Incorporating Variability into Life Cycle Cost Analysis and Pay Factors for Performance-Based Specifications

Leanne Whiteley, BASc.
MASc Candidate

Susan Tighe, Ph.D., P.Eng.
Canada Research Chair in Pavement and Infrastructure Management

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INTRODUCTION

Problem definition

- 80% of Civil Infrastructure Systems activities are focused on:
  - Repairs
  - Rehabilitation
  - Renewal of structures

- Low-bid procurement only accounts for initial cost

Need to account for life cycle cost and promote innovation

Source: CSCE 2004
INTRODUCTION

Scope
- Examine how the variability associated with input parameters affects
  - Pavement performance models
  - Life cycle cost analysis

Objectives
- How does pavement performance input parameters affect service life?
- How does overlay service life affect life cycle costs?
- How can life cycle cost analysis be used to determine pay factors?
Performance Model Variables → Monte Carlo Simulation → Service Life Prediction → Life Cycle Costs → Discount Rate → Monte Carlo Simulation → Pay Factors → Sensitivity Analysis → Life Cycle Cost Analysis

RESEARCH METHODOLOGY
SERVICE LIFE PREDICTION

Roughness performance model
(C-LTPP asphalt overlays)

\[
\sqrt[3]{PDS} = 0.16 - 0.0012 \times OT + 0.000578 \times TC - 0.0000805 \times FI + 0.00147 \times DP
+ 0.0000000232 \times ESAL_8
\]

- \( PDS \) = slope of the pavement deterioration (IRI/year)
- \( OT \) = overlay thickness (mm)
- \( TC \) = total prior cracking (m/150 m)
- \( FI \) = annual freezing index (degrees C x days)
- \( DP \) = annual days with precipitation
- \( ESAL_8 \) = accumulated Equivalent Single Axle Loads (ESALs) after eight years

Source: Raymond 2001
Input Parameter Variability

- Overlay thickness variation
  - Normal and lognormal distributions
  - Thin (10-35 mm), medium (35-80 mm), thick (80+ mm)

- Total prior cracking variation
  - Triangular distribution
  - Mean = 175, min = 166, max = 183 m / 150 m of pavement

- Accumulated ESALs after eight years variation
  - Triangular distribution
  - Mean = 1,000,000, min = 750,000, max = 1,250,000 ESALs
## Overlay Service Life Results*

<table>
<thead>
<tr>
<th>Thickness-Distribution</th>
<th>Mean</th>
<th>10th</th>
<th>90th</th>
<th>Service Life Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thin-normal</td>
<td>22</td>
<td>21</td>
<td>24</td>
<td>Normal</td>
</tr>
<tr>
<td>Thin-lognormal</td>
<td>22</td>
<td>21</td>
<td>24</td>
<td>Lognormal</td>
</tr>
<tr>
<td>Medium-normal</td>
<td>27</td>
<td>23</td>
<td>31</td>
<td>Normal</td>
</tr>
<tr>
<td>Medium-lognormal</td>
<td>27</td>
<td>24</td>
<td>31</td>
<td>Lognormal</td>
</tr>
<tr>
<td>Thick-normal</td>
<td>35**</td>
<td>35</td>
<td>N/A</td>
<td>Lognormal</td>
</tr>
<tr>
<td>Thick-lognormal</td>
<td>37**</td>
<td>37</td>
<td>N/A</td>
<td>Undetermined</td>
</tr>
</tbody>
</table>

* Years ** Service lives established at 10th percentile
LIFE CYCLE COST ANALYSIS

Net Present Worth Method

– Net present worth factor

\[
(P \mid F, i, N) = \frac{1}{(1 + i)^N}
\]

\(P = \text{present value}\) \(F = \text{future value}\)

\(i = \text{discount rate (variable)}\)

\(N = \text{number of periods}\)

– Analysis period

\(30\) years

– Discount rate variability

- Triangular distribution

- mean = 4%, min = 3 %, max = 5 %
Life Cycle Cost Input Parameters

- Initial construction cost
  - Based on functional category
    - Pavement thickness (thin, medium, thick)
    - Mix design (conventional)
    - Traffic volume (moderate, high)
    - Subgrade strength (strong)

- Maintenance and rehabilitation
  - Cost based on MTO project value system
  - Timing dependent on overlay service life prediction

- Residual life
Life Cycle Cost Analysis Results*

<table>
<thead>
<tr>
<th>Thickness-Distribution</th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>Percentile</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>10&lt;sup&gt;th&lt;/sup&gt;</td>
</tr>
<tr>
<td>Thin-normal</td>
<td>$167,637</td>
<td>$4,383</td>
<td>$162,110</td>
</tr>
<tr>
<td>Thin-lognormal</td>
<td>$167,625</td>
<td>$4,361</td>
<td>$162,072</td>
</tr>
<tr>
<td>Medium-normal</td>
<td>$175,771</td>
<td>$11,133</td>
<td>$160,347</td>
</tr>
<tr>
<td>Medium-lognormal</td>
<td>$175,846</td>
<td>$10,658</td>
<td>$160,538</td>
</tr>
<tr>
<td>Thick-normal</td>
<td>$223,364**</td>
<td>$19,908</td>
<td>$223,364</td>
</tr>
<tr>
<td>Thick-lognormal</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

* per km  **LCCA established at 10th percentile

All LCCA fit a normal distribution
PAY FACTORS

- ERS/EPS contracts in Canada
- Contracts accompanied by price adjustment factor
  - Bonus for exceeding the specifications
  - Penalty for not meeting the specifications
- More research required
Life Cycle Cost Sensitivity Analysis

LCC Percent Difference (%)

Pavement Design Life (% Difference Relative to Design)

-20% -15% -10% -5% 0% 5% 10% 15% 20%

30% below 20% below 10% below Design 10% above 20% above 30% above

Thin-Normal
Thin-Lognormal
Medium-Normal
Medium-Lognormal
Thick-normal
Pay Factor Calculation

Pay factor formula

\[ PF = \frac{LCC_D \times \Delta LCC\%}{100} \]

- \( PF \) = pay adjustment factor
- \( LCC_D \) = design life cycle cost
- \( LCC\% \) = percent difference in life cycle costs between the design and the end result specification
# Pay Factor Results

<table>
<thead>
<tr>
<th>Overlay Thickness</th>
<th>Above specification</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10%</td>
<td>20%</td>
<td>30%</td>
<td></td>
</tr>
<tr>
<td>Thin</td>
<td>$7,660</td>
<td>$18,247</td>
<td>$17,680</td>
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<tr>
<td>Medium</td>
<td>$8,902</td>
<td>$17,391</td>
<td>$13,039</td>
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<tr>
<td>Thick</td>
<td>$3,455</td>
<td>$5,935</td>
<td>$8,397</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Overlay Thickness</th>
<th>Below Specification</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10%</td>
<td>20%</td>
<td>30%</td>
<td></td>
</tr>
<tr>
<td>Thin</td>
<td>$8,951</td>
<td>$19,585</td>
<td>$24,016</td>
<td></td>
</tr>
<tr>
<td>Medium</td>
<td>$8,224</td>
<td>$16,442</td>
<td>$31,620</td>
<td></td>
</tr>
<tr>
<td>Thick</td>
<td>$4,261</td>
<td>$8,793</td>
<td>$15,543</td>
<td></td>
</tr>
</tbody>
</table>

* per km of adjustment
CONCLUSIONS

**Advantage of using agency-specific performance model**
- Many transportation agencies have performance models based on their network level data
- These models can be used to determine pay factors: Normal and lognormal pavement thickness yield similar LCCA

**Advantages of the LCCA approach**
- Rational and defensible
- Payment based on material and construction quality

**Life cycle costs fit a normal distribution**

**Pay factor disincentives > pay factor incentives**
RECOMMENDATIONS

- Generate pay factors for other typical pavement construction projects
  - Rewards large enough to provide an incentive
  - Penalties small enough to not cause financial hardship

- Ensure performance specifications are realistic and “user friendly”

- Incorporate variability into performance specifications