USDOT Region V Regional University Transportation Center Final Report

NEXTRANS Project No 083PY04

Using Regional Freight Traffic Assignment Modeling to Quantify the Variability of Pavement Damage for Highway Cost Allocation and Revenue Analysis

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TECHNICAL SUMMARY

NEXTRANS Project No 083PY04 Final Report, December 31

Using Regional Freight Traffic Assignment Modeling to Quantify the Variability of Pavement Damage for Highway Cost Allocation and Revenue Analysis

Introduction

While indicative of a vibrant economy, large volumes of freight traffic have been associated with accelerated wear of pavements particularly. In seeking to adopt operational policies that reduce undue deterioration of their infrastructure, state highway agencies in the United States strive to quantify the damage caused by vehicle loads so that it is possible to update loading polices and to implement fee structures that are commensurate with the pavement damage.

An INDOT-commissioned research study, SPR 3502, provided a methodology to estimate the pavement damage costs. That study reported these costs on the basis of systemwide average levels of traffic loading. In reality, however, traffic loading and climatic severity at specific road segments can differ significantly from what their systemwide averages suggest. This Nextrans study therefore investigated the issue of pavement damage cost estimation from a purely disaggregate level in order to establish potentially more reliable estimates of pavement damage costs. It is envisaged that doing so would not only increase the efficiency and effectiveness but also would enhance equity in the highway cost allocation and revenue generation.

To address the issue at a disaggregate level, the study first established more reliable projections of highway freight traffic volumes at each individual pavement segment on the highway network using the results from a freight assignment and volume prediction tool. Next, for each road segment the expected axle loadings on the basis of the projected traffic volumes, were calculated and the expected pavement damage costs were determined from the expected level of truck volume (and thus, estimated loading). Further, the study quantified the deviation, for each pavement segment, of the damage cost using disaggregate and aggregate approaches.

Findings

To address the issue at a disaggregate level, the study first established more reliable projections of highway freight traffic volumes at each individual pavement segment on the highway network using the results from a freight assignment and volume prediction tool. Next, for each road segment, the expected axle loadings on the basis of the projected traffic volumes, were calculated. Then the expected pavement damage costs were determined from the expected loadings. Further, the study quantified the deviation, for each pavement segment, of the damage cost using disaggregate and aggregate approaches.

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Recommendations

The research product can be used to estimate the cost of pavement damage for individual pavements section on a state highway network. This can be done using the expected axle loadings on the basis of the projected traffic volumes. The deviation of pavement damage costs at each pavement segment relative to the aggregate damage cost reported all pavements, can be quantified. Thus, the dangers of using aggregate estimates for pavement damage cost, can be demonstrated.

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CHAPTER 1 INTRODUCTION

1.1 Introduction

In past practice and research, the charging of road users for their “consumption” of the highway infrastructure has mostly been analyzed on the basis of data on aggregate measures of consumption. However, this is expected to become increasingly based on disaggregate data. It is interesting to observe the gradual evolution of the level of individual responsibility for their highway use: several decades ago, users generally and indirectly paid for highway use irrespective of their weight. This was followed by an era where charges were established for users on the basis of the collective responsibility of the users in each group (also referred to as vehicle classes). For example, all trucks of a certain size or weight paid a certain fee. Across the user groups, fees were gradated on the basis of size or weight, but within in group, each user paid the same amount. In the current era, the group-based charging policy seems to be waning, as there seems to be greater demand from stakeholders for each individual vehicle even within each group, to pay according to the amount of damage it inflicts individually on the facility. The underlying cause of these shifts is not certain but is often surmised to have roots in the changing voter attitudes in the country.

Notwithstanding these evolutions of user-based charging, the fact remains that highway agencies worldwide that have stewardship of billions of dollars’ worth of taxpayer-owned and infrastructure continue to seek policies that prevent accelerated deterioration of their pavements through excess loading and other factors. As such, highway agencies pursue knowledge of the infrastructure damage caused by heavy vehicles so that the true costs of overweight vehicle operations in terms of pavement and bridge damage repair as well as the costs of enforcing permitting regulations can be ascertained and the existing license or overweight fees can be updated. Over the past 3 decades, several states have carried out studies related to the estimation of pavement damage cost or as part of highway cost allocation, in a bid to restructure the existing user charges.

These studies can be categorized as those that provided and implemented a framework to:

(i) assess the increase in pavement or bridge 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;
(ii) provide a framework to identify the operational degradation costs (safety and mobility impairment) related to the use of trucks;
(iii) provide a framework to identify the wider systemwide benefits associated with truck operations (specifically, the traffic volume reduction because fewer trips are required due to carry the same amount of goods) and the concomitant overall benefits in terms of lower exposure to crashes, reduced emissions, reduced congestion, reduced energy use, and so on;
(iv) estimate all revenue sources and respective amounts, associated with the use of trucks;
(v) investigate the inequities of each vehicle class (i.e., different axle configurations and gross vehicle weights) in terms of their revenue generated vs. the infrastructure damage (physical and/or operational) they inflict;
(vi) establish an equitable license or permit fee structure by each heavy vehicle class that would not adversely affect the productivity of the trucking industry;

The results of such studies have been used for a variety of highway management functions or to drive highway use policies including fuel tax rate adjustment.

1.2 Problem Statement and Study Objective

It has been shown in previous studies that the current road-user charging systems do not recover the full cost caused by heavy vehicles; thus most vehicles are paying less than their fair share of highway repair expenditures (HVCRS, 1984; FHWA, 1997, 2000; RAC, 2002). Also, there is spatial inequity: in other words, for trucks of the same vehicle class, the use an average damage cost value for both a high-trafficked road and a low-trafficked road would underestimate the total damage cost for the former and overestimate the total damage cost for the latter.

Ahmed et al (2013) estimated pavement damage costs in order to update the existing fee structure. However, an issue that remains with the past and current studies that are related to cost allocation is that the infrastructure damage is estimated on the basis of systemwide average levels of traffic loading and climatic severity. In reality, however, traffic loading and climatic severity at specific road segments can differ significantly from what their systemwide averages suggest.

Also, annual field counts at specific segments may not be sufficient for the purpose of fee structure determination at specific highway segments because they only reflect current conditions and even with growth adjustment factors, may fail to provide reliable future projections. Furthermore, the relative contribution of climate and traffic in pavement deterioration are known to differ for each pavement type (concrete and asphalt) and also across the different functional classes (interstates, US Roads, and state roads). It is therefore needed to investigate the issue of pavement damage cost estimation from a purely disaggregate level in order to establish potentially more reliable estimates of pavement damage costs. It is envisaged that doing so would not only increase the efficiency and effectiveness but also would enhance equity in the highway cost allocation and revenue generation.

The reliability that is associated with segment-specific cost allocation could be realized if the future volumes of truck traffic at each segment could be estimated with greater accuracy. The use of existing tools for assignment of future freight traffic on the highway network system, on the basis of projected socio-economic developments, could yield more reliable estimates of truck traffic volumes at each individual link on the highway system. In this respect, the use of a regional freight traffic assignment modeling could be beneficial.

Thus, there is a need to report the total damage costs not for families of pavements but for individual pavement segments within a family. That way, highway agencies can establish appropriate segment-specific costs of pavement damage and thus establish a foundation upon which existing fees for overweight vehicles could be reviewed. As such, the objective of the study is to develop and implement a methodology that estimates the damage cost of highway pavements in a disaggregate manner. Figure 1.1 presents the overall study framework.

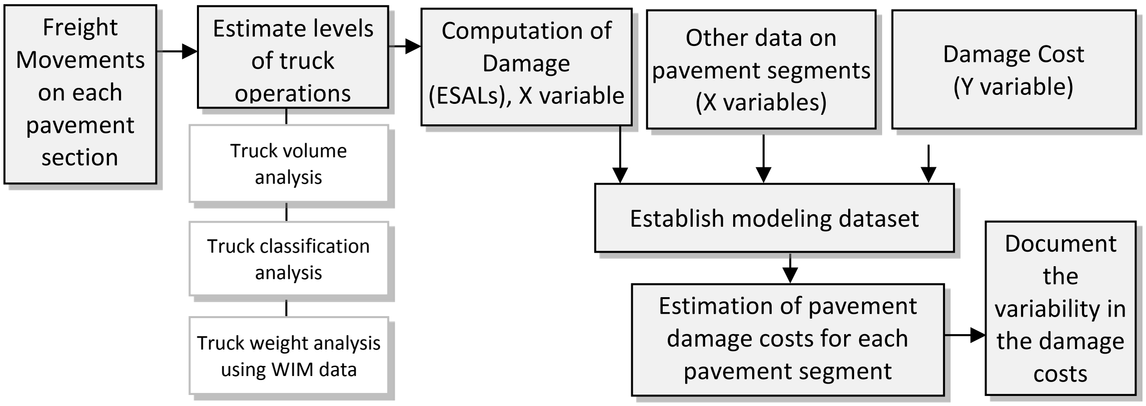


Figure 1.1 Overall Study Framework

1.3 Organization of this Report

This report is organized in seven chapters. In Chapter 1, we present the study objectives and study approach. In Chapter 2, we present a review of existing literature while Chapter 3 presents the estimations traffic loading, while Chapter 4 discusses the life-cycle activity profiles (timings of pavement maintenance and rehabilitation) associated with each pavement family. This followed by Chapter 5 that presents the data preparation for costs and service lives of MR&R treatments. Chapter 6 shows how the marginal cost of pavement damage was estimated using a small data sample for purposes of illustration. Finally, in Chapter 7, we present the research summary and conclusions.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

There are two categories of studies that have addressed the issue of pavement damage cost: (i) studies on highway cost allocation that included projects on highway capacity expansion and pavement strengthening (ii) studies that assessed the cost of pavement damage only (Fig 2.1).

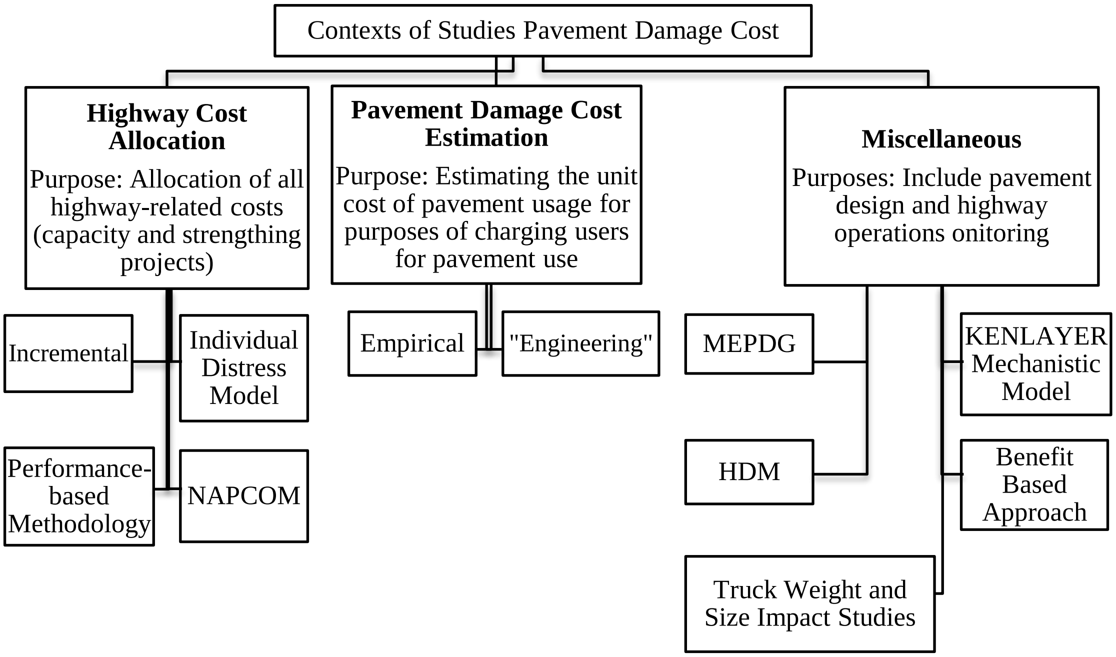


Figure 2.1: Contexts of Pavement Damage Cost Estimation (Ahmed et al., 2013)

2.2 Past Studies Motivated By Pavement Cost Allocation (PCA)

Highway pavement cost allocation studies seek to assign fees to each user class of a pavement network system and are generally based on the principle or seek to evaluate the equity and efficiency of equity. 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”. These studies that typically cover a wide scope of costs including vehicle operating cost, repair costs (maintenance, rehabilitation, and reconstruction), congestion cost, safety cost, and the costs associated with other externalities. Also, pavement cost allocation studies consider a wide swath of project types including capacity addition (such as reconstruction and major widening), operational enhancements (such as safety- and mobility-geared projects), and system preservation. The cost categories include new construction, major widening, reconstruction with lane addition, minor widening and maintenance, and rehabilitation, and subcategories include pavement and shoulder, right-of-way, grading and earthwork, and drainage and erosion control (Ahmed et al., 2013). The methods used in past PCA studies can be categorized as: traditional incremental (FHWA, 1982), thickness incremental (Sinha et al., 1984; Fwa and Sinha, 1985), performance-based methodology (Fwa and Sinha, 1986), facility consumption (FHWA, 1982), individual distress models (FHWA, 1982; FHWA, 2000; Balducci and Stowers, 2008), and game theory (Castano-Pardo and Garica-Diaz 1995). These methodologies are discussed in the paragraphs below.

2.2.1 Allocating the Costs of Pavement Work using the Incremental Method

In the traditional incremental method (Fwa and Sinha, 1985; Balducci and Stowers, 2008), the cost of facility construction and maintenance for the lightest vehicle class, that is, the “base cost” is determined first. This base cost is made to be shared by all vehicles in proportion to their use of the pavement facility, that is, the number of vehicle-miles travelled. Next, the pavement thickness in increased one inch at a time in order to accommodate successively heavier vehicles (trucks); the cost of these subsequent thickness increments is assigned to the heavier vehicle classes.

2.2.2 Allocating the Costs of Pavement Work using the Facility Consumption Method

In this method, the cost of new pavement construction is allocated not in successive increments but on the basis of a uniform removal technique: first, a base facility cost is established and allocated to all vehicle classes on the basis of VMT; then successive enhancements to the facility cost are allocated by using a reverse incremental approach: the traffic loading is reduced gradually by removing vehicle classes systematically until the minimum pavement thickness is reached. For each vehicle class that is removed, the associated savings in cost is assigned to the vehicle class under consideration on the basis of its Equivalent Single Axle Load (ESAL).

2.2.3 Allocating the Costs of Pavement Work using the Individual Distress Models

In the IDM method, models are developed for the individual distresses that not only reflect pavement deterioration but also influence highway rehabilitation decisions. The cost responsibilities are 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. For this, models for flexible and rigid pavements were developed and collectively referred to National Pavement Cost Models (NAPCOM).

2.3 Studies Motivated By Pavement Damage Cost Estimation

Unlike PCA studies, PDC studies consider only the costs that are associated directly with the pavement structure, mostly, maintenance and rehabilitation costs, 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 (Ahmed et al., 2013). PDC estimation studies seek to estimate either the average PDC for full cost recovery of the pavement “consumed” by different vehicle classes, or the marginal PDC so that a fee for vehicles could be established based on 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.

2.3.1 Using the Indirect Approach to Estimate the Marginal Cost of Pavement Damage

In past literature, this approach has been termed in a number of ways including: perpetual overlay indirect approach, indirect approach, engineering approach, or bottom-up approach. In this approach, a unit dimension of the infrastructure (specifically, one lane-mile); the present value of the recurring costs of fixed-thickness overlays over an infinite analysis period, is established as a function of traffic loading, and such repair cost vs. usage relationship is generalized for the entire network. Bossche et al. (2001), Bruzelius (2004), and Anani and Madanat (2010) and other past studies that used this approach considered only a single type of overlay treatment for estimating the marginal cost of pavement repair. By doing so, the researchers seem have assumed (implicitly, or more likely, explicitly) that these overlays constitute the dominant share of pavement maintenance and rehabilitation efforts and that all other maintenance activities and even the reconstruction cost are either negligible or dispensable for analyzing the marginal costs of pavement damage. Expressing an opposing view, Ahmed et al. (2013) argued that the simplifying assumption of a single overlay at constant interval does not adequately reflect practical agency decision-making processed and showed that this leads to unrepresentative estimates of pavement damage costs over the life cycle.

A brief discussion of studies using this approach is presented in the ensuing paragraphs. The basic theorem for estimating the marginal cost of pavement overlays (that is, rehabilitation treatments) over an infinite analysis period was posited by Newbery (1988), using the expression of marginal cost as a function of the overlay cost per km, *C*; the total annual traffic loading in ESALs, *Q*; the road deterioration caused by traffic, φ; and the life of the overlay, *T*.

$$\text{Marginal Cost} = \varphi \left(\frac{C}{TQ}\right)$$

This postulation assumed that (i) the age of all the highway sections of the network is distributed uniformly between zero and t, (ii) traffic loading does not change over the pavement life, (iii) all pavement deterioration is attributed to traffic loading and none to climate effects, (iv) the overlays dominate the efforts on towards the rehabilitation and maintenance of the pavement, (v) the overlay is applied any time that the roughness reaches a certain threshold of pavement condition. Using pavement surface roughness as the indicator of pavement performance and ESAL as the measure of usage or traffic loading, Newbery developed average estimates of the marginal cost of pavement damage. As the effect of climate was not accounted for, the cost of marginal pavement damage was estimated simply as a ratio of the overlay cost per lane-km and the total loading (ESALs) over the overlay treatment life. In an extension of the study to include the climate effects, Newbery argued 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 Tunisian roads with different traffic volumes, design lives, and maintenance schedules, the author estimated that the marginal overlay cost ranges from \$0.0013 to \$0.0258 per ESAL-km in 1983 dollars. Ahmed et al. (2013) argued that the underlying assumptions of Newbery's analysis posed significant limitations to the efficacy of the results; for example, any highway pavement network, in reality, consists of pavement segments of different ages, some young, some old; and varying traffic volumes; also, traffic volume typically never remains constant but grows over time; furthermore, while overlays often dominate pavement repair costs, the cost of pavement damage can be grossly underestimated if reconstruction, periodic maintenance, and routine maintenance costs are not included in the analysis. Ahmed et al. (2013) advocated that the development of pavement damage costs should be based upon realistic schedules of highway pavement reconstruction, rehabilitation, and maintenance.

Using data from the Swedish long-term pavement performance program and the Newbery approach, Lindberg (2002) estimated the marginal costs of pavement damage. Cracking was used as the indicator of pavement performance; however, the study eschewed consideration of climate effects for the sake of simplicity; also, only rehabilitation cost was considered. The marginal cost of pavement damage was estimated to range from \$0.0007 to \$0.0176 per ESAL-km in 2002 dollars for high class and low class roads, respectively; in terms of vehicle-kilometers, this was estimated as \$0.020/veh-km for combination trucks and \$0.0034/veh-km for passenger cars. The authors, in a seeming acknowledgement of a shortcoming of their study approach, recognized that new overlay (rehabilitation) accounted for 30% of the overall maintenance budget. For this reason, other researchers such as Ahmed et al. (2013) stated that the methodology did not yield results that represented the actual and comprehensive cost of maintenance and rehabilitation.

Small et al. (1989) enhanced Newbery’s analysis by duly accounting for climate effects. The net present cost of resurfacing was expressed as a function of pavement durability D (number of ESALs to failure) and annual traffic loading Q. A single lane of a flexible pavement was considered, and was assumed to receive recurring overlays of constant intensity at T intervals and at a cost of C. The interval between two resurfacing or overlays was expressed as T = D/Q. For the effect of climate, Small et al. (1989) used the results of a World Bank study (Paterson, 1987) that established relationships between cumulative ESALs and pavement roughness, on the assumption that pavement roughness increases exponentially with time and linearly with cumulative loading. The relationship between pavement quality and durability (number of ESALs to failure) was established using the AASHTO road test and the interval between two successive overlays was written as a function of the annual rate of pavement roughness increase (m):

$$T = \frac{D}{Q}(e^{-mT})$$

It was assumed that the unit cost of resurfacing is C (\$/Lane-mile), incurred every T years and the interest rate is r. From economic analysis, the present worth of the recurring overlay costs, M, is:

$$M = \frac{C}{(e^{-rt} - 1)}$$

This cost was estimated by partially differentiating the annualized resurfacing cost (*rM*) by annual traffic loading to yield the marginal costs of the overlays:

$$MC = \mathrm{r}\left(\frac{\partial M}{\partial Q}\right) = \mathrm{r}\left(\frac{\partial M}{\partial T}\frac{\mathrm{d}T}{\mathrm{d}Q}\right) = -\left(\frac{r^2 \mathrm{e}^{-rT} C}{(e^{-rT} - 1)^2}\right) * \left(\frac{\mathrm{d}T}{\mathrm{d}Q}\right)$$

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

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

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

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

Small et al. (1989) concluded that at the existing investment levels, the marginal cost of pavement damage varied between $0.0148 and $1.2545 per ESAL-mile; also, and under optimal investment levels for different road functional classes, the marginal cost of pavement damage varied from 0.33 to 101.30 cents per ESAL-mile, in 1985 constant dollars. Ahmed et al (2013) stated the finding, that an optimal investment decision results in a lower overall cost to each group of society was a key contribution of the Small study and that the study duly incorporated the effect of climate into MPDC estimation formulation. However, Ahmed et al pointed out that the study did not consider the costs of pavement periodic and routine maintenance and reconstruction; also, the fixed rate of pavement roughness increase with respect to traffic loading is not realistic, and the assumption of constant-length overlay intervals is not justified, from a practical perspective.

The following year, a similar study was carried out that used data from roadway segments in New York; this also was based on the concept of recurring fixed-intensity overlays over an infinite analysis period (Vitaliano and Held, 1990) and the present worth of such costs. Also, Vitaliano and Held assumed that the shares of pavement deterioration are equally split between traffic loading and climate effects. The estimated marginal costs of pavement damage (and hence, as the average road user charge) were determined to be $0.076 per ESAL-mile in 1990 dollars.

The Transportation Research Board (TRB), its landmark 1996 study, published a report that investigated whether shippers were paying the full social cost they cause in using the public transportation infrastructure. With regard to highway transportation, the TRB study examined the marginal cost not only of pavement damage but also of congestion, noise, air pollution, unsafety, energy security, and other externalities. Using an approach similar to that of Newbery (1988) not explicitly accounting for reconstruction and routine maintenance cost (but including climate effects), the TRB study determined the marginal costs in terms of dollars per truckload: the road-use revenue ($/truckload) from truck operators for two-lane roads was more than the DAAMGE cost they inflicted on the infrastructure; for Interstate highways, the study found the road-use revenue from truck operators was almost equal to the cost of the infrastructure damage they caused.

In yet another similar formulation, Anani and Madanat (2010) estimated the marginal cost of pavement damage but duly considered rehabilitation and periodic maintenance costs. The assumption was a recurring overlay of constant intensity, and the authors assumed that periodic maintenance activities are performed more frequently (and have lower cost) compared to rehabilitation activities. The authors advocated that marginal cost of pavement damage should be based on realistic and practical highway agency maintenance strategies and should include all costs associated with pavement maintenance, but it is not clear that this was done in their analysis. In a critique of that study, Ahmed et al. (2013) argued that the researchers of that study did not use field data to demonstrate the application of their proposed methodology but rather utilized simulation on the basis of hypothetical values for periodic maintenance and rehabilitation.

2.3.2 Using the Empirical Approach to Estimate the Marginal Cost of Pavement Damage

Often described by researchers as an “econometric” method, the “empirical” approach for estimating the marginal cost of pavement damage follows the following steps: (a) using field data, models are developed to describe the cost of pavement reconstruction, rehabilitation, and repair as a function of traffic loading, climatic severity, and pavement structural characteristics; and (b) differentiating the estimated models with respect to the traffic or road-use variable: this yields the marginal cost. Ahmed et al. (2013) described past studies that used this approach:

In a study for the Australian Road Research Board, Martin (1994) estimated the costs of load-related pavement maintenance and construction as a function of attributes related to traffic and those can be allocated among heavy vehicle on the basis of ESAL-Km. Li and Sinha (2000) developed regression models to establish the relationship between the factors of pavement deterioration and rehabilitation. 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.

Using a Cobb-Douglas model, Gibby et al. (1990) estimated the relationship between traffic and maintenance cost, estimated the average annual maintenance cost per passenger car and heavy truck, and determined the extent to which trucks cause more damage to road infrastructure compared to autos (approximately \$0.08 and \$7.60 per mile, respectively).

In the province of Ontario, Canada, Hajek et al. (1998) simulated the impact of traffic loading on pavement maintenance and estimated the change in pavement cost in \$/ESAL-km resulting from different loading regulation scenarios. In another Ontario study, Ghaeli et al. (2000) estimated the life-cycle pavement maintenance and rehabilitation costs (\$/ESAL-Km) and developed the relationship between the pavement life-cycle costs and traffic loading. In Austria, Herry and Sedlacek (2002) estimated marginal maintenance and renewal (rehabilitation) costs using data and OLS regression models, and determined marginal cost of \$0.0007 per vehicle-kilometers for vehicles up to 3.5 tons (gross vehicle weight (GVW)) and \$0.023/vehicle-km in 2002 dollars for vehicles weighing more than 3.5 tons. In Switzerland, Schreyer et al. (2002) and Link (2003) developed marginal cost models that had a log-linear general form. The marginal pavement damage cost was determined as follows: \$0.0005per VKm for passenger cars and \$0.0472 (2002 Constant \$) per VKm for trucks. In a similar study, Link (2002) used cross-sectional data from Germany's road network for estimating the renewal cost (rehabilitation cost). The author calculated the marginal cost of pavement damage for one additional truck by fixing the annual average daily traffic of passenger cars. The marginal cost of pavement damage was calculated on the assumption that all cost is attributed to heavy vehicles. The marginal cost of pavement damage for trucks ranged from \$0.009 to \$2.000 per VKm. The average value of marginal cost of pavement damage was found to be \$1.486 per VKm .

Using data from the state of New Jersey Ozbay et al. (2007) estimated MPDC using data from rehabilitation and periodic maintenance projects in 2004-2006 in. On the basis of the specified resurfacing cost and the design period, the marginal cost was estimated as follows:

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

Where: t = trip duration in hours; Cost (M) = marginal maintenance cost \$ per vehicle (\$2005); Q = traffic volume (vehicles/hour); L = roadway length in miles, N = number of lanes, and P = time (years) between consecutive resurfacing activities.

Haraldsson (2007) estimated the marginal cost of pavement damage for the Swedish national road network using the following functional form:

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

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. The model showed that the overall marginal cost of pavement damage for heavy vehicles ranged from \$0.0957 to \$0.1860per VKm in 2007 constant dollars. Liu et al. (2009) used field data to estimate a pavement decay rate due to environmental factors as follows:

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

Where: Θ = decay rate due to environmental loss; P_{Env} = pavement decay rate due to environmental factors; P_{ini} = Initial PSR (load-related pavement damage); L = design life of pavement. The study estimated a PDC of \$1,727 per mile per year attributable to the beef industry.

2.4 Summary and Discussion

2.4.1 Studies that used the “Engineering” Approach or the Indirect Approach

Highway cost allocation studies differ from pavement damage cost studies in the sense that in estimating the cost responsibility across the vehicle classes, they consider different cost categories.

The key aspects of highway cost allocation studies that addressed pavement damage cost are presented in Tables 2.1, 2.2, and 2.3. As Ahmed et al (2013) noted, a primary limitation of a majority of cost allocation studies is that in developing estimates of cost responsibility factors for each vehicle class, a dichotomy was not established between expenditures that were driven by capacity enhancements and those that were driven by strength enhancement. As such, the resulting road repair and replacement expenditures were not distributed across the vehicle in a manner that accounts for nonload contribution to damage (these should be shared equally across the vehicle classes) and load contribution to damage (these should be shared across the vehicle classes on the basis of their load contributions). Thus, the underlying basis for establishing the road user charges may have been biased.

Ahmed et al. (2013) also pointed out that the variation in attributes within each user group (vehicle class) is an issue with past studies on highway cost allocation: vehicles are placed in different weight classes, and then the equity for each vehicle class was analyzed separately. Weight groups within each class were not investigated. Recognizing that there could be marked weight variability within certain vehicle classes, particularly, the higher classes, it could very well be the case that such analyses may yield results which upon implementation, would mean that vehicles in certain weight groups will not be paying their fair share for road damage cost recovery. Some researchers recommend the use of road use measures that is more reflective of vehicle loads, such as ESAL-mile.

Table 2.1 Past HCA Studies – Methods & Cost Allocators

STUDY	APPROACH/METHOD	DETAILS
1965 Federal Study	Incremental Method (Traditional) o Base facility cost – VMT o Enhanced facility – Traffic volume increments (ESAL)	Incremental Method o VMT or incremental method o Maintenance cost not considered o Rehab formed small part of total cost
1982 Federal Study	Uniform removal technique (Reverse Incremental Method) o Base facility – VMT o Enhanced facility – Traffic volume decrements (ESAL)	Individual Distress Models (Consumption Method) o Cost allocated on the basis of distress contribution (Not ESAL) o Maintenance cost not considered
1984 Indiana Study	Thickness incremental Method (Pavement Thickness increments) o Base facility – VMT o Enhanced facility – Pavement thickness increments (ESAL) o Reconstruction – Similar to new construction	Aggregate damage model (performance based methodology) o Concept of PSI-ESAL loss introduced o Costs estimated on the basis of proportionality assumption o Load-related cost, ESAL o Non-load related cost – VMT
1997 Federal Study	Thickness incremental Method (Pavement Thickness increments) o Base facility – VMT-PCE o Enhanced facility – ESAL	NAPCOM– Individual Distress Models o Load- related cost allocated on the basis of distress contribution (Not ESAL) o Non-load related cost – VMT
2009 Oregon Study	Incremental Method	NAPCOM – Individual Distress Models

Source: Ahmed et al. 2013

Table 2.2 A Synthesis of PDC Estimation Studies based on the Indirect Approach

STUDY	INDEPENDENT VARIABLE (COST/KM OR MILE OF ROAD SEGMENT)	TRAFFIC VARIABLE & PERFORMANCE INDICATOR	MAINTENANCE ACTIVITIES /DATA	CLIMATE EFFECT	COST ESTIMATES
Newbery (1988)	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. (1989)	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 and Held (1990)	Rehab cost over an infinite planning period Non-linear cost model	ESAL PCR	Rehab; New York data	50% damage by climate	$0.030-0.742 per ESAL mile (For a 5-Axle Truck)
TRB, 1996	Rehab cost over infinite planning period	ESAL	Rehab	Considered	No PDC estimates
Lindberg (2002)	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) per ESAL-Km
Anani and Madanat (2010)	Rehab and periodic maint cost over an infinite planning period Non-linear cost model	ESAL	Periodic maint and rehab; Assumed data	Not Considered	No PDC estimates

Notes: Maint – Maintenance; Rehab – Rehabilitation; PI – Pavement Performance Indicator;Expend – Expenditure; PCR – Pavement Condition rating; AADT – Annual average daily traffic. Source: Ahmed et al. 2013

Table 2.3 A Synthesis of PDC Estimation Studies based on the Empirical Approach

STUDY	INDEPENDENT VARIABLE/ COST MODEL FUNCTION	TRAFFIC VARIABLE & PERFORMANCE INDICATOR	MAINTENANCE ACTIVITIES / DATA DETAILS	CLIMATE/AGE VARIABLE FOR ESTIMATION	COST ESTIMATES
Gibbyet al., (1990)	Total maint $ over 3yrs (for 1mile section) Cobb-Douglas	AADT (cars & small trucks) AADT trucks (>5axles)	Total maintenance $; California data (1984-1987)	Temperature Age	Trucks- $7.60/m/yr Cars - $0.08/m/yr
Martin (1994)	Annual routine, periodic, & total $; Linear and non-linear	ESAL, GVW, PCU, AADT	Routine, Periodic, and total maint $; Australia data	Age	50% (±7) load related expend
Hajek at al., (1998)	Total life-cycle Cost; 60-yr analysis period; OLS	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 and Sinha (2000, 2001, 2002)	Rehab and periodic maint $; one life cycle; Annual routine maintenance $; OLS & system of Equations	ESAL IRI	Routine maint, Rehab & periodic maint expenditure Indiana (1994-1998)872 Highway segments	Age Freeze index Temperature	$0.0143-$0.024 per ESAL-mi; 28 %,78 % , and 38% load shares of damage, for flexible, rigid, composite pavements respectively
Ghaeli et al., (2000)	Total life-cycle Cost; 30 yr analysis period	ESAL	Construction, maint. &rehab Ontario data	Two climatic regions	No estimates for PDC
Herry and Sedlacek (2002)	Annual maint & rehab $’ OLS	AADT trucks & cars Gross tons Total axle load	Annual maint & Rehab $; Austria (1987-2004); 46 road segments	–	€0.0016($.0017)/Vkm
Schreyer et al., (2002)	Total maint & rehab. $ 1985-1988 data Log-linear	Total VKm Total Weight-distance Total ESAL	Total maint& rehab; Sweden 1985-1998 data; 127 Highway segments	–	€0.00046 ($0.0005) per VKm (Cars) €0.044 ($0.0472) per VKm (Trucks)
Link (2002)	Total rehab $/km (1980-999)Log-linear	AADT Cars AADT Trucks	Rehabilitation cost Germany Data1980-1999	Age	€0.008- 1.87 ($0.009-2)/VKm
Ozbey et al., (2007)	Maintenance and rehab. $per lane-mile; Non-linear	ESAL	Maint and rehab; 2004-2006 data	–	No estimates for PDC
Haraldsson (2007)	Total maintenance $ for region; Non-linear	Heavy Vehicle Km	Maint and rehab Sweden (1998-2002) 145 small regions	–	0.22 SEK ($0.0305) per/Heavy VKm
Liu et al., (2009)	Annual average maintenance expenditure AASHTO Eqn HERS Decay functions	ESAL PSR Loss	Maintenance expenditure; Kansas data (1985-2003); 127 road segments	HERS Decay Functions (non-load damage)	$1727/mi/yr

Notes: Maint–Maintenance; Rehab–Rehabilitation; VKm –Vehicle kilometer; AADT– Annual average daily traffic; PI – Pavement Performance Indicator; Expend–Expenditure; mi/yr–mile per year; Source: Ahmed et al. 2013.

2.4.2 Studies that used Other Approaches

A number of approaches besides the so-called empirical and engineering approaches have been used to estimate the marginal cost of pavement damage (Table 2.4). In New York, Parker and Hussain (2006) developed a methodology to quantify the vehicle load-induced pavement damage due to vehicles with different tire pressures, speeds, gross weights, number of axles, and load distribution per individual axle. Alison and Walton (2010) proposed a framework for establishing appropriate fees for commercial vehicles at toll facilities; their framework was based on the number of axles and axle weights of a truck instead of the trucks operating weight. In the World Bank, the HDM Model uses detailed pavement and traffic data to develop estimates of pavement deterioration cost and user cost that requires calibration for local conditions (Boile et al., 2001). Hong et al. (2007) proposed a project-level methodology for estimating the cost of load-related pavement construction using AASHTO's Mechanistic Empirical Pavement Design Guide as a basis; the study presented the relative pavement damage by different truck classes in terms of truck passes; however, as at least one other researcher has pointed out, that study did not report their findings in monetary values. Djakfar and Roberts (2000) and Hewitt et al. (1999) investigated the impact of a change in gross vehicle weight limits (and not specifically the marginal cost of pavement damage) for each vehicle class.

Table 2.4 Studies Using Miscellaneous Methods for PDC Estimation

STUDY	MAINTENANCE ACTIVITIES /DATA	TRAFFIC VARIABLE	PERFORMANCE INDICATOR	CLIMATE EFFECT	COST ESTIMATES
Hewitt et al. (1999)	Maint & Rehab Cost 20 yr analysis period	ESAL	–	Not Considered	No estimates for PDC
Roberts and Djakfar (2000)	Maint and Rehab Cost Difference in cost for alternative scenarios 1999-1918	ESAL	–	Not Considered	No estimates for PDC
Parker and Hussain (2006)	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 60 mph avg. speed
Hong et al. (2007)	New Construction	Axle load spectra	Surface rutting	Considered	Relative damage by single pass of each truck class was estimated
Alison and Walton (2009)	New Construction Maintenance Debt Servicing	Axle Axle-weight	–	Not Considered	No explicit estimates for PDC

Source: Ahmed et al. 2013

The studies listed in Table 2.4 had their respective significant contributions by pointing toward new directions for estimating the marginal costs of pavement damage; however, it is difficult to argue that their results can be extended at this time for application to an entire network for purposes of developing equitable road user charges. As Ahmed et al. (2013) pointed out, these studies were based on rather limited sets of data on traffic loading, climatic severity pavement condition, and MR&R contract cost data. Further, they do not reflect the practical schedules for MR&R used in a typical highway agency. For example, some of the studies yielded results that can be useful for specific facilites such as toll roads but cannot be applied to network of sizes of thousands of miles and with very different traffic loading conditions, different functional classes (and hence different standards for thickness and other design features; and also for life-cycle rehabilitation and maintenance), diffefernt road surface types (flexible, rigid, and composite), and different compositions of the trafic stream.

2.4.3. Overall Comments

It can be argued, from the evidence presented in the synthesis of available literature and from the Ahmed et al. (2013) synthesis of past work, that very few past studies had adopted a comprehensive approach for estimating the marginal costs of pavement repair damage. A majority of the past studies had used data from a few weigh-in-motion stations, considered only a single recurring overlay treatment applied to a pavement at regular intervals perpetually, and accounted little for the effect of climate. Most of the studies used a life cycle pavement repair schedule that was far from actual field practices. In actual practice, agencies apply very different treatments to pavements of different functional class and surface type, at different intervals. Furthermore, methodologies that implicitly or explicitly used project-specific data and practices may produce biased estimates if generalized for application to an entire, heterogeneous network. Thus, for estimating the marginal costs of pavement damage, it is argued that because the data preparation is inherently arduous, researchers need to carry out this task with due diligence so that reliable and representative estimates of pavement damage cost can be derived. It is indeed necessary to take pains to collect data on the contractual and in-house costs of reconstruction, rehabilitation, and maintenance, pavement performance, traffic loading, and climatic severity from representative sample sections in each of the specified pavement families. Pursuant to this consideration, it is important that all (not just one or a select few) of the categories of the costs associated with pavement damage and repair, need to be considered in the analysis:

reconstruction rehabilitation, and routine and periodic maintenance. This also means that an appropriate horizon period must be used for the analysis; that way, a better picture is obtained for the actual expenditures incurred in all three cost categories, but also for the trends of traffic and performance within the intervals of reconstruction; short-window snapshots tend to mask actual trends and introduce bias. This also means that the effectiveness of the individual pavement repair categories (and better still, of the specific treatments in each category) treatments, in terms of the extension in pavement service life or treatment life, must be ascertained as a prerequisite to the analysis, using the appropriate indicator of pavement performance and the agency-specified performance thresholds. Also, to adequately match the expenditures of repair to the usage, an appropriate measure road usage (such as load-miles) should be used for the analysis such that it captures the intent of the research. Further, as past researchers pointed out, there need to be a clear dichotomy between expenditure driven by strength requirements and that driven by capacity requirements. Capacity-driven expenditure must be shared by all vehicle classes equally. Strength-driven expenditure must be shared by vehicle classes in the proportion of the damage they cause to the pavement.

CHAPTER 3. ESTIMATION OF TRAFFIC LOADING

3.1 Introduction

The cost of pavement damage is influenced by the number of users of the highway pavement as well as the characteristics of the operating environment as well as the vehicle (total gross vehicle weight and axle configurations). For data on current usage levels, this information may be readily available through the traffic statistics divisions of the highway agency. However, what is needed for analysis of future situations and possible changes in highway policies, is the set of future vehicular flows and loadings on each highway segment. These vehicle flows form a basis for subsequent engineering analyses that are used in operational and planning-level decision-making processes.

Vehicle flows on highway segments are determined traditionally by performing a static traffic assignment – the last step in the four-step transportation planning process. Unfortunately, the static model fails to model traffic flow dynamics (including congestion, spillovers in bottlenecks, and queue buildup) and fails to account for time-variant travel conditions. As Duthie et al. (2009) pointed out, to fully overcome these limitations, the network must be represented at a resolution finer than what traditional planning tools typically support; also, "due to the inability of planning models to fully represent traffic dynamics, operational microscopic models are typically employed to achieve precise time and vehicular movement resolution". Researchers realize, however, that while microscopic models perform well in modeling the traffic flow dynamics, their applicability is limited to corridors or small networks, a limitation which Duthie et al. attributed to "their lack of regional travel behavior models such as equilibrium-based route choice". This limitation demonstrates the need for tools that fill the gap by modeling dynamic traffic at regional scales with expanded and unique functional capabilities.

Dynamic traffic assignment (DTA) is one such tool that is gaining wide acceptance in the transportation community. DTA has the ability to address realistic transportation planning and operational problems while doing away with the unrealistic assumptions of static approaches (Peeta and Ziliaskopoulos, 2001). DTA models provide more realistic traffic flow patterns by accounting for changing traffic conditions by time of day. DTA models produce space-time vehicular trajectories consistent with the modeling objective, which is typically one of the following two: minimize total system travel cost or model traffic equilibrium conditions in a network. Vehicular trajectories contain complete information about the state of a transportation system, and form the basis to obtain all other variables characterizing traffic operation in a transportation network.

After refining estimates of the marginal pavement damage cost described in previous chapters, the next step was to establish freight traffic volumes at each individual pavement segment (link) on the highway network using an appropriate freight assignment and volume prediction tool. This was followed by estimating the expected axle loadings on the basis of the projected traffic volumes at each road segment. While acknowledging the suitability of DTA for developing such traffic volumes, it must be noted that DTA could not be used in the present study due to lack of adequate data on the network. Data used were based on the projections from the freight demand prediction module of the state highway demand model of the Indiana Travel Demand Model.

From the pavement damage costs and axle loadings, the pavement damage associated with the predicted traffic at each road segment was estimated for each individual segment of the network. Such a project-level approach for a system level problem is expected to provide a better picture of the variability of pavement loading and damage. That way, greater confidence can be placed on predictions of the consequent pavement damage at individual segments.

3.2 Traffic Estimates

For this study, traffic (AADT) data were obtained for over 6,000 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. 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 3.1. A growth factor of 1.5% was used for the study.

Table 3.1 AADT and Truck AADT – Summary Statistics

STATISTICAL PARAMETERS	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	

Source: Ahmed et. al, 2013

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 by Ahmed et al. in their 2013 study. The summary of the truck traffic composition data is presented in Table 3.2. 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 Interstate, approximately 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 classes 6 and 8.

Table 3.2 Average Truck Class Percentages on the Highway Functional Classes

TRUCK CLASS FUNCTIONAL 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
Non Interstate NHS	24.53	3.34	1.57	6.06	60.61	1.53	1.25	0.58	0.53
NON-NHS	43.91	3.71	0.96	7.48	42.40	0.82	0.45	0.16	0.13

Source Ahmed et al. (2013).

3.3 Traffic Growth Factor

For reliable estimation of marginal pavement damage cost a correct estimation of traffic loading is necessary. For estimating the future traffic, the appropriate traffic growth factor must be determined. The annual average traffic growth rates were estimated using past traffic growth trends in Indiana. 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 by using the total traffic growth information from year 2001-2010 (INDOT, 2011). INDOT recommends the use of 2.8% to 3.3% as the compound annual growth rate (INDOT, 2010). In view of the traffic growth pattern noted for the past ten years in Indiana, this study used a growth factor of 1.5%.

3.3 Traffic Loading Estimation

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 period. 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:

$$\sum_{\mathrm{k}=1}^{50} ESAL \quad = Truck\ AADT * 365 * D_{\mathrm{d}} * \mathrm{G_f} * L_d * \sum_{i=1}^{m} (LEF_i * \%Class_i)$$

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; $\%\mathrm{Class}_{\mathrm{i}}$ = Percentage of trucks in Class i; m = number of truck classes.

3.4 Selecting the Appropriate Measure of Road Use and Estimating the Road Use Levels

This is a vital step in estimating the marginal cost of pavement damage. In most previous studies the road-use measures were: vehicle-mile, mile/year, GVW-mile, or 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 (AASHTO, 1993). 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 this 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 3.4.

Table 3.4 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

CHAPTER 4 LIFE-CYCLE ACTIVITY SCHEDULES FOR PAVEMENT RECONSTRUCTION, REHABILITATION AND MAINTENANCE

4.1 Introduction

From a viewpoint of practicality, any research on pavement damage cost estimation needs to consider the actual schedules that agencies establish for reconstructing, rehabilitating, and maintaining their pavements. Also, referred to as MR&R activity profiles, these schedules are a prescription of treatment types and timings; timing may be based on pavement age or condition.

A time-based pavement MR&R activity schedule is one where the pavement is reconstructed, rehabilitated, or maintained on the basis of the age of the pavement. The intervals of treatment application may be large or small depending upon the asset age, traffic, and climate. Khurshid (2010) argued that at agencies that suffer a dearth of reliable data, on individual pavement segment condition, time-based activity schedules are most appropriate. Examples of time-based strategies in the literature include those of Zimmerman et al. (2002), Hicks et al. (2000), Lamptey et al. (2005), Labi and Sinha (2003).

On the other hand, a condition-based pavement MR&R activity schedule is one where the pavement work is carried out on the basis of the pavement condition (often referred to in literature as performance). Indicators of pavement performance include roughness, rutting, cracking, and faulting. For each indicator, a threshold is established; agencies may use tight or relaxed thresholds depending on the asset functional class, and in certain cases, availability of funding. A well-functioning pavement management system is indispensable for the use of condition-based activity profiles. Examples of performance-based MR&R strategy formulation include those of Ahmed et al. (2004; Lamptey et al. (2005); AI&T (2006), Hicks et al. (2000), Lamptey (2004), Khurshid et al. (2010a) and Irfan (2010).

4.2 Formulating MR&R Activity Schedules

For formulating a life-cycle activity schedule for pavement reconstruction, rehabilitation, and maintenance over an infinite analysis period, it is useful to consider one lane of a pavement section for which the agency applies an overlay of constant intensity at fixed, recurring intervals of time. From a practical perspective, this is mostly applicable to flexible pavements only. It is assumed that the overlay treatment is applied whenever the pavement deterioration reaches a specified trigger level. Let *C* be the unit cost ($/lane-mile) of the overlay; *Q* is the annual traffic loading (ESALs) of the pavement segment; *D* is the pavement durability in terms of the number of ESALs to failure. The interval between any two successive resurfacing actions (rehabilitation), T is *D*/*Q*. Let *r* represent the real compound interest rate and P represent the present value of all the recurring future overlay treatments. If *m* is the number of interest periods annually, then the interest rate for each compounding period is given by *r*/*m*. The continuously-compounded value, *V*, of a single expenditure *C* every time *T* is given by:

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

This can be rewritten as:

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

As *m* becomes very large, 1/*m* approaches zero and the expression $(1 + r/m)^{(m/r)}$ approaches *e*. In that case, the present worth of the continuously-compounded single pavements after *T* years is:

$$V = \frac{C}{e^{rT}}$$

And thus the present worth, P, of all the recurring future overlays is given by:

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

For an overlay of constant intensity, the above equation can be rewritten as:

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

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

Assuming that (*rT*) is negative and finite, the finite geometric series converges as follows:

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

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

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

The pavement damage cost for a unit road-use measure is obtained by differentiating the annualized cost with respect to the annualized level of road use (traffic loading) as follows:

$$MC = \frac{d}{dQ}(AC) = \frac{d}{dQ}[P(e^r-1)] = C = \left(\frac{dP}{dT}\right)\left(\frac{dT}{dQ}\right)(e^r-1)$$

Thus,

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

Also,

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

From the above equations, the expression for the marginal cost of pavement damage ($/ESAL-mile) can be derived as follows:

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

The last equation represents the basic formulation used by studies that used the indirect approach. The simplification of the MR&R schedule and simulation of the consequences over an infinite analysis period, while tractable, represents a troubling departure from practicality. As we indicated in the literature review (Chapter 2 of this report), most of these studies had assumed that the expenditures on pavement upkeep are dominated by resurfacing (overlay) cost and thus had declined, implicitly or explicitly, to consider the cost of routine maintenance, periodic maintenance, or even reconstruction. In the real world, reality, every highway agency uses a very wide range of different treatments for effective management of its highway network. Agencies apply a wide range of rehabilitation, periodic maintenance, and routine maintenance activity types to prevent the onset of deterioration, to address non-structural or structural defects, and generally to retard the rate of pavement deterioration, and also reconstruct the pavement when it has completed it service life. In this study therefore, this assumption was eschewed in favor of more practical considerations of the actual MR&R activity schedules of any typical highway agency.

Similar to most civil infrastructure, highways are meant to provide service perpetually; however, like any man-made system, they do not last forever and must be replaced anytime they reach their end of life. The initial expenditure of highway provision includes one-time amounts incurred on right-of-way acquisition, clearing, grading, earthworks, relocation of utilities, drainage and erosion control, environmental mitigation. The subsequent costs, or the rest-of-life cost, include reconstruction of the basic structure, rehabilitation, periodic maintenance, and routine maintenance activities that are repeated after a certain number of years. As this study addresses the marginal costs of pavement damage, it excludes the one-time initial costs and only considers the rest-of-life (ROL) costs. Thus, the study also excludes the initial (new) construction cost but included future reconstruction costs. The ROL costs are a direct result of pavement damage that in turn arises as a result of traffic loading and climate.

The selection of treatments that comprise a MR&R activity schedule is typically influenced by the nature and severity of the existing defects and the overall pavement condition. Table 4.1 presents a list of standard treatments at a typical highway agency. For flexible pavements, thin HMA overlay is often the most common preventive maintenance treatment. For rehabilitation of flexible pavements, besides 3R/4R rehabilitation, HMA overlay (structural) and resurfacing of asphalt pavements (partial 3R) are very common. For rigid pavements, crack and joint sealing, and fault grinding are widely used as preventive maintenance treatments; for rehabilitation, PCC patching, Repair PCC and HMA Overlay, Crack-and-seat PCC and HMA overlay, Rubblize PCC and HMA Overlay were common.

For each standard MR&R treatment listed in their preservation manuals, agencies have established appropriate trigger values or ranges (see Table 4.1). For the purposes of formulating pavement MR&R activity schedules, it is critical that these trigger values are specified clearly. As Khurshid (2010) determined, a treatment applied too early when the asset is in good or excellent condition or too late when the asset is in a very deteriorated state is not cost effective.

Table 4.1 Standard Treatments at a Typical Highway Agency

PAVEMENT TYPE &TREATMENT CATEGORY	TREATMENT TYPE
Flexible Pavement Reconstruction and Rehabilitation	Reconstruction
	HMA Overlay, Structural
	HMA Overlay, Functional
	Resurfacing (Partial 3R Standards)
	Mill Full-depth and Asphalt Concrete Overlay
Flexible Pavement Preventive Maintenance	Thin HMA Overlay
	Microsurfacing
	Seal Coat (Chip Seal)
	Asphalt Crack Seal (Route and Seal)
Rigid Pavement Reconstruction and Rehabilitation	Reconstruction
	Repair PCCP & HMA Overlay
	PCC Overlay of PCC Pavement
	Crack and Seat PCCP and HMA Overlay
	Rubblize PCCP and HMA Overlay
Rigid Pavement Preventive Maintenance	HMA Overlay, Functional
	PCCP Patching
	Crack Seal
	Concrete Pavement Restoration (CPR)
	PCCP Patching

Source: INDOT (2010), Ahmed et al. (2013)

Table 4.2 Pavement Performance Standards at a Typical Highway Agency

PERFORMANCE INDICATOR	INDOT STANDARDS (THRESHOLDS)		
	(M/KM)	(IN/MI)	DESCRIPTION
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

Source: INDOT (2001), Ahmed et al. (2013)

4.3 The Effect of Discounting over Pavement Life Cycle

Due to the combined impact of inflation and opportunity cost, the value of money diminishes over time. Opportunity cost is the economic return that is sacrificed in some future year by demurring to invest in the current year; and inflation is the increase in the prices of goods and services with time or a general trend of higher prices of goods with time. Any analysis of pavement damage cost should be carried out in a life cycle context, and such context is associated with the changing value of money over time. In most analysis of this nature, the monetary amounts used in the analysis are already adjusted for inflation and therefore expressed as dollars of some base year. In that case, any change in the value of money over time is purely due to the effect of opportunity cost. The total life cycle cost associated with a specific activity schedule for pavement reconstruction, rehabilitation, and maintenance (at occur at different times within the life cycle) should proceed only after duly accounting for effect of the opportunity cost through discounting. FHWA recommends using a real interest rate of 3-5% (Walls and Smith, 1998).

CHAPTER 5 COSTS AND SERVICE LIVES OF MR&R TREATMENTS

5.1 Introduction

In Chapter 3, we presented the framework for estimating the marginal cost of pavement damage, specifically, the development of realistic MR&R activity schedules over the pavement life cycle. In the present chapter, we show how we prepared the input data for the damage cost analysis by estimating for the treatment costs and service lives of MR&R treatments for each segment, and analyzing the traffic data for each segment. This is done using data from in-service pavements in a Midwestern state of the United States. The chapter begins with a discussion of the pavement families that were used in an earlier study (Ahmed et al., 2013). This is followed by, 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. This is consistent with past studies in Indiana that classified pavements on the basis of their NHS functional class (Interstate, NHS-NIS, and NNHS) and surface material type (rigid and flexible). The MR&R activity schedules were established for each pavement segment on the basis of the activity schedules defined for their corresponding pavement family. Further details of sub-grouping based on traffic loading are discussed in subsequent sections.

5.3 The Cost of MR&R Activity Schedules

5.3.1 Activity Schedules and Individual Treatment Costs

The costs of MR&R activity schedules were determined first by establishing the MR&R activity schedules, which was in turn established by determining the effectiveness of the individual treatments associated with the schedules. The effectiveness therefore specified the frequency of applications. The results of a recently completed study (Ahmed et al., 29013) provided information on the effectiveness of different rehabilitation and periodic maintenance treatments; specifically, (i) the rest period of newly-reconstructed pavements, i.e., the years that elapse before applying the first major rehabilitation or periodic maintenance treatment) and (ii) the treatment service lives. The Ahmed et al. study carried out pavement performance modeling in order to establish the rest periods. Information on treatment effectiveness were obtained from earlier studies (Labi and Sinha, 2003; Irfan et al., 2009; INDOT, 2010; Irfan, 2010; Khurshid et al., 2011) as shown in Table 5.1. Table 5.1 presents the service lives of typical standard treatments. Tables 5.2 and 5.3 present the costs of standard treatments typically applied to flexible and rigid pavements, respectively. Using the determined frequency of application of the treatments and their cost models, the overall cost of each MR&R activity profile was established.

Table 5.1 Service Lives of Typical Standard Treatments

PAVEMENT TYPE &TREATMENT CATEGORY	TREATMENT TYPE	INDOT MANUAL	OTHER INDIANA STUDIES	
			AVG. SL	SL RANGE
Flexible Pavement Reconstruction and Rehabilitation	Reconstruction	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 Pavement 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 Pavement Reconstruction and Rehabilitation	Reconstruction	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 Pavement Preventive Maintenance	HMA Overlay, Functional	12	-	-
	PCCP Patching	-	10	8 – 14
	Crack Seal	-	4	-
	Concrete Pavement Restoration (CPR)	6	-	-
	PCCP Patching	8	-	-

Sources: (Labi and Sinha 2003; Irfan et al., 2009; INDOT, 2010; Irfan2010; Khurshid et al., 2011)

Table 5.2 Flexible Pavement Treatment Costs

(a) Interstate

Treatment Type	Unit Cost ($/lane-mile) in 2010 dollars				Sample Size
	Mean	Min.	Max.	Std. Dev.	
Thin HMA Overlay	$94,900	$46,700	$180,300	$47,700	10
Microsurfacing	$22,400	$15,500	$27,400	$6,100	3
Crack Sealing	$2,800	$240	$14,500	$3,100	17
Chip Seal (Seal Coating)	$8,000	$2,500	$19,000	$9,500	3
Functional HMA Overlay	$89,500	$47,800	$409,600	$93,400	14
Structural HMA Overlay	$370,400	$44,300	$2,714,900	$659,400	14
Resurfacing (Partial 3R)	$152,900	$11,900	$408,200	$119,200	13
Mill Full Depth & AC Overlay	$171,800	$17,600	$380,500	$148,200	6
Road Reconstruction	$2,504,800	$517,800	$4,471,900	$1,125,700	9

(b) Non-Interstate but NHS

Treatment Type	Unit Cost ($/lane-mile) in 2010 dollars				Sample Size
	Mean	Min.	Max.	Std. Dev.	
Thin HMA Overlay	$88,100	$31,600	$206,800	$36,500	31
Microsurfacing	$39,500	$20,400	$77,900	$21,900	7
Crack Sealing	$2,800	$240	$14,500	$3,100	17
Chip Seal (Seal Coating)	$8,100	$2,500	$19,000	$9,500	3
Functional HMA Overlay	$127,000	$56,700	$209,800	$46,200	31
Structural HMA Overlay	$179,500	$38,000	$537,100	$156,300	21
Resurfacing (Partial 3R)	$119,400	$14,100	$392,500	$69,500	160
Mill Full Depth & AC Overlay	$171,800	$17,600	$380,500	$148,300	6
Road Reconstruction	$1,706,500	$483,100	$2,469,000	$563,900	9

(c)Non-National Highway System

Treatment Type	Unit Cost ($/lane-mile) in 2010 dollars				Sample Size
	Mean	Min.	Max.	Std. Dev.	
Thin HMA Overlay	$84,600	$26,800	$250,700	$38,400	100
Microsurfacing	$39,700	$20,400	$77,900	$22,000	7
Crack Sealing	$2,800	$240	$14,700	$3,100	17
Chip Seal (Seal Coating)	$8,100	$2,500	$19,000	$9,500	3
Functional HMA Overlay	$125,600	$20,300	$250,400	$52,400	81
Structural HMA Overlay	$207,800	$30,500	$448,300	$151,800	7
Resurfacing (Partial 3R)	$103,000	$8,700	$301,700	$56,600	396
Mill Full Depth & AC Overlay	$171,800	$17,600	$380,500	$148,300	6
Road Reconstruction	$1,706,500	$483,100	$2,469,100	$563,900	9

Source: Ahmed et al. (2013)

Table 5.3 Rigid Pavement Treatments Costs

(a) Interstate

Treatment Type	Unit Cost ($/lane-mile) in 2010 dollars				Sample Size
	Mean	Min.	Max.	Std. Dev.	
Cleaning and Joint Sealing	$213,800	$97,100	$36,300	$56,400	8
CPR	$150,000	$24,000	$550,000	$173,000	7
HMA Functional Overlay on Concrete	$89,500	$47,800	$409,600	$93,400	14
Repair PCCP & HMA Overlay	$491,900	$2,900	$844,400	$345,800	15
PCCP Overlay on PCCP Pavement	$737,600	$737,600	$737,600	-	1
Crack and Seat PCCP & HMA Overlay	$519,400	$117,700	$209,800	$864,900	11
Rubblize PCCP & HMA Overlay	$757,000	$425,900	$1,256,000	$239,800	12
Road Reconstruction	$2,793,000	$358,500	$10,665,000	$2,918,000	12

(b) Non-Interstate NHS and No-Interstates

Treatment Type	Unit Cost ($/lane-mile) in 2010 dollars				Sample Size
	Mean	Min.	Max.	Std. Dev.	
Cleaning and Joint Sealing	$212,900	$97,100	$36,280	$56,400	8
CPR	$150,000	$24,000	$550,000	$173,000	7
HMA Functional Overlay on Concrete	$127,000	$56,700	$209,800	$46,200	31
Repair PCCP & HMA Overlay	$491,900	$2,800	$844,300	$345,800	15
PCCP Overlay on PCCP Pavement	$737,600	$737,500	$737,600	-	1
Crack and Seat PCCP & HMA Overlay	$440,800	$143,400	$324,700	$1,114,000	7
Rubblize PCCP & HMA Overlay	$757,000	$425,900	$1,256,100	$239,800	12
Road Reconstruction	$1,902,900	$334,400	$5,888,800	$1,461,900	16

Source: Ahmed et al. (2013)

5.3.2 Estimating the Overall Cost of MR&R Activity Schedules

The cost of each MR&R strategy over a 50-year analysis period was determined. Consistent with FHWA and INDOT recommendations, a 4% interest rate was used (Walls and Smith, 1998; INDOT, 2010). The total MR&R cost over the analysis period is the sum of the reconstruction, rehabilitation, and periodic and routine maintenance costs over the period. Using interest equations, the present worth (PW) of all costs of the MR&R was determined using the expression below:

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

Where: $\mathrm{PW(P)_{M\&R}}$ = present worth of total reconstruction, rehabilitation and maintenance cost of 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:

$$\mathrm{EUAC_{MR\&R}} = [\mathrm{PW(P)_{MR\&R}}] \times r$$

Where: $\mathrm{EUAC_{MR\&R}}$ = equivalent uniform annual cost of MR&R activity schedule over 50 years.

CHAPTER 6 ESTIMATING THE COSTS OF PAVEMENT DAMAGE

6.1 Introduction and Overview

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 EUAC was used as the dependent variable, and the data for this variable were obtained as the cost of the individual MR&R strategies. For each MR&R activity schedule, the average annual ESALs sustained by the pavements were estimated and used as one of the explanatory variables. MR&R activity schedules were developed separately for the different highway functional classes and also for flexible and rigid pavements. 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. 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 activity schedule and used as an explanatory variable n the model. Separate MR&R strategies were formulated for different 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 (SAS, 2008). Several alternative functional forms were tested and evaluated for the model. The general functional forms of the investigated models are:

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

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

$$\mathrm{EUAC}_{\mathrm{MR\&}R} = \beta_0 + \beta_1 * \ln(\mathrm{ESALs}) + \beta_2 * \mathrm{X}$$

Where: β_0, β_1, β_2 = Constant term and parameter estimates for model explanatory variables; $\mathrm{EUAC}_{(\mathrm{MR\&R})}$ = 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; X = Vector of other attributes.

6.2 Data Collection and Collation

For the estimation of M&R marginal cost, historical M&R cost and traffic data is used. In this study, data were collected from number of sources and a comprehensive database was prepared. Cost and road inventory (individual segments identification and reference points, mileposts, county, sub-district) data for maintenance and rehabilitation treatments for state of Indiana for year 1994-2006, were obtained from Indiana Department of Transportation (INDOT) contracts and construction division, and program development division. Traffic data (AADT, % of trucks and traffic growth factors) were obtained from INDOT's traffic monitoring section. Climatic data (annual average freeze index, mean annual temperature, the average annual precipitation, and average number of wet days) were obtained from the (NOAA, 1995; INDOT, 2011). Pavement condition data were obtained from INDOT Pavement Management Division, and INDIPAVE-2000. The treatment service lives of commonly used maintenance and rehabilitation treatments were obtained from past Indiana studies (Labi and Sinha, 2003; Irfan et al., 2009; Irfan, 2010; Khurshid et al., 2011; INDOT, 2011). For the present study, a number of maintenance and rehabilitation treatments used for flexible and rigid pavement were considered. The flexible pavements, maintenance treatment include microsurfacing, thin HMA overlay, functional HMA overlay, structural HMA overlay, resurfacing partial 3R standards, and mill asphalt concrete and bituminous overlay. The rigid pavements maintenance treatment include rubblize Portland cement concrete (PCC) pavement, HMA overlay, crack-and-seat PCC, and HMA overlay. The treatments were applied at different years, therefore the cost data were converted into cost per lane-mile in 2010 constant $ using highway consumer price indices (CPI) (Sinha and Labi, 2007). Summary statistics of important variables are presented in Table 6.1.

Table 6.1 Summary Statistics of Key Traffic and Climatic Variables

VARIABLE	MEAN	S.D.	MINIMUM	MAXIMUM
Dependent variable: Cost per lane-mile of M&R treatment (2010 Constant $)	118,320	76,531	9,936	542,202
Total ESALs sustained by the pavement segment	2,375,610	2,819,633	8,095	18,883,667
Annual Average daily traffic (AADT)	10,819	10,660	58	70,880
Annual Average daily truck traffic (AADTT)	1,659	2,219	5	14,817
Annual average freeze index (degree-days)	514	238	0	889
Average precipitation (inches)	40	3	35	48
Average number of wet days (average days with precipitation)	117	12	95	134
Total freeze index (degree-days)	5,857	3,031	0	12,852
Total precipitation (inches)	461	102	188	738
Total number of wet days	1,336	300	580	2,304

6.3 Model Development

For estimation of pavement M&R marginal cost as a first step, a functional relationship is established between pavement M&R cost and different factors responsible for cost (traffic and climatic loading sustained by the pavement, geographic location, treatment types etc.). The differentiation of estimated function with respect to some road-use variable (e.g., ESAL) yields marginal M&R cost. In order to explore the relationship between explanatory variables and a dependent variable, cost functions estimated using ordinary least square (OLS) regression is a widely-used technique in the literature for purposes similar to this study. In the present study, OLS models that uses the total maintenance or rehabilitation expenditure per-lane mile as its dependent variable were estimated using LIMDEP (statistical software package) as developed by Greene (2007). An OLS model was used since the cost per lane-mile is a continuous variable and can take any value between zero to infinity. A number of functional forms were investigated and the best estimated model (log-linear) is presented and discussed in the ensuing paragraphs. The general functional form of the model is as follows:

$$\ln C_{(i)} = \alpha + \beta_o\left(lnX_{i(t)}\right) + \sum_{i=1}^{j}\left(\beta_i X_{i(nt)}\right) + \varepsilon_i \qquad (6.1)$$

Where: $C_{(i)}$ is the rehabilitation or periodic maintenance cost per lane mile; i denotes observation, α and β's are model coefficients; $X_{i(t)}$ are the traffic related independent variables and $X_{i(nt)}$ is the set of independent variables representing climatic loading of the pavement, regional features, pavement surface type, and highway functional class; and $\varepsilon's$ are the error terms.

Linear regression models can be estimated with random parameter specifications for both panel and cross-sectional data. Green found that Random parameter models help to account for the latent heterogeneity of individual observations (Greene, 2010). It is assumed that each pavement segment is unique in characteristics in terms of geographic location, traffic and climatic loading, surface and structural deterioration, quality of initial pavement construction and rehabilitation/periodic maintenance treatment application, weather condition at time of treatment application, and contractor skill and workmanship. Therefore, it was considered appropriate to explore for segment-specific heterogeneity, whereby each treatment application is considered as a unique project with specific characteristics, which are reasonably distinct from the other applications. It was assumed that the model parameters are randomly distributed and there is heterogeneous distribution across the individual pavement segments. The model structure, for the random parameter linear regression model is based on the conditional mean (Greene, 2010) as follows:

$$E[C_i/(X_i, \beta_i)] = E[\beta_0 + \beta_i{}^* X_i + \varepsilon_i] \quad \text{i}= 1, 2, \ldots\ldots \text{N} \qquad (6.2)$$

Or simply:

$$C_i = \beta_i{}^* X_i \qquad (6.3)$$

Where:

$$\beta_i{}^* = \beta_i + \omega_i \qquad (6.4)$$

Where: β_i^*represents a vector of the estimable parameters which has β_i as deterministic component and ω_i as stochastic component. β_i^* is considered as random draw from a probability distribution which has β_i as mean; ε_i are the normally distributed disturbance error term with zero mean and constant variance.

6.4 Model Results and Discussion

Using data from 508 pavement segments that received rehabilitation or periodic maintenance treatments between 1994 and 2006, random- and fixed parameter linear regression models were estimated (Table 6.2). A random parameter model was estimated in a bid to improve the overall parameter estimates and to enable the estimation of pavement segment-specific estimates. The parameters of the model were estimated using maximum simulated likelihood method. Craig et al. noted that method of maximum simulated likelihood has been found effective in overcoming the higher dimensional numerical integration issues arising from efforts to maximize the log likelihood function containing an unobserved heterogeneity term (Craig et al., 2003). Halton draws have been found effective in such situation which speeds up the convergence and are based on the assumption that it is not the random sample of draws rather it is "intelligent" draws that are more effective (Train, 1999; Bhat, 2003; Anastasopoulos and Mannering, 2009). Random parameters are assumed to be normally distributed and 200 Halton draws were found to be sufficient for model parameter estimation.

Out of seven significant variables, three variables had statistically significant random parameters. The standard deviations of the parameter density for total ESALs, total precipitation, and microsurfacing indicator variable were found to be statistically significant. These random parameters had standard deviations, which are statistically different from zero. For all random parameters, best statistical fit was obtained using normal distribution. To test the overall significance of random parameter model over the fixed parameter model a likelihood ratio test was used. As of Washington et al., knowing the log likelihood for fixed- and random parameter models at convergence, the likelihood ratio test statistic is given as follows (Washington et al., 2010):

$$\chi^2 = -2[LL(\beta_R) - LL(\beta_F)] \tag{6.5}$$

Where $LL(\beta_R)$ and $LL(\beta_F)$ are the log-likelihood values for fixed- and random parameter models at convergence. The resulting χ^2 value is 10.14 with 3 degrees of freedom. The critical value of $\chi 2$ ($\chi^2_{(0.05,3)}$) is 7.815. Thus, it is seen that there is at least 95% confidence that the random parameter model provides statistically superior results as compared to its fixed parameters counterpart.

Table 6.2 Estimation Results of Random- And Fixed-Parameter Linear Regression Models

Variable description	Random parameter		Fixed parameter	
	Coeff.	t-stat	Coeff.	t-stat
Constant	10.381	0.572	0.465	19.529
Pavement type indicator variable (1 if pavement is flexible, 0 otherwise)	-1.232	17.111	1.222	-8.482
Annual average freeze index (degree-days)	0.0005	9.183	0.0005	4.666
Functional HMA overlay indicator variable (1 if treatment is functional HMA overlay, 0 otherwise)	0.160	6.588	0.157	3.075
District indicator variable (1 if district is Seymour, 0 otherwise)	0.239	6.147	0.239	2.871
Average number of wet days (the average number of days with precipitation)	0.006	4.948	0.006	2.295
Random Parameters				
Natural Logarithm of Total Traffic (Total ESALs) *Std. Dev. of Parameter Distribution*	0.0623 *(0.0243)*	6.013 *(33.445)*	0.0548	2.538
Total precipitation (inches) *Std. Dev. of Parameter Distribution*	0.0010 *(0.0005)*	7.170 *(22.591)*	1	3.434
Microsurfacing indicator variable (1 if treatment is microsurfacing, 0 otherwise) *Std. Dev. of Parameter Distribution*	-0.851 *(0.474)*	-15.299 *(9.673)*	-0.883	-7.579
Log-likelihood at convergence	-349.486		-354.558	
Number of observations	508		508	

The significant variables included in the final model were divided into four groups: (1) traffic variable, (2) climatic variables, (3) geographic location, and (4) treatment characteristics. A discussion on these variables is provided below.

6.4.1 Influence of the Road-use Variable

The positive sign of traffic loading (total ESALs over the treatment service life) indicates that pavement segments with higher traffic loadings are associated with increased pavement periodic maintenance or rehabilitation expenditure. The parameter estimate for total traffic (natural logarithm of total ESALs over treatment service life) was found to be normally distributed with a mean of 0.0623 and a standard deviation of 0.0243. The mean and standard deviation are statistically significant, indicating that the influence of the variable is different for different pavement segments. It is seen that approximately 99.47% of the distribution is greater than zero (Figure 6.1). This indicates that for almost all road segments, an increase in total ESALs over treatment service resulted in increased M&R expenditure albeit with varying magnitude across the roadway segments. Since M&R marginal cost is obtained by differentiation of the estimated model with respect to traffic variable (ESAL), the differences in the parameter estimates for traffic load from segment to segment therefore means that the M&R marginal cost is different across the pavement segments. This is an important finding, indicating that it is appropriate to charge highway users, different fee on different highway functional classes and on different road segments (same functional class), as M&R marginal cost varies from segment to segment.

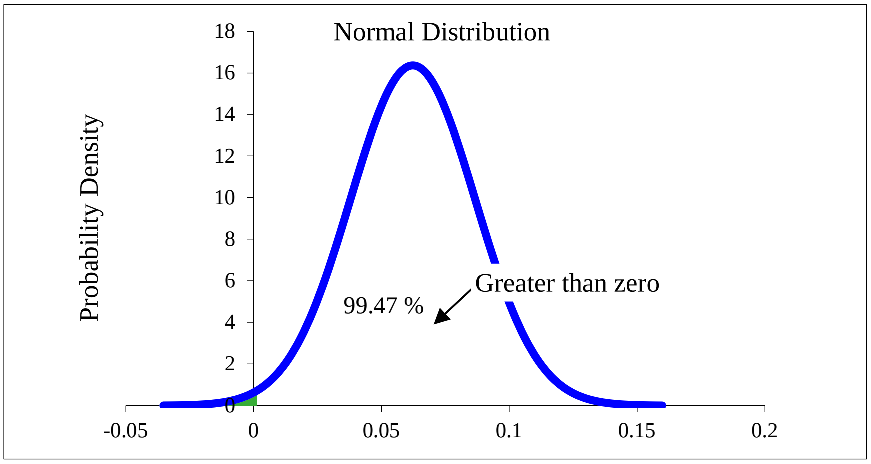


Figure 6.1 Random Parameter Distribution – Total Traffic (ESALs)

6.4.2 Influence of the Climate Variable

The model results indicate that a higher annual average freeze index results in higher total rehabilitation or periodic maintenance expenditures during treatment service life, which is consistent with Khurshid et al., findings indicating that pavement segments located in a high freeze-index zone are likely to deteriorate faster and may result in higher maintenance expenditure (Khurshid et al., 2014). State of Indiana is located in the wet-freeze climatic region of the United States, thus those pavement segments that are subject to higher annual average freeze index shall experience higher number of annual freeze–thaw cycle, hence rapid deterioration.

The parameter estimate for total precipitation variable was found to be normally distributed with a mean of 0.001 and a standard deviation of 0.0005. For given distributional parameters, 98.14% of the distribution is greater than zero and 1.86% is less than zero (Figure 6.2), indicating that for a majority of the road segments, the total precipitation has an intuitive impact: an increase in total precipitation leads to an increase in the M&R marginal cost. This is also consistent with past findings of Ahmed et al., indicating that higher precipitation is likely to result into more water entering into pavement through cracks/seals and thus resulting into pothole formation and pumping (ejection of water and fines slurry) (Ahmed et al., 2013) .

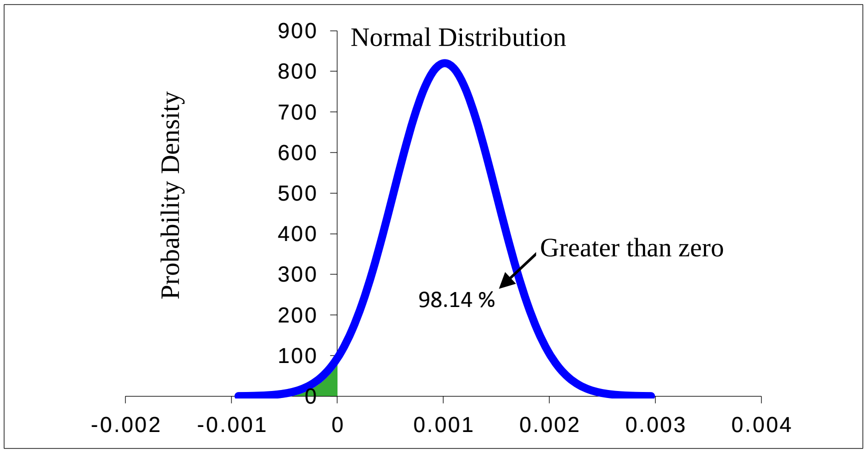


Figure 6.2 Random Parameter Distribution – Total precipitation

The total number of wet days in year (the average number of days with precipitation annually) to which a pavement segment remains exposed has also significant influence on pavement M&R expenditure. Table 6.1 indicates that all else being constant higher the total number of days to which a pavement segment is subjected to precipitation, higher shall be the pavement maintenance expenditure.

6.4.3 Influence of the Treatment Type Variable

The indicator variable for a functional HMA overlay treatment indicate that those pavement segments that received this treatment are associated with higher rehabilitation and maintenance costs compared to pavement segments that received other treatments. This indicates a treatment-specific characteristic pointing toward lower effectiveness of functional HMA overlay treatment compared to other treatments. This finding should prompt highway agencies to revisit the current design and construction standards of functional HMA overlay treatment.

The model parameter of microsurfacing treatment was found to be associated with lower M&R cost per lane-mile. This finding is intuitive. Microsurfacing is a preventive maintenance treatment used to retard the pavement deterioration, thus those pavement segments that received this treatment had overall lower M&R cost per lane-mile. Lower M&R cost per lane-mile of microsurfacing indicates the higher suitability/effectiveness of this treatment. The parameter estimate for the microsurfacing indicator variable was found to be normally distributed with a mean of -0.851 and a standard deviation of 0.474. For given distributional parameters, almost 96.38% of the distribution was less than zero (Figure 6.3), indicating that for majority of the road segments, microsurfacing treatment resulted in decreased M&R expenditure at varying rates.

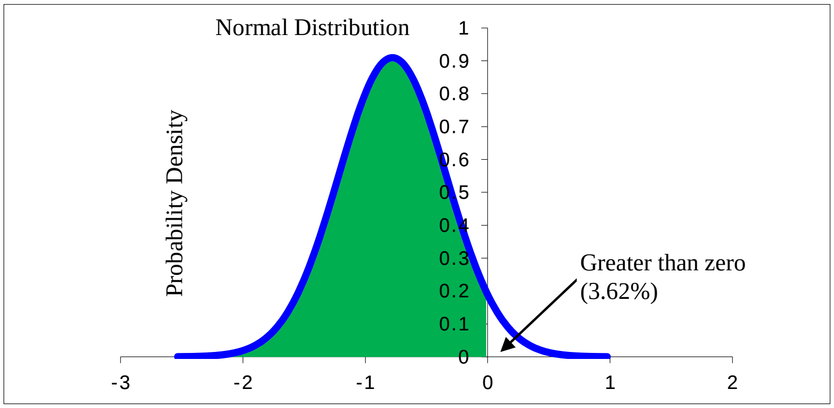


Figure 6.3 Random Parameter Distribution – Microsurfacing Treatment

6.4.4 Influence of the Geographic Location Variable

The positive sign of the indicator variables for the Seymour district of Indiana revealed that this district has higher rehabilitation and periodic maintenance expenditures per lane mile compared to other districts of Indiana. This district has the highest precipitation rate in Indiana (CIWRP, 2003; Volovski, 2011). Higher precipitation can result in faster pavement deterioration and higher maintenance and rehabilitation expenditure, which is quite logical. This may also indicate district specific characteristics that might be the result of specific policies or the local maintenance practices at such different locations. For example, if a certain district has stricter enforcement of overweight truck limitations as compared to another district, better weight enforcement may prevent the pavements from experiencing excessive loading and will lead to a lower pavement damage rate and lower rehabilitation or periodic maintenance expenditures. Also, for example, if a certain district has a well-established pavement maintenance system as compared to another district, timely maintenance will prevent the pavements from undue deterioration and will lead to lower pavement M&R expenditures.

6.5 Estimation of Marginal Pavement M&R Cost

The marginal pavement MR&R cost is the cost of an additional traffic unit (ESAL) on a given pavement segment. The pavement M&R marginal cost was estimated by differentiating the estimated model (Equation 1) with respect to the road-use variable (ESAL). Following Johansson and Nilsson (2004) and Anderson (2007), the marginal pavement M&R cost is determined as:

$$\mathrm{M}_{(M\&R)} = \frac{\partial C}{\partial ESAL} = \left(\frac{\partial LnC}{\partial LnESAL}\right) * \left(\frac{C}{ESAL}\right) \tag{6}$$

$$\mathrm{M}_{(M\&R)} = (\varphi) * \left(\frac{C}{ESAL}\right) = (Elasticity) * (Average\ cost) \tag{7}$$

Where; $M_{(M\&R)}$ is the marginal pavement M&R cost, φ is the cost elasticity and in log-log specification the corresponding parameter estimate (0.0623) represents the elasticity. Thus, marginal cost is the product of cost elasticity and average cost.

6.6 Application of the Model

In order to demonstrate the applicability of the developed model, in-service pavement sample datasets for each of the three functional classes (Interstate, Non-Interstate NHS, and non-NHS) were used. These pavements are located on the Indiana state highway system. These pavement segments straddle the entire length and breadth of the state and experience a wide range of traffic volumes, from low loads on the I-64 to very high loads on the I-80 in the northern Indiana area and I-70 in the Indianapolis beltway area; and significant variations in climate, from freeze-susceptible northern Indiana to relatively warm southern Indiana. Using the Interstate segments as an illustration, Table 6.1 presents the basic data on the pavement segments used to demonstrate the applicability of the model; Tables 3.2 and 3.3 present, for the pavement segments, the estimated traffic volume by vehicle class and the estimated annuals ESALs by vehicle class.

Figures 6.4 to 6.7 provide the developed marginal costs of pavement damage, and show that there is significant variation compared to what would otherwise be obtained if a uniform damage cost had been assumed and calculated for these pavement segment on the basis of their parent families. Figure 6.5 presents a scatter plot of the total cost of pavement damage cost estimates for highway sections on each of the three different functional classes, and Figure 6.6 and Figure 6.7 present the probability distribution of these cost estimates and the distribution of the marginal cost of pavement damage.

It can be seen from Figure 6.4 that the life-cycle damage cost (life cycle cost of pavement upkeep associated with traffic loads), on average, is approximately $85,000/lane-mile, $70,000/lane-mile and $55,000 per lane-mile, for the vehicles that use the pavements on Interstates, non-Interstate NHS, and non-NHS, respectively. After taking account of the traffic loads experienced, the marginal effect model yields the results that are shown in Figure 6.5; the marginal damage cost over the life cycle (life cycle cost of pavement upkeep associated with the addition of one ESAL), on average, is approximately $0.01/ESAL per lane-mile, $0.014/ESAL per lane-mile and $0.04/ESAL per lane-mile respectively, for the vehicles that use the pavements on Interstates, non-Interstate NHS, and non-NHS, respectively. These figures are indicative of the wide disparity in pavement damage costs across the different functional classes and also across individual pavement segments in a given functional class. Such disparity is also evident in Figure 6.6 which presents the probability distribution of the cost of pavement damage cost estimates, and Figure 6.7 which presents the probability distribution of the marginal cost of pavement damage.

These results support the notion that greater reliability is associated with segment-specific cost allocation, and that if the future volumes of truck traffic at each segment are estimated with greater accuracy, greater confidence could be placed on pavement damage cost estimates. Also, it may be argued that annual field counts at specific segments (that are available at most agency websites) may not be appropriate for purposes of fee structure determination for a specific highway segment because such traffic levels reflect current conditions only and even with growth adjustment factors, may fail to provide reliable future projections. Furthermore, the relative contribution of climate and traffic in pavement deterioration are known to differ across the different functional classes. By addressing the issue of pavement damage cost estimation from a disaggregate level, this study helps to establish more reliable estimates of pavement damage costs. It is envisaged that this could not only increase the efficiency and effectiveness but also enhance equity in the highway cost allocation and revenue generation.

The prediction of future traffic volumes is most promising when done in the context of a regional freight assignment model. In other words, the assignment of future freight traffic on the highway network system, on the basis of projected socio-economic developments, could yield more reliable estimates of truck traffic volumes at each individual link on the highway system. That way, it will be possible to report the total damage costs not for families of pavements but for individual pavement segments within a family highway agencies can establish appropriate segment-specific costs of pavement damage and thus establish a foundation upon which existing fees for overweight vehicles could be reviewed.

Table 6.1 Basic Data on the Pavement Segments

(Sample data shown for Interstate Highway Segments)

INTERSTATE SEGMENT	ROUTE NAME	START	END	LENGTH (MI)	START MP	END MP
1	I64	IL stateline	I69	29.5	0.01	29.4
2	I64	I69	I265	92.8	29.4	121.5
3	I64	I265	KY stateline	2.2	121.5	123.33
4	I265	I64	I65	6.6	0	6.73
5	I265	I65	IN 62	3.5	6.73	10.23
6	I865	I65	I465	4.1	0	4.72
7	I469	I69	I69	30.5	0	30.85
8	I164	KY stateline	I69/I64	21.5	0	21.5
9	I465	I65	I865	5.2	19.8	24.26
10	I465	I865	I69	12	24.26	36.5
11	I465	I69	I70	6.9	36.5	43.43
12	I465	I70	I74	4.9	43.43	48.33
13	I465	I74	I65	4.5	48.33	52.79
14	I465	I65	I70	9.1	0	9.32
15	I465	I70	I74	6.6	9.32	15.55
16	I465	I74	I65	4	15.55	19.8
17	I69	I90	MI stateline	1.8	155.47	157.3
18	I69	I469	I90	43	114.72	155.47
19	I69	I469	I469	20.2	96.29	114.72
20	I69	I465	I469	96.5	0	96.29
22	I70	IL stateline	I465 (exit 9B)	72.8	0	72.75
23	I70	I465 (exit 9B)	I65	7.9	72.75	80.72
24	I70	I65	I65	2.4	80.72	82.2
25	I70	I65	I465 (exit 44)	6.6	82.2	89.04
26	I70	I465 (exit 44)	OH stateline	66.5	89.04	156.6
27	I74	IL stateline	I465	72.8	0	73.19
27A	I74	I465	I465		73.19	93.42
28	I74	I465	OH stateline	77.4	93.42	171.54
29	I65	KY stateline	I265	5.6	0	5.7
30	I65	I265	I465 (Exit 106)	103	5.7	105.9
31	I65	I465 (Exit 106)	I465 (Exit 110B)	4.7	105.9	110.1
31A	I65	I465 (Exit 110B)	I70	2.0	110.1	111.6
32	I65	I70	I465 (Exit 123B)	10.3	111.6	122.69
33	I65	I465 (Exit 123B)	I865	5.9	122.69	129.09
34	I65	I865	I80	131	129.09	259.06
35	I65	I80	US12	2.3	259.06	261.27
36	I94	I80/I90	MI stateline	29.6	15.51	45.75
37	I80	IL stateline	I65	11.7	0	11.8
38	I80	I65	I90/I94	4.2	11.8	15.51

Table 6.2 Pavement Segments: Estimated Traffic Percentages by Vehicle Class

(Sample data shown for Interstate Highway Segments)

Interstate Segment	Weighted AADT	% Class 1	% Class 2	% Class 3	% Class 4	% Class 5	% Class 6	% Class 7	% Class 8	% Class 9	% Class 10	% Class 11	% Class 12	% Class 13
1	13,457	0.00393	0.569	0.19289	0.00228	0.02531	0.0042	0.00067	0.01318	0.17681	0.00208	0.00654	0.00247	0.00064
2	20,946	0.004	0.57804	0.19595	0.00241	0.0267	0.00443	0.00071	0.0166	0.15639	0.00262	0.00824	0.00311	0.00081
3	55,268	0.00438	0.6332	0.21465	0.00259	0.02878	0.00478	0.00076	0.01077	0.09049	0.0017	0.00535	0.00202	0.00053
4	49,133	0.00434	0.62747	0.21271	0.00256	0.02843	0.00472	0.00075	0.01179	0.09672	0.00186	0.00585	0.00221	0.00058
5	30,422	0.00394	0.56947	0.19304	0.00229	0.02537	0.00421	0.00067	0.02783	0.14839	0.0044	0.01381	0.00522	0.00136
6	27,611	0.00438	0.63319	0.21464	0.00259	0.02878	0.00478	0.00076	0.00106	0.10887	0.00017	0.00052	0.0002	5.2E-05
7	21,620	0.00409	0.59226	0.20077	0.00242	0.02684	0.00446	0.00071	0.00807	0.15319	0.00127	0.004	0.00151	0.00039
8	24,701	0.00414	0.59841	0.20286	0.00267	0.02958	0.00491	0.00079	0.02861	0.10257	0.00452	0.0142	0.00536	0.0014
9	86,203	0.00438	0.63319	0.21465	0.00259	0.02878	0.00478	0.00076	0.00106	0.10886	0.00017	0.00052	0.0002	5.2E-05
10	111,813	0.00433	0.6266	0.21241	0.0038	0.04214	0.007	0.00112	0.00106	0.1006	0.00017	0.00052	0.0002	5.2E-05
11	157,214	0.00442	0.63953	0.21679	0.00213	0.02369	0.00393	0.00063	0.00472	0.09994	0.00075	0.00234	0.00089	0.00023
12	102,701	0.00437	0.63291	0.21455	0.00262	0.02903	0.00482	0.00077	0.00306	0.10514	0.00048	0.00152	0.00057	0.00015
13	105,891	0.00423	0.61137	0.20725	0.00528	0.05854	0.00972	0.00155	0.00106	0.10006	0.00017	0.00052	0.0002	5.2E-05
14	75,484	0.00427	0.61843	0.20964	0.00298	0.03308	0.00549	0.00088	0.00292	0.11971	0.00046	0.00145	0.00055	0.00014
15	113,913	0.0044	0.63614	0.21565	0.00231	0.02559	0.00425	0.00068	0.00174	0.10769	0.00028	0.00087	0.00033	8.5E-05
16	99,151	0.00438	0.63319	0.21465	0.00259	0.02878	0.00478	0.00076	0.00106	0.10886	0.00017	0.00052	0.0002	5.2E-05
17	21,403	0.00394	0.56945	0.19304	0.00229	0.02538	0.00422	0.00067	0.02179	0.15982	0.00344	0.01081	0.00408	0.00107
18	30,308	0.00419	0.60641	0.20557	0.00269	0.0298	0.00495	0.00079	0.00918	0.12824	0.00145	0.00456	0.00172	0.00045
19	52,566	0.00433	0.62615	0.21226	0.00204	0.02269	0.00377	0.0006	0.00546	0.11784	0.00086	0.00271	0.00102	0.00027
20	40,303	0.00402	0.58104	0.19697	0.00309	0.03431	0.0057	0.00091	0.00804	0.15877	0.00127	0.00399	0.00151	0.00039
22	32,313	0.00406	0.58716	0.19904	0.00237	0.02632	0.00437	0.0007	0.01136	0.1545	0.00179	0.00564	0.00213	0.00056
23	79,293	0.00424	0.61368	0.20803	0.00296	0.03279	0.00545	0.00087	0.00343	0.1255	0.00054	0.0017	0.00064	0.00017
24	88,519	0.00433	0.62613	0.21225	0.00272	0.03018	0.00501	0.0008	0.00434	0.11036	0.00069	0.00215	0.00081	0.00021
25	120,144	0.00436	0.63026	0.21365	0.00272	0.03022	0.00502	0.0008	0.00323	0.10684	0.00051	0.00161	0.00061	0.00016
26	42,071	0.00399	0.57724	0.19568	0.00232	0.02578	0.00428	0.00068	0.01203	0.16727	0.0019	0.00597	0.00226	0.00059
27	19,230	0.00407	0.58912	0.19971	0.00232	0.02574	0.00428	0.00068	0.00857	0.15789	0.00135	0.00425	0.00161	0.00042
27A	37,498	0.00439	0.63538	0.21539	0.00249	0.02765	0.00459	0.00073	0.00106	0.10737	0.00017	0.00052	0.0002	5.2E-05
28	19,377	0.00407	0.58906	0.19969	0.00238	0.02642	0.00439	0.0007	0.01915	0.1371	0.00302	0.0095	0.00359	0.00094
29	72,008	0.00438	0.63314	0.21463	0.00259	0.02878	0.00478	0.00076	0.01077	0.09058	0.0017	0.00534	0.00202	0.00053
30	42,919	0.00419	0.60565	0.20531	0.00253	0.02803	0.00466	0.00074	0.01286	0.12458	0.00203	0.00638	0.00241	0.00063
31	89,764	0.00436	0.63141	0.21404	0.00277	0.03073	0.0051	0.00082	0.00287	0.10533	0.00045	0.00143	0.00054	0.00014
31A	127,952	0.00447	0.64644	0.21914	0.0019	0.02111	0.00351	0.00056	0.00622	0.09112	0.00098	0.00309	0.00117	0.0003
32	97,515	0.00438	0.63319	0.21465	0.00259	0.02878	0.00478	0.00076	0.00185	0.10736	0.00029	0.00092	0.00035	9.1E-05
33	42,029	0.00438	0.63319	0.21464	0.00259	0.02879	0.00478	0.00076	0.00106	0.10886	0.00017	0.00052	0.0002	5.2E-05
34	43,607	0.00384	0.55511	0.18818	0.0025	0.02769	0.0046	0.00074	0.00899	0.20036	0.00142	0.00446	0.00169	0.00044
35	43,966	0.00438	0.6332	0.21465	0.00259	0.02878	0.00478	0.00076	0.00106	0.10886	0.00017	0.00052	0.0002	5.2E-05
36	54,851	0.00381	0.55113	0.18683	0.00386	0.04278	0.00711	0.00114	0.00707	0.19	0.00112	0.00351	0.00132	0.00035
37	136,756	0.0039	0.56473	0.19144	0.00167	0.01849	0.00307	0.00049	0.01816	0.18187	0.00287	0.00901	0.0034	0.00089
38	92,942	0.00381	0.55161	0.18699	0.0032	0.0355	0.0059	0.00094	0.01133	0.19063	0.00179	0.00562	0.00212	0.00055

Table 6.3 Pavement Segments: Estimated Traffic Volume by Vehicle Class

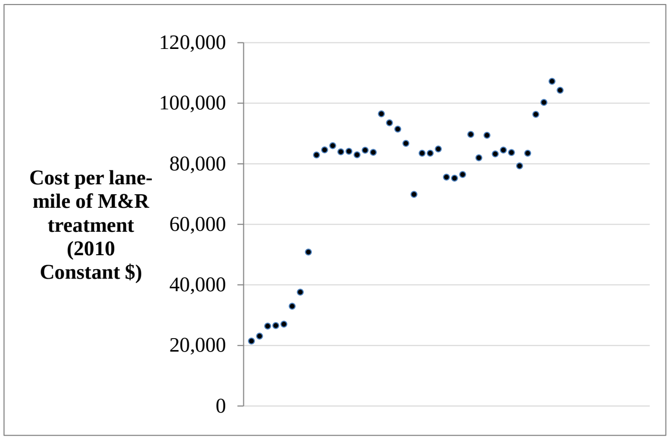
(Sample data shown for Interstate Highway Segments)

Interstate Segment	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6	Class 7	Class 8	Class 9	Class 10	Class 11	Class 12	Class 13
1	53	7,657	2,596	31	341	57	9	177	2,379	28	88	33	9
2	84	12,107	4,104	50	559	93	15	348	3,276	55	173	65	17
3	242	34,995	11,863	143	1,591	264	42	595	5,001	94	296	112	29
4	213	30,830	10,451	126	1,397	232	37	579	4,752	92	288	109	28
5	120	17,324	5,873	70	772	128	20	847	4,514	134	420	159	41
6	121	17,483	5,927	72	795	132	21	29	3,006	5	14	5	1
7	89	12,805	4,341	52	580	96	15	174	3,312	28	87	33	9
8	102	14,781	5,011	66	731	121	19	707	2,534	112	351	132	35
9	377	54,583	18,503	224	2,481	412	66	91	9,384	14	45	17	4
10	484	70,062	23,750	425	4,712	783	125	118	11,248	19	59	22	6
11	695	100,543	34,083	336	3,724	619	99	742	15,713	117	368	139	36
12	449	65,000	22,035	269	2,981	495	79	315	10,798	50	156	59	15
13	448	64,738	21,946	559	6,199	1,030	165	112	10,595	18	56	21	5
14	323	46,681	15,824	225	2,497	415	66	220	9,036	35	109	41	11
15	501	72,465	24,565	263	2,915	484	77	199	12,267	31	99	37	10
16	434	62,782	21,282	257	2,854	474	76	105	10,794	17	52	20	5
17	84	12,188	4,132	49	543	90	14	466	3,421	74	231	87	23
18	127	18,379	6,230	81	903	150	24	278	3,887	44	138	52	14
19	228	32,914	11,158	107	1,193	198	32	287	6,194	45	142	54	14
20	162	23,418	7,938	125	1,383	230	37	324	6,399	51	161	61	16
22	131	18,973	6,432	77	850	141	23	367	4,992	58	182	69	18
23	336	48,660	16,495	234	2,600	432	69	272	9,952	43	135	51	13
24	383	55,425	18,788	241	2,672	444	71	384	9,769	61	191	72	19
25	523	75,722	25,669	327	3,631	603	96	389	12,837	61	193	73	19
26	168	24,285	8,232	98	1,085	180	29	506	7,037	80	251	95	25
27	78	11,329	3,840	45	495	82	13	165	3,036	26	82	31	8
27A	165	23,826	8,077	93	1,037	172	28	40	4,026	6	20	7	2
28	79	11,414	3,869	46	512	85	14	371	2,657	59	184	70	18
29	315	45,591	15,455	187	2,072	344	55	775	6,523	122	385	145	38
30	180	25,994	8,812	108	1,203	200	32	552	5,347	87	274	103	27
31	392	56,678	19,213	249	2,759	458	73	258	9,455	41	128	48	13
31A	572	82,713	28,039	243	2,701	449	72	796	11,659	126	395	149	39
32	427	61,746	20,931	253	2,807	466	75	181	10,469	29	90	34	9
33	184	26,612	9,021	109	1,210	201	32	44	4,575	7	22	8	2
34	167	24,207	8,206	109	1,208	201	32	392	8,737	62	195	73	19
35	192	27,839	9,437	114	1,265	210	34	47	4,786	7	23	9	2
36	209	30,230	10,248	211	2,347	390	62	388	10,422	61	192	73	19
37	534	77,231	26,180	228	2,529	420	67	2,483	24,872	392	1,232	466	121
38	354	51,268	17,379	297	3,300	548	88	1,053	17,717	166	523	197	51

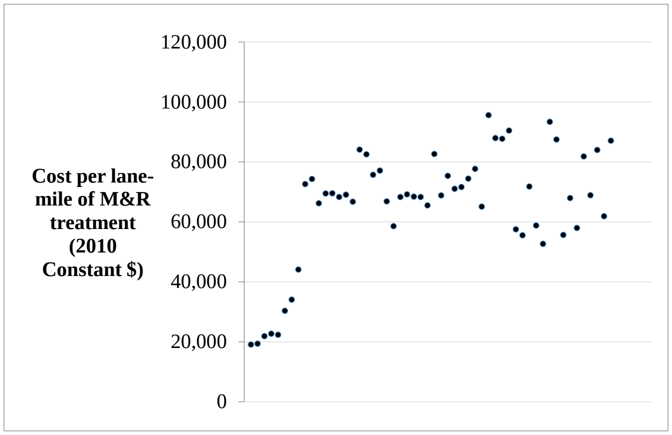
Table 6.4 Pavement Segments: Estimated Annuals ESALs by Vehicle Class

(Sample data shown for Interstate Highway Segments)

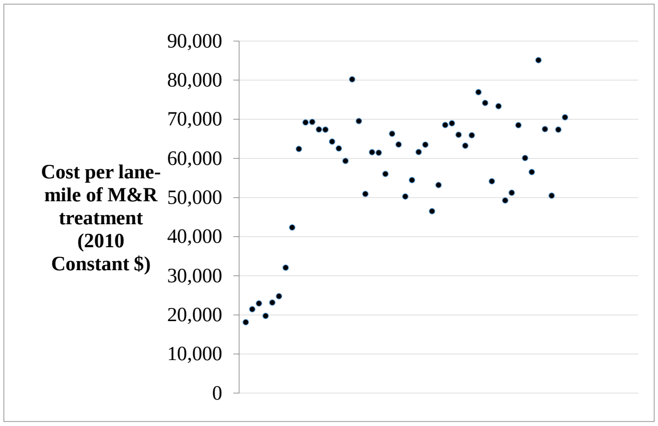
Interstate Segment	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6	Class 7	Class 8	Class 9	Class 10	Class 11	Class 12	Class 13
1	0	0	0	10,913	28,466	17,138	2,740	47,436	1,429,529	21,085	66,510	15,285	8,327
2	0	0	0	17,917	46,738	28,139	4,499	93,013	1,968,051	41,342	130,413	29,971	16,328
3	0	0	0	50,966	132,946	80,040	12,797	159,321	3,004,710	70,815	223,383	51,338	27,968
4	0	0	0	44,751	116,736	70,281	11,237	155,036	2,855,191	68,911	217,376	49,957	27,216
5	0	0	0	24,729	64,507	38,836	6,209	226,544	2,712,085	100,695	317,637	72,999	39,769
6	0	0	0	25,464	66,424	39,990	6,394	7,815	1,806,003	3,474	10,957	2,518	1,372
7	0	0	0	18,595	48,505	29,203	4,669	46,656	1,989,725	20,738	65,417	15,034	8,190
8	0	0	0	23,412	61,073	36,769	5,879	189,064	1,522,128	84,036	265,087	60,922	33,190
9	0	0	0	79,502	207,386	124,856	19,962	24,399	5,638,029	10,845	34,209	7,862	4,283
10	0	0	0	150,977	393,832	237,106	37,908	31,647	6,757,864	14,067	44,373	10,198	5,556
11	0	0	0	119,325	311,264	187,396	29,961	198,598	9,440,033	88,273	278,453	63,994	34,863
12	0	0	0	95,530	249,195	150,027	23,986	84,177	6,487,131	37,415	118,024	27,124	14,777
13	0	0	0	198,633	518,144	311,948	49,874	29,971	6,365,368	13,322	42,022	9,658	5,261
14	0	0	0	79,999	208,681	125,636	20,087	58,993	5,428,608	26,221	82,713	19,009	10,356
15	0	0	0	93,399	243,637	146,681	23,451	53,147	7,370,076	23,623	74,518	17,126	9,330
16	0	0	0	91,451	238,554	143,621	22,962	28,063	6,484,661	12,474	39,348	9,043	4,926
17	0	0	0	17,406	45,403	27,335	4,370	124,764	2,055,043	55,455	174,931	40,203	21,902
18	0	0	0	28,945	75,504	45,457	7,268	74,466	2,335,090	33,099	104,408	23,995	13,072
19	0	0	0	38,216	99,690	60,018	9,596	76,749	3,721,575	34,113	107,609	24,731	13,473
20	0	0	0	44,312	115,589	69,590	11,126	86,689	3,844,274	38,532	121,546	27,934	15,218
22	0	0	0	27,247	71,074	42,790	6,841	98,231	2,999,428	43,662	137,729	31,653	17,244
23	0	0	0	83,311	217,322	130,838	20,918	72,694	5,978,771	32,311	101,924	23,424	12,761
24	0	0	0	85,613	223,326	134,453	21,496	102,824	5,869,102	45,703	144,169	33,133	18,050
25	0	0	0	116,341	303,481	182,710	29,212	103,979	7,712,119	46,217	145,789	33,505	18,253
26	0	0	0	34,756	90,664	54,584	8,727	135,438	4,227,862	60,200	189,898	43,642	23,776
27	0	0	0	15,859	41,369	24,906	3,982	44,069	1,824,072	19,588	61,788	14,200	7,736
0	0	0	0	33,226	86,673	52,181	8,343	10,613	2,418,866	4,718	14,881	3,420	1,863
28	0	0	0	16,401	42,783	25,758	4,118	99,263	1,596,018	44,121	139,176	31,985	17,425
29	0	0	0	66,403	173,215	104,284	16,673	207,410	3,918,838	92,190	290,809	66,834	36,410
30	0	0	0	38,548	100,555	60,539	9,679	147,667	3,212,292	65,635	207,043	47,583	25,922
31	0	0	0	88,396	230,586	138,824	22,195	69,009	5,680,398	30,673	96,757	22,237	12,114
0	0	0	0	86,554	225,779	135,930	21,732	212,926	7,004,631	94,642	298,544	68,611	37,378
32	0	0	0	89,936	234,603	141,242	22,582	48,370	6,289,749	21,500	67,820	15,586	8,491
33	0	0	0	38,766	101,123	60,881	9,734	11,896	2,748,881	5,287	16,679	3,833	2,088
34	0	0	0	38,695	100,937	60,769	9,716	104,886	5,249,200	46,620	147,060	33,797	18,412
35	0	0	0	40,541	105,752	63,668	10,179	12,444	2,875,422	5,531	17,448	4,010	2,185
36	0	0	0	75,188	196,132	118,081	18,879	103,726	6,261,147	46,104	145,433	33,423	18,209
37	0	0	0	81,040	211,396	127,270	20,348	664,383	14,943,018	295,306	931,529	214,084	116,630
38	0	0	0	105,728	275,797	166,043	26,547	281,773	10,644,323	125,243	395,074	90,796	49,464



(a) Interstate Highway Pavements

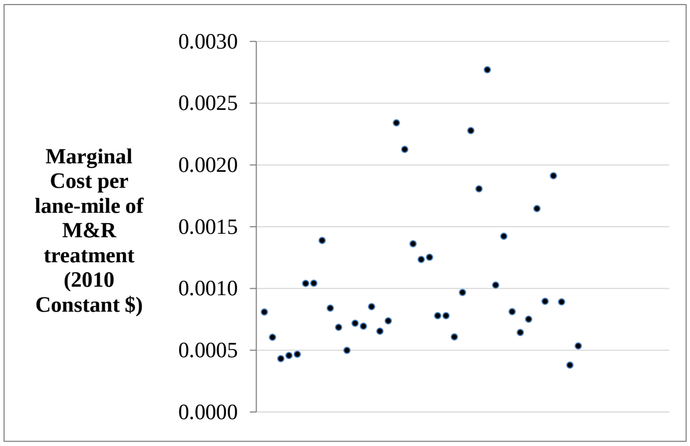


(b) Non-Interstate NHS Highway Pavements

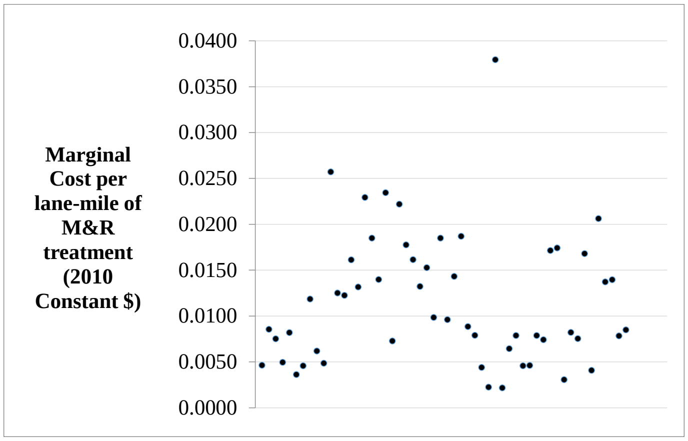


(c) Non-NHS Highway Pavements

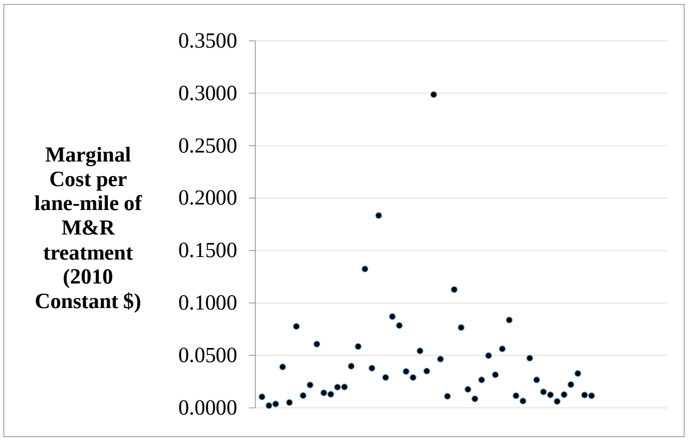
Figure 6.4 Scatter Plot of Cost per lane-mile of Pavement Damage by Road Class



(a) Interstate Highway Pavements

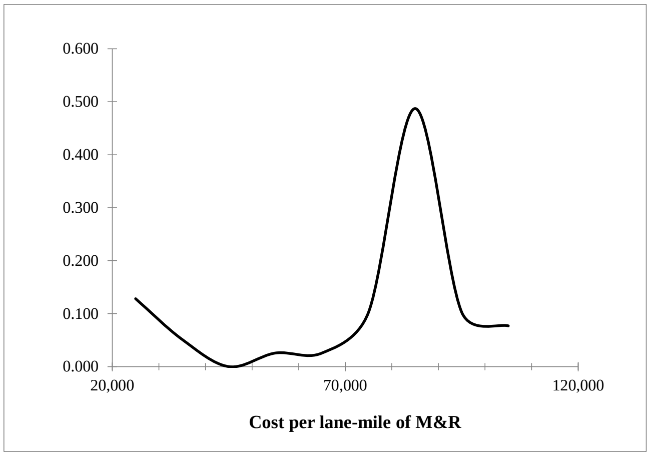


(b) Non-Interstate NHS Highway Pavements

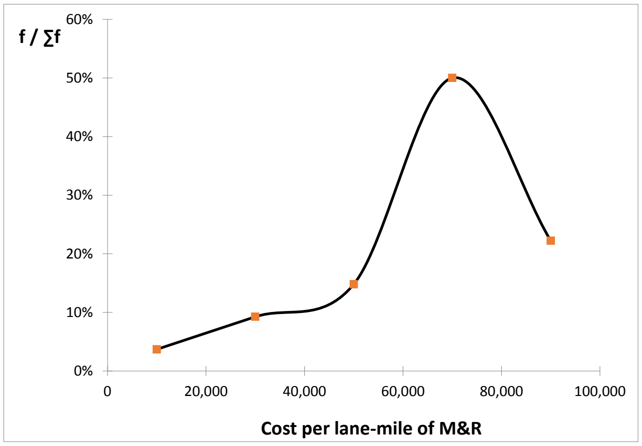


(b) Non-NHS Highway Pavements

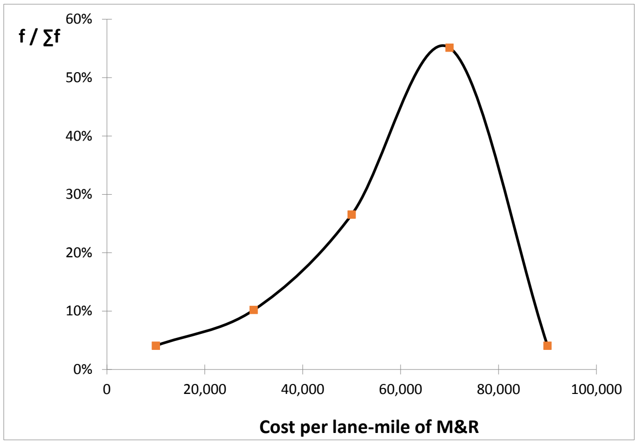
Figure 6.5 Scatter Plots of Pavement Damage Cost Estimates by Road Class



(a) Interstate Highway Pavements



(b) Non-Interstate NHS Highway Pavements



(c) Non-NHS Highway Pavements

Figure 6.6 Probability Distribution of Pavement Damage Cost Estimates

CHAPTER 7 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

This study addressed the issue of marginal pavement damage cost estimation that highway agencies worldwide continue to grapple with. The study developed an analytical framework for estimating and checking the variability of marginal pavement damage cost estimates. 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.

A regional freight demand prediction model was used to determine the movements on each pavement section, and the actual levels of truck operations, in terms of traffic volumes, classifications, and weights, were determined from traffic databases. Then the truck damage to the pavement was computed in terms of ESALs; this served as a key independent variable in the modeling process. Other data obtained for the pavement segments included the functional class, and climatic condition. The response variable was the damage costs, which were determined on the basis of life cycle costs and M&R activity profiles. The independent and the response variables were collated to build the dataset which was subsequently used to model damage cost as a function of the given explanatory variables, for each pavement segment.

For the modeling, linear regression models with fixed and random parameter specifications were estimated for M&R marginal cost estimation. Segment-specific heterogeneity of individual M&R treatment was explored by considering each treatment application as a unique project with specific characteristics that are reasonably distinct from the other applications. It is assumed that each pavement segment is unique in characteristics in terms of geographic location, traffic and climatic loading, surface and structural deterioration, quality of initial pavement construction and maintenance history in terms of rehabilitation or periodic maintenance treatment application. Using data from pavement segments, fixed-parameter and random parameter linear regression models were developed. The factors that were found to significantly influence the M&R marginal cost include: traffic loading (total ESALs over the treatment service life), annual average freeze index, total precipitation, annual average number of wet days, microsurfacing treatment indicator variable, functional HMS overlay treatment, pavement surface type, and geographical location (district). The variables that had statistically significant random parameters were: traffic loading, total precipitation and indicator variable for microsurfacing treatment. The random parameters for these variables had standard deviation values that were statistically different from zero. For all random parameters, the best statistical fit was obtained using the normal distribution. It was confirmed that pavement segments that are subjected to higher traffic loading levels or located in a region which has higher climatic severity (higher precipitation and/or freeze index) deteriorate faster and thus incur higher M&R expenditures albeit in magnitudes that vary significantly across the pavement segments. It was also observed that the segment geographic location and treatment type significantly influences the M&R marginal cost; this could be attributed to jurisdiction-specific attributes such as pavement maintenance culture and administrative practices, and pavement construction standards. The parameter estimate for total traffic (total ESALs over treatment service life) was found to be normally distributed with a statistically significant mean and standard deviation (random parameter), indicating that the influence of the traffic on the response variable is significantly different for the different pavement segments. This is an important result because it indicates that it is appropriate to charge highway users different fees not only across the different highway functional classes but also across the different road segments in a given functional class. This seems to support the practices of highway agencies that have resorted to weight-distance tax (in addition to traditional means such as fuel taxes) for heavy vehicles (Alison and Walton, 2009). The model results showed that random parameter models are more promising compared to their fixed-parameters counterpart as they help to explore the segment-specific heterogeneity of the M&R marginal cost.

To demonstrate the applicability of the developed model, the study used a dataset containing 38 in-service Interstate pavements, 50 non-Interstate pavements on the National Highway System (NHS), and 50 non-NHS pavement segments. The results suggest that there is significant variation compared to what would otherwise be obtained if a uniform damage cost had been assumed and calculated for these pavement segments collectively as is traditionally done.

The results also suggest that the life-cycle damage cost (life cycle cost of pavement upkeep associated with the traffic loads), on average, is approximately $85,000/lane-mile, $70,000/lane-mile and $55,000 per lane-mile, for the vehicles that use the pavements on Interstates, non-Interstate NHS, and non-NHS, respectively. The number of users was taken into account in terms of their loads, and the marginal effect indicated that the marginal damage cost over the life cycle (life cycle cost of pavement upkeep associated with the addition of one additional load), on average, is approximately \$0.01/ESAL per lane-mile, \$0.014/ESAL per lane-mile and \$0.04/ESAL per lane-mile respectively, for Interstate, non-Interstate NHS, and non-NHS pavements, respectively. These results indicate that there exists a wide disparity in pavement damage costs across the different functional classes and also across individual pavement segments in a given functional class. The probability distribution of the cost of pavement damage cost estimates and the marginal cost of pavement damage also suggest the existence of such disparity.

The results in this study strongly support the notion that there is far greater reliability that associated with segment-specific estimation of pavement damage costs. A stronger argument, therefore, is made in advocating for tools that enable highway agencies to estimate future truck traffic volumes at each segment with greater accuracy so that greater confidence can be placed on the pavement damage cost estimates. This report also argued for a reliable prediction tool for traffic volume: the annual field counts at specific segments may not be sufficient for the purpose of fee structure determination at specific highway segments because they only reflect current conditions and even with growth adjustment factors, may fail to provide reliable future projections. Also, the relative contribution of climate and traffic in pavement deterioration are known to differ for each pavement type (concrete and asphalt) and also across the different highway functional classes. This study, in addressing the issue of pavement damage cost estimation from a purely disaggregate level, helps make the case that potentially more reliable estimates of pavement damage costs can be established. Achieving a good measure of reliability would not only increase the efficiency and effectiveness but also enhance equity in the highway cost allocation and revenue generation.

In summing up, it is necessary to address the lingering question on how best to achieve reliable future traffic volumes. This can be realized using regional freight assignment models, particularly those of a dynamic nature. Appropriate and accurate assignment of future freight traffic on the highway network system on the basis of projected socio-economic developments, could yield more reliable estimates of truck traffic volumes at each individual link on the highway system. That way, it will be possible to report the total damage costs not for families of pavements but for individual pavement segments within a family highway agencies can establish appropriate segment-specific costs of pavement damage and thus establish a foundation upon which existing fees for overweight vehicles could be reviewed.

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APPENDICES

APPENDIX 1 OTHER APPROACHES OR CONTEXTS FOR HCA/PDC ESTIMATION

In the past, most endeavors to develop estimates of the marginal cost of pavement damage repair were either part of a cost allocation study or a more specific study on pavement damage cost, with relatively very few addressing contexts besides these two. This appendix, culled largely from Ahmed et al. (2013) and other sources, presents a number of these studies.

A1.1 Studies on Truck Size and Weight Characteristics

Hewitt et al. (1999) determined the impacts of truck weight and size changes in Montana on that state’s highway infrastructure condition, cost of truck operations, and economy. The researchers analyzed the consequences of a change in maximum GVW on the cost of pavement maintenance, using real or hypothetical cost and traffic data from scenarios involving maximum Gross Vehicle Weight (GVW). For each scenario, the authors estimated the cost of pavement damage associated with a hypothetical traffic stream considered, using standard AASHTO equations. The authors carried out the analysis using data for a small sample of pavement segments and then generalized the results to the population. The authors quantified the change in the equivalent uniform annual maintenance cost for each scenario, and it no significant difference was found in the impacts across the alternatives. As Ahmed et al. (2014) noted, the report contained little or no information on the length of the analysis period or maintenance and rehabilitation activities. In Louisiana, Roberts and Djakfar (2000) carried out a similar study that investigated the effect of a proposed increased GVW limits from 80,000 to 100,000 lbs. Using the AASHTO design equation and ESAL concept, they estimated the changes in the costs of pavement rehabilitation and maintenance due to a proposed increase in GVW limits. The base scenario involved a two-axle truck (GVW of 49,000 lbs.) and a five-axle semi-trailer (86,000 lbs.), and three load scenarios were developed, each with different composition of traffic streams. The costs of rehabilitation activity required to accommodate the traffic associated with each scenario were determined, and the present worth (using a 5% discount rate) of these costs were determined for each scenario and traffic stream was calculated. The research in Louisiana determined that compared to Interstate pavements, the effect of higher GVW limits is more injurious for non-interstate highway pavements; the researchers therefore recommended higher road-use fees for heavy vehicles particularly at non-Interstate pavements to recover fully or partially, the damage inflicted.

A1.2 Studies that used Mechanistic Models for Pavement Damage Analysis

Of the several studies that sought to quantify highway pavement damage caused by vehicles on the basis of the number of axles, GVW, and the axle load distribution on individual axles of a truck, at least one has used the KENLAYER mechanistic model (Parker and Hussain (2006). The KENLAYER model expresses the load not in ESALs but as an load spectrum (operating weight distributions). Using flexible pavement load and maintenance data from weigh-in-motion stations in New York, and data on pavement thickness, and layer characteristics, the model was used to calculate tensile and compressive strains that result from trucks on the basis of their GVW and axle load distribution. The relationship between load and strain was found to be consistent more with the third-power law rather than the fourth power; this observation corroborated Small et al. (1989)'s finding (that at higher loads, the damaging power of an axle is closer to the third and not the fourth power). The curves that were fitted to the tensile strain were found to be more consistent with the AASHTO fourth-power curve, thus validating the AASHTO results at comparatively lower loads. The Parker and Hussain study was a landmark effort that demonstrated the cost of pavement damage can vary significantly depending on the truck axle weights, axle load spectra, and even, speed. On the basis of a truck speed of 58 miles mph, 80 psi tire pressure, a typical flexible pavement structure, the authors obtained an inventory-normalized cost of $0.11 per lane-mile for a truck of GVW 80,000lbs and five axles, in 2006 dollars.

A1.3 Studies that used Mechanistic-Empirical Pavement Design Parameters

In a Texas study, Hong et al. (2007) estimated the load-related cost of pavement construction using the Mechanistic-Empirical Pavement Design Guide (MEPDG) which, like KENLAYER, uses axle load spectra instead of ESALs. Using a 4-year span of traffic data from a weigh-in-motion station, the authors generated the axle load spectra for the analysis. Climatic data were included in the analysis. The base and subbase thickness were fixed at 12" and 6", respectively, and surface layer thicknesses ranged from 3" to 8" inches. For 20-year pavement design life and using rutting as the performance indicator (0.5" threshold), MEPDG was used to establish the maximum allowable number of repetitions to failure (R_i) for each truck class. The maximum number of repetitions to reach a caertain failure threshold was determined for each truck class as well as for mixed traffic conditions. Lastly, the cost share for each individual truck class was calculated.

A1.4 PDC Estimation based on Axle Loads

Alison and Walton (2009b, 2010) allocated the cost of new toll road construction, maintenance, and debt servicing on the basis of axle loads. The authors assigned the costs to “axle-load classes” and applied their methodology on the basis of data from a one WIM station and a 30-year analysis period. First, the authors defined “axle-load classes” on the basis of truck axle loads and the number of axles, and divided the total common cost by the number of vehicles expected to use the facility over its life cycle to give the “common base toll”. Then, the authors allocated the load-related cost associated with construction, maintenance, and debt servicing using the incremental approach as done in the 1997 FHWA cost allocation study. In doing so, the researchers ensured that for each axle-load class, the ESALs imposed is proportional to the load-related toll. Then the load-related toll was added to the base toll (that is, the common toll) to yield the total toll for each axle class. Climatic effects on infrastructure damage were not considered explicitly.

A1.5 Highway Development and Management Model (HDM) Approach

The World Bank has often used its HDM software to estimate the cost of pavement deterioration, in terms of wear and damage and the user cost. The package includes a suite of empirical deterioration models that calculates the severity or extent of the pavement distress in terms of potholes, cracking, and rut depth. Using the HDM model, Bruzelius (2004) estimated the cost of pavement damage for a 9m-width road with AADT 6,000 vehicles, a 50-year analysis period, and a 4% interest rate; also, the study assumed that the trigger for pavement overlay is 22m rutting or 10% structural cracking.

A1.6 The Benefits-based Approach

As noted by Sinha and Labi (2007), highway maintenance and construction often yields benefits including safety, mobility, economic development, and reductions in vehicle operating cost, travel time, and shipping costs. Benefit-based approaches for user charging allocate different costs to users on the basis of the positive externalities or “benefits” received by the different vehicle classes from the highway system. A vehicle class receiving higher benefits is assigned a higher user fee irrespective of the level of its damage contribution. The approach assumes that highways are designed to provide benefits both to highway users and non-users alike and that using benefits as a basis for establishing the system-use fees ensures fairness and efficiency. As

Ahmed et al. (2014) noted, the intertwining of the non-user benefits with user benefits has caused difficulties in identifying (and in some cases, quantifying) the non-user benefits and thus has stymied the implementation of this approach in the practice.

APPENDIX 2 COST ISSUES IN PAVEMENT DAMAGE COST ANALYSIS

A2.1 Classification of Project Types (Project Cost Categories)

The range of pavement upkeep project types includes expansion and preservation. Expansion includes lane addition and pavement widening; while system preservation has been defined to include reconstruction, rehabilitation, and periodic and routine maintenance. The objective of each category is different, as some address load traffic capacity, other address non-load capacity; or both. In developing estimates of pavement damage cost as a prelude to the establishment of user fees, it is critical to identify the categories of costs that are appropriate to be recovered by load-related user charges and by non-load related user charges. Ahmed et al (2013) discussed these cost categories, which we summarize herein.

A2.1.1 Maintenance

Maintenance, which comprises periodic maintenance (often, preventive treatments) and routine maintenance (treatments of preventive or corrective nature), is aimed at repairing surface defects and prolonging the life of the pavement by retarding its deterioration rate. Periodic maintenance is a non-structural enhancement that includes functional overlays, while routine maintenance represents the day-to-day activities carried in in-house by the agency on a force account basis. Routine maintenance may be preventive, such as crack sealing; or corrective, such as patching. As Ahmed et al. (2013) noted, most past studies on pavement damage cost estimation did not consider periodic maintenance; the few exceptions include Martin (1994), Hajek et al. (1998), Ghaeli et al. and (2000) Li and Sinha (2000). On the other hand, Newbery (1988), Small et al. (1989), Vitaliano and Held (1990), TRB (1996), and Lindberg (2002) did not consider explicitly, periodic and routine maintenance, and reconstruction. Gibby et al. (1990), Herry and Sedlacek (2002), Schreyer et al. (2002), Haraldsson (2007), and Liu et al. (2009) included maintenance in their analysis but did not indicate what treatments they considered as maintenance.

A2.1.2 Rehabilitation

Hall et al. (2002) defined rehabilitation as the functional or structural improvement of an existing pavement so that its service life can be extended, its rate of deterioration can be slowed, and its ride quality and condition can be improved. Rehabilitation treatments include resurfacing, milling of the existing pavement and overlay, PCCP slab reduction or rubblization and overlay, and concrete pavement restoration. All the past studies considered the cost of rehabilitation cost.

A2.1.3 Pavement Widening

The pavements of existing roads are widened for a variety of reasons including safety enhancement, highway capacity increase, shoulder widening, curve alignment upgrade, or provision of median to separate opposing traffic on undivided highways. This project type is a capacity-driven expenditure that does not alter the structural capacity of a pavement, and thus should be excluded from consideration in the estimation of pavement damage cost although it is relevant to cost allocation studies.

A2.1.4 Pavement Reconstruction/Replacement

Existing pavements that are structurally damaged to such extent that they cannot be restored in a cost-effective manner via rehabilitation are often slated for reconstruction/replacement. This treatment category consists of removing entirely the existing pavement structure (surface courses, base, and subbase), and constructing a new pavement structure in its place. The new pavement may have same or wider lanes or a different number of lanes compared with the original pavement, and may incur non-pavement expenditures on traffic control, grading, drainage, shoulders, and guard rails (Sinha et al., 2005). Notwithstanding the inclusion of such non-load expenditures in pavement replacement/reconstruction, this treatment category is generally considered a strength-driven expenditure and is therefore appropriate inclusion in the estimation of pavement damage costs.

A2.1.5 Construction of New Pavement

Unlike pavement reconstruction, the new construction involves the provision of a new pavement where none existed hitherto. Thus, besides the cost of the pavement structure, this pavement treatment category includes costs associate with a wide range of activities such as preliminary engineering, design, right-of-way acquisition, and grading and earthworks. Also, unlike reconstruction, new construction of pavement is carried in response to the deficiency (non-existence) of needed capacity and not to any strength deficiency of existing pavement. As such, new pavement construction is not considered in the estimation of pavement damage cost, unlike pavement reconstruction. A number of past studies failed to make this subtle but important distinction between these two cost categories.

A2.3 Attribution Classification (Attributable vs. Non-attributable or Load vs. Non-load)

From the perspective of highway cost allocation, non-attributable costs (or “common costs”) are those occasioned by the effects of climate, weather, aging of the pavement materials, deicing salts applied to the pavement in wintertime, and other deleterious agents that are not related to the vehicle loads. Attributable costs are expenditures that can be allocated to different vehicle classes on the basis of their contributions to the pavement damage; these contributions vary across the different vehicles due to differences in vehicle weights and axle configurations. Small et al. (1989), Martin (1994), and Li and Sinha (2000) are examples of the few studies that recognized this dichotomy explicitly and thus duly separated the attributable and non-attributable costs.

A2.2 Classification of Cost Incurrence Purposes

As discussed in the previous section, a distinction is needed to be made between strength-driven costs and capacity-driven costs so that the relevant costs can be considered in pavement damage cost studies. The construction of new pavements and the widening of roads via lane addition are geared toward congestion mitigation and not addressing the effect of traffic loads on pavements. On the other hand, the reconstruction, rehabilitation, and periodic and routine maintenance of existing pavements are undertaken to address defects that arise due to strength inadequacies. Ahmed et al. (2013) argued that all the past studies on pavement damage costs did not explicitly define the costs that should or should not be included in such analysis. Thus, none of the past studies included all of the relevant strength-driven cost categories (and hence, expenditures) in their analysis. Newbery (1988), Small et al. (1989), Vitaliano and Held (1990), TRB (1996), Lindberg (2002), Schreyer et al. (2002), Haraldsson (2007), Liu et al. (2009) and Anani and Madanat (2010) did not include at least one category of strength-driven expenditure; also, Hajek et al. (1998) and Ghaeli et al. (2000) did not distinguish between expenditures that were strength-driven and those that were capacity- driven.

A2.4 Classification of Road-use Measures

The measure of road use refers to a certain variable that represents the extent to which the pavement is used; and serves as a useful basis for charging vehicles for their consumption of the highway pavement. Common measures of road use include vehicle-mile, ton-mile, dollar-mile mile/year, GVW-mile, axle load-mile, and ESAL-mile. The ratio of dollars to the measure of road use is used as a basis for reporting the cost of damage and/or the fee level to be charged, for example, \$/GVW-mile, \$/vehicle-mile, \$/ESAL-mile. The use of each road-use measures is associated with certain issues as discussed in Table A2.1 below.

Table A2.1 Measures of Road Use

Road-use Measure	Description	References
Vehicle-mile	This measure assumes implicitly that the same amount of damage is inflicted by each vehicle irrespective of its weight or class. Thus, issue of non-homogeneity arises, and the reported pavement damage costs may be inequitable.	Link (2002), Herry and Sedlacek (2002), and Schreyer et al. (2002)
Mile/year	This measure does not differentiate between different vehicle classes. For example, a past study reported a pavement damage cost of \$1,727 per mile per year attributable to the beef industry.	Gibby et al. (1990); Liu et al. (2009); Haraldsson, (2007)
GVW-mile	This measure implicitly assumes that two vehicles with the same weight but different axle configurations inflict the same damage, and thus should pay the same cost. Thus, there are problems related to equity.	Martin (1994)
Axle Weight-mile	This measure assumes implicitly that a 100% increase in axle weight causes a 100% increase in pavement damage. However, the relationship between axle loading and pavement deterioration is non-linear as it is characterized by the so-called “fourth power law” Using this measure could lead to problems related to equity.	Alison and Walton (2010)
ESAL-mile	This road measure is the most appropriate road use measure because it assigns user charges to individual vehicles in direct proportion to the pavement damage they cause.	Newbery (1988); Small et al., (1989); Vitaliano and Held (1990); Hajek et al., (1998); and Li and Sinha (2000).

APPENDIX 3: MAINTENANCE TREATMENT GUIDELINES

Table A3.1 INDOT HMA Preventive Maintenance Treatment Guidelines

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

Notes: 1. For mainline pavement; 2. Unless traffic can be adequately controlled; 3. Treatment may reduce skid numbers; 4. Treatment does not address this. Source: INDOT (2010).

Table A3.2. INDOT PCC Preventive Maintenance Treatment Guidelines

Treatment	AADT[1]	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

1. For mainline pavement. Source: INDOT (2010).

Table A3 Annual Number of M&R Treatment Applications at a Typical Highway Agency

Activity	Treatment	Nr. 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 3/R Standards)	8
	Road Rehabilitation (3R/4R Standards)	148
Composite Rehabilitation	Crack and Seat Composite Pavement and HMA Overlay	30
	Rubblize Composite &HMA Overlay	8