	1
First Sergeant	4.70	57
Sergeant	16.80	206
Corporal	1.00	13
Trooper	71.00	871
TOTAL	100.00	1,226

Figure IV.D.2 Number of Indiana State Police officers by rank. (Source: (*182*).)

	Assigned to GHQ	Assigned to GHQ-Field
Office of the Superintendent	4	9
Office of the Assistant Superintendent	1	1
Office of Professional Standards	2	5
Deputy Superintendent of Enforcement	1	2
Capitol Police Section	0	3
Commercial Vehicle Enforcement Division	0	81
Human Resources Division	4	0
Operations Support Division	[illegible]	33
Special Operations (ERS/Special Events)	[illegible]	40
Deputy Superintendent of Financial Management	1	0
Facilities Management	0	1
Fiscal Division	0	0
Continuous Improvement Section	0	3
Logistics Division	0	1
Deputy Superintendent of Investigations	1	0
Criminal Investigation Division	7	210
Fusion Center	1	7
Training Division	5	2
Deputy Superintendent of Support Services	1	0
Criminal Justice Data Division	5	4
Laboratory Division	0	37
Public Information Office	0	20
Records Division	5	0
TOTAL	43	459

Now 93 (as of 2012)

Figure IV.D.3 General Headquarters (GHQ) manpower allocation. (Source: (*182*).)

	Capt.	Lt.	F/Sgt.	Sgt.	Cpl.	Tpr.	TOTAL
Area I	1						1
District 13 - Lowell		1	1	8	2	62	74
District 14 - Lafayette		1	1	4		35	41
District 16 - Peru		1	1	4	1	30	37
Area II	1						1
District 21 - Toll Road		1	1	7		58	67
District 22 - Fort Wayne		1	1	6		48	56
District 24 - Bremen		1	1	4		37	43
District 25 - Redkey		1	1	3	1	28	34
Area III	1						1
District 32 - Terre Haute		1	1	4	3	30	39
District 33 - Bloomington		1	1	4	1	31	38
District 34 - Jasper		1	1	4		32	38
District 35 - Evansville		1	1	5	1	45	53
Area IV	1	1					2
District 41 - Connersville		1	1	3	1	28	34
District 42 - Versailles		1	1	5	1	27	35
District 43 - Seymour		1	1	4	1	33	40
District 45 - Sellersburg		1	1	5	2	44	53
Area V	1						1
District 51 - Pendleton		1	1	4	1	35	42
District 52 - Indianapolis		1	1	8		61	71
District 53 - Putnamville		1	1	3	1	30	36
TOTAL	**5**	**19**	**18**	**85**	**16**	**694**	**836**

Figure IV.D.4 District Traffic Enforcement manpower allocation. (Source: (*216*).)

Enforcement Personnel Resignations

Rank	Number	Average Years of Service
Trooper Trainee	12	> 1
Probationary Trooper	1	> 1
Trooper	18	7.4
Sergeant	1	9
First Sergeant	1	10
Lieutenant	1	8

Figure IV.D.5 Average years of service for Indiana State Troopers. (Source: (*217*).)

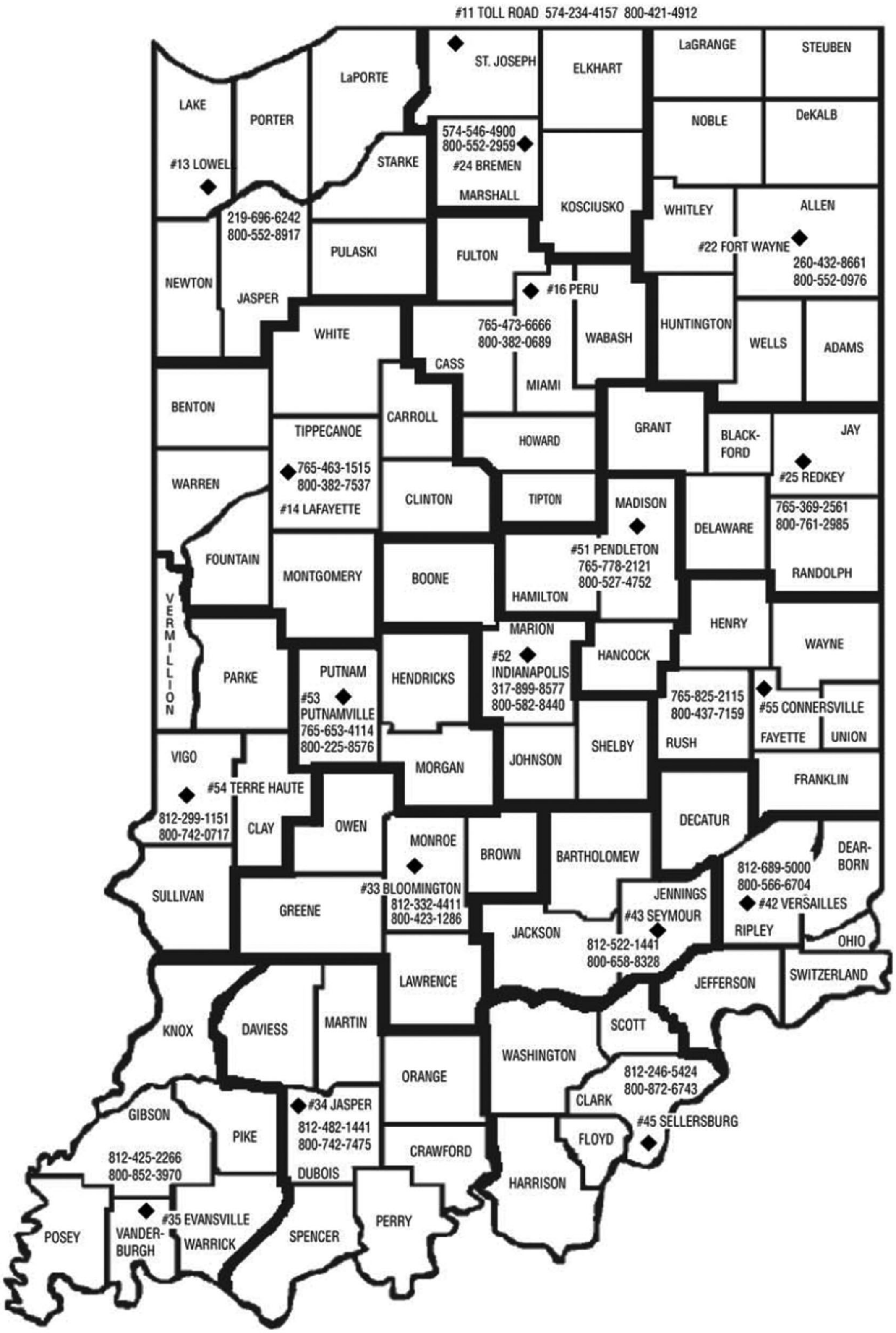


Figure IV.E.1 Map of traffic enforcement districts in Indiana.

PART IV. APPENDIX F. INDIANA STATE ENFORCEMENT CERTIFICATION (SOURCE: FHWA)

FHWA Operations Vehicle Size and Weight Enforcement - State Enforcement Certificati... Page 1 of 2

VEHICLE SIZE AND WEIGHT ENFORCEMENT

State Enforcement Certification

Indiana 2009

Statement:

At the Governor¿s request and in response to the requirements of 23 U.S.C., I am submitting Indiana¿s Annual Certification of Enforcement for Fiscal Year 2008 (October 1, 2008 through September 30, 2009). This certification and supporting documentation provides the information to address the requirements of 23 CFR 657.

I, Michael W. Reed, Commissioner, INDOT of the State of Indiana do hereby certify:

(1) That all State laws and regulations governing size and weight are being enforced on those highways which, prior to October 1, 1991, were designated as part of the Federal-Aid Primary, Federal-Aid Secondary, or Federal-Aid Urban systems;

(2) That the State is enforcing the freeze provisions of the Intermodal Surface Transportation Efficiency Act of 1991 [23 U.S.C. 127(d) and 49 U.S.C. 31112]; and

(3) That all State laws governing vehicle weight on the Interstate System are consistent with 23 U.S.C. 127 (a) and (b).

Attached to this document is a letter from Governor Mitchell E. Daniels, Jr. designating me as the official to make the certification statement and to submit the certification document. The certification contains all the elements required by Title 23 CFR Part 657. If you have any questions you may contact me at (317) 232-5526

Copy of the document designating the official:

Copy of delegation letter is attached.

Copy of any State law or regulation pertaining to vehicle size and weight adopted since the State's last certification:

None

Actual operations as compared with those forecasted by the plan:

Scale Types	Forecasted Number	Actual Number
Fixed platform scales	0	330,126
WIM scales	0	382,255
Portable scales	0	1,823
Semi-portable scales	0	0

Impacts of the process as actually applied:

Violation Type	Current Year	Last Year
Oversize	0	0
Overweight	2,671	2,578

Measures of activity:

(1) Vehicles weighed

Scale Type	Number of Vehicles Weighed
Fixed platform scales	330,126

Figure IV.F.1 Indiana State Enforcement Certification 2009.

FHWA Operations Vehicle Size and Weight Enforcement - State Enforcement Certificati... Page 2 of 2

WIM scales	382,255
Portable scales	1,823
Semi-portable scales	0

(2) Penalties

Violation Type	Number of Citations or Civil Assessments
Axle	1,836
Gross	773
Bridge formula	62

Number of vehicles whose loads are either shifted or offloaded

Load shifting	844
Offloading	248

(3) Number of permits issued for overweight loads

Permit Type	Number Issued
Non-divisible trip permits	216,405
Non-divisible annual permits	1,917
Divisible trip permits	65,019
Divisible annual permits	2,914

Attached Document:

Signed Certification Letter.pdf (Certification Letter)
Delegation Letter.pdf (Letter of Delegation)

To view the document, you may need to download the following software:
Adobe Acrobat

FHWA

Figure IV.F.1 Continued.

VEHICLE SIZE AND WEIGHT ENFORCEMENT

State Enforcement Certification

Indiana 2010

Statement:
A copy of the INDOT Commissioner's letter certifying compliance to 23 CFR 657 is attached.

Copy of the document designating the official:
A copy of the delegation letter is attached.

Copy of any State law or regulation pertaining to vehicle size and weight adopted since the State's last certification:
None

Analysis of the changes made:
No Changes made

Actual operations as compared with those forecasted by the plan:

Scale Types	Forecasted Number	Actual Number
Fixed platform scales		424,987
WIM scales		1,021,494
Portable scales		2,673
Semi-portable scales		0

Impacts of the process as actually applied:

Violation Type	Current Year	Last Year
Oversize		
Overweight	4,030	2,671

Measures of activity:
(1) Vehicles weighed

Scale Type	Number of Vehicles Weighed
Fixed platform scales	424,987
WIM scales	1,021,494
Portable scales	2,673
Semi-portable scales	0

(2) Penalties

Violation Type	Number of Citations or Civil Assessments
Axle	3,054
Gross	924
Bridge formula	52

Number of vehicles whose loads are either shifted or offloaded

Load shifting	744
Offloading	217

Figure IV.F.2 Indiana State Enforcement Certification 2010.

FHWA Operations Vehicle Size and Weight Enforcement - State Enforcement Certificati... Page 2 of 2

(3) Number of permits issued for overweight loads

Permit Type	Number Issued
Non-divisible trip permits	177,651
Non-divisible annual permits	6,115
Divisible trip permits	67,850
Divisible annual permits	2,467

Attached Document:

FHWA OSOW Delegation Letter 1-20-11.pdf (Governor's Delegation Letter)
FHWA Cert Letter Signed 3-23-11.pdf (INDOT Certification Letter 3/23/11)

To view the document, you may need to download the following software:
Adobe Acrobat

FHWA

Figure IV.F.2 Continued.

FHWA Operations Vehicle Size and Weight Enforcement - State Enforcement Plan printa... Page 1 of 3

VEHICLE SIZE AND WEIGHT ENFORCEMENT

State Enforcement Plan

Indiana 2011

Fixed platform scales:
- **Total number:** 10
- **Locations:**
- I-65 SB Lake County- located north of SR2, near Lowell
- I-65 NB jackson County- located north of US 50, near Seymour
- I-65 SB Jackson County- located north of US 50, near Seymour
- I-69 SB Huntington County-located north of SR 5 at SR124, ten (10) miles south of Huntington.
- I-70 WB Wayne County-located west of US 35, one (1) mile west of Richmond.
- I-74 EB Fountain County- located east of US41, fifteen (15) miles northwest of Crawfordsville.
- I-74 WB dearborn County- located at the Indiana / Ohio state line.
- I-94 EB Porter County-located two(2) milesnortheast of Chesterton.
- I-94 WB Porter County- located two(2) miles northeast of Chesterton.
- I-70 EB Vigo County- located at the Indiana Illinois state line.
- **Public Private:**

Portable wheel weigher scales:
- **Number:** 289
- **Type:**
- Haenni Low Profile scales 4 scales per car.

Semiportable or ramp scales:
- **Number:** 0
- **Type:**

Weigh-in-motion (WIM) equipment:
- **Total number:** 6
- **Locations:**
- I-94 Porter County (2)
- I-65 Lake County (1)
- I-70 Wayne county (1)
- I-74 Dearborn County (1)
- I-70 Vigo County (1)

Enforcement Agencies:

Agencies:

The enforcement of truck size and weight limits in the State of Indiana is a partnership arrangement between the Indiana State Police, the Indiana Department of Transportation and the Indiana State Board of Health, Division of Weights and Measures. The Indiana State Police is responsible for the enforcement of the federal and state laws. The Department of Transportation historically has been responsible for the purchase and maintenance of weighing equipment. The State Board of Health, Division of Weights and Measures, has the responsibility for certifying the weigh scales, both permanent and portable.

Lead agency:

Indiana State Police Commercial Vehicle Enforcemen

Personnel numbers from respective agencies assigned to weight enforcement:

Total number: 105

Description:

41 MCI'S / 64 Troopers

Presently, there are fortyone(41) Motor Carrier Inspector positions. However, of the 41 positions seven(7)are supervisors. MCI's are assigned to the permanent and portable scale operations throughout the state. The Motor Carrier Inspectors are supervised by Area Coordinators. The Area

Figure IV.F.3 Indiana State Enforcement Certification 2011.

Coordinators are supervised by the Assistant MCI Administrator. The MCI Assistant Administrator is supervised by the MCI Administrator,who reports to the Captain. The sixtyfour troopers assist with size and weight enforcement throughout the state as well as at the scale facilities.

Funding:

Facilities total: $0

Facilities detail:

The total annual costs for only size and weight enforcement is approximately $1,770,038.00. These figures are budgeted and do not necessarily reflect active costs incurred.

Personnel total: $1,770,038

Personnel detail:

The above cost figure reflects only salaries and fringe benefits for those units assigned to size and weight enforcement.

Total: $1,770,038

Proposed plan of operation, including geographical coverage and hours of operation, in general terms:

Proposed schedule of operation of fixed scale equipment:

Average 12 hours a day 5 days a week

Strategy for prevention of bypassing of fixed weighing facility location:

Portable scales are operated a minimum of eight (8) hours per day, five (5) days per week to allow for various traffic patterns. The portable scales are used in conjunction with the permanent scales to deter trucks using bypass routes.

Proposed schedule of deployment of portable scale equipment:

4 portable in each commission for a total of 200 units. With the exception of units assigned to the Toll Road which carry 6 units per car.

Proposed schedule of deployment of semi-portable equipment:

n/a

Policy and practices with respect to overweight violators:

Overweight violators:

Enforcement Action Taken on all Overweight violations detected.

Offloading requirements for divisible loads:

Offloading required if load cannot be made legal.

Administrative variance from the legal requirement (if offloading is mandatory by law):

N/A

Administrative guidelines (if off-loading is permissible by law):

Whenever a vehicle is found in excess of the legal limit, the vehicle is held until such time it is made legal. This can be done in three (3) ways:

1. By moving the axles to redistribute the weight;
2. To move the product on the vehicle to redistribute; or
3. To unload the excess.

Policy and practices with respect to penalties:

Penalties:

Indiana law provides a penalty for truck related violations. Violations of the Federal Motor Carrier Safety Regulations (FMCSR) along with Indiana regulatory issues are punishable as Class B infractions with a maximum fine of $1000.00. All other truck related violations, with the exception of overweight, are punishable as a Class C infraction with a maximum fine of $500.00.

Overweights are punishable in the following manner:

1. Up to 5,000 lbs overweight is a Class C Infraction with a maximum fine of $500.00;
2. 5,001 lbs to 10,000 lbs overweight is a Class B. Infraction with a maximum fine of $1000.00;
3. And 10,001 lbs or more overweight is a Class A Infraction with a maximum fine of $10,000.00.

After the officer makes the arrest for the violations, the courts are responsible for the fine assessment. The courts may also suspend the registration of the vehicle up to ninety (90) days and may recommend suspension of the license in excessive overweight gross weight violations.

Penalties for repeated violations:

Figure IV.F.3 Continued.

N/A
Administrative directives, booklets or other written criteria:
N/A

Policy and practices with respect to special permits for overweight:
Policy and practices:
See Oversize and Overweight Permit Manual.
Administrative directives, booklets or other written criteria:
See Oversize and Overweight Permit Manual.

Changes in Vehicle Size and Weight Laws and Regulations:
None.

Goals:
Short term:
The short-term goals identified are to be completed within the 2010-2011 Fiscal Year. To conduct at least one (1) special enforcement project in Northern Indiana focused on apprehending overweight steel haulers.
Medium term:
Design and implement a comprehensive information system for all permanent scale facilities that integrates all motor carrier related activities in Indiana. Such a system would include INDOT, Department of Revenue, Bureau of Motor Vehicles and Indiana State Police, incorporating oversize/overweight permits, proper registration, and insurance requirements. This information could be accessed at the scale facility by utilizing a computer and modem system. Upgrade the current Prepass system.
Long term:
Continue to acquire size and weight enforcement tools at scale facilities. Items to be considered for installation would include transponders, WIM equipment and height detectors; ITS CVO technology and remote sensors to detect violations on by-pass routes commonly known as virtual scales. In addition upgrade each scale facility to incorporate in line WIM's coupled with the Prepass system.
Provision for annual review and update of vehicle size and weight enforcement plan:

Evaluation of enforcement operations:
N/A

FHWA

Figure IV.F.3 Continued.

PART V. REVENUE ANALYSIS

17. INTRODUCTION

It is important for a state to have knowledge of how much revenue can be generated from a truck permit scheme. Two levels of aggregation were used for the analysis. First a simple trend analysis was carried out to predict the revenue expected from truck permitting if the current permit rates and permit request volumes follow the trend they have been following over the past decade.

17.1 Aggregate Revenue

Figure 17.1 presents the cumulative monthly revenue streams for Indiana in 2008 and the first part of 2009, from the issuance of overweight and oversize permits. From the issuance of overweight and oversize permits, the figure shows that in 2008, just over $14 million was collected. The source data is from the Indiana Department of Revenue. The trends for 2009 suggest that a slightly lower amount will be obtained. From a rough extrapolation of the 2009 data, it seems that the state will collect approximately $12 million by the end of 2009. The difference between 2008 and 2009 could be attributed to the recessive state of the economy in the latter year.

Table 17.1 and Figure 17.2 present the yearly revenue streams from extra-legal truck operations in Indiana from Year 2002 to 2006 and part of 2007. The source data is from the Indiana Department of Revenue. The figure shows that the annual amount collected is approximately $12 million.

The next step would be to ascertain whether this amount covers the sum of the pavement and bridge damage cost and the expenditure incurred in the administration of the permitting process. While the case study in a subsequent chapter provides a methodology for answering this issue for a hypothetical trucker, the analysis could be extended to the entire state in a future research study.

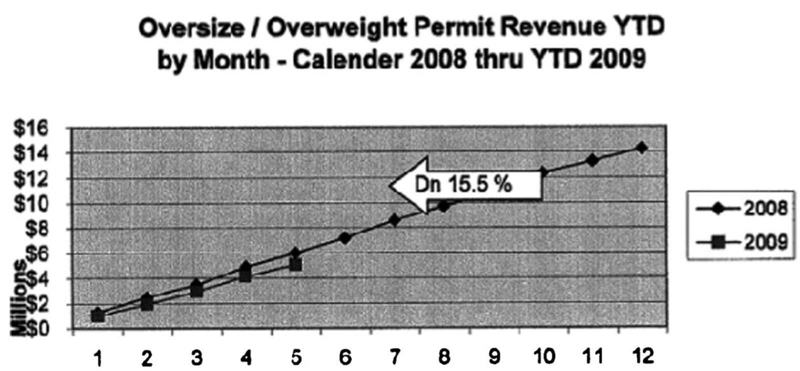


Figure 17.1 Cumulative monthly revenue streams (in $millions) from overweight/oversize truck operations in Indiana, years 2008 and 2009 (partial).

TABLE 17.1
Yearly Revenue Streams from OSW Truck Operations in Indiana, 2002–2009

	2002	2003	2004	2005	2006	2007	2008	2009
January	$1,258,036	$1,162,141	$976,927	$949,931	$1,016,483	$1,142,243	$1,282,549	$1,013,324
February	$695,353	$578,608	$687,268	$1,100,233	$1,225,636	$461,664	$1,189,449	$920,415
March	$677,994	$788,729	$861,011	$917,367	$949,984	$763,568	$994,771	$1,017,590
April	$1,091,486	$1,104,585	$1,164,910	$907,877	$834,369	$660,230	$1,435,513	$1,191,024
May	$1,199,505	$760,533	$635,277	$1,083,217	$1,556,480	$819,032	$1,116,064	$941,679
June	$834,912	$755,190	$1,184,574	$951,632	$963,147	$565,541	$1,180,131	$1,063,284
July	$1,319,582	$1,438,807	$1,330,948	$1,071,073	$1,512,325	$750,370	$1,391,342	$1,218,774
August	$764,280	$527,309	$1,033,130	$1,002,639	$903,982	$720,737	$1,128,387	$991,070
September	$643,471	$1,040,805	$588,779	$1,379,288	$963,212	$903,312	$1,163,554	$988,285
October	$1,443,616	$1,156,842	$1,406,763	$1,099,095	$819,670	$849,997	$1,485,650	$1,200,840
November	$882,074	$852,140	$986,319	$1,037,379	$1,172,514	$1,077,313	$935,437	$827,099
December	$838,297	$972,978	$834,219	$865,932	$1,123,311	$973,535	$975,999	$978,758
Total	**$11,650,607**	**$11,140,669**	**$11,692,130**	**$12,367,669**	**$13,043,118**	**$9,689,548**	**$14,280,855**	**$11,373,384**

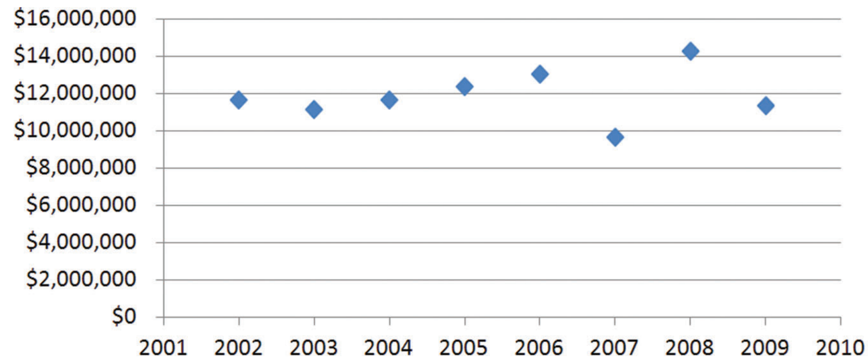


Figure 17.2 Annual revenue from overweight and oversize truck permits 2002–2009.

18. PERMITTING OPTIONS

18.1 Single-Trip Permit versus Annual Blanket Permits

Permitting options may be examined from the perspective of the spread of time over which the infrastructure use is to be made. Often the choice is between charging for a single trip or charging a blanket fee to cover use over an extended period of time such as one year. Regarding the issue of revenue neutrality: highway agencies that have switched from a single-trip permit system to an annual permit system report that they benefited from cost savings due to reduced monitoring efforts of each single trip but lost significant revenue overall (*218*).

Specifically, in the late eighties and early nineties, a number of highway agencies switched from single-trip permit systems to annual blanket flat fee permit systems. It is reported that these agencies benefited from enhanced convenience (and as previously noted, monitoring cost savings) due to reduction in the efforts towards truck monitoring. However, they lost significant revenue overall due to the fact that heavy vehicle operators had no limit to the number of trips they could make in one year on an annual permit (*218*). It was also discovered that many trucking companies, under the blanket fee system, tended to consolidate their overweight operations from many vehicles that on occasion would obtain a single-trip overweight permit, to a few vehicles with annual overweight permits that were dedicated to handle as many of a company's overweight movements as possible in order to maximize the investment made in permit purchases. Clearly, such practices were favorable to the truckers but unfavorable to the revenue generation efforts of the highway agencies, particularly considering the additional wear and tear caused by these overweight trucks, and the fact that maintenance of further deteriorated infrastructures requires additional funding. Findings from the Moffett and Whitford survey (*218*) of commercial vehicle operators showed that officials in states having annual permits complained that their state could not adequately deal with added road and bridge damage done by overweight trucks, a sentiment that echoed a previous study in Texas (*219*).

As such, highway agencies interested in annual permitting sought (and still seek) to establish fee levels that are "revenue neutral" in other words, fee levels that would not jeopardize the amounts of revenue generated in comparison to the single-trip permit systems. However, in the case of annual permits, maintaining revenue neutrality in an agency's fee structure may require significant and regular monitoring of the overweight truck movements (number of trips, weights, and distance traveled) so that the permit fee amounts can be updated as needed. Thus a strong driving force remains for the practice of single-trip permit structures, particularly for highway agencies unwilling or unable to undertake the extra monitoring efforts to ensure revenue neutrality.

From the case studies developed in Khurshid et al. (*220*) for Indiana, it was observed that at states with a blanket annual permit, the permit fee is very low compared to the benefits, and cannot be realistically expected to generate adequate revenue in the long term. It is not certain whether the agencies at these states are unwilling or unable (for reasons that may include political considerations) to increase these fees to more realistic levels. In this regard, it was also observed that for the hypothetical trucker (having a fleet of a certain distribution), relatively little total annual permit expenditure is incurred if the trucker operates at states that have a blanket annual permit; on the other hand, the trucker incurs relatively high expenditure at states that lack a blanket permit, that is, states in which the annualized trucker expenditure is calculated as an accumulated sum of multiple single-trip permit fees. This result suggests that adoption of an annual blanket fee may be unfavorable from the perspective of the agency's revenue generation. This is consistent not only with the findings of the Texas DOT but also with the admonitions of Moffett and Whitford (*218*). However, the opportunity exists for INDOT and INDOR to issue special blanket permits to "favored" clients. These include industries and truckers who undertake a large number of OW trips and for whom seeking permits for each trip would be time consuming, laborious, and disruptive to their operations. It is the recommendation of this report that the state can deal with such truckers on a case-by-case basis.

18.2 Weight-Distance Fee Concept—The State of Practice

Permitting options may also be examined from the perspective of what is being charged. In a recent SPR study, Khurshid et al. (*220*) determined that with the exception of Illinois, and to some extent, Indiana and Ohio, no Midwest state has adopted explicitly the weight-distance concept as a basis for the permit fee structure for its overweight or oversize trucks. It is noteworthy to mention that the state of Oregon (outside the Midwest region) is the most well-known leader in implementing this policy explicitly for all commercial vehicles (overweight and oversize trucks included) and in monitoring compliance. In general, the trucking industry has voiced opposition to weight-distance taxation. However, as reported by Moffett and Whitford in 1994 (*218*), trucking companies that deal regularly with overweight trucks were significantly less opposed to weight-distance taxation compared to those who regularly deal with legal weight trucks. It is not certain whether these stakeholders hold such perspectives at the current time.

As indicated in the preceding paragraph, the practice of weight-distance fees has existed at some states even if only implicitly. At certain states (Indiana, Ohio, and Illinois), the fees charged for overweight vehicles is different for different weight groups and distances traveled: for a given weight group, a higher fee is charged for a greater distance; and for a given distance, a higher fee is charged for a greater weight. Clearly, at these states, the overweight fee structure shows significant resemblance to the weight-distance concept of permitting practiced in Oregon. This probably explains the 1994 Moffett and Whitford observation (*218*) (that companies that deal regularly with overweight trucks were significantly less opposed to weight-distance taxation): for such truck operators, such taxation schemes are similar to the status quo of their fee paying structures because weight-distance taxation yields a form of permit fee structure that is similar to the fee structure to which they are accustomed.

19. OTHER REVENUE-RELATED ISSUES

19.1 Exceptions to OSW Regulations in Indiana

Figure 19.1 presents a list of Indiana permits and fees. The amount of revenue can be generally higher when fewer exceptions are made to OSW regulations. In Indiana, there are a number of exemptions from oversize/overweight permits (*221*). When traveling on any road other than an Interstate highway, certain vehicles are exempt from the permitting requirements. They include vehicles engaged in the construction of highways, when the movement of the vehicle is confined to highways, roads, or sections that are under construction and not yet open to the public. The only exception to this would be if the authority having jurisdiction over the construction of a public highway gives notice that a permit is needed. Another exception is machinery or equipment used in highway construction or maintenance by the Indiana Department of Transportation, or by Indiana counties or municipalities. Also, implements of agriculture when used during farming operations or when so constructed that the implements can be moved without material damage to highways. Other exemptions are the width or height of a farm vehicle loaded with a farm product (this includes a truck hauling unprocessed tobacco leaf) and fire-fighting apparatus owned or operated by a political subdivision or volunteer fire company. Furthermore, the movement of a disabled vehicle or combination of vehicles for a distance that does not exceed fifty (50) highway miles by a registered recovery vehicle or by a vehicle described in The Motor Carrier Services Division Handbook of 2008, is exempt from the dimension and weight limits under this article. The source of this information is the Oversize-Overweight Vehicle Permitting Handbook, Permit Unit, published by the Motor Carrier Services Division of the Indiana Department of Revenue (*221*).

Category	Type	Forms	Single Trip Fee	90 Day Fee	Annual Fee
Oversize Permit	Single Trip 90 Day Annual	M-233, Permit M-233, Permit M-233, Permit	**$20:** up to 95' in length, 12'4" wide & legal height **$30:** between 96' and 110' in length, 12'5" and 16' wide or 13'7" and 15' tall **$40:** over 110' in length, 16' wide, 15' tall and 80,000 pounds	**$100**	**$405**
Overweight Permit	Single Trip (15 Days)	M-233, Permit	$20 + $.35 per mile for vehicles up to 108,000 lbs. *$20 + $.60 per mile for vehicles over 108,000 to 150,000 lbs. **$20 + $1.00 per mile for vehicles over 150,000 lbs.		
Oversize & Overweight Permit	Single Trip (15 Days)	M-233, Permit	Greater of the oversize or overweight fee calculated above		
Special Weight Permit	Multiple Trip (1 Day) Quarterly billing	M-233ST, Permit M-211, Registration M-219, Bond Form	$42.50		
12'4" Mobile Home Rig Permit	Single Trip (15 Days) Annual Quarterly Dealer's	M-233, Permit M-233DR, Permit	$10.00	$250.00	$1000.00 $40.00 for dealers.
14'4" Mobile Home Rig Permit	Single Trip (5) Days Quarterly Annual	M-233, Permit	$18.00	$500.00	$2000.00
Toll Road Gate Permit	Annual	M-233T, Permit			$20 per gate, per truck.

* Vehicles over 120,000 lbs charged $10 executive fee.
** Vehicles over 200,000 lbs charged $10 executive fee + $25 design and review fee + bridges fees.

Figure 19.1 List of Indiana permits and fees.

PART VI. SUMMARY AND CONCLUDING REMARKS

20. SUMMARY

As discussed in the introduction to this report, it is important that INDOT continues to regulate and monitor overweight vehicle operations on Indiana's highways. This admonition is based on the hypothesis that overweight vehicles continue to inflict significant damage to highway pavement and bridge infrastructure in addition to the safety or mobility hazard they pose to other motor operators, pedestrians, and the general public. In addressing this hypothesis among other objectives, this study focused on the damage costs only, and excludes the safety and congestion consequences of overweight vehicle operations.

The study developed a framework in order to establish the unit costs of infrastructure (pavement or bridge) damage by relating overweight permit fees to infrastructure damage so that heavy vehicles pay their fair share of costs. There were two key aspects of the framework: one aspect addressed the cost of providing the infrastructure and the other aspect addressed the extent of the infrastructure use over its life cycle. A synthesis of these two aspects yielded the cost per usage, in other words, the unit (that is, the per-user) cost of infrastructure use. The life-cycle cost of the infrastructure reconstruction, rehabilitation, and maintenance was modeled as a function of its user demand (vehicle frequency and/or loading), among other explanatory factors. From this model, the unit cost associated with the infrastructure upkeep due to user damage was established. This was done for each family of the infrastructure in question.

The costs of enforcement were also established in the study. These include personnel costs and other costs incurred by the Indiana State Police (ISP) associated with enforcement of the overweight permitting process involving weighing tasks.

Also in this study, the adequacy of revenue collected under the current permitting structure was carried out not for the entire highway system collectively but for individual vehicle classes and weight groups. For the former, the study report also presents the annual revenue streams yielded from the permits issued for overweight trucking operations in Indiana. For the latter, the established per-user cost associated with the infrastructure upkeep due to user damage was compared with the existing permit fee (unit revenue) collected from each overweight user. The study also discussed the pros and cons of INDOT establishing permit fees on the basis of axle weight as opposed to gross vehicle weight.

21. CONCLUSIONS

21.1 Estimation of Pavement Damage Cost due to OW Vehicle Operations

The literature review confirmed that very few studies adopted a truly comprehensive approach for marginal pavement damage cost estimation on the basis of appropriate input considerations such as practical maintenance, rehabilitation and reconstruction schedules and treatments, use of appropriate data on truck weights, treatment cost and performance, traffic volumes and trends, separation of strength- and capacity-driven expenditure, use of an appropriate data horizon period, road-use measure, and pavement rest period. On the basis of the identified gaps in the existing practices of pavement damage cost estimation, this study developed a framework for estimating the pavement damage cost. In applying the developed framework to estimate the cost of pavement damage for different families and ages, the study showed that pavement damage cost is influenced significantly by pavement class: the marginal pavement damage costs were found to range from \$0.006 per ESAL-mile for Interstate highways to \$0.218 per ESAL-mile for the non-national highway system.

The results also showed that non-consideration of reconstruction costs and/or routine maintenance costs results in approximately 80% underestimation of the actual marginal costs of pavement damage. Furthermore, the analysis showed that the impractical approach of considering only rehabilitation treatments applied at fixed intervals (a failing associated with a significant number of past studies) leads to as much as 86% underestimation of the actual marginal cost of pavement damage. Additionally, the results suggest that non-consideration of non-truck traffic has an insignificant impact on marginal pavement damage cost estimates; therefore, it is concluded that it is appropriate to exclude automobiles from pavement damage cost analysis.

The study conducted a sensitivity analysis of the pavement damage cost with respect to a number of input factors for the analysis: incorrect estimation of the rest period or the rehabilitation treatment service life can lead to significantly different estimates of the marginal cost of pavement damage; and the estimates were found to be more sensitive to the specified rest period compared to the rehabilitation treatment service lives. An assessment of the impact of inaccuracy in the pavement reconstruction and rehabilitation treatment costs revealed that such inaccuracies can cause some variations in the marginal pavement damage cost estimates, albeit to a relatively minor degree compared to the other factors.

21.2 Estimation of Bridge Damage Cost due to OW Vehicle Operations

A truck is considered to be overweight when it has a GVW above the legal limit of 80,000 lbs; however, the damage it causes is a function of its GVW, axle spacing and number of axles. As such, the FHWA vehicle classes were correlated to AASHTO's vehicle classes based on the modified equivalent vehicle (MEV) model that was developed in this study; and the bridge life-cycle cost was estimated for each bridge family. The bridge damage cost due to overweight trucks was estimated using the incremental cost methodology. This methodology allocated cost of bridge damage to all of the vehicle classes based on the vehicle configurations and their average frequency of using the bridge.

The studied bridges were classified by material type as steel, prestressed concrete, or concrete. Each bridge material type was also sub-classified into four different age groups: 0 to 20 years, 21 to 35 years, 36 to 55 years, and 56 to 70 years. The bridges were considered to be designed in a repetitive and incremental fashion based on the highest vehicle load available. The incremental designs were carried out and cost functions were developed on the basis of AASHTO design vehicles. Each FHWA vehicle weight group was classified into an equivalent AASHTO loading using the modified equivalent vehicle model which is based on vehicle GVW, axle loading, and axle spacing. The results were used to incrementally assign the bridge life-cycle damage costs to each vehicle class.

Costs were estimated over the bridge life cycle. The practice of allocating bridge damage costs on the basis of only one (or a narrow, unrepresentative set) of the individual activities for bridge upkeep (that is, bridge replacement, deck rehabilitation, or deck replacement) was considered unsuitable for the present study because such approaches fail to mimic the true agency practices of bridge upkeep, namely, a combination of maintenance, rehabilitation, and replacement activities over the bridge life. Furthermore, bridges are designed for continual replacement/reconstruction after several decades, to perpetuity; hence, using the costs of only one or an unrepresentative few individual treatments instead of the expenditure incurred over the entire bridge life-cycle could result in underestimation or overestimation of the true cost of bridge damage.

The present study pertains to overweight trucks. Thus, the final results presented do not pertain to weights lower than or equal to 80,000 lbs. The total cost allocated to a vehicle class was calculated as the sum of its cost responsibilities; and the bridge damage cost per overweight vehicle class was computed as the cost responsibility divided by the average volume of overweight trucks that typically uses the bridge. The bridge damage cost in the present study was estimated for two options. Option 1 considers the damage caused by the entire load of an overweight vehicle while option 2 considers the damage caused by the overweight portion only of an overweight vehicle. The second option is recommended for use.

In order to issue a permit that is efficient, effective, and equitable, considerations must be given to the full information on a bridge (material type, age, and dimensions) and overweight truck (GVW and axle configurations). Three approaches (disaggregate, semi-disaggregate, and aggregate) were considered in this study. For the disaggregate analysis, the bridge damage cost for each individual class of overweight truck and for each highway class was computed. This was done using available information on each bridge type as well as its users (vehicles). For the semi-disaggregate analysis, the bridge damage cost was for all overweight vehicles combined for each highway class. For the aggregate analysis, the bridge damage cost was estimated for all overweight vehicles combined and for all highway classes combined.

21.3 Estimation of Enforcement Costs Associated with OW Vehicle Operations

The enforcement chapter of the report reviews Indiana's OW enforcement situation and presents a number of recommendations pertaining to the static monitoring and mobile enforcement, and truck inspections which are part of the duties of the Indiana State Police Commercial Vehicle Enforcement Division.

With regard to static weight enforcement, a number of additional stations were recommended for implementation across the state. The following factors were considered in making the recommendations: proximity to the Indiana state border; truck traffic volumes; ability to weigh incoming trucks before their detouring to avoid a weigh station; proximity to regions/industries which produce a significant amount of truck traffic; and proximity to and capacity of nearby weigh stations. On the basis of these factors, a number of locations were recommended for new or revitalized weigh stations at Interstate 64, Interstate 65 at Remington and Seymour, Interstate 69 at Warren, Evansville-Indianapolis Extension, and Interstate 74. These recommendations are intended to serve as a general guidance only for the locations of these stations; the final locations should be the subject of a separate detailed study. Recognizing that unpermitted OW operators tend to avoid weigh stations when they are aware of the station staffing hours, it is recommended that one of two different policies could be implemented: transitioning from 16-hour weigh station shifts to around-the-clock shifts at weigh stations; and maintaining the current 16-hour shifts at weigh stations, but implement a randomized scheduling process for the individual shifts.

For existing WIM stations, a review is needed of their locations and how they fit into the overall statewide plan of truck monitoring. For example, installation of additional WIM stations could be considered for installation at selected locations on the highway network in order to assist in the monitoring of overweight trucks. This could reduce congestion at the static weigh stations, and could achieve savings in time and fuel usage for the trucking operators.

Regarding the deployment of commercial vehicle enforcement officers across the state, a number of recommendations could be made to enhance their effectiveness further. First, the allocation of officers across the various districts could be reviewed, and an assessment of any imbalance between manpower and need at any location, could be made. Furthermore, a thorough audit should be conducted within the division to identify the various duties that these officers perform on a daily basis, in order to ensure that their time spent on patrol for weight, length, and safety violations, is put to maximum use. For the recommended new static weigh stations, it is recommended that until these stations become operational, the manpower for commercial vehicle enforcement be temporarily increased in order to accommodate the additional patrols that are needed to ensure thorough and complete enforcement of the state's commercial vehicle regulations. After the new weigh stations become operational, the manpower could be gradually reduced to a level commensurate with the needs at that future time.

Finally, it is recommended that the Indiana State Police investigate the possibility of more thoroughly integrating the processes of weight and physical inspections. Because substantial federal dollars are currently available through the FMCSA to assist in funding troopers to conduct physical inspections of vehicles, it is felt that incorporating weight inspections into this process will result in a significantly higher rate of compliance with minimal additional staffing required. This can be facilitated in part by ensuring that all static weigh stations within the state have functioning indoor inspection facilities. Additionally, and perhaps in order to further support the case for integrating weight and physical inspections, a study could be conducted to investigate the relationship between overweight truck violations, physical safety violations, and even crash records. It is hypothesized that a positive correlation exists between overweight operations and safety; that is, overweight trucks may tend to have higher rates or severities of safety violations. As such, an effort to more aggressively identify and remove from the road, trucks with weight or physical safety problems is expected to also have a substantial impact on reducing the other type of violations.

These recommendations will provide INDOT and the Indiana State Police with a broad-level roadmap for future commercial vehicle enforcement efforts, from which they could perform further studies to assess different strategies and impacts of implementing these recommendations.

21.4 Revenues Associated with OW Vehicle Operations

The study report also presents the annual revenue streams yielded from the permits issued for overweight trucking operations in Indiana and reports that the approximate amount obtained by the Indiana Department of Revenue is approximately $12 million per year. Obviously, this amount falls far short of what is needed to offset the cost of pavement and bridge damage due to overweight truck operations even without including their direct and indirect costs of reduced safety and mobility. A past study in Texas found that the fees paid by overweight trucks are typically a very small fraction of the actual damage costs they cause on the pavements alone.

The study also discussed briefly the issue of revenue neutrality: highway agencies that have switched from a single-trip permit system to an annual permit system report that they benefited from cost savings due to reduced monitoring efforts of each single trip but lost significant revenue overall. This result suggests that adoption of an annual blanket fee may be unfavorable from the perspective of revenue generation. However, the opportunity exists for INDOT and INDOR to issue special blanket permits to "favored" clients. These include industries and truckers who undertake a large number of OW trips and for whom seeking permits for each trip would be time consuming, laborious, and disruptive to their operations. It is the recommendation of this report that the state can deal with such trucking operators on a case-by-case basis.

22. POTENTIAL BENEFITS OF THE STUDY

It is hoped that the results of this study provides a valuable knowledge base for INDOT as the agency moves forward to update or streamline its overweight truck permitting processes. The ultimate intention is to help the state preserve its investments in highway infrastructure without sacrificing the competitive position of the state in attracting and retaining commercial entities and businesses that foster the state's economic development. Specific potential benefits of this study are discussed below.

22.1 Equity in User Charging

It is expected that INDOT will be able to use the study results to establish a more equitable structure for its overweight permit fees by charging vehicles in each class on the basis of the damage inflicted on the infrastructure due to their axle weights.

22.2 Potential Revenue Generation

By establishing permit fee structures that are **more representative of the actual costs of infrastructure upkeep** due to heavy vehicle loading (compared to current fees), the state of Indiana's departments of transportation and revenue stand to earn more direct revenues, thus reducing the gap between revenue and damage. Studies at other states have confirmed that the revenues earned from overweight permits are typically a very small fraction of the actual damage costs caused to the highway infrastructure by overweight vehicles.

22.3 Cost Avoidance and Reduction

By establishing permit fee structures that duly penalize excessive loads, the study results, will help preserve pavement and bridge assets by **extending their service lives** which, ultimately, will translate into **lower costs over the life-cycle** of such infrastructure. This will be a direct benefit to INDOT (through reduced need for repairs) which would translate into indirect benefit to users (through lower user costs due to **lower frequency of work zones**), and lower user vehicle operating cost due to superior condition of the infrastructure.

22.4 Customer Satisfaction and Public Relations

By providing permitting alternatives such as an overweight permit fee structure that takes due cognizance of the weight and the distance traveled, it is envisaged that road users and the general public would acknowledge and appreciate the **inherent fairness** in such a fee structure. This will contribute to intangible benefits including enhanced INDOT accountability of the stewardship of the public highway infrastructure reputation and improved public relations.

23. CONCLUDING REMARKS

In sum, the research provided a study product that will assist INDOT in a variety of ways. First, by providing a detailed methodology for attributing the costs of pavement and bridge repair damage on the basis of the damage occasioned by each class of heavy vehicles, the research results will help INDOT relate heavy vehicle permit fees to infrastructure damage caused by excess axle weights. That way, INDOT is provided a means for establishing an updated and equitable fee structure that would ensure that all heavy vehicles pay their fair share of damage costs. Estimation of the costs of enforcement can also help establish the unit cost of enforcement for each highway user is responsible. It is envisaged that an updated fee structure based on the results of this study will help INDOT establish reasonable fees in order to attract and retain industries that regularly haul heavy loads, protect the highway infrastructure from undue excess loads, and ensure that heavy vehicles pay their fair share of costs. In sum, the foundation is herein built for INDOT upon which the agency can develop a balanced fee structure that avoids impairment of economic activities without sacrificing the longevity of the highway infrastructure.

PART VI. APPENDIX A. EXCEPTIONS TO OSW REGULATIONS IN INDIANA (*221*)

There are certain exemptions from oversize/overweight permits. When traveling on any road other than an Interstate highway, certain vehicles are exempt from the permitting requirements. They include:

1. A vehicle engaged in the construction of highways, when the movement of the vehicle is confined to highways, roads, or sections that are under construction and not yet open to the public. The only exception to this would be if the authority having jurisdiction over the construction of a public highway gives notice that a permit is needed.
2. Machinery or equipment used in highway construction or maintenance by the Indiana Department of Transportation, or by Indiana counties or municipalities.
3. Implements of agriculture when used during farming operations or when so constructed that the implements can be moved without material damage to highways.
4. The width or height of a farm vehicle loaded with a farm product. This includes a truck hauling unprocessed tobacco leaf.
5. Fire-fighting apparatus owned or operated by a political subdivision or volunteer fire company.
6. The movement of a disabled vehicle or combination of vehicles for a distance that does not exceed fifty (50) highway miles by a registered recovery vehicle or by a vehicle described in MCSD (*221*) is exempt from the dimension and weight limits under this article.

List of Permits and Fees

Any questions that you have regarding information in this handbook should be directed to:

Indiana Department of Revenue
Permit Unit
5252 Decatur Boulevard, Suite R
Indianapolis, IN 46241
(317) 615-7320

All permit applicants must file Form M-203, Transporting Company Permit Application!

Category	Type	Forms	Single Trip Fee	90 Day Fee	Annual Fee
Oversize Permit	Single Trip 90 Day Annual	M-233, Permit M-233, Permit M-233, Permit	**$20:** up to 95' in length, 12'4" wide & legal height **$30:** between 96' and 110' in length, 12'5" and 16' wide or 13'7" and 15' tall **$40:** over 110' in length, 16' wide, 15' tall and 80,000 pounds	**$100**	**$405**
Overweight Permit	Single Trip (15 Days)	M-233, Permit	$20 + $.35 per mile for vehicles up to 108,000 lbs. *$20 + $.60 per mile for vehicles over 108,000 to 150,000 lbs. **$20 + $1.00 per mile for vehicles over 150,000 lbs.		
Oversize & Overweight Permit	Single Trip (15 Days)	M-233, Permit	Greater of the oversize or overweight fee calculated above		
Special Weight Permit	Multiple Trip (1 Day) Quarterly billing	M-233ST, Permit M-211, Registration M-219, Bond Form	$42.50		
12'4" Mobile Home Rig Permit	Single Trip (15 Days) Annual Quarterly Dealer's	M-233, Permit M-233DR, Permit	$10.00	$250.00	$1000.00 $40.00 for dealers.
14'4" Mobile Home Rig Permit	Single Trip (5) Days Quarterly Annual	M-233, Permit	$18.00	$500.00	$2000.00
Toll Road Gate Permit	Annual	M-233T, Permit			$20 per gate, per truck.

* Vehicles over 120,000 lbs charged $10 executive fee.
** Vehicles over 200,000 lbs charged $10 executive fee + $25 design and review fee + bridges fees.

Figure VI.B.1 List of OSOW permits and fees. (Source: (*221*).)

PART VI. APPENDIX C. ADDITIONAL REFERENCES AND RESOURCE MATERIAL

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About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,500 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at: http://docs.lib.purdue.edu/jtrp

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About This Report

An open access version of this publication is available online. This can be most easily located using the Digital Object Identifier (doi) listed below. Pre-2011 publications that include color illustrations are available online in color but are printed only in grayscale.

The recommended citation for this publication is:

Ahmed, A., B. R. D. K. Agbelie, S. Lavrenz, M. Keefer, S. Labi, and K. C. Sinha. *Costs and Revenues Associated With Overweight Trucks in Indiana*. Publication FHWA/IN/JTRP-2013/01. Joint Transportation Research Program, Indiana Department of Transportation and Purdue University, West Lafayette, Indiana, 2013. doi: 10.5703/1288284314987.