Incorporating Variability into Pavement Performance Models and Life Cycle Cost Analysis for Performance-Based Specification Pay Factors

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ABSTRACT
This paper describes a recent research study that examined how changes in design life impacts
the pavement life cycle cost (LCC) and ultimately how the reduction or addition in LCC
attributed to inferior or superior in-service performance could be used as a basis for establishing
a pay factor for a performance based specification.

Models have been developed using data from the Canadian Long Term Pavement
Performance (C-LTPP) that indicate that overlay thickness, total prior cracking, annual freeze
index, annual days with precipitation, and accumulated ESALs after eight years, affect the slope
of pavement deterioration for asphalt overlay pavements. One of these models, as well as data
from the United States Long Term Pavement Performance (LTPP) test sites, is used to determine
the service life of asphalt overlay pavements.

This paper examines how the variability associated with overlay thickness, total prior
cracking, and accumulated ESALs after eight years affects the service life. Furthermore, this
paper considers the variability associated with the discount rate and incorporates all associated
variability into the life cycle cost analysis (LCCA). The life cycle cost distributions are
calculated using Monte Carlo techniques. Based on a recent study, distributions for service life
and life cycle costs are developed using both the normal and lognormal distributions for overlay
thickness.

Using the LCCA values for typical design lives, a sensitivity analysis is subsequently
performed to evaluate the impact of 10%, 20% and 30% differences in the in-service
performance as compared to the design life. These LCCA differences are then used as a basis for
establishing pay factors. Overall the paper attempts to relate design to in-service performance
LCC and ultimate use of pay factors.
INTRODUCTION

Most pavement designs in Canada do not include a formal life cycle cost (LCC) procedure as part of the design stage. If a life cycle cost analysis (LCCA) is carried out, then it is usually a deterministic analysis (1). Unfortunately, a deterministic approach to LCCA does not account for the variability associated with the input parameters (2). Therefore, the purpose of this paper is to evaluate the variability associated with life cycle cost input parameters.

With the introduction of new technologies and mix designs, there has been a shift in the way in which transportation agencies prepare their specifications. Performance related specification have been developed in order to promote construction innovation. These specifications place more emphasis on the performance of the final product, rather than the methods of construction and/or materials used (3). In order to encourage contractors to comply with these new specifications, pay factors have been introduced into contract documents. Unfortunately, limited work has been done to incorporate these pay factors into life cycle costs. Therefore, once the LCC models have been developed based on the variability associated with the input parameters, a discussion of how to incorporate pay factors into the life cycle costs will be presented.

SCOPE & OBJECTIVES

The scope of this paper will be examining how the variability associated with input parameters impacts pavement performance models for performance specifications, life cycle cost, and pay factors.

The objectives of this paper are as follows:

- To evaluate how the variability associated with pavement input parameters affects the service life of an overlay.
- To evaluate how the variability associated with overlay service life affects the life cycle cost for a pavement design.
- To determine how pay factors can be incorporated into life cycle cost analyses.

Figure 1 provides the framework for approach in this research. Initially the probabilistic in-service design is calculated for a typical design. The LCC value is then calculated for this design. Following that, a sensitivity analysis is performed to compare the expected design to a series of in-service designs which are either above or below the expected design, i.e., at 10%, 20% and 30%. The LCCA for these varying designs, which represent superior and inferior performance, is calculated. The difference is then determined as a percentage of the overall LCCA. This information is then used as a basis for examining pay factors.

VARIABILITY

From a probabilistic approach, variability can be represented by probability distribution functions. There are a number of probability distribution functions available to best describe a variable or process. However, based on the literature and an examination of pavement performance factors and LCCA, in this paper normal distribution, lognormal distribution, and triangular distribution are used. They can be briefly described as follows:

The normal distribution is a continuous probability distribution that can describe many natural phenomena. The equation of the normal probability density is shown in Equation 1 (4).

\[ f(x; \mu, \sigma^2) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}, \quad -\infty < x < \infty \]  (1)
where, Error! Objects cannot be created from editing field codes. is an unknown variable, Error! Objects cannot be created from editing field codes. is the mean, and Error! Objects cannot be created from editing field codes. is the standard deviation. 
The lognormal distribution is a continuous probability distribution that is positively skewed, which means that most of the values are near the lower bound. The lognormal probability density is shown in Equation 2 (4).

\[
f(x) = \frac{1}{\sqrt{2\pi \beta}} e^{-(\ln x - \alpha)^2 / 2\beta^2} \quad \text{for } x > 0, \beta > 0
\]

\[
f(x) = 0 \quad \text{elsewhere}
\]

where, Error! Objects cannot be created from editing field codes. is a variable, Error! Objects cannot be created from editing field codes. is the mean and Error! Objects cannot be created from editing field codes. is the variance.

The triangular distribution is a continuous probability distribution. The triangular probability density is shown in Equation 3 (5).

\[
P(x) = \begin{cases} 
\frac{2(x-a)}{(b-a)(c-a)} & \text{for } a \leq x \leq c \\
\frac{2(b-x)}{(b-a)(b-c)} & \text{for } c \leq x \leq b
\end{cases}
\]

where, \(a\) is the lower limit, \(b\) is the upper limit, \(c\) is the most likely value, and \(x\) is a variable.

**LIFE CYCLE COST ANALYSIS**

According to a recent paper prepared for the Ohio Department of Transportation, there are no fixed values when performing a life cycle cost analysis (6). There are cost variations with respect to materials and maintenance and rehabilitation treatments. Furthermore, there are variations associated with the year in which the maintenance and rehabilitation techniques are performed. This paper investigates the variation associated with the year in which maintenance and rehabilitation techniques are performed.

Although there are several methods that can be used, for the purpose of this research, the net present value method will be used to conduct the LCCA.

The net present value brings all future costs to the present via the present worth factor shown in Equation 5. The present worth factor gives the present amount that is equivalent to a future amount.

\[
\text{(5)}
\]

where, Error! Objects cannot be created from editing field codes. is the present amount, Error! Objects cannot be created from editing field codes. is the future amount, Error! Objects cannot be created from editing field codes. is the discount rate, and Error! Objects cannot be created from editing field codes. is the number of periods (7).

To determine the total LCC, all costs, including initial construction, maintenance and rehabilitation costs, are converted to their present worth with the use of the present worth factor. The resulting summation is the total life cycle cost.

**PAY FACTORS & LIFE CYCLE COST ANALYSIS**

Within the last few years, there have been an increasing number of end result/end product specification (ERS/EPS) contracts in the Canadian and United States pavement construction
industry (8). These types of contracts are typically accompanied by a price adjustment factor or a pay factor either in terms of a bonus (for exceeding the specifications) or a penalty (for not meeting the specifications).

The service life is an obvious performance measure for highway pavements. If the measured characteristics on the jobsite do not meet the design standards, then the service life will be shortened. Performance models can be used to estimate the reduction in service life, which can be combined with a LCCA to compute the expected loss in net present value. This expected loss in net present value can then be used to justify an appropriate amount of pay reduction to the contractor (9).

Another way of examining these pay factors or pay adjustments is based on the difference between the LCCA for the as-designed pavement and the predicted life cycle cost for the as-built pavement. The advantage of using a LCCA approach for determining pay adjustments is that it provides a rational and defensible way to adjust a contractor’s payment based on material and construction quality. Unfortunately, this approach can become complex, especially when construction variability and uncertainty are also considered (10). In this work the difference between predicted and as-built roughness is compared.

The variability associated with the input parameters is examined as demonstrated in Figure 2, which represents the variability associated with pavement thickness. After considering the variability associated with all of the input parameters, the variability is incorporated into Monte Carlo simulations to predict overlay service life and its associated variability. Service life and its variability can then be incorporated into a maintenance and rehabilitation schedule which can be used to determine the probabilistic life cycle cost.

**PERFORMANCE MODEL**

The performance model used in this work was developed based on asphalt overlay sections in the Canadian Long Term Pavement Performance (C-LTPP). The model was developed using seventeen SPS-5 sites, which are asphalt overlays placed over existing flexible pavements with granular based courses, located across Canada. The model incorporates roughness and service life as presented in Equation 6 and was selected to predict the service life of an overlay. The equation calculates the slope of the pavement deterioration in terms of the International Roughness Index per year (IRI/yr) for the first eight years after the overlay. The equation is limited to asphalt overlay pavements with adequate structural design, which are subjected to Canadian climatic conditions. (11)

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

\[
+ 0.000000232 \times ESAL_8
\]

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

The overlay thickness is the as-built thickness of the asphalt overlay placed during rehabilitation and accounts for the replacement of any milled pavements (12). Three different types of overlay thicknesses and their associated variability will be examined in this paper: thin (10mm – 38 mm), medium (25mm – 80 mm), and thick (more than 80mm).

The total prior cracking is the summation, in terms of length, of all types of sealed and unsealed pavement cracks prior to the overlay rehabilitation (12). Total prior cracking is expressed in terms of total length of cracks per 150 metre length of pavement (m/150 m). The
variability associated with total prior cracking will be further examined in the subsequent sections.

The annual freezing index is the sum of the negative mean air temperatures (e.g., 5 day at -2 °C equal a freezing index of 10 °C-days) (12). The annual freezing index varies from region to region. However, the values obtained for the annual freezing index are well documented and recorded by the weather stations. Based on a paper prepared by (13) using LTPP data, the average annual freezing index for Ontario is 376 °C x day, which will be the value used in this analysis.

The annual days with precipitation as it states is the total number of days in a year that there is precipitation in the pavement location. Once again, annual days with precipitation data are collected by local weather stations and therefore will not vary throughout the analysis. A value of 134 days will be used for the purpose of this analysis (14).

The accumulated ESALs after eight years are an estimation of the number of ESALs during the first eight years immediately following the overlay. Traffic data are more difficult to monitor and collect than climate data as traffic varies constantly throughout the day, as does the type of traffic. Therefore, the variability associated with the accumulated ESALs after eight years is one of the variables examined.

Variability Factors
In this research several factors were incorporated into the variability analysis. These factors include: overlay thickness, total prior cracking, accumulated ESALs after eight years, overlay service life, and life cycle cost. A discussion of how the variability of each of these factors was incorporated into the analysis is presented herein.

Overlay Thickness Variation
Overlay thickness can vary significantly from rehabilitation to rehabilitation. Therefore, overlay thicknesses will be grouped into three separate categories: thin, medium, and thick. The range of values, mean, and standard deviation for each of the overlay thickness categories used in the analysis is shown in Table 1 (15). These values were based on core thickness measurements from the Canadian Long Term Pavement Performance (C-LTPP) test sites.

In order to account for the variability associated with overlay thickness, a distribution function needs to be selected to represent the distribution of overlay thickness. In general, transportation material characteristics are assumed to be normally distributed (16). However, a recent study indicates that thickness is better represented by lognormal distributions (15). Therefore, both normal and lognormal distribution functions representing overlay thickness will be examined.

Total Prior Cracking Variation
As previously discussed, total prior cracking includes the length of all types of cracking in terms of metre of cracking per 150 metre of pavement. There is a variability associated with the data collection methods used to calculate the length of the cracks. A total prior cracking value of 600 m/150 m would mean a variability of +/- 25 m/150 m using a triangular distribution. Through observation of the total prior cracking presented in (11), the average total prior cracking in the LTPP sections was approximately 175 m/150 m. Therefore, by interpolation the minimum and maximum values for total prior cracking using a triangular distribution are 166.25m/150m and 183.75m/150m, respectively.
**Accumulated ESALs After Eight Years Variation**

The last variable in Equation 4 whose variability will be accounted for in the analysis is ESAL_{8}. The Equivalent Single Axle Load (ESAL) is calculated according to Canadian Best Practice \( (8) \).

In order to account for ESAL variability, an average value of 1,000,000 ESALs, a minimum value of 750,000 ESALs, and a maximum value of 1,250,000 ESALs will be incorporated into a triangular distribution and used in the analysis. These are typical values obtained from LTPP test sites for accumulated ESALs after eight years \((14)\).

**OVERLAY SERVICE LIFE VARIABILITY**

There are two scenarios or distributions (normal and lognormal) for overlay thickness and three thickness categories for each scenario presented in this paper. All six overlay thickness categories and their associated input variable distribution functions are described in Table 2. By incorporating the variability of overlay thickness, total prior cracking, and accumulated ESALs into Equation 6, service life distribution functions can be determined for each of the overlay thickness categories. To do so, the values previously discussed were inputted into Crystal Ball, where Monte Carlo simulations with 100,000 trials at a 95% confidence interval were run for each overlay thickness category. Through this assessment a total of six expected overlay service lives are produced. These overlay service lives are carried forward to calculate LCCA and subsequent pay factors.

An analysis period of 30 years was used for all of the simulations. The LCCA accounts for the initial cost of construction, as well as, future maintenance and rehabilitation costs. The proposed pavement categories, initial pavement structure, and associated costs for subsequent maintenance and rehabilitation treatments for each overlay thickness are shown in Table 3 \((17)\).

Rout and seal, mill and patch 10% spot repair, mill & patch 20% spot repair, mill 40 mm asphalt pavement, resurface with HL 4-40mm, and resurface with a premium material, known locally as a Dense Friction Course (DFC) 80 mm, are considered in the LCCA. The unit costs for these treatments are based on the Ministry of Transportation Ontario (MTO) project value system.

The year in which these treatments occur will depend on the overlay service life and the current MTO practice \((18)\). Accordingly, it is assumed that a mill & patch spot repair will last no more than 10 years before an overlay or another mill & patch repair is required. Furthermore, rout and seal treatments are only applied to pavements within the first 3 to 7 years of new construction (initial construction or resurface).

Another component of the LCCA is the residual life at the end of the analysis period. The residual life of the pavement was calculated by linearly prorating its initial cost. For example, for a pavement with a service life of 22 years (indicated by resurface at year 22), which was resurfaced 8 years before the end of the study period, the residual value would be \((22-8)/22 \times (\text{initial cost})\) \((19)\).

For the purpose of this assessment, it is assumed that only roughness is considered as a reason for overlay. In reality, other performance indicators, such as deflection, surface distresses, and riding comfort may reduce the life of the overlay and the time required for a new overlay.

An important aspect of the LCCA is the discount rate used in the present worth factor to bring future values from the future to the present. Since the discount rate can significantly influence the LCCA, a reasonable value that reflects historical trends over long periods of time should be used. Previous papers have indicated that a typical discount rate of 4% is used in LCCA \((2, 20)\). Furthermore, a paper prepared by the Federal Highway Administration indicates
that discount rates in life cycle cost analysis can be represented by a triangular distribution with a most likely value of 4%, a minimum value of 3%, and a maximum value of 5% (2).

**DATA ANALYSIS**
The results of the Monte Carlo simulations for both the overlay design service life and LCCA are discussed herein.

**Overlay Service Life Results**
The results for thin and medium overlay thickness using either lognormal or normal distributions based on Monte Carlo simulations, are very similar as shown in Table 4. The service life of an overlay increases as the thickness of the overlay increases. However, it should be noted that the thickness cannot increase indefinitely. Although the mean service lives obtained for each of the overlay thicknesses appear to be high, they closely resemble service lives obtained in another study relating to roughness as a performance measure (21). Nevertheless, a service life of 67 years for a thick overlay appears unrealistic. This is most likely a result of only using roughness as a performance measure, instead of including other performance measures like cracking or rutting.

Another observation resulting from the overlay service life distributions is that the standard deviation and the skewness increase as the thickness increases. This means that there is more variation expected in performance as the asphalt thickness increases. For thin and medium overlays with a normal distribution, the service life appears to fit a normal distribution. However, as the thickness increases, the service life distribution curve starts to resemble a lognormal curve (due to the increase in skewness). In the case of overlay thicknesses being represented by lognormal distribution functions, the resulting service lives appear to be best represented by lognormal functions, with the exception of a thick overlay, whose distribution function cannot be determined from the resulting frequency chart and statistics.

Upon review of the sensitivity charts, it can be seen that the contribution to variance for overlay thickness increases as the overlay thickness increases. This may be a result of the increase in standard deviation from thin thicknesses to thick thicknesses. In all simulations, overlay thickness contributes more than 80% to the variance in service life predictions; whereas ESALs accumulated after eight years and total prior cracking variables combined account for less than 20% of the variance.

**Life Cycle Cost Models**
Based on the results provided in the previous section for predicted overlay service lives, a life cycle cost was performed for the first five thickness category simulations. The results of the life cycle costs analyses are as follows:

The mean values obtained for the normal and lognormal distributions for thin and medium overlays are very close. However, the results obtained with the lognormal distributions for the overlays have a lower standard deviation. Similar to the previous set of Monte Carlo simulations, the standard deviation increases as the overlay thickness increases. However, unlike the results obtained in service life predictions, there are no noticeable trends with the skewness as the overlay thickness increases.

Figure 3 summarizes the LCC distribution curves resulting from the three Monte Carlo simulations in the normal distribution scenario.
Pay Factors
Once the LCC results were obtained, a sensitivity analysis was conducted to investigate inferior and superior in-service performance relative to the design. The difference in LCC is shown in Figure 4. As expected, the percent difference in LCC increases as the end results deviate from the design specifications. Furthermore, the reductions in LCC due to inferior in-service performance are greater than the additions in LCC due to superior in-service performance. This result is practical since the contractor’s disincentive should be greater than the incentive. The result of a pavement that does not meet performance expectations far outweighs the results of a pavement that exceeds performance expectations, since the increase in maintenance and rehabilitation costs at an earlier stage in the pavement service life increase the life cycle cost. Therefore, it is more important to discourage contractors from not achieving in-service performance than it is to encourage contractors to exceed the designed in-service performance.

The difference in LCC between the design specifications and the end results can be related back to pay factors through Equation 7.

\[ PF = LCC_D \times \frac{\Delta LCC\%}{100} \] (7)

where, \( PF \) is the pay adjustment factor, \( LCC_D \) is the design life cycle cost, and \( \Delta LCC\% \) is the percent difference in life cycle costs between the design and the end result specification. Note that a negative difference in life cycle cost based on an inferior in-service performance will result in a negative pay factor (penalty) and a superior in-service performance will result in a positive pay factor (reward).

The pay factors for the given in-service performances are shown in Table 5. The largest pay factor reduction is $31,620 for a medium overlay pavement that is 30% below specification. The largest pay addition is $18,247 for a thin overlay pavement that is 20% above specification. It should be noted that the values obtained for pay factors are only valid under the assumptions and conditions used in this research. Moreover, the life cycle cost values are per unit kilometre, therefore, the pay factor values are per unit kilometre.

Once the pay factor has been calculated, it should be combined with the initial cost of construction and the result will be the sum of money that should be received by the contractor.

INCORPORATING PAY FACTORS INTO LIFE CYCLE COSTS
The previous sections have demonstrated the complexity of introducing variability into life cycle cost analysis. Nonetheless, if a transportation agency has reliable performance models, which are based on historical data, typical loading (traffic information) and environmental conditions specific to the agencies network of pavements, then the agency should feel confident to use those models to determine pay factors in pavement construction contracts. The range in which contractors are rewarded or penalized should be comparable to other pavement construction projects. The reward should be large enough to actually provide an incentive to the contractor. However, the penalty should not be so large as to cause financial hardship to the contractor.

Some types of performance specifications include, but are not limited to, “no cracking after 10 years”, “permanent deformation less than 10 mm after 5 years”, Present Serviceability Index (PSI) greater than 3.0 after 15 years” (8). The performance specifications must be realistic and attainable for the contractor. Furthermore, there should be variability incorporated into the performance specifications. For example, in the case of the “no cracking after 10 years”, a contractor should not be penalized if there is a minute amount of cracking. Therefore, “no
“cracking” should include a tolerable amount of cracking. The toleration should be obtained through an analysis of the agency’s performance models.

Life cycle cost analysis can be a useful tool for developing pay factors. An agency can predict the life cycle cost of a pavement design based on the performance specifications. Then once the pavement has been constructed and the time indicated in the performance specification has expired, another life cycle cost should be conducted based on the as-built measurements. The difference between the two life cycle costs should be used to apply a pay factor. An as-built life cycle cost greater (to at least some extent) than the as-designed life cycle cost would result in a penalty to the contractor; whereas, an as-built life cycle cost less than the predicted design life cycle cost would result in a reward to the contractor.

Pay factors can also be incorporated into LCCA in a similar manner to what is presented in this paper. If an agency specifies a tolerable variation for pavement thickness, then that variation can be incorporated into a life cycle cost analysis. Once the pavement is built, the actual as-built thickness and variation can be measured. The new measurements should be incorporated into another life cycle cost analysis and the results compared to that obtained for the tolerable variation specified by the agency.

CONCLUSIONS
Based on the information provided in this paper, the following conclusions are made:

- The skewness of the overlay service life models increase (positively) as the thickness increases.
- Thin and medium overlay thicknesses represented by a normal distribution produce a normal service life prediction model.
- Thick overlay thicknesses represented by a normal distribution as well as thin and medium overlay thicknesses represented by a lognormal distribution produce a lognormal service life prediction model.
- In all simulations, overlay thickness contributes more than 80% to the variance in service life predictions; whereas ESALs accumulated after eight years and total prior cracking variables combined account for less than 20% of the variance.
- The life cycle costs for overlay thicknesses based on both normal and lognormal distribution functions yield similar results.
- The standard deviations associated with the life cycle cost curves based on lognormally distributed thicknesses appear to be smaller than those obtain from normally distributed thicknesses.
- Regardless of the type of distribution used to represent overlay thickness, the resulting life cycle costs fit a normal distribution.
- Despite the complexity involved, pay factors can be incorporated into life cycle cost analysis to determine pay factors associated with performance specifications.
- The pay factor disincentives for inferior in-service performance are greater than the pay factor incentives for superior in-service performance.
- Pay factor rewards range from $3,500/km for a thick overlay pavement 10% above specification to $17,600/km for a thin overlay pavement 30% above specification.
- Pay factor penalties range from $4,300/km for a thick overlay pavement 10% below specification to $31,620/km for a medium overlay pavement 30% below specification.
- The pay factor values presented in this paper are only valid under the assumptions and conditions described in this research.
RECOMMENDATIONS

Based on the information provided in this paper, the following recommendations are suggested:

- There were 100,000 trials run in the Monte Carlo simulation. It was noted through the data analysis procedure that the results obtained from the simulation did not always yield the same results. Therefore, the Monte Carlo simulations should be run using more trials in order to yield similar results from simulation to simulation. Therefore, further analysis is required to determine the number of simulations required for this type of research.

- There were limited treatments considered in the maintenance and rehabilitation schedule for the life cycle cost analyses. Further analysis is required to better estimate the appropriate types of treatments and when they should be applied.

- The analysis period for the life cycle costs was 30 years. Due to the high predicted service lives for the thick overlay thicknesses, resurfacing was not considered in the 30-year period. It is therefore recommended that the analysis period be increased to 40 years.

Acknowledgements

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References


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<th>Range (mm)</th>
<th>Mean (mm)</th>
<th>Standard Deviation (mm)</th>
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* 40 or 50 mm lifts
### TABLE 2 Distribution Functions for Model Input Variables

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Qty=Quantity  
HL=Hot Laid Asphalt  
DFC=Dense Friction Coarse  
HDB=Heavy Duty Binder
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* per km of adjustment
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