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Center for Environmentally Sustainable Transportation in Cold Climates

An Empirical Model for Optimal Highway Durability in Cold Regions

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METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4		mm
ft	feet	0.3048		m
yd	yards	0.914		m
mi	Miles (statute)	1.61		km
		AREA		
in^2	square inches	645.2	millimeters squared	
	cm^2 ft^2	square feet	0.0929	
	meters squared	m^2		
yd^2	square yards	0.836	meters squared	m^2
mi^2	square miles	2.59	kilometers squared	km^2
ac	acres	0.4046	hectares	ha
		MASS (weight)		
oz	Ounces (avdp)	28.35	grams	g
lb	Pounds (avdp)	0.454	kilograms	kg
T	Short tons (2000 lb)	0.907	megagrams	mg
		VOLUME		
fl oz	fluid ounces (US)	29.57	milliliters	mL
gal	Gallons (liq)	3.785	liters	liters
ft^3	cubic feet	0.0283	meters cubed	m^3
yd^3	cubic yards	0.765	meters cubed	m^3

Note: Volumes greater than 1000 L shall be shown in m^3

Symbol	When You Know	Multiply By	To Find	Symbol
		TEMPERATURE (exact)		
^oF	Fahrenheit temperature	5/9 (^oF-32)	Celsius temperature	^oC
		ILLUMINATION		
fc	Foot-candles	10.76	lux	lx
fl	foot-lamberts	3.426	candela/m^2	cd/cm^2
		FORCE and PRESSURE or STRESS		
lbf	pound-force	4.45	newtons	N
psi	pound-force per square inch	6.89	kilopascals	kPa

These factors conform to the requirement of FHWA Order 5190.1A *SI is the symbol for the International System of Measurements

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles (statute)	mi
		AREA		
mm^2	millimeters squared	0.0016	square inches	in^2
m^2	meters squared	10.764	square feet	ft^2
km^2	kilometers squared	0.39	square miles	mi^2
ha	hectares (10,000 m^2)	2.471	acres	ac
		MASS (weight)		
g	grams	0.0353	Ounces (avdp)	oz
kg	kilograms	2.205	Pounds (avdp)	lb
mg	megagrams (1000 kg)	1.103	short tons	T
		VOLUME		
mL	milliliters	0.034	fluid ounces (US)	fl oz
liters	liters	0.264	Gallons (liq)	gal
m^3	meters cubed	35.315	cubic feet	ft^3
m^3	meters cubed	1.308	cubic yards	yd^3
		TEMPERATURE (exact)		
^oC	Celsius temperature	9/5 ^oC+32	Fahrenheit temperature	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/cm	candela/m^2	0.2919	foot-lamberts	fl^2
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	pound-force	lbf
kPa	kilopascals	0.145	pound-force per square inch	psi

32 98.6 212^oF

-40^oF 0 40 80 120 160 200

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EXECUTIVE SUMMARY

The objective of this project was to develop an empirical model that would quantify optimal highway durability in cold regions. In the model that resulted from this work, optimal highway durability is determined by pavement thickness, which minimizes lifetime total pavement costs (dollar per lane mile). Calculation of the lifetime total pavement cost of a highway includes three components: resurfacing or maintenance cost, duration of highway, and construction cost. All three components are affected by pavement thickness. An increase in pavement thickness increases highway duration and therefore reduces lifetime maintenance costs, but using thicker pavement increases the cost of construction. Additionally, in cold regions, highway duration is affected by winter operations. Deicers used on roadways accelerate the deterioration of highway pavement. When total pavement cost, which is a function of pavement thickness, traffic loading, and winter operations, is known, it can be used as a tool to find optimal pavement thickness and to guide winter operations practices.

The empirical approach in estimating the highway total pavement cost function developed in this project was to use data from highway projects collected by state Departments of Transportation (DOTs). State DOTs normally track various contracted highway projects, such as resurfacing, widening, and construction. This data can be used to estimate maintenance and construction costs of highways in a particular region. Moreover, the time length between two resurfacing activities on the same segment of highway provides information for estimating highway duration function. The highway duration function accounts for winter operations if the data are from highways located in cold regions. Especially when data on winter highway

operation practices (e.g., use of deicers) are available, the effects of the practices on highway durability can be quantified.

We adopted a flexible way to specify the highway cost and duration equations and use data to identify the relationship between cost/duration and pavement thickness. We considered various nonparametric approaches to estimate the flexible functional forms. To demonstrate the approaches, we compiled data of highway projects from Washington and Arizona. Using the data, we first estimated maintenance cost, highway duration, and construction cost as functions of pavement thickness and traffic loading. Results from different estimation approaches are presented and compared in order to draw robust findings. Based on the literature, we then calibrated the impacts of winter operations on highway duration and costs. The highway total pavement cost function is constructed based on estimated and calibrated duration and cost equations. Using the empirical total pavement cost equation, we solved for optimal highway durability in cold regions.

The demonstration outlines the steps used in implementing the empirical approach to estimate optimal highway durability and guides data collection at state DOTs. When information on highway projects and winter operation practices is carefully recorded and stored, such information can be used to design tools for guiding highway pavement and winter operation decisions.

CHAPTER 1.0 INTRODUCTION

1.1 Problem Statement

In cold regions, highways are built with great durability in order to reduce road wear caused not only by traffic loadings, but also by weather-related factors and anti-icing operations during the winter months. The durability of highways can be increased in different ways including thicker pavement, better pavement materials and drainage, and less corrosive deicing chemicals. The cost of increasing durability is compensated by the reduction in maintenance costs during the lifetime of the highway infrastructure. With such a trade-off, optimal policymaking requires answers to the question, What is the optimal highway durability in cold regions? The answer to this question is useful for designing optimal highway pavement and winter maintenance strategies.

1.2 Background

Through experimentation, engineering studies on highway durability have led to useful empirical findings on how the deterioration rate of highway pavement is affected by traffic loadings (American Association of State Highway and Transportation Officials [AASHO] 1986), by seasonal changes in temperature and soil moisture (Simonsen and Isacsson 1999), and by the corrosion damage of deicing chemicals (Shi et al. 2009). Economics studies on this topic are very limited. Compared with engineering approaches, an economic approach has the advantage of incorporating various factors that affect highway durability into a simple framework from which economic cost of highway durability can be quantified. The seminal paper by Small and Winston (1988) provides a modeling framework to quantify the economic cost of highway durability. Empirical findings from the paper indicate that AASHO results overestimate the lifetime of thick pavements. However, the focus of Small and Winston's analysis is only on highways in warm regions; the effects of weather factors and winter maintenance operations on pavements are not considered. Our work extends the analysis by Small and Winston (1988) to highways in cold regions.

1.3 Outline of the Approach

Our economic analysis of highway durability was based on total pavement cost per lane mile (TPC), which is an extension from Small and Winston (1988) to account for winter operations:

$$TPC(M,D,Q)=S(M,D)\times\frac{1}{e^{rT(M,D,Q)}-1}+K(M,D) \tag{1}$$

In Equation (1), M represents pavement materials; D represents the thickness of pavement; Q represents annual traffic loading. On the right-hand side of Equation (1), $K(M,D)$ is the construction cost per lane mile; $S(M,D)$ is the resurfacing (maintenance) cost per lane mile; $T(M,D,Q)$ is the duration between two resurfacing tasks, and the duration is affected by winter operations. Given that r is the interest rate, $S(M,D)\times\frac{1}{e^{rT(M,D,Q)}}$ is the present value of lifetime maintenance cost per lane mile of the highway.

The optimal highway pavement thickness (and thus optimal highway durability) that serves a given traffic loading is the one to minimize the TPC; that is, the optimal pavement thickness can be found by solving

$$D^{*}(M,Q)=\arg\min_{D} TPC(M,D,Q). \tag{2}$$

The key objective of this project is to derive the solution in Equation (2). The derived solution can be used by planners to optimize highway durability and winter operation practices in cold regions. The solution is derived by first estimating $S(M,D)$, $T(M,D,Q)$, and $K(M,D)$ empirically and then calibrating the effects of deicing practices on highway pavement using evidence from both lab and field experiments. Integrating the estimated and calibrated models into Equation (1), we obtain an empirical model of highway total pavement cost, which allows us to find optimal highway durability and to optimize winter operation practices through solving the optimization problem in Equation (2). We demonstrate the proposed approach using data compiled from Washington State Department of Transportation (WSDOT) and Arizona State Department of Transportation (ASDOT).

CHAPTER 2.0 AN EMPIRICAL HIGHWAY TOTAL PAVEMENT COST EQUATION IN COLD REGIONS

In this chapter, the empirical approaches used to estimate the components in the highway total pavement equation specified in Equation (1) are outlined[1]. In reality, resurfacing costs, construction costs, and pavement duration depend on pavement materials and the pavement thickness of different layers. However, data available for estimating the models are limited to asphalt concrete, which is used in the top layer of highway pavement. Because of limitations in the data, we restricted our analysis to the optimal pavement thickness of asphalt concrete in cold regions. As noted in Small and Winston (1998), the aggregate thickness, which is known as the structural number, is a linear combination of (top layer) pavement, base, and subbase thickness with coefficients 0.44, 0.14, and 0.11. The optimal aggregate pavement thickness can be obtained, therefore, by dividing the optimal top layer thickness by 0.44.

2.1 Empirical Estimation of Highway Resurfacing Cost

Given that our focus is on asphalt concrete, the resurfacing cost $S(D)$ is a function of the top-layer pavement thickness of that material. We model the functional relationship in a flexible way to obtain the following empirical equation,

$$S_i = m(D_i) + \varepsilon_i \tag{3}$$

[1] Our method is different from current literature (i.e., Fwa et al, 1985; Castaño-Pardo et al, 1995; Saleh, 2008; Markow et al, 2011; Link, 2014) by considering the lifetime cost of highway. Lee and Madanat (2014, 2015) consider the optimization of construction and maintenance strategies. McDonald and Madanat (2012) study the life-cycle cost minimization. Our approach differs from those works by considering winter operation. There are also literature only focusing on maintenance costs, such as, Potter and Hudson(1981), Rouse and Putterill(2000), Markow et al.(2011), National Cooperative Highway Research Report(2011).

where S_i is the resurfacing expenditure of a highway project i; $m(\cdot)$ denotes an unknown conditional mean function (CMF); and ε_i captures measurement error in the data. The unknown function $m(\cdot)$ can be estimated nonparametrically using data available at state DOTs. We use three nonparametric approaches—local polynomial smoothing, cubic splines, and polynomial regressions—to arrive at robust estimates.

In applying local polynomial smoothing, our goal is to estimate $m(d_0) = E(S|D = d_0)$ without making any assumption about the functional form of $m(\cdot)$. After defining a kernel function $\Gamma(\cdot)$, a local polynomial regression estimate at $D = d_0$ can be obtained by choosing α and β to minimize

$$\sum_i \Gamma\left(\frac{D_i - d_0}{h}\right) \times \left(S_i - \alpha - \beta \times (D_i - d_0)^p\right)^2 \tag{4}$$

where p is an integer power that denotes the degree of the polynomial, and h is the bandwidth of the kernel function.

A cubic spline is a twice continuously differentiable piecewise cubic function that can be expressed by the parametric form

$$m(D) = \alpha + \beta_1 D + \beta_2 D^2 + \beta_3 D^3 + \sum_{j=1}^{J} \lambda_j \left(D - d_j\right)_+^3 \tag{5}$$

which contains J distinct knots $d_1 < \ldots < d_J$ in support of D. The “+”term instructs us to take the positive part of the argument. A general problem of this method is how the number and position of knots are selected.

Finally, the frequently used nonparametric technique—polynomial regression—is used to approximate the unknown conditional mean function. Specifically, a 3-degree (cubic) polynomial regression is used here by the function form

$$m(D) = \beta_0 + \beta_1 D + \beta_2 D^2 + \beta_3 D^3, \beta_3 \neq 0 \tag{6}$$

The polynomial approximation can be poor if the conditional mean function is very irregular. However, the polynomial regression can be estimated easily by the Ordinal Least Squares (OLS), which gives a smoother linear regression.

2.2 Empirical Estimation of Highway Duration

Turning to the duration function, we assume that duration is decreasing in traffic loadings and increasing in pavement thickness. In cold regions, the deicers and deicing instruments used accelerate pavement deterioration. We specify the following semi-nonparametric partially linear model,

$$y = m_1(x) + \delta D + \mu \tag{7}$$

where y and x denote the log of duration and log of traffic loadings, respectively, and m_1 is an unknown univariate smooth function. For optimization purposes, we still prefer polynomial approximations. In order to test the validity of a polynomial regression, we use the fractional polynomial model, $m_1(x) = \sum_{j=1}^{k} \gamma_j x^{p_j}$, where powers p_j are taken from a predetermined set.[2] Generally, $k = 2$ is sufficient to have a good fit, but the smooth function may not satisfy our assumption. Thus, we try alternative degrees to choose the functional form that accounts for the trade-off between fitness and the decreasing assumption.

---

[2] The predetermined set is $S = \{-2, -1, -0.5, 0, 0.5, 1, 2, 3\}$, where x^0 is taken as $\ln(x)$.

The highway duration model should vary across regions (cold vs. warm) under different winter operation practices (e.g., deicers used on roadways). As such, to have an empirical model to guide highway pavement and winter operation practices in cold regions, we need to use data from highways located in cold regions and under different winter operation practices to estimate the duration equation[3].

2.3 Empirical Estimation of Highway Construction Cost

We follow the literature to specify the unit capital cost of construction $K(D)$ as a linear function of pavement thickness. Hence, we simply specify the capital cost as

$$K(D) = k_0 + k_1 D \tag{8}$$

The construction costs of highways in cold regions are expected to differ from those in warm regions. The parameters in Equation (8) should be estimated using data from highway projects located in cold regions.

In sum, we propose an empirical approach to estimate the highway total pavement cost, which allows us to find optimal highway durability. In the next chapter, we demonstrate that data used to estimate the components of the highway total pavement cost equation are, in general, available at state DOTs. The empirical approach accounts for the heterogeneity of highway durability caused by weather-related factors and winter operations. The traditional engineering approach of relying on lab experiments to obtain a highway duration model cannot control for such unobserved factors.

[3] The Influence of deicer on highway can be found in Hassan et al.(2002), Darwin et al.(2008), Shi et al.(2009), Shi et al.(2010), and Shi et al.(2013).

CHAPTER 3.0 A DEMONSTRATION OF THE EMPIRICAL TOOL BASED ON DATA FROM ASDOT AND WSDOT

After the components in the highway total pavement cost function are specified in a flexible way, data can be used to estimate the flexible functions. Armed with the estimated functions, optimal highway durability can be determined by solving Equation (2). In this chapter, we demonstrate how data collected by state DOTs can be used to estimate the empirical total pavement cost equation and how the estimated model can be used to guide optimal pavement decisions in cold regions.

For demonstration purposes, we have compiled a data set from Arizona State Department of Transportation (ASDOT) and from Washington State Department of Transportation (WSDOT). The limitations of our data set are that no highways in Arizona require winter operations, and only a few highways in Washington State require winter operations. Estimates from the data cannot account for the impacts of winter operations on highway durability and construction cost. We overcome the limitations by drawing from the literature to calibrate the effects and then adjust the parameter estimates using the calibrated effects to account for the impact of winter operations on highway durability and construction cost. The main purpose of the empirical exercises presented here is not to provide quantitative evidence on optimal highway durability in cold regions, but to demonstrate how the empirical tool outlined in the previous chapter can be applied in practice. Planners in states such as Alaska and Montana can follow the approach and use their own data to estimate highway duration, construction, and resurfacing costs to establish optimal highway durability in their regions. This empirical demonstration can also guide state DOTs in data collection.

3.1 Data

We used both real-life and calibrating data to conduct the empirical analysis. Real-life data were obtained from WSDOT and ASDOT, while calibrated data were based on literature. We will present real-life data first, followed by the introduction of what data were calibrated, why we needed those data, and how we calibrated them. The real-life data have three components: duration, maintenance cost, and construction cost.

3.1.1 Duration Data

Road Life Reports from WSDOT and a Project History Report from ASDOT contain contract-specific information on state routes, such as resurfacing, reconstruction, and lane widening, with detailed pavement type, pavement thickness on each layer, and the length of project section. Figure 3.1 presents the basic information contained in the Road Life Reports of WSDOT (the Project History Report from ASDOT contains similar information).

The Road Life Reports contain all project details from the 1950s, but the Project History Report from ASDOT contains only projects after 1990. Moreover, the Road Life Report from WSDOT enables us to observe the historical road operation (e.g., resurfacing and reconstruction) on a specific route section, which provides information on duration between two road operations using different pavement materials and pavement thickness. The Project History Report from ASDOT does not contain such information. Thus, we only used the Washington State sample to construct the duration data.

```
DOT-RNB160V                    STATE OF WASHINGTON - DEPARTMENT OF TRANSPORTATION              DATE 04/17/15
                                           T R I P S   S Y S T E M                             TIME 08:53:18
                                               ROAD LIFE REPORT

HEADER                         DATA ELEMENT

RELATED ROADWY QUALIF          RELATED ROADWAY QUALIFIER
SRMP                           STATE ROUTE MILEPOST
B                              STATE ROUTE MILEPOST AHEAD BACK INDICATOR
ARM                            ACCUMULATED ROUTE MILE
STATE FUNCT CLASS              RURAL/URBAN CODE / STATE FUNCTIONAL CLASSIFICATION
CONT SECT NUMB                 CONTROL SECTION
HWY TYP                        HIGHWAY TYPE
INV DIR                        ROADWAY INVENTORY DIRECTION
SURFACE CONTRACT DATA
     CONTRT NUMBER             CONTRACT NUMBER
     SEQ #                     CONTRACT SEQUENCE NUMBER
     TYPE CONT                 CONTRACT TYPE
     PAVE TYPE                 CONTRACT SURFACE TYPE
     PAVE THCK                 CONTRACT SURFACE THICKNESS
     DATE MN DY YEAR           CONTRACT CONSTRUCTION END DATE
     EXCP                      CONTRACT EXCEPTION CODE
BASE DATA
     TREATED BASE TYPE         CONTRACT TREATED BASE TYPE
     TREATED BASE THCK         CONTRACT TREATED BASE THICKNESS
     TREATED BASE YEAR         CONTRACT CONSTRUCTION END YEAR
     UNTREATED BASE THCK       CONTRACT UNTREATED BASE THICKNESS
     UNTREATED YEAR            CONTRACT CONSTRUCTION END YEAR
OLD PCC
     WID                       CONTRACT OLD PORTLAND CONCRETE WIDTH
     LOC                       CONTRACT OLD PORTLAND CONCRETE LOCATION CODE
THICKNESS SUMM
     TOTL PCC SURF THCK        TOTAL PCC SURFACE THICKNESS
     TOTL FLEX SURF THCK       TOTAL FLEXIBLE SURFACE THICKNESS
     TOTL BASE THCK            TOTAL BASE THICKNESS

*  IN CONTRACT CONSTRUCTION END DATE FIELD INDICATES CONTRACT IS IN PROGRESS
$  IN CONTRACT DATA FIELDS SHOWS END OF CONTRACT
```

Figure 3.1 Data information contained in a WSDOT Road Life Report

Figure 3.2 gives a sample of the Road Life Report and illustrates how data are extracted for analysis. As highlighted, the contract in 1997 resurfaces section 0602 of route U5 using C5 pavement materials.[4] The required pavement thickness is 0.15 feet. The next resurfacing on this section happened in 2011 (the year of the next contract). This road project gives us one data observation for empirical analysis: resurfacing the road with 0.15 feet of material C5, given the road traffic loading, the duration is 15 years (2011 minus 1997). We examined all Road Life Reports of Washington State dating back to the 1950s to extract data, which eventually gave 97 valid observations. Therefore, the Road Life Reports allowed us to obtain information on duration between projects, and on the pavement type and thickness the previous time. Such information enabled an estimate of the duration equation in our model.

---

[4] Figure 3.2 provides the description and definition of Road Life Reports.

```
1  DOT-RNB160V                          STATE OF WASHINGTON - DEPARTMENT OF TRANSPORTATION                       DATE 04/17/15
                                                     T R I P S   S Y S T E M                                    TIME 08:53:18
                                                         ROAD LIFE REPORT                                       PAGE        1

            SR 005     OREGON ST LINE TO CANADA    DISTRICT 4    (06) CLARK
                       MAINLINE
                                          ********** SURFACE CONTRACT DATA ********* ****** BASE DATA ******  **OLD**  THICKNESS SUMM
                                                                                   TREATED BASE  UNTREATED  **PCC**  TOTL TOTL
 RELATED               STATE CONT                                                                                    PCC  FLEX TOTL
 ROADWY                FUNCT SECT HWY INV CONTRT SEQ TYPE PAVE PAVE   DATE                        BASE               SURF SURF BASE
 QUALIF SRMP   B ARM   CLASS NUMB TYP DIR NUMBER  #  CONT TYPE THCK  MN DY YEAR EXCP TYPE THCK YEAR THCK YEAR WID LOC  THCK THCK THCK
 ______ _______ ______ _____ ____ ___ ___ ______ ___ ____ ____ ____  __ __ ____ ____ ____ ____ ____ ____ ____ ___ ___  ____ ____ ____

        000.00  000.00            BEG ROUTE
        000.00  000.00   U5   0601  3   I  005884      30  PA   0.00  04 01 1958                                   BRIDGE
        000.05  000.05   U5   0601  3   I  005884      30  PA   0.00  04 01 1958                                   BRIDGE
        000.27  000.27   U5   0601  3   I  005884      $$  $$$$ $$$$  04 01 1958
        000.27  000.27   U5   ****  9
        000.00  000.00   U5   0601  3   D  005216      30  PA   0.00  01 01 1957                                   BRIDGE
        000.27  000.27   U5   0601  3   D  005216      $$  $$$$ $$$$  01 01 1957
        000.27  000.27   U5   ****  9
        000.27  000.27   U5   0602  3   I  018148  1   20  B2   0.15  09 02 2011
                                           018148  2   90  Z2   0.15  09 02 2011
                                           015147  1   20  C5   0.15  10 15 1997
                                           015147  2   90  Z2   0.15  10 15 1997
                                           013044      20  BA   0.06  08 01 1986
                                           012156      20  BA   0.35  01 01 1983
                                           000000      20  BA   0.15  01 01 1970
                                           000000      10  BA   0.33  01 01 1954       2  0.17 1954 0.50 1954           0.00 0.89 0.67
        000.31  000.31   U5   0602  3   I  018148  1   20  B2   0.15  09 02 2011
                                           018148  2   90  Z2   0.15  09 02 2011
                                           015147  1   20  C5   0.15  10 15 1997
                                           015147  2   90  Z2   0.15  10 15 1997
                                           013044      20  BA   0.06  08 01 1986
                                           012156      10  BA   0.50  01 01 1983       2  0.60 1983
                                           000000      $$  $$$$ $$$$  01 01 1970
                                           000000      $$  $$$$ $$$$  01 01 1954                                    0.00 0.56 0.60
```

Figure 3.2 A sample of a Road Life Report

In our data, about 90% of projects used asphalt concrete pavements (ACP) as pavement material. Due to lack of enough data points for analyzing Portland cement concrete pavements (PCCP), we focused on the optimal durability design for ACP. Although the focus of the analysis is on ACP, it can be easily extended to other pavement materials such as PCCP when data are available.

Estimating the duration equation requires information on traffic loading between two highway projects on a highway section. The Annual Traffic Reports (ATRs) from WSDOT were used to construct the annual average daily traffic loadings (AADT) between two projects. The data contain information from 1997 through 2013 on annual average daily traffic loadings recorded by milepost. We averaged traffic loadings every 10 miles each year based on the milepost. We then calculated the AADT that belonged to the same route section in four consecutive years before the resurfacing project. Finally, we assigned the AADT in a given route section to a project if its main body was located in this area. We used 97 observations to estimate the duration equation. The average duration between two road operations was 12.07 years. The average pavement thickness was 2.16 inches. The average daily traffic was 55,000.

3.1.2 Maintenance Cost Data

Following Small and Winston (1988), we used the resurfacing cost to measure the maintenance cost. When constructing the maintenance cost, we used data from both Washington and Arizona. Project data spans from 1990 to 2014 for WSDOT and from 2000 to 2014 for ASDOT. In addition to the Road Life Reports, WSDOT provided a summary of all projects, referred to as a Project History, containing contract number, contract completion date, the amount paid, and so on. To estimate the maintenance cost function, except for the amount paid extracted from the Project History, we also needed information such as pavement material and pavement thickness for each contract. Thus, for each contract in the Project History, we went back to the Road Life Report and, using the unique contract number, determined the specific content of the contract (e.g., the length of pavement, pavement materials, pavement thickness).

Two documents were provided by ASDOT: Contract Information and Project History. The former contains information on contracts such as type of construction, amount paid, and contract completion date; the later includes specific information for each contract such as pavement materials and thickness, and the contracted route. We combined these two files to acquire the maintenance cost data for Arizona.

3.1.3 Construction Cost Data

We did not directly observe the construction cost of the interstate highway. Instead, we used Project History data from Arizona to infer the cost. As mentioned earlier, Project History data contains information on the type of construction. We thus categorized a project as construction if its type of construction was “Reconstruction.” After identifying a project as construction, we used the contract number to extract more information on the contract, such as pavement materials and thickness, from the Contract Information document.

Summary statistics are given in Table 3.1. Combining data from Washington with data from Arizona eventually provided 210 observations. As shown in Table 3.1, the average paid maintenance cost is 0.19 million. The minimal and maximum costs are $0.01 and $1.79 million, respectively. The average pavement thickness of resurfacing is 3.07 inches. As for construction cost, the average amount paid for construction is $0.65 million,[5] which is significantly greater than the average amount paid for maintenance: $0.19 million. Moreover, the average thickness is 4.16 inches, which is thicker than the thickness of maintenance: 3.07 inches.

Table 3.1 Summary statistics

Variable	Obs.	Mean	Std. Dev.	Min	Max
Variables used in the duration equation					
Duration (years)	97	12.07	5.52	2	33
Thickness(inch)	97	2.16	1.08	0.72	8.4
Annual average daily traffic (AADT) (1000s)	97	55.5	44	8.2	173.89
Variables used in the maintenance cost equation					
Unit maintenance cost ($ million)	210	0.19	0.32	0.01	1.79
Thickness (inches)	210	3.07	2.52	0.5	17.4
Variables used in the construction cost equation					
Reconstruction cost ($ million)	14	0.65	1.07	0.05	4.27
Thickness (including base)	14	4.16	1.99	1	7.5

[5] This is the bid amount on the contract, rather than the construction cost per lane mile.

3.1.4 Calibrated Data

The presented data on duration, maintenance, and construction are indispensable in estimating the empirical model, which offers planners a simple tool to optimize highway pavement in cold regions. The empirical model accounts for winter operations through the duration equation when the duration equation is estimated using data from highways located in cold regions. However, we estimated the duration equation using data from Washington State, where many highways do not require winter operations. Moreover, real-life data based on parameter estimates do not normally reveal how various winter operation practices, such as choosing deicers, affect highway duration. As such, if only real-life data are used in estimating the empirical model, the major limitation is that the data cannot guide the practices of winter operations on highways. Because winter operation data and information on how winter operation affects the durability of a highway are generally not available, we obtained relevant data using calibration.

Based on the literature[6], one important variable is the deterioration rates on both Portland cement concrete and asphalt concrete pavement due to different types of deicers. Although the focus of this paper is mainly on asphalt concrete pavement, we will discuss the calibration of deterioration rates of different types of deicers on both pavement materials, since, as stressed before, once data are available, the method applied to asphalt can be easily extended to Portland cement concrete.

Following the research by Pavement Interactive (2007),[7] and given the number of freeze/thaw cycles at which the test should be terminated, the performance of Portland concrete

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[7] "PCC Durability" 16 August 2007. http://www.pavementinteractive.org
<http://www.pavementinteractive.org/article/pcc-durability/> 30 December 2015

cement pavement is proportional to the dynamic modulus of elasticity. We thus used loss in the dynamic modulus of elasticity as a reference value to measure the corrosion rate of deicers.

In a South Dakota DOT study (2002), the effects of different deicers—NaCl, $CaCl_2$, and $MaCl_2$—on Portland cement concrete were investigated using lab experiments. The results of this study are summarized in Column 2 of Table 3.2. Column 1 of the table**Table 3.2** lists deicers used in the experiments. The numbers in the parentheses are concentration rates of deicers. In the 300 freezing/thawing-cycle experiments, concrete's loss in the dynamic modulus of elasticity is 5%, 40%, and 50% in NaCl (18%), $CaCl_2$ (15%), and $MaCl_2$ (14%), respectively.

There are also findings for corrosion rates of deicers from field experiments. As shown in Column 3 of Table 3.2, the freezing/thawing cycles of deicers on PCCP are much lower in real life. According to Zhang et al. (2003), during the winters of 1997/1998 and 1998/1999, the number of near-surface soil freezing/thawing cycles in the continental U.S. varied from 1 to more than 11. We used the average, 6, as the value of freezing/thawing cycles per year in the U.S. We thus calculated the loss in dynamic modulus elasticity in real life by dividing the values of elasticities in the lab by 50, which is the ratio between freezing/thawing cycles in the lab and in real life. Although the loss in dynamic modulus elasticity may not be directly proportional to the number of freezing/thawing cycles, this calculation provides a reference number. In sum, we used 0.1%, 0.8%, and 1% as the corrosion rate per year of NaCl, $CaCl_2$, and $MaCl_2$, respectively.

Table 3.2 Loss in dynamic modulus elasticity of Portland concrete cement in lab and field experiments

Deicer	Loss in dynamic modulus elasticity in lab (300 freezing/thawing cycles)	Loss in dynamic modulus elasticity in real life (5 freezing/thawing cycles per year)
NaCl (18%)	5%	0.1%
$CaCl_2$ (15%)	40%	0.8%
$MaCl_2$ (14%)	50%	1%

Some research indicates that asphalt pavement is less affected by deicers (Shi et al., 2009). The results of laboratory tests by Hassan et al. (2002) confirm this finding by using four deicers—urea, sodium formate, potassium acetate, and road salt (sodium and calcium chlorides)—on asphalt samples for 25 and 50 freeze/thaw cycles. The research team found that, compared with distilled water, the modulus of elasticity of asphalt pavement does not differ significantly for sodium formate, potassium acetate, and road salt (sodium and calcium chlorides). With urea, however, the modulus of elasticity decreased around 50% (distilled water is 26.242, while urea is 13.201). Therefore, the reference number that we used to calculate the per-year corrosion rate of urea was 50%, which is approximately 5% per year.

3.2 Estimation Results

In this section of the report, we present estimation results of components of the highway total pavement cost using real-life data from ASDOT and WSDOT.

3.3 Resurfacing Cost

The baseline estimation results from local polynomial smoothing with different degrees are presented in Figure 3.3, where it can be seen that the local polynomial smoothing estimates using degrees 1 and 3 fit the data well, but the corresponding lines have several spikes, indicating large variability and a potential overfitting problem. If the degree of the polynomial is increased to 5, the obtained curve is smoother and captures a more reasonable relationship between the resurfacing cost and the pavement thickness. Therefore, we chose 5-degree local polynomial smoothing to estimate $m\left(d_0\right)$. We experimented with alternative kernel functions to test the goodness of the fit of our model. For example, as shown in Figure 3.4, compared with kernel

Epan2, the baseline-estimates using the Epanechnikov kernel function provides a better fit for our data in terms of smoothness.

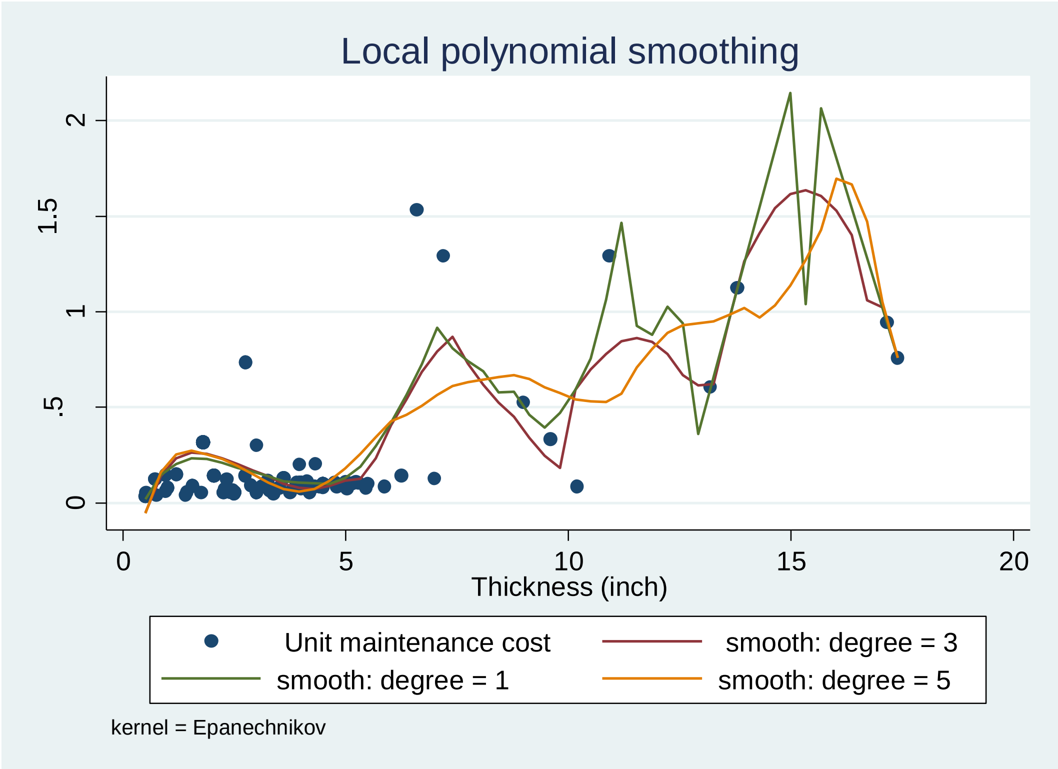

Figure 3.3 Local polynomial smoothing with different degrees

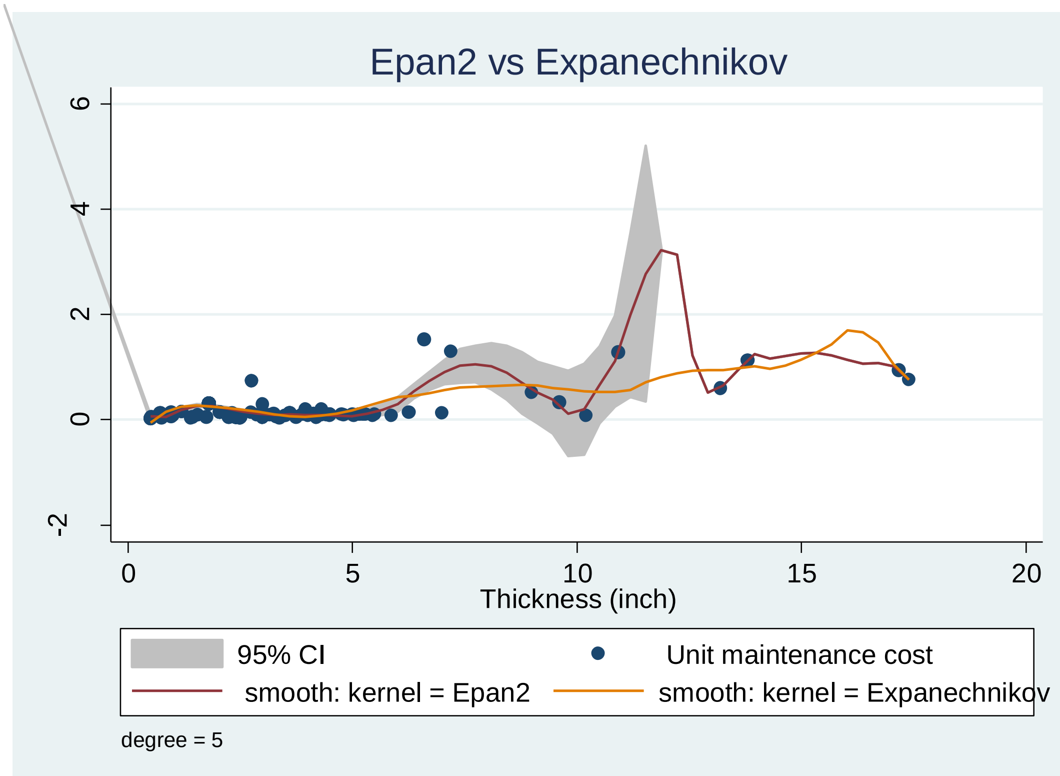

Figure 3.4 Local polynomial smoothing using different kernel functions

The baseline results from local polynomial smoothing were compared with the results from other nonparametric approaches, namely cubic spline regression and polynomial regression. The comparison is shown in Figure 3.5, where it can be seen that the cubic spline does a better job of smoothing the data compared with the 5-degree kernel-weighted polynomial smoothing denoted on the green dotted line. A simple 3-degree polynomial regression (the black real line), which can be estimated easily by OLS, also does a good job of smoothing the data.

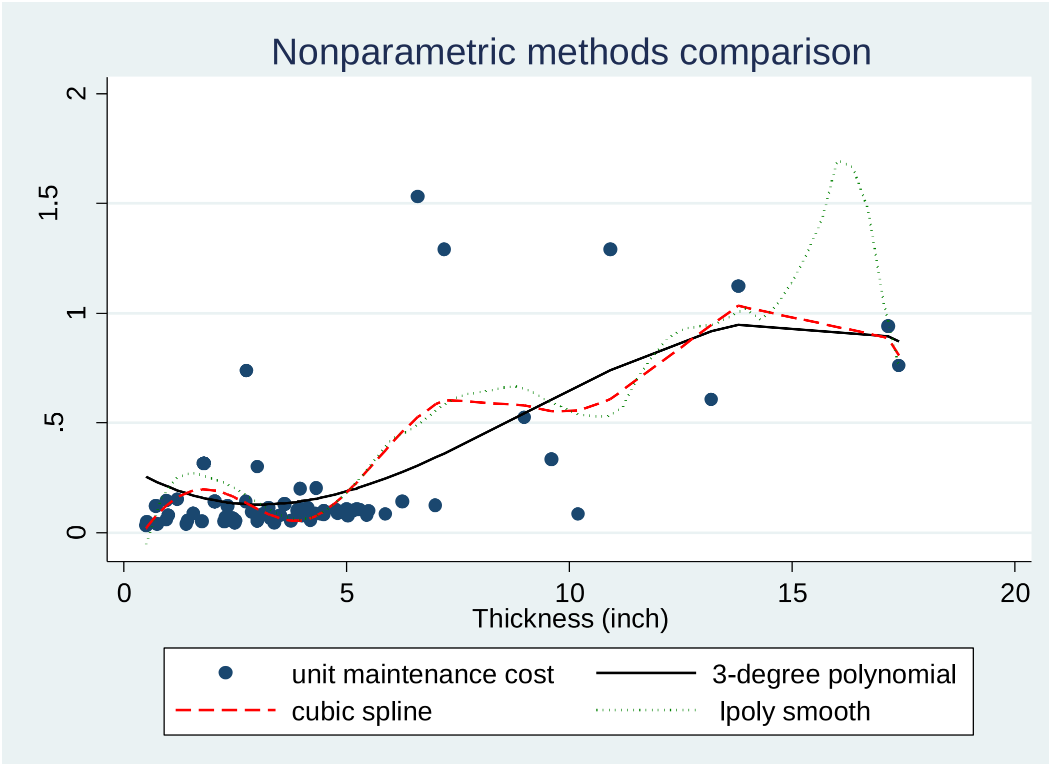

Figure 3.5 Goodness-of-fit of different nonparametric methods

3.3.1 Highway Duration

When estimating the highway duration equation, we smoothed the data variation by taking the group mean of durations and traffic loadings by highway number and pavement thickness. Using the average data, we fit the fractional polynomial model as follows,

$$m_1(x) = \underset{(9.61)}{35.42}\, x^{-2} + \underset{(4.00)}{17.46}\, x^{0.5} - \underset{(0.02)}{0.07}\, x^{3}, \qquad (9)$$

which fits and predicts the data very well as shown in Figure 3.6 and in Figure 3.7 (the red dashed line).[8] The approximation satisfies our assumption that duration is a decreasing function of traffic loadings. This estimation implies that it is appropriate to just use a cubic polynomial

[8] Standard errors are in parentheses.

regression. As shown in Figure 3.7, the cubic polynomial regression fits the data almost the same as the fractional polynomial. As a result, the duration is specified as

$$\ln T_i = \gamma_0 + \gamma_1 \ln Q_i + \gamma_2 \left(\ln Q_i\right)^2 + \gamma_3 \left(\ln Q_i\right)^3 + \delta D_i + \mu_i \tag{10}$$

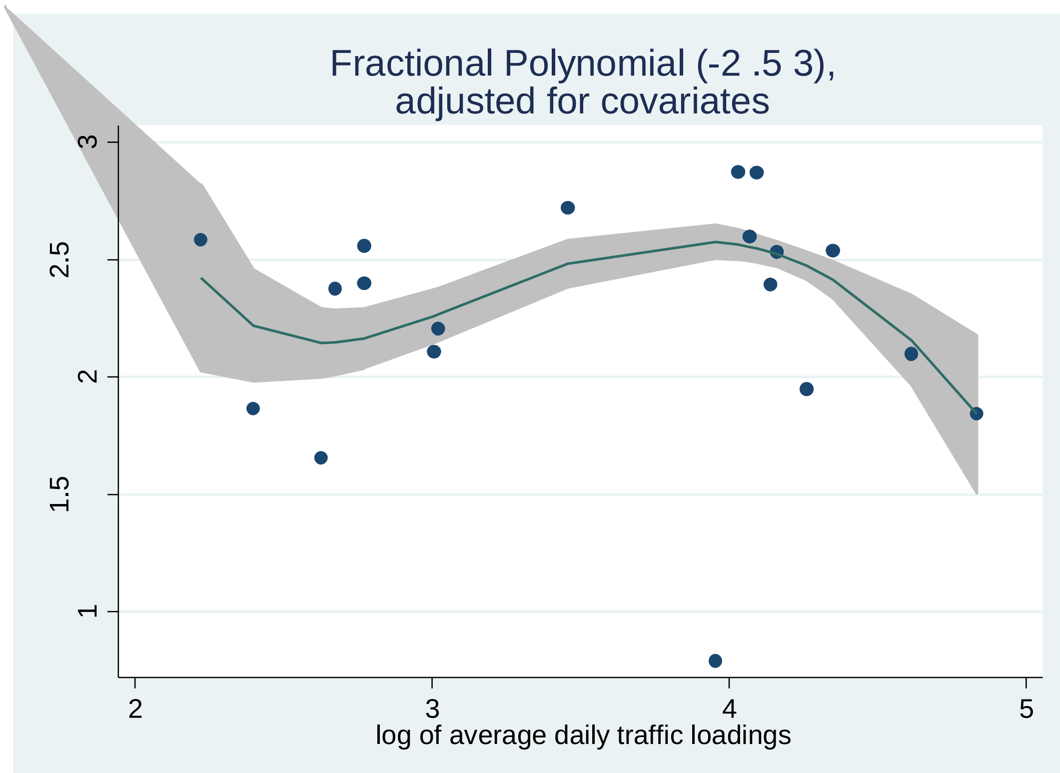

Figure 3.6 Fractional polynomial prediction

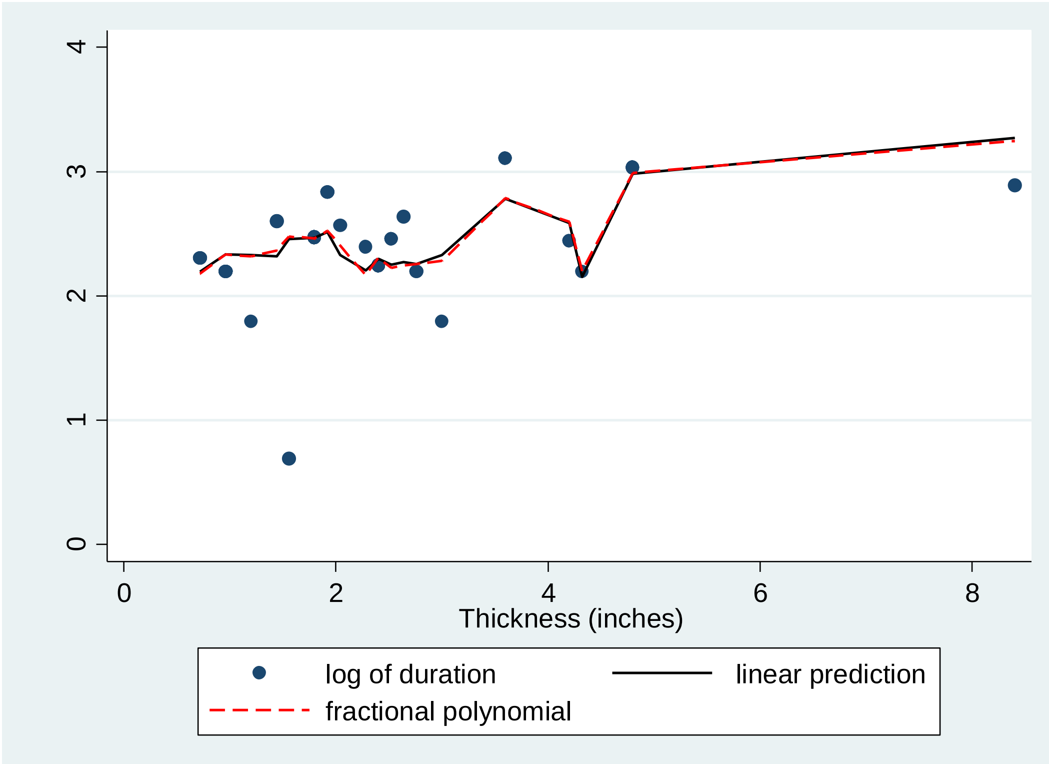

Figure 3.7 Fractional polynomial vs. cubic polynomial for duration model

3.3.2 Highway Construction Costs

Parameters in the construction cost equation were obtained from Arizona's average contract price for asphalt concrete pavements. The average construction cost in Washington is similar to that in Arizona (as reported in Kishore and Abraham [2009], Figure 2.6, and Table 2.4). The cost per lane mile per unit of thickness is $15,279, which is smaller than the cost of $24,820 used by Small and Winston (1988). The lower construction cost in our data is probably due to the advance in construction techniques.

3.3.3 Summary of Estimation Results

The coefficient estimates for final specifications of the resurfacing cost and highway duration are summarized in Table 3.3. Column 1 lists our estimates, using the resurfacing cost equation (Equation 7). This calculation suggests that the minimum maintenance cost is reached at 3.07

inches of pavement thickness, which coincides with the data sample mean. The duration estimation as shown in Column 2 suggests a negative relationship between duration and traffic loadings, as long as the daily traffic loadings exceed 50,000.

Table 3.3 Estimates of maintenance cost and highway duration equation

Variable	**Dependent variable: resurfacing cost (*C*) (1)**	**Variable**	**Dependent variable: Log of duration (ln*T*) (2)**
Constant	0.3154 (0.0811)	Constant	13.2305 (3.7413)
D	-0.1319 (0.0261)	D	0.1646 (0.0260)
D^2	0.0261 (0.0087)	$\ln Q$	-11.0304 (3.0902)
D^3	-0.0010 (0.0004)	$(\ln Q)^2$	3.4638 (0.8407)
		$(\ln Q)^3$	-0.3489 (0.0760)
Observations	210	Observations	97
R-squared	0.177	R-squared	0.376

Note: Robust standard errors are in parentheses. D = pavement thickness, and Q = daily traffic loadings.

3.4 Finding Optimal Highway Durability in Cold Regions

With the estimated resurfacing cost function, highway duration function, and highway construction cost function at hand, the optimal thickness D^* to minimize the total pavement cost is found by plugging the estimated equations into Equation (1) and solving numerically D^* holding daily traffic loadings constant. The real interest rate r used in the simulation is 3.95%, which is the average real interest rate in the U.S. from 1991 to 2014.[9] To account for the impacts of winter operations on highway durability, we rescaled the coefficients of the highway duration

[9] Source: The World Bank Group: http://data.worldbank.org/indicator/FR.INR.RINR.

equation (Equation 10) by $1-\alpha$, where α is the calibrated corrosion rate of urea deicer to asphalt pavement.

Figure 3.7 shows the optimal pavement thickness and corresponding highway duration for a range of daily traffic loadings. The figure shows that both thickness and duration are sensitive to traffic loadings when traffic load is "light" (less than 10,000 vehicles per day). As traffic loadings increase, however, the optimal thickness is not sensitive to the change in traffic loadings. The optimal pavement thickness is between 8 and 8.5 inches, which is 1 to 1.5 inches more than the average thickness in the data. The mean daily traffic loadings in our data are 55,500, and the calculated optimal durability at the sample mean is 8.07 inches, which corresponds to 16 years of pavement lifetime. The average duration of highway pavement in the data is 12 years.

Figure 3.8 plots the annualized total pavement cost (rTPC), defined by total pavement cost in Equation (1) multiplied by real interest rate. With traffic loadings held constant, rTPC is an increasing function of pavement thickness. The rTPC increases sharply, as the pavement is thicker than 8 inches. This increase in rTPC is largely due to the increase in traffic loadings, which in turn decreases duration. That is, all else being equal, the increase in lifetime pavement cost is mainly caused by an increase in maintenance cost. At mean daily traffic loadings, the rTPC is $3,673 higher in cold regions than in warmer regions.

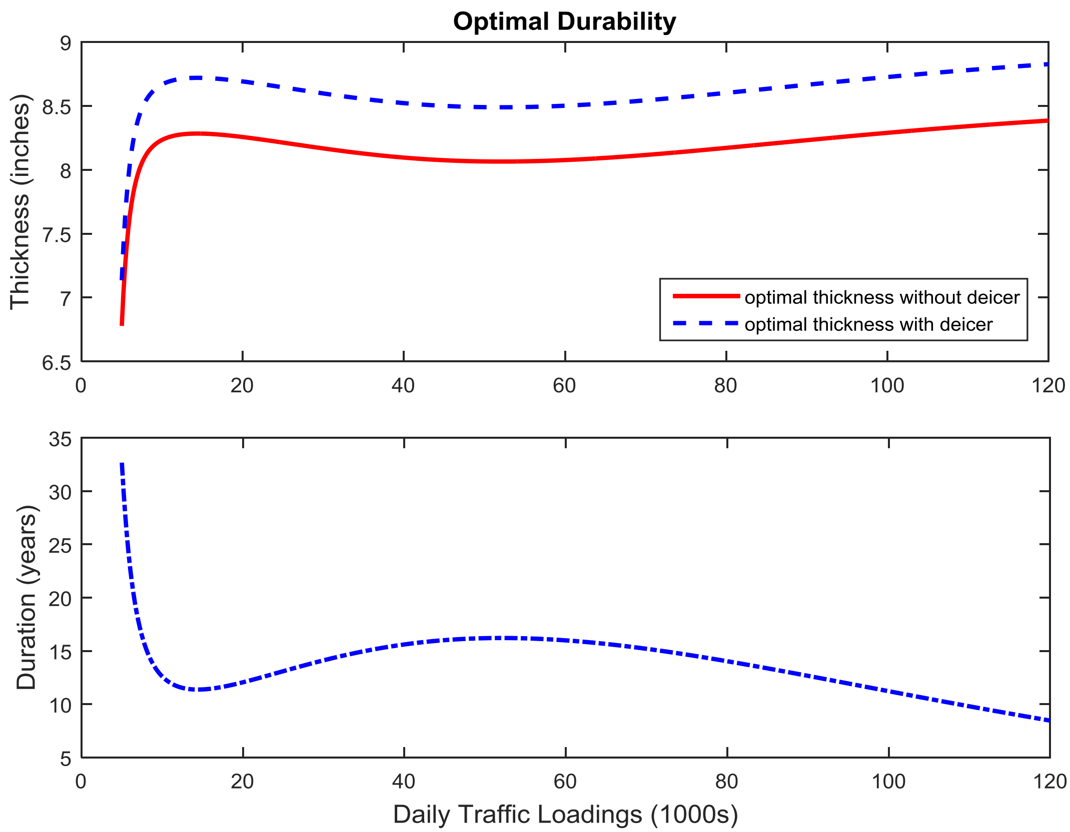

Figure 3.8 Optimal durability and corresponding duration, holding traffic loadings constant

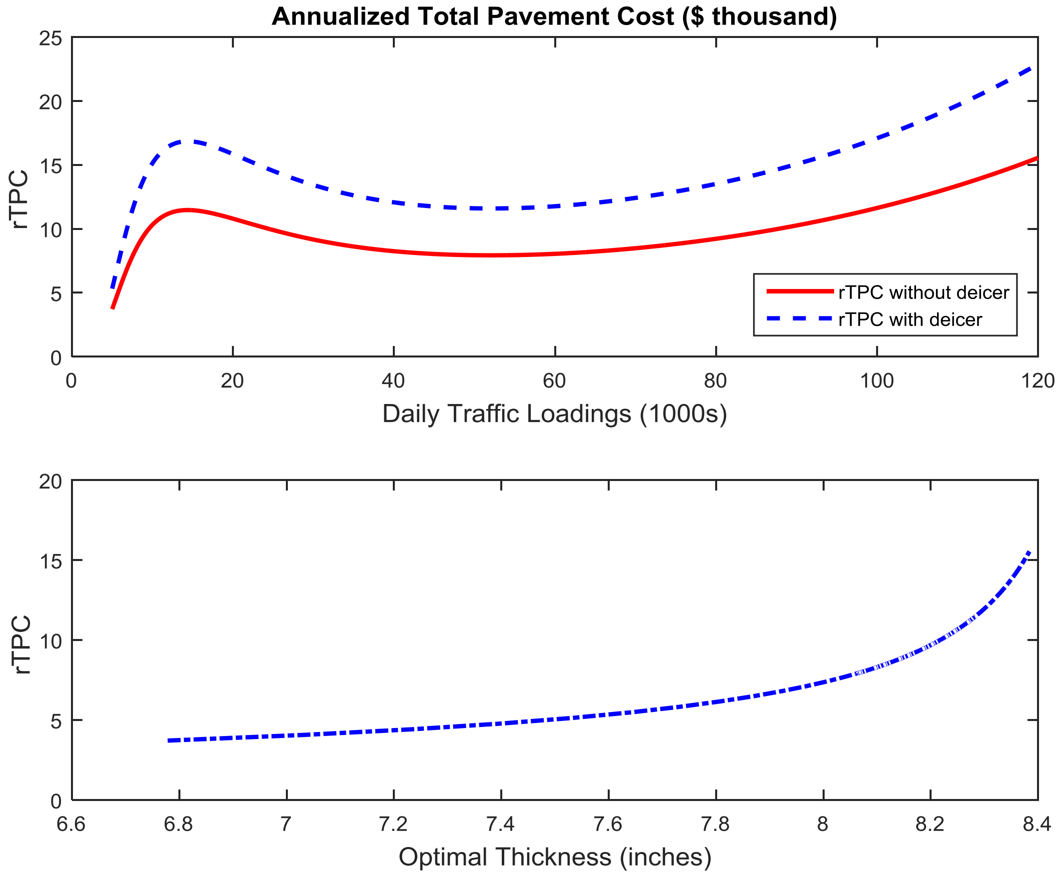

Figure 3.9 Annualized total pavement cost with respect to traffic loading and optimal thickness

CHAPTER 4.0 SUMMARY

Economically, the approach to finding optimal highway durability in cold regions is based on the total highway pavement cost function, which represents the relationship between lifetime total pavement expenditure of a highway and pavement thickness, given traffic loadings. Three components are used to determine the total pavement cost function—resurfacing cost, highway duration, and construction cost—each of which can be estimated using historical data of highway projects collected by state Departments of Transportation. Given the estimated cost and duration equations, the optimal highway durability in cold regions can be obtained by finding the pavement thickness that minimizes the total pavement cost.

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