Modeling of Life-Cycle Costs of Pavement Rehabilitation

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ABSTRACT

The rehabilitation of pavements can be regarded as a cycle of gradual depreciation and subsequent replacement of the capital invested in the pavement layers of roads. The capital recovery cost is functionally related to the strength of the pavement and the life-cycle length between rehabilitation measures, which is the basis for annual-worth cost analysis of any rehabilitation measure. Whereas the cost of such measures is composed of a fixed term and a term that varies with overlay thickness, the life-cycle length is dependent on the acceptable minimum performance or serviceability level and the strength of the rehabilitated pavement structure. These relationships and a financial equation for annualized costs are the basic modules of the proposed modeling. The problem of salvage value is illustrated but can be avoided by applying the repeatability assumption of financial analysis. This means, with regard to pavements, that the same measure of rehabilitation must be used at the same trigger point of acceptable minimum performance. Based on the author's earlier modeling of the AASHTO Road Test and Brampton Road Test data, and on inventory data collected and modeled in Ontario, a form for the life-cycle length function has been derived and discussed. Ontario 1984 cost data were used to give an example of calculation of annualized costs. If user costs are not included in the analysis, more frequent single overlays would appear to be economical compared with multicourse overlays and less frequent rehabilitations.

The rehabilitation of pavements can be understood as part of the financial management of highway investments. Each section of a road periodically deteriorates and must subsequently be restored to its full level of service. What is being restored is a certain amount of depreciated capital. Depreciations can occur through obsolescence when roads are rerouted or become redundant as a result of, for example, a loss of traffic. Depreciation in the context of pavement rehabilitation, however, is mainly physical (i.e., a decrease in performance or serviceability because of the deterioration of surface layers and/or support structures).

CAPITAL INVESTMENT AND DEPRECIATION

This concept of capital depreciation of pavement investment is shown in Figure 1. It is shown that total cash flows for rehabilitation can be at different levels--sufficiently high (X) to maintain the value of investment, or lower (Y and Z), resulting in a smaller or larger loss of value (A_2 and A_3) during a certain period of time (N). The diagram in Figure 1 is valid with regard to all levels of planning, from local to regional or national road networks.

The actual life-cycle costs (X, Y, or Z) for a planning horizon, N, depend on the pavement performance as a function of time. The use of performance indicator curves in life-cycle cost analysis has been proposed and discussed before (1), most recently in Sheflin (2) and Baladi (3). It is necessary to look at this in more detail with respect to the concepts of financial analysis.

Periodic capital investment and annual depreciation in correspondence to performance curves is shown in Figure 2. In this figure, capital recovery (CR) costs are calculated for two cases, A and B, using compounding factors as defined in De Garmo (4). Complete depreciation of the rehabilitation capital spending at year zero, say, 110,000.00, is reached at performance cost index (PCI) = 40, after 12 years. Early rehabilitation after 10 years (A) results in a salvage value of, say, 25,000.00 and postponed rehabilitation would lead to a negative salvage value (or additional cost) of 35,000.00 (B). The actual figures are not significant as they are used only to illustrate and clarify the concepts of depreciation and salvage value of a rehabilitation expenditure.

The modeling of life-cycle costs, as presented here, deals with one pavement section of known performance characteristics. However, it is generally true for any section that pavements, and other major parts of the transportation infrastructure, after being constructed, go through cycles of gradual deterioration and periodic rehabilitation. Any measure of rehabilitation, such as a bituminous overlay, can be regarded as a capital expenditure to replace a depreciated asset. The "when and how to replace" decision is similar to that of a firm when it must decide on the replacement of machines in its shop, or of trucks in its fleet. A life-cycle cost analysis can help to find the most economical replacement schedule.

PERFORMANCE LEVEL AND LIFE CYCLE

As long as pavement performance is maintained within acceptable limits, there is no need to consider the benefit side of the economic equation because any advantage gained through performance differences is uncertain and probably small. Thus, the economic study may be confined to minimizing the cost. However, it is important to annualize the cost over the true life span or cycle and, in such studies, it is

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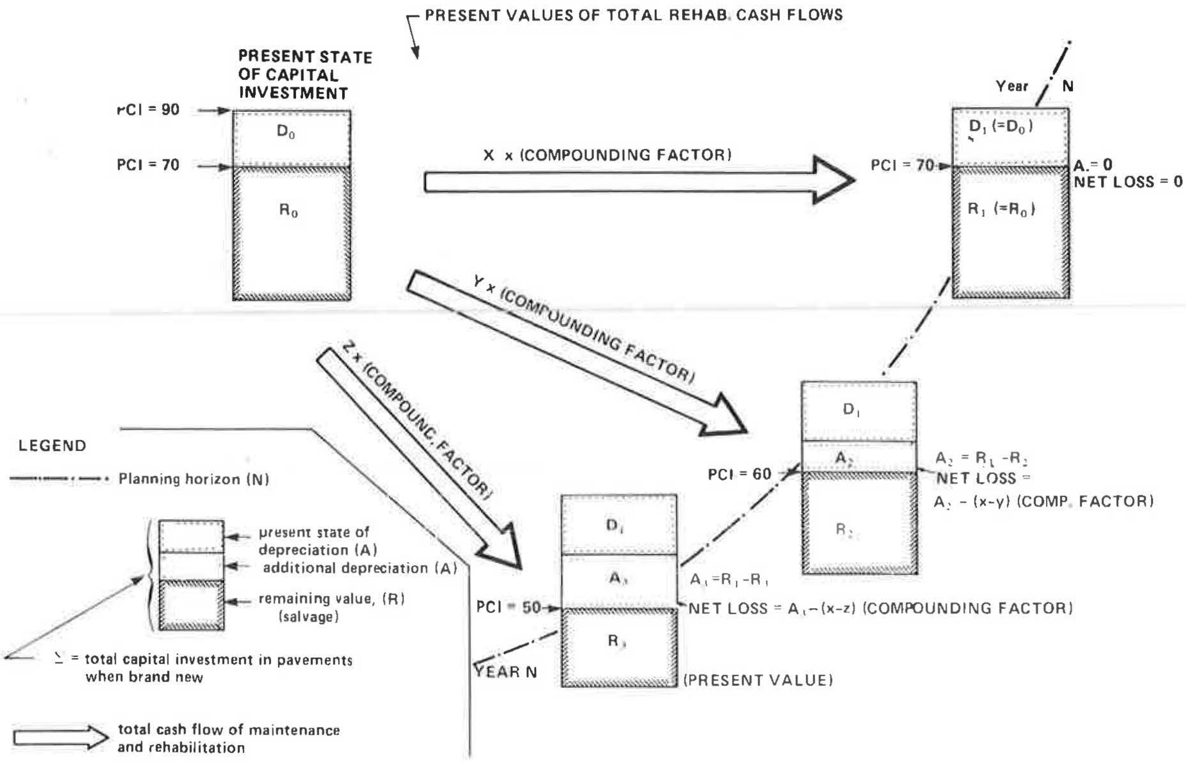

FIGURE 1 Capital depreciation scenarios of pavements.

customary to assume that expenditures and performance cycles are repeated. As in the case of any capital asset, this means that the depreciated part, after its life span, has to be replaced by a new part of equal first value. In this way, present worth or equivalent annual worth costs can be calculated, which depend on the life span and its corresponding or related degree of deterioration in terms of performance (the "PCI-drop").

Because future decisions on the timing and the particular measure of rehabilitation are uncertain, lifecycle costs should be based on the same PCI-drop, and on the same kind of rehabilitation measure after each replacement period. This corresponds to the well-known repeatability assumption in financial analysis.

The relationship between first cost, C, and the ensuing performance cycle is shown in Figure 3,

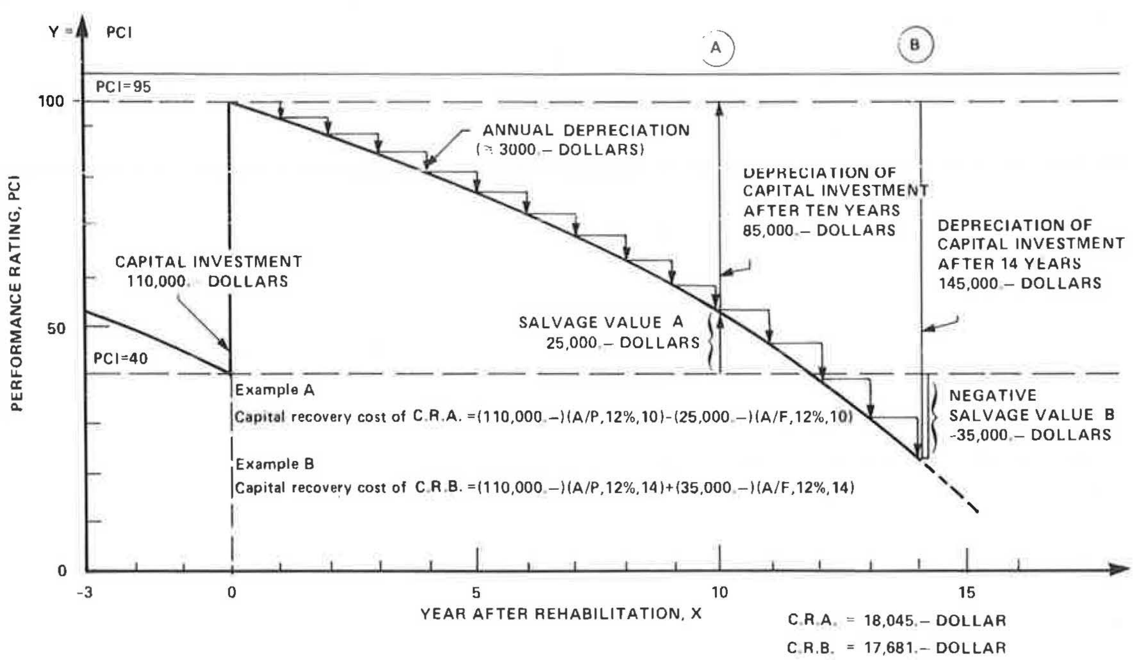

FIGURE 2 Complex example of investment depreciation and capital recovery costs.

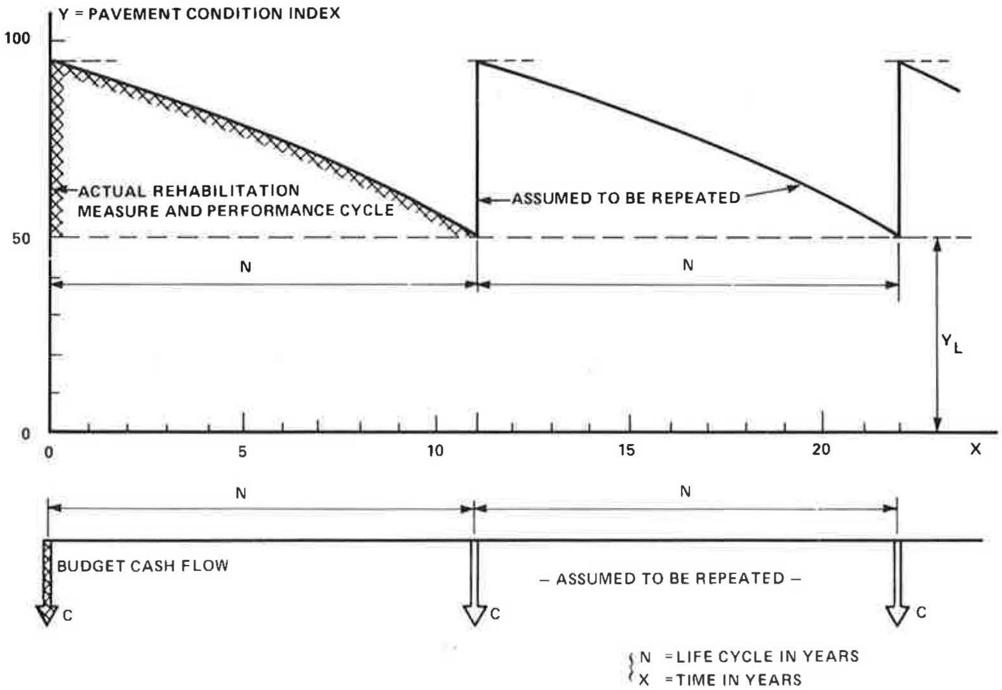

FIGURE 3 Repeatability assumption for matching cash flow and performance cycle.

which also shows how the cycle is assumed to repeat. Only the first shaded terms are used in the analysis. Note that the life cycle, N, in conjunction with the performance trigger point, Y_L, is the most important technical parameter of this cost study, rather than the exact shape of the performance curve. If an analytical expression of the performance curve is given, then the value N can be calculated (5).

Thus, in assuming consistent periodical performance drops and jumps, there is a first-level optimization that is related to the choice of PCI-jump or magnitude of allowable deterioration and its related rehabilitation cost, C. Note that this choice of deterioration jump and rehabilitation measure entails a choice of life-span or life-cycle length, N. Also note that salvage values, as shown in Figure 2, do not play a part in this approach to modeling.

The methods of pavement rehabilitation range from relatively inexpensive treatments, such as hot-mix patching or single-course overlays, to heavy expensive treatments, such as multicourse overlays with crack sealing and padding. In general (i.e., all other circumstances being equal), the heavier treatments last longer. This entails a second level of optimization that is related to the choice of stronger and weaker designs as shown in Figure 4. This choice again influences the life-cycle length.

PAVEMENT STRENGTH AND REHABILITATION COST

One of the most important technical facts to be considered is that the life-span, N, is a function of the added pavement strength after rehabilitation. Depending on the strength of the overlay, the life-span or life-cycle length, N, can be shorter or longer than the length of the previous cycle, as is shown in Figure 4. Again, the actual shape of the performance curve is not important, except that it determines the trigger point, Y_L, and the cycle length, N. Further, even with this in mind, the repeatability assumption is applied to the future, assuming the same treatment is repeated with the same ensuing life span as the current one, so that the concepts shown in Figure 3 remain valid.

In studying data on various rehabilitation costs, C, it is certain that such costs are also a function of pavement strength. At this point, it is advantageous to remember the concept of equivalent thickness (5). Depending on the material, various courses of overlay have thicknesses that could be converted into an equivalent surface course thickness, t, by an equivalency factor, e. This idea requires further study.

Cost data from 1984 have been processed in this way and are shown in Figure 5. In this diagram, the solid lines represent the cost as a function of bituminous layer thickness. The dashed line is an attempt to establish such a function based on equivalent surface layer thickness. In this case, the granular bases can be included with an assumed equivalency factor of e = 1/3.

The general form of a cost-thickness relationship is probably the usual combination of fixed and variable cost, as shown in Figure 5 (broken line). Alternatively, the function could be processed as a table of benchmark costs for different measures related to discrete overlay thicknesses and other features. In general, it should be relatively easy and straightforward to determine the functional relationship between costs and overlay thicknesses for bituminous layers, although such cost functions are subject to change with time and regional conditions. However, it is more difficult to estimate the life-cycle length, N, as a function of thickness, t, even if the PCI-jump is fixed.

The Ontario Pavement Analysis of Cost (OPAC) performance prediction model, developed from 1974-1976 (6), can be used to calculate the life-cycle length, N, as a function of overlay thickness, t, and the minimum acceptable level of performance, Y_L. Although this prediction model is limited, one must recognize that such a model is needed to determine the relationship between the strength, t, of an overlay and the ensuing life span, N, for a chosen lower limit of performance, Y_L. Figure 6 shows the

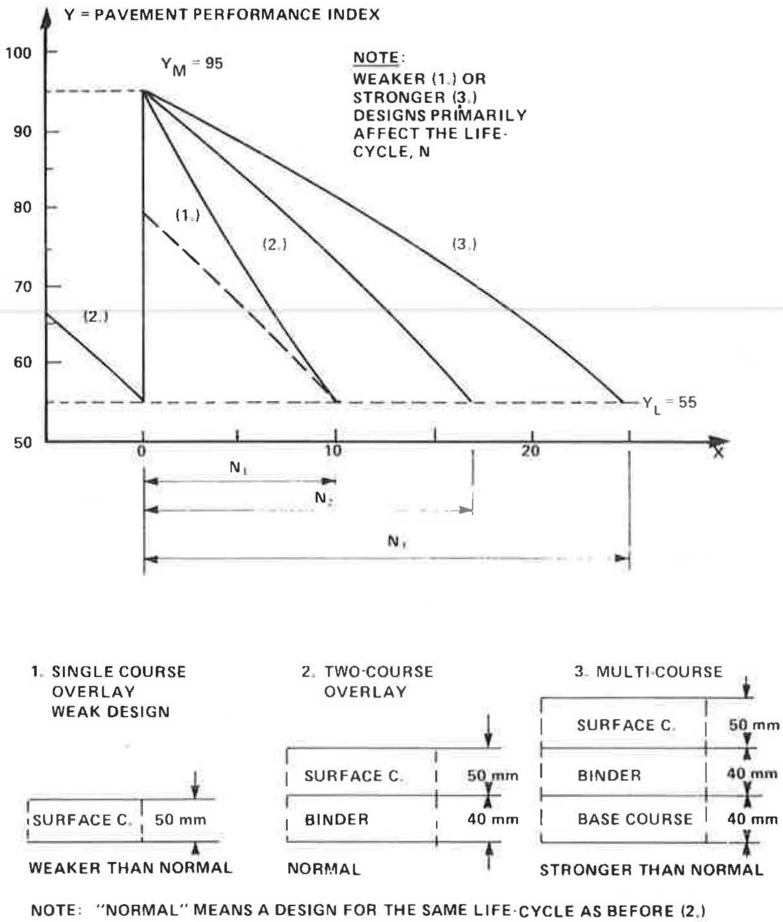

FIGURE 4 Alternative rehabilitation treatments and their effect on performance.

result of a calculation for two different designs of a secondary road, with a silt (1) and a soft clay (2) as subgrade. The lower limit of performance has been chosen alternatively as $Y_L = 45$ and as $Y_L = 55$. As expected, the life cycles are longer for $Y_L = 45$, the lower of the two limits. In the relevant range between 40- and 150-mm overlay thickness, the curves can be expressed approximately by a function of the form

$$N = A\ t^b$$

in which A and b are constants dependent on the chosen Y_L value and other conditions.

ECONOMIC MODEL

The relationships described so far, and shown in Figures 3 to 6, can be expressed as a simple economic model by the following set of equations, which are all to be understood as simple prototypes of various parts or modules of the model:

$$C = C_c + C_v t \quad (1)$$

$$N = A\ t^b;\ < 25 \text{ years} \quad (2)$$

$$Q = C \cdot i \cdot (1 + i)^N / [(1 + i)^N - 1] + M \quad (3)$$

where

C_c = constant rehabilitation cost, per km (2 lanes);
C_v = variable rehabilitation cost, per km, per mm;
t = equivalent surface layer thickness of rehabilitation overlays in mm;
C = rehabilitation cost, first cost, per km (2 lanes);
M = annual maintenance cost, per km (2 lanes);
N = life-cycle period, in years;
i = combined interest rate, in percent/100 (real interest rate and rate of inflation);
Q = annualized life-cycle cost or annual worth cost, per km, per 2 lanes; and
A,b = constants for function $N = A\ t^b$.

By neglecting the annual maintenance cost, M, and assuming an interest rate of zero, the annualized life-cycle cost is simply Q = C/N. For the variable part of C only, the following simple relationship can be derived:

$$Q_v = C_v \cdot t^{(1-b)}/A \quad (4)$$

[Note that the fixed or constant cost, C_c, is only constant with respect to the thickness, t, as an independent variable. In reality, C_c and, to a lesser extent, C_v, are functions of other conditions such as contract size (number of kilometers), and remoteness of location.]

For this case, according to Equation 4, the an-

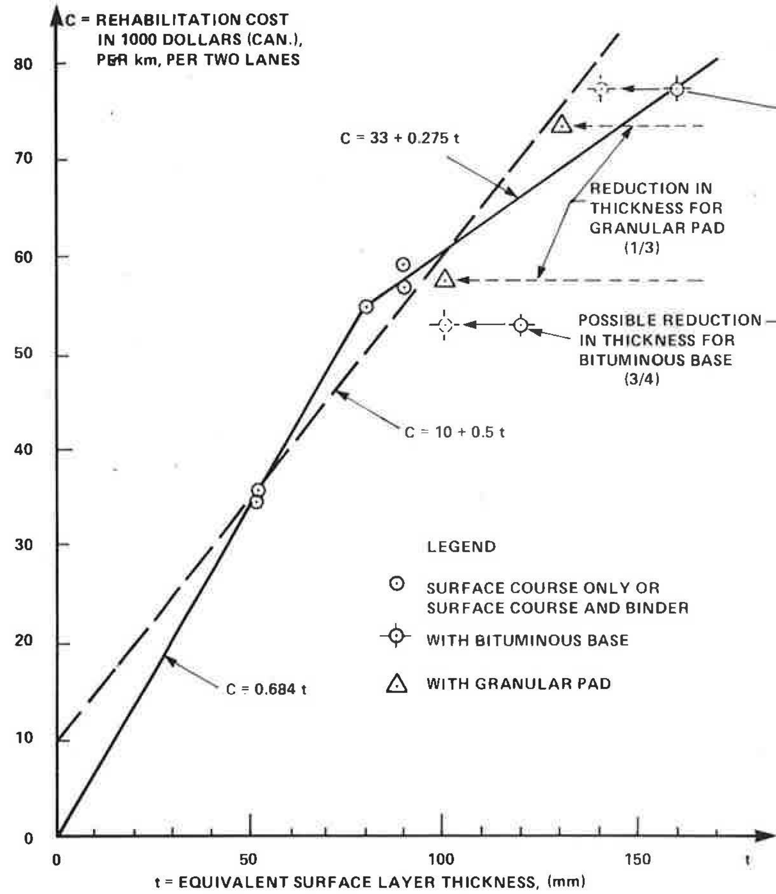

FIGURE 5 Cost function (from 1984 cost data).

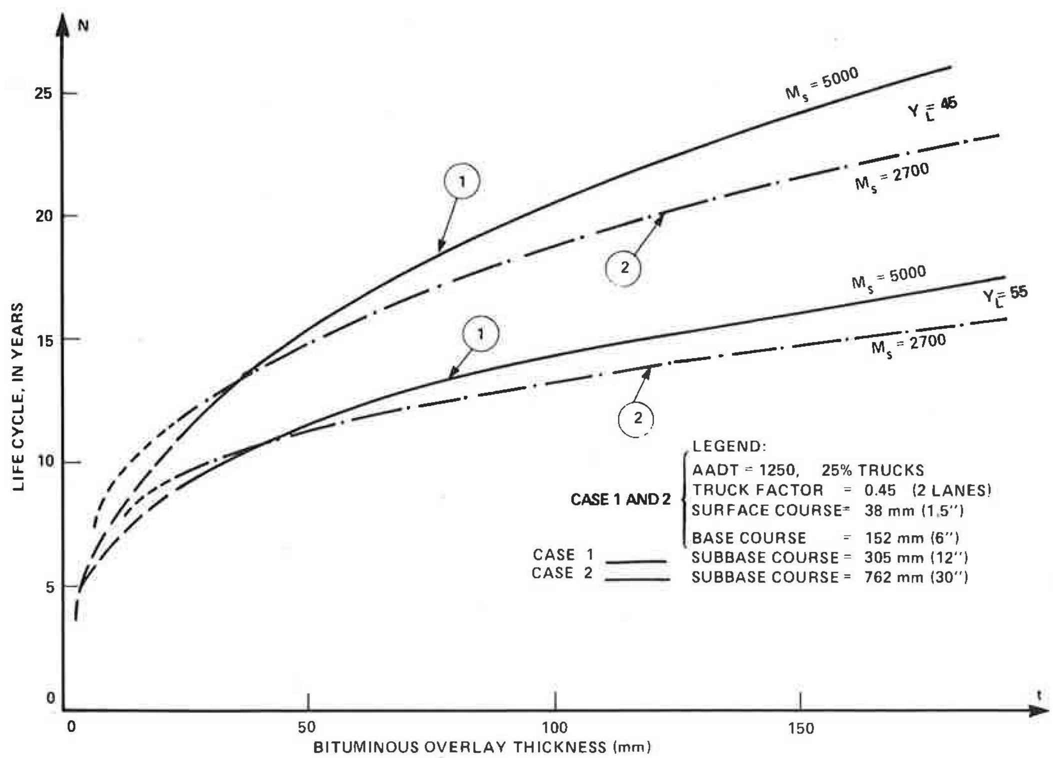

FIGURE 6 Life-cycle length versus overlay strength (thickness).

nual life-cycle cost increases with t, for $b < 1$; and it decreases with t, for $b > 1$; whereas it is indifferent for $b = 1$. When an interest rate is introduced, using Equation 3, the life-cycle cost increases even more with thickness, t, as higher interest rates favor solutions of lower first cost, C. The conclusion is that expensive multicourse overlays are economical only if the parameter b is distinctly larger than one.

The calculations based on the OPAC model are summarized and plotted in Figure 6. The curves show that b is most probably smaller than one, at least for all the curves shown in the figure. This would mean that inexpensive, single-course overlays combined with shorter ensuing life cycles are more economical, but only if user costs are small enough to be neglected.

Equation 1 represents the relationship between the first costs of rehabilitation measures and the strength or thickness of overlays. Equation 2 is a prototype for the relationship between the strength or thickness of overlays and the life-cycle length, which is significant as it is also a function of the chosen lower limit of performance (Y_L). Equation 3 is the known formula of financial analysis.

With reference to Figure 6 and Equation 2, the optimization on the two project levels can be understood as follows. For Level 1, depending on the choice of the lowest allowable limit of performance level (Y_L or PCI_L), there are shorter or longer life cycles, N, which influence the compounding factor (Equation 3) and the present or annual worth cost. For Level 2, depending on the shape of the curves in Figure 6 (being concave when looking from below), the exponent, b, is smaller than one. Therefore, the annual worth cost increases with increasing thickness, t, at least for the cases presented here and calculated by the OPAC method. This leads to an optimization along the constraint boundary of minimum overlay thickness. An example follows.

With reference to the examples presented in Figure 6, costs are calculated for a subgrade modulus of $M_s = 2700$, the 762-mm subbase on clay subgrade. Optimization is achieved by minimizing the annual worth costs, Q, based on Equations 1 to 3. The constraints can be visualized as the minimum acceptable level of performance and as the smallest possible thickness of overlay as follows:

1. min $Y_L = 45$ (upper curves in Figure 6)
2. min t = 40 mm (1.5 in.)

The combined interest rate is assumed to be 11 percent. The following equations apply:

$C = (10 + 0.50\ t) \times 1{,}000$ (refer to Figure 5)

$$\left.\begin{array}{l} N = 3.65\ t^{0.357};\ \text{for } Y_L = 45 = \min Y_L \\ N = 3.94\ t^{0.265};\ \text{for } Y_L = 55 = \min Y_L \end{array}\right\} \text{(Curve-fitted from Equation 6.)}$$

$Q = C \times 0.11 \times 1.11^N/(1.11^N - 1)$; for M = 0

Annual worth costs, Q, have been calculated for various overlay thicknesses, t, and the results are presented in the following table.

	$Y_L = 45 = \min Y_L$		$Y_L = 55 > \min Y_L$	
t (mm)	Q ($ Canada)	N (Years)	Q ($ Canada)	N (Years)
40	4,350.00	13.6	4,964.00	10.5
50	4,901.00	14.8	5,609.00	11.1
75	6,286.00	17.0	7,207.00	12.4
100	7,668.00	18.9	8,780.00	13.4

For this secondary road of lower traffic volume, a rehabilitation strategy of low, minimum-performance limit ($Y_L = 45$) seems to be economical, gaining in life-cycle length without too much additional deterioration. However, there is no gain in economy by going beyond a minimum layer thickness (40 or 50 mm) when applying an overlay at the chosen trigger point of $Y_L = 45$. The economy of a stronger overlay may improve when user costs are taken into account because the optimum solution of t = 40 mm entails more frequent construction work (lane closures) and rougher driving conditions (2).

COMPARISON WITH PERFORMANCE PREDICTION IN PARS

It has been demonstrated that the life-cycle, N, can be expressed as a function of overlay thickness (or strength) by Equation 2, as follows:

$N = A\ t^b$

where A and b are dependent on the performance trigger point, Y_L, and where b is less than 1. This was based on a model derived from the AASHTO Road Test and Brampton Road Test data (6). Later, in the development of the PARS model (7), pavement performance was modeled differently, using inventory data collected in Ontario during or before 1978. The same form of function as expressed by Equation 2 can be derived from the PARS modeling. In accordance with an unpublished report, the PARS performance modeling has the following formula:

$$Y = 95 - K\ X^a\ t^{-b'}\ T^c \qquad (5)$$

where

- Y = performance condition rating (PCR or PCI),
- K = coefficient,
- X = time in years after rehabilitation,
- t = thickness of overlay in mm,
- 95 = maximum Y,
- T = traffic in terms of annual average daily traffic (AADT), and
- a,b',c = constants.

The coefficients and constants depend on the class or group of roads that are identified as exhibiting similar performance.

For a certain chosen trigger point, $Y = Y_L$, as the lowest acceptable performance index, the life-cycle, X = N, can be calculated by the following equation, derived from Equation 5.

$$N = [(95 - Y_L)/K\ T^c]^{(1/a)} \times t^{(b'/a)} \qquad (6)$$

Equation 6 has the same form as Equation 2. Note that with regard to the coefficients

$$A = [(95 - Y_L)/K\ T^c]^{(1/a)} \qquad (7)$$

$$b = b'/a \qquad (8)$$

For example, the following coefficients were derived for the Southwest and Central regions of Ontario by regression analysis of 1978 data for average performance as follows:

K = 4.8306 a = 1.0894

C = 0.2202 b' = 0.6358

If an AADT of T = 2,000 is assumed, the following

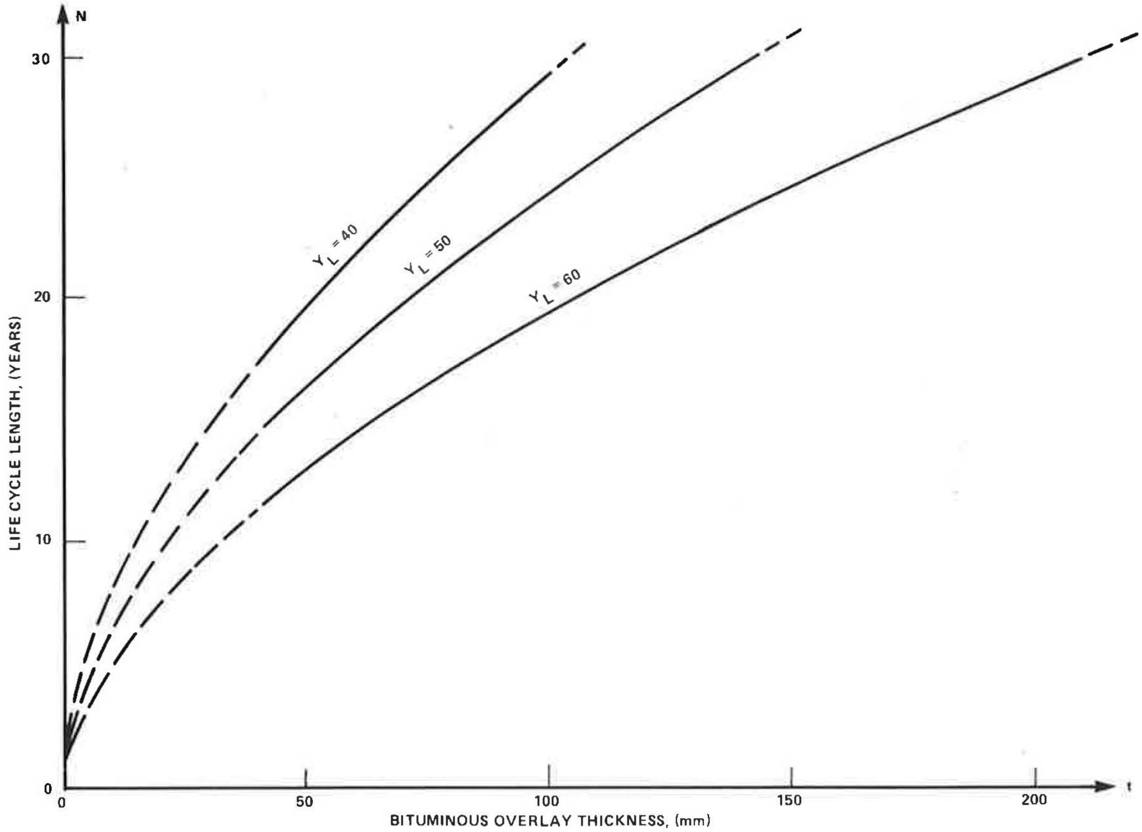

FIGURE 7 Life-cycle versus overlay strength (thickness), PARS.

values can be calculated for trigger points of Y_L = 40, 50, and 60:

a) $b = b'/a = 0.6358/1.0894 = 0.5836$

b) $A_{40}\ [55/(4.8306 \times 2000^{.2202})]^{0.91793} = 2.006$

$A_{50}\ [45/(4.8306 \times 2000^{.2202})]^{0.91793} = 1.669$

$A_{60}\ [35/(4.8306 \times 2000^{.2202})]^{0.91793} = 1.325$

Equation 2 may now be plotted for the preceding coefficients to illustrate the trend of the life-cycle function with regard to the variable t and Y_L (refer to Figure 7). Life-cycle lengths according to this PARS model are longer, especially for multiple overlays.

The life-span function $N = A\ t^b$, with $b < 1$, and A and b depending on the performance trigger point Y_L, traffic, and so forth, seems to be well established in its basic form or trend. Because of the limitations of the underlying data (OPAC, PARS), it is only valid for overlays between approximately 40 and 150 mm. Below and above these limits, the life spans could be much shorter but not much longer than calculated. The OPAC model, with generally lower values of N and with smaller exponents, b, seems to be closer to reality, although this is still subject to further analysis of data. There are two kinds of analysis that should be further explored:

1. Inventory data on performance should be processed by grouping road sections into more homogeneous classes with identifiable strength and traffic characteristics, so that N and b can be determined with more certainty (less variance).

2. Experimental data may improve structural performance prediction modeling beyond the present limitation of OPAC (6).

CONCLUSIONS

An economic model for the life-cycle or annual-worth cost analysis of pavement rehabilitation of a particular road section (project level) as outlined previously is based on several equations or functions as follows:

1. First cost as a function of overlay strength or thickness (Equation 1).
2. Life-cycle length as a function of pavement performance standard and overlay strength or thickness (Equation 2).
3. Annual-worth cost (Equation 3).

Optimization based on this model has been illustrated by minimizing life-cycle costs, with constraints on pavement performance level and overlay thickness, by specifying minimum values.

Whereas a lowering of the performance trigger point and the ensuing increase in life-cycle length appears to be economical, it seems to be uneconomical to increase the overlay thickness beyond a minimum required design value. This is only true if user costs are negligible.

The model of annual-worth cost analysis outlined in this paper depends on valid information on costs for various rehabilitation measures, preferably expressed as a function of overlay thickness. More difficult to obtain is valid information on the life-span or life-cycle length as a function of overlay strength or thickness, for selected, lowest-acceptable PCI-trigger points of rehabilitation. This requires a comprehensive performance prediction model similar to the one presented by the author in 1975 (6). A computer program of this OPAC prediction model was used to illustrate the function $N = A \times t^b$. The examples chosen were pavements of low strength, for which the model predicts better than for stronger pavements.

Finally, the performance modeling of PARS (8) was used to determine the coefficients A and b in Equation 2 (based on 1978 data), for average performance in the regions of Ontario.

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