An Empirical Model for Optimal Highway Durability in Cold Regions

Jia Yan[1]

[1]School of Economic Sciences, Washington State University

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Acknowledgment

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Research Question

- Durability of highway in cold region is affected by : pavement thickness, pavement materials, deicers.
- Trade-off:
  - Thicker pavement, better pavement materials, less corrosive deicing chemicals $\Rightarrow$ High construction costs, low maintenance costs.
- This research aims to find the optimal thickness in cold regions to minimize the total costs.

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Methodology–Total costs

- As an extension of Small and Winston(1988), our empirical analysis model is

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

Where

M : pavement materials;
D : the thickness of pavement;
Q : annual traffic loading;
$K(M,D)$: construction cost per lane mile;
$S(M,D)$: resurfacing (maintenance) cost per lane mile;
$T(M,D,Q)$: duration between two resurfacing tasks;
r: interest rate;

Methodology–Optimal Durability

- The optimal pavement thickness can be found by solving

$$D^*(M,Q) = argmin_D TPC(M,D,C)$$

- The key objective of this project is to derive the solution of this Equation.

Methodology–Derivation of Solution

- First, the total costs is

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

Using data from WSDOT and ASDOT, We first estimate $K(M,D)$ (construction cost per lane mile), $S(M,D)$ (resurfacing/maintenance cost per lane mile), and $T(M,D,Q)$ (duration between two resurfacing tasks).

- Second, we calibrate the effects of deicing.
- Lastly, integrating the estimated and calibrated models into the total costs function, we obtain the optimal durability by solving the optimization problem of

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Empirical Estimation of Highway Resurfacing Cost

- Considering asphalt concrete, the resurfacing cost $S(D)$ is a function of the top-layer pavement thickness of that material. We model the resurfacing cost as

$$S_i = m(D_i) + \varepsilon_i$$

where

S_i : resurfacing expenditure of highway project i;
$m(D_i)$: unknown conditional mean function (CMF);
ε_i disturbance term;

- The unknown function can be estimated nonparametrically.
- We use three nonparametric approaches—local polynomial smoothing, cubic splines, and polynomial regressions—to arrive at robust estimates.

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Empirical Estimation of Highway Duration

- Duration is decreasing in traffic loadings and increasing in pavement thickness. In cold regions, deicers and deicing instruments used accelerate pavement deterioration.
- We thus specify the highway duration as

$$y = m_1(x) + \delta D + \mu$$

where y and x denote the log of duration and log of traffic loadings, respectively;

$m_1(x)$: an unknown smooth function to be estimated;

Empirical Estimation of Highway Construction Cost

- Following Small and Winston(1988), we specify the construction cost as

$$K(D) = K_0 + K_1 D$$

- where D is the pavement thickness.

Data

- Real-life data were obtained from WSDOT and ASDOT, while calibrated data were based on literature.
  - No winter operations in Arizona and only a few highways require winter operation in Washington State.
  - We calibrate the effects of winter operation on highway durability and construction cost.
- This approach can be easily extended to establish optimal highway durability in other regions when relevant data are available.

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Duration Data

- Road Life Reports from WSDOT and a Project History Report from ASDOT
  - Road Life Reports contain information such as resurfacing, reconstruction, and lane widening, pavement type, pavement thickness on each layer. (Figure 1)
  - The Project History Report from ASDOT does not contain such information. Thus, we only used the Washington State sample to construct the duration data.
- The Annual Traffic Reports (ATRs) from WSDOT

A sample of a Road Life Report

1 DOT-RNB160V

STATE OF WASHINGTON - DEPARTMENT OF TRANSPORTATION
T R I P S   S Y S T E M
ROAD LIFE REPORT

DATE 04/17/15
TIME 08:53:18
PAGE 1

SR 005 OREGON ST LINE TO CANADA DISTRICT 4 (06) CLARK
MAINLINE

RELATED ROADWY QUALIF	SRMP	B ARM	STATE FUNCT CLASS	CONT SECT NUMB	HWY TYP	INV DIR	********** SURFACE CONTRACT DATA ********* CONTRT NUMBER	SEQ #	TYPE CONT	PAVE TYPE	PAVE THCK	DATE MN	DY	YEAR	EXCP	****** BASE DATA ****** TREATED BASE TYPE	THCK	YEAR	UNTREATED BASE THCK	YEAR	**OLD** **PCC** WID	LOC	THICKNESS SUMM TOTL PCC SURF THCK	TOTL FLEX SURF THCK	TOTL BASE THCK
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							012156		20	BA	0.35	01	01	1983											
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							000000		$$	$$$$	$$$$	01	01	1970											
							000000		$$	$$$$	$$$$	01	01	1954									0.00	0.56	0.60

Maintenance Cost Data

- Following Small and Winston (1988), we used the resurfacing cost to measure the maintenance cost.
- Project data spans from 1990 to 2014 for WSDOT and from 2000 to 2014 for ASDOT.
- Data include information such as contract number, contract completion date, the amount paid, and so on.
- For each project, we extract the content of the contract (e.g., the length of pavement, pavement materials, pavement thickness) from the Road Life Report (or Project History Report).

Construction Cost Data

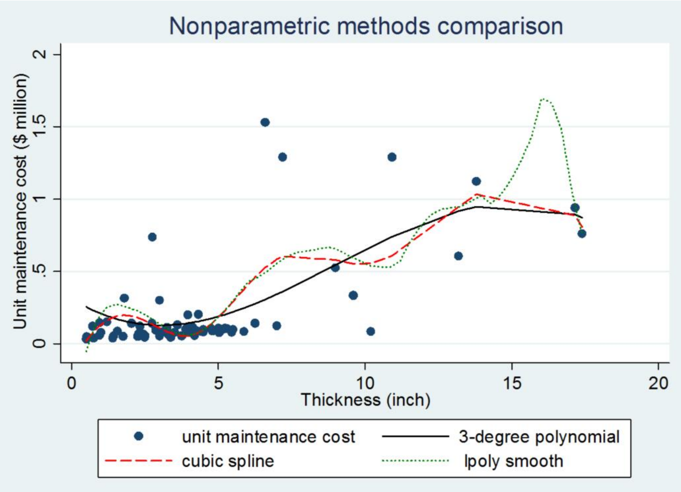
- We did not directly observe the construction cost of the interstate highway.
- Instead, we used Project History data from Arizona to infer the cost.

Summary statistics

Table 3.1 Summary statistics

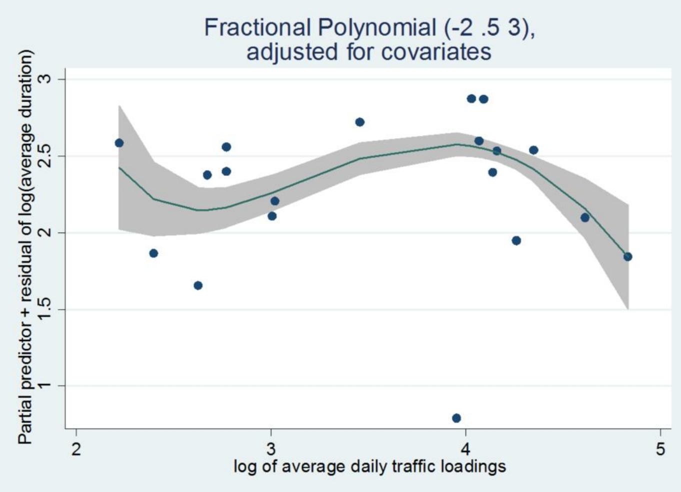
Variable	Obs.	Mean	Std. Dev.	Min	Max
Variables used in the duration equation					
Duration (years)	97	12.07	5.52	2	33
Thickness(inch)	97	2.16	1.08	0.72	8.4
Annual average daily traffic (AADT) (1000s)	97	55.5	44	8.2	173.89
Variables used in the maintenance cost equation					
Unit maintenance cost ($ million)	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

Figure 1. Goodness-of-fit of different nonparametric methods



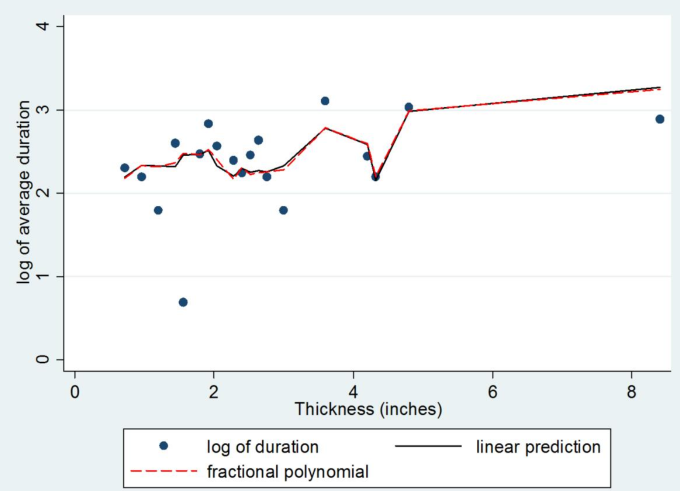
Estimation Results–Highway Duration

Figure 2. Fractional polynomial prediction



Estimation Results–Highway Duration

Figure 3. Fractional polynomial vs. cubic polynomial for duration model



Estimation Results–Highway Duration

- As shown in Figure 3, the cubic polynomial regression fits the data almost the same as the fractional polynomial.
- As a result, the duration is specified as

$$lnT_i = \gamma_0 + \gamma_1 lnQ_t + \gamma_2 (lnQ_t)^2 + \gamma_3 (lnQ_t)^3 + \delta D_t + \mu_t$$

Estimation Results–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.

Summary of Estimation Results

Variable	Dependent variable: resurfacing cost (C) (1)	Variable	Dependent variable: Log of duration (lnT) (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

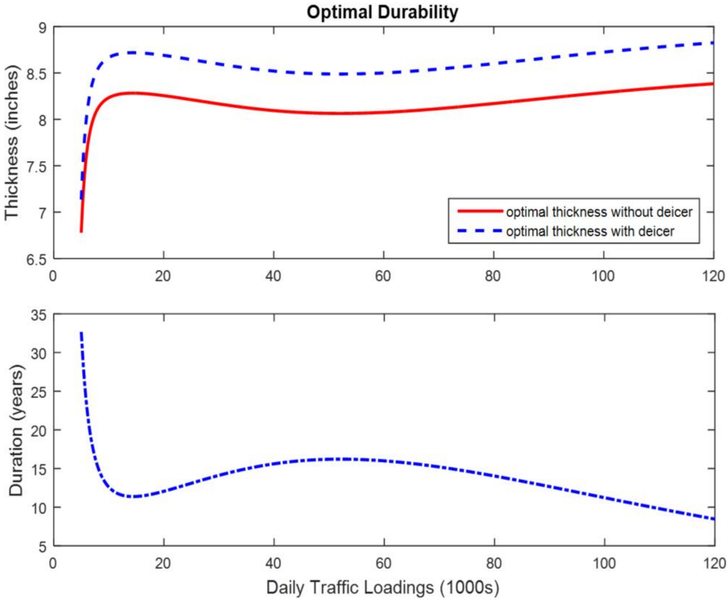
Note: Robust standard errors are in parentheses. D = pavement thickness, and Q = daily traffic loadings.

- Plug the estimated resurfacing cost function, duration function, and construction cost function into the total cost function.
- The real interest rate used in the simulation is 3.95%, which is the average real interest rate in the U.S. from 1991 to 2014.
- To account for the impacts of winter operations on highway durability, we rescaled the coefficients of the highway duration equation

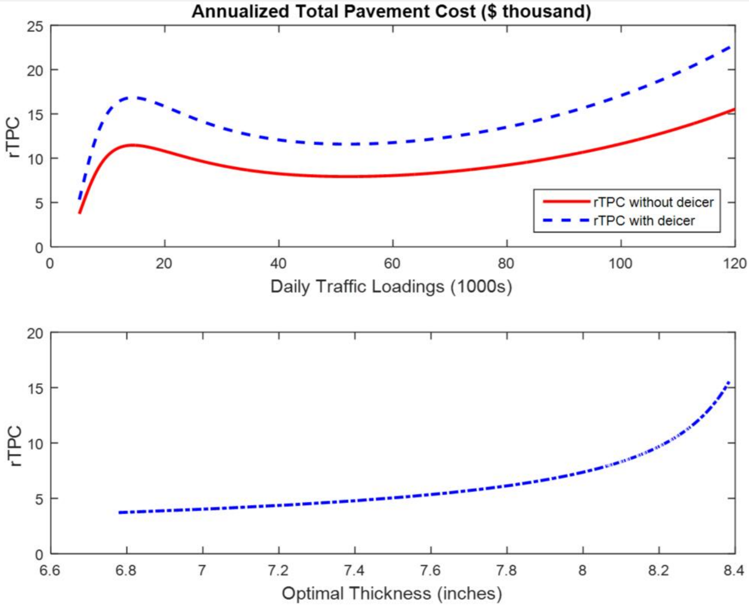
$$lnT_i = \gamma_0 + \gamma_1 lnQ_t + \gamma_2 (lnQ_t)^2 + \gamma_3 (lnQ_t)^3 + \delta D_t + \mu_t$$

by $1-\alpha$, where α is the corrosion rate of deicer. α is calibrated from literature (Hassan et al., 2002; South Dakota DOT, 2002; Zhang et al., 2003; Shi et al., 2009). The magnitude is approximate 5%.

Result–Optimal Durability



Result–Total Pavement Cost



Summary

- Three components are used to determine the total pavement cost function—resurfacing cost, highway duration, and construction cost.
- Given the estimated cost, 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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