Optimal Highway Durability in Cold Regions

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Background

• In cold regions, durability of highways is affected by both traffic loading and anti-icing operations during the winter months.

• Durability can be increased by ways such as increasing the pavement thickness and using better pavement materials.

• The cost of increasing durability is weighed against the benefits of doing so.
  • Lower maintenance cost during the life-time
  • Lower time cost of travelers
Research Question

• Develop a model to compute the optimal highway durability in cold regions

• The model can be an operational tool for government agencies.
Tasks

• Compiling data

• Estimate cost functions
  • The annualized highway maintenance costs: estimated from data on periodic resurfacing
  • Capital cost of highway construction: calibrated from literature
  • Time cost of users caused by highway maintenance: calibrated from literature

• Develop the operational model: An optimization model which finds optimal durability by minimizing the sum of maintenance, capital and time cost.
What we have done

• The project was started in March.

• We have been working on compiling data from various state DOTs (Washington, Montana, Minnesota, Wisconsin and Michigan).

• At the same time we have reviewed related literature and develop the statistic models that we will estimate from the compiled data.
Data for Estimating Highway Maintenance Cost

Data source:
  State DOTs
  Federal Highway Administration (FHWA) of U.S. Department of Transportation

Dataset:
  Construction Project Reports:
    contract number, contract title, state route number, completion date, contract amount
  Road Life Reports:
    contract information such as resurfacing, reconstruction, bridge widening, and replacement, with detailed pavement type, pavement thickness, length of project section.
  Annual Traffic Reports:
    Interstate highway information summary, such as route number, length, lane miles, traffic loadings.
## Example of Data

<table>
<thead>
<tr>
<th>Contract #</th>
<th>State Route</th>
<th>Completion Date</th>
<th>Amount Paid($)</th>
<th>SEQ #</th>
<th>Length(miles)</th>
<th>Lanes</th>
<th>Pave Type</th>
<th>Pave Thick(inch)</th>
<th>Traffic Loading</th>
</tr>
</thead>
<tbody>
<tr>
<td>8148</td>
<td>5</td>
<td>9/2/2011</td>
<td>2017496.87</td>
<td>1</td>
<td>2.23</td>
<td>6.3</td>
<td>B2</td>
<td>0.15</td>
<td>108000</td>
</tr>
<tr>
<td>8148</td>
<td>5</td>
<td>9/2/2011</td>
<td>2017496.87</td>
<td>2</td>
<td>2.23</td>
<td>6.3</td>
<td>Z2</td>
<td>0.15</td>
<td>108000</td>
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<tr>
<td>7252</td>
<td>82</td>
<td>9/17/2007</td>
<td>1036366.4</td>
<td>1</td>
<td>2.61</td>
<td>4</td>
<td>H2</td>
<td>0.15</td>
<td>13367</td>
</tr>
<tr>
<td>7252</td>
<td>82</td>
<td>9/17/2007</td>
<td>1036366.4</td>
<td>2</td>
<td>2.61</td>
<td>4</td>
<td>Z2</td>
<td>0.15</td>
<td>13367</td>
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<tr>
<td>7870</td>
<td>90</td>
<td>5/2/2013</td>
<td>13388091.96</td>
<td>1</td>
<td>1.27</td>
<td>4.6</td>
<td>PA</td>
<td>1.08</td>
<td>146000</td>
</tr>
<tr>
<td>7870</td>
<td>90</td>
<td>5/2/2013</td>
<td>13388091.96</td>
<td>2</td>
<td>1.27</td>
<td>4.6</td>
<td>B2</td>
<td>0.3</td>
<td>146000</td>
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<tr>
<td>7008</td>
<td>182</td>
<td>4/13/2006</td>
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<td>2/23/2004</td>
<td>31182927.5</td>
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<td>0.21</td>
<td>7.6</td>
<td>B5</td>
<td>0.95</td>
<td>102500</td>
</tr>
</tbody>
</table>

Notes:
- SEQ # = Contract sequence number;
- Length = the end accumulated route mile (ARM) nets the begin ARM;
- Lanes = the average lanes of rural section and urban section, measured as the lane miles divided by length;
- Pave Type = pavement types, which includes the following types: AA, BA, B2, C5, HA, H2, GA, PA, PD, PE, OZ, Z2, and Z3; Pave Thick = pavement thickness;
- Traffic Loading = the average of the average daily traffic volume between begin ARM and end ARM in completion year.
Next Steps

- We plan to finish data cleaning within this summer
- Using the data, we will estimate the maintenance cost function:

\[ c(Q,G,M,H,W) = \frac{T}{\tau(Q,G,M,H)} S(G,M,W) \]

\( T \): the life-time of the highway.
\( S(G,M,W) \): one-time resurfacing expenditure
\( \tau(Q,G,M,H) \): duration between two resurfacing tasks
- The whole project is expected to be finished in the Fall semester.
Model Set-up

Two costs components—construction cost and maintenance cost-- comprise the life-time cost of a highway. We denote the annualized highway maintenance and capital costs as

\[ C(Q, G, M, H, W) = rc(Q, G, M, H, W) \]  \hspace{1cm} (1)

and

\[ K(W, M) = rk(G, M, W) \]  \hspace{1cm} (2)

Where:
- \( r \): interest rate;
- \( Q \): the traffic loadings;
- \( G \): pavement material;
- \( M \): pavement thickness;
- \( H \): deicer used
- \( W \): width of highway (measured in number of lanes).
- \( c(\cdot) \) and \( k(\cdot) \) are present discounted value of highway maintenance costs and construction cost, respectively.
Specification of maintenance costs $c(\cdot)$

- The dominant component of maintenance cost is the periodic resurfacing expenditure, denoted by $S(G, M, W)$ with

$$lnS(G, M, W) = \alpha_0 + \alpha_1 G + \alpha_2 lnM + \alpha_3 W +$$
$$+\alpha_4 G \times lnM + \alpha_5 G \times W + \alpha_6 lnM \times W$$
$$+\alpha_7 G^2 + \alpha_8 W^2 + \alpha_9 (lnM)^2$$

- The duration between two resurfacing tasks is influenced by traffic loadings, pavement materials, pavement thickness and deicers and thus the duration is measured by $\tau(Q, G, M, H)$ with

$$\tau(Q, G, M, H) = \tau$$

- As a good approximation, the present discounted value of maintenance cost $c(\cdot)$ is given by

$$c(Q, G, M, H, W) = \frac{S(G, M, W)}{e^{\tau(Q, G, M, H)} - 1}$$
Specification of construction cost $k(\cdot)$

Following Small and Winston (1988), the present discounted value of highway construction cost, $k(\cdot)$, is a function of width, pavement materials and pavement thickness,

$$k(G, M, W) = k_0 + k_1 W + k_2 G \times W \times M$$  \hspace{1cm} (6)
The optimal problem

The optimal highway durability in cold regions is thus the solution of the problem

\[ \min_{G,M,H} [rc(Q,G,M,H,W) + rk(G,M,W)] \]
Estimation Procedures

Step 1 Estimate $S(G, M, W)$ using ordinary least square method.

$$\ln S(G, M, W) = \hat{\alpha}_0 + \hat{\alpha}_2 G + \hat{\alpha}_3 \ln M + \hat{\alpha}_4 W +$$
$$+ \hat{\alpha}_5 G \times \ln M + \hat{\alpha}_6 G \times W + \hat{\alpha}_7 \ln M \times W$$
$$+ \hat{\alpha}_8 G^2 + \hat{\alpha}_9 W^2 + \hat{\alpha}_{10} (\ln M)^2$$

Step 2 Estimate $\tau(Q, G, M, H)$

$$\hat{\tau}(Q, G, M, H) = \hat{\beta}_0 + \hat{\beta}_1 Q + \hat{\beta}_2 G + \hat{\beta}_3 M + \hat{\beta}_4 H$$

Step 3 Estimate $k(G, M, W)$

$$\hat{k}(G, M, W) = \hat{k}_0 + \hat{k}_1 W + \hat{k}_2 G \times W \times M$$
Estimation Procedures

Step 4 Calculate the optimal thickness $M$. Plug equation (8), (9) and (10) back to equation (5) and take the derivative with respect to $M$ to get the optimal thickness $M^*$. Thus, we have

$$M^* = M^*(Q, G, H, W)$$  \hspace{1cm} (11)

Step 5 Calculate the total cost using equation (7).

$$\min_{G, M, H}[rc(Q, G, M, H, W) + rk(G, M, W)]$$  \hspace{1cm} (7)
## Application Example

<table>
<thead>
<tr>
<th>Step</th>
<th>Used Equation</th>
<th>Dependent Variable</th>
<th>Independent Variable</th>
<th>Data Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(8)</td>
<td>Expenditure of Resurfacing</td>
<td>G: pavement material; M: pavement thickness W : width(measured by lanes)</td>
<td>Construction Project Reports(From WSDOT) Road Life Reports(From WSDOT)</td>
</tr>
<tr>
<td>2</td>
<td>(9)</td>
<td>Duration Between two surfacing tasks.</td>
<td>Q :traffic loadings G: pavement material; M: pavement thickness H : deicer.</td>
<td>Road Life Reports(From WSDOT) Annual Traffic Reports(From FHWA)</td>
</tr>
<tr>
<td>3</td>
<td>(10)</td>
<td>Expenditure of Constructing</td>
<td>G: pavement material; M: pavement thickness W : width(measured by lanes)</td>
<td>Construction Project Reports(From WSDOT) Road Life Reports(From WSDOT)</td>
</tr>
</tbody>
</table>
Application Example

Step 4 : Calculate the optimal thickness $M$.

\[
M^* = \text{argmin}[r\hat{c}(Q,G,M,H,W) + r\hat{k}(G,M,W)]
\]

Where

\[
\hat{c}(Q,G,M,H,W) = \frac{\hat{S}(G,M,W)}{e^{r\hat{\tau}(Q,G,M,H)-1}}
\]

\[
\hat{k}(\cdot) = \hat{k}_0 + \hat{k}_1 W + \hat{k}_2 G \times W \times M
\]
Application Example—Expected Results

The combinations of different $Q$ (traffic loadings), $G$ (pavement materials) and $H$ (types of deicers) generate different optimal thickness $M^*$. For example, given $Q \in \{50, 100\}, G \in \{A, C\}, H \in \{1, 2\}$ and $W = 2$, the combination of $Q, G$ and $H$ generates eight $M^*$’s and thus eight total costs.

<table>
<thead>
<tr>
<th>Q(traffic load)</th>
<th>G(pavement materials)</th>
<th>H(deicers)</th>
<th>Optimal Thickness</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>A</td>
<td>1</td>
<td>$M_1^*$</td>
<td>$C_1^*$</td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>2</td>
<td>$M_2^*$</td>
<td>$C_2^*$</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>1</td>
<td>$M_3^*$</td>
<td>$C_3^*$</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>2</td>
<td>$M_4^*$</td>
<td>$C_4^*$</td>
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<td>100</td>
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<td>1</td>
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<td>$C_5^*$</td>
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<td></td>
<td>A</td>
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<td>$M_6^*$</td>
<td>$C_6^*$</td>
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<tr>
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<td>C</td>
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<td>$M_7^*$</td>
<td>$C_7^*$</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>2</td>
<td>$M_8^*$</td>
<td>$C_8^*$</td>
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</table>