Cost Relationships for Concrete Bridge Protection, Repair, and Rehabilitation

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Cost information on chemical and physical techniques for concrete bridge protection and rehabilitation is provided. This information constitutes an essential component in determining life-cycle costs for ranking alternative protection and rehabilitation techniques. Most of the cost data were obtained from bid tabulations provided by state highway agencies (SHAs). Fourteen SHAs and two toll road agencies were visited, and 12 of these provided bid tabulation data. The costs obtained from bid tabulations were converted to mid-1991 national average values by using published cost indexes. The national average cost data for each protection and rehabilitation treatment were then subjected to detailed statistical analysis to develop cost models reflecting the effects of four independent variables: work quantity, number of bids, total contract cost, and cost of maintenance and protection of traffic. Eight combinations of these four variables were developed to be the independent variables in the regression analysis. An inverse power model was used. The ultimate choice of factors in each case rested with the regression coefficient (R^2).

The ultimate goal of the Strategic Highway Research Program (SHRP) C100 series of projects is to develop the technology to minimize the life-cycle costs of reinforced concrete bridge components. This implies the development and use of economic models that will be used to evaluate life-cycle costs.

The mechanics of economic models for the evaluation of alternatives based on life-cycle costs are relatively simple and widely understood and accepted. The difficulty is in the identification of suitable alternatives and the input variables for these alternatives. The input variables consist of the costs and service lives of the definable constituents for each alternative.

The purpose of this work is to provide cost information on a number of techniques used to repair or protect bridge components. The data can be used in combination with the respective service lives for determination of life-cycle costs.

The seven systems for which cost information were developed are

- deck patching,
- deck protection systems,
- experimental deck protection systems,
- structural patching,
- structural protection systems,
- "new" deck protection systems, and
- "new" structural patching.

Patching was considered for both decks and structural elements by using portland cement concrete (PCC), quick-set hydraulic cements, and polymer concrete. Protection systems were considered to be applied to the entire deck or structural component. Latex-modified concrete (LMC) overlays, membranes plus asphalt cement concrete overlays, low-slump dense concrete overlays, and sealers were considered for deck systems. Thin polymer overlays, microsilica concrete overlays, and polyester overlays were considered experimental because of limited experience. Structural protection systems included encasement with PCC, sealers, shotcrete, and coatings. New deck protection systems included deep polymer impregnation and posttreatment corrosion inhibitor treatments. New structural patching included corrosion inhibitor treatment systems.

To promote valid comparisons among bridge component patching and protection systems by life-cycle cost analysis it was necessary that the costs be consistent and composed of the appropriate cost components. These included engineering costs, installation costs, user costs, effects on the regional economy, and environmental impact. Not all cost components are applicable in all situations. For a given treatment the applicable cost components will depend on whether the work is accomplished by contract or maintenance force account. It was also evident that some of the cost components would vary widely as functions of additional factors. Examples include maintenance and protection of traffic (MPT), which is primarily dictated by traffic volume, and contractor-related costs, which are heavily influenced by work volume at the site and regional business climate.

Because of the national or broad regional scope of these cost evaluations, cost components that were highly site specific generally were not included in determining costs. Judgment was required to determine if a highly site-specific cost component was a key factor in the cost of a particular alternative. An example might be the ability of one technique to significantly reduce the costs associated with MPT. Since traffic maintenance is a highly site-specific cost component these costs cannot be ignored.

Because of the variations in cost with time due to inflation or deflation it was necessary to include the applicable dates (years) associated with the cost data. This permitted reducing the data to a common base year by using published price indexes. Also, cost data for each applicable cost component should be collected from as wide a population (geographically and chronologically) as possible to establish the variability and dependability for sensitivity analyses.

Two basic approaches can be used to acquire the required cost information. The first involves the use of classical engineering estimating techniques. It is the most rational approach, and it provides an established and a rigorous regimen. The second approach is the empirical procedure involving the systematic examination and evaluation of archival cost data. The major problem associated with the latter approach is that there is usually insufficient documentation of details regarding components of the cost figures. Thus, wide variations often occur between different jurisdictions because the components of the generated cost figures are not totally comparable.

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Likewise, it is generally not possible to find empirical data that exactly match the sought after cost figure in terms of the desired cost components. However, the empirical approach does have the advantage of inherently incorporating subtle influences on cost figures that generally cannot be accounted for by using straight estimating procedures (e.g., business climate, quantity effects, and productivity). The approach originally proposed was a hybrid of the rational and empirical techniques, attempting to take the maximum advantage of the attributes of each methodology. Unfortunately, this becomes costly, and it was for this reason that the empirical approach was used in the present study.

DATA ACQUISITION

Research Plan

The primary source of these archival cost data was contract bid tabulations from state highway agencies (SHAs). The cost associated with a specific treatment system is reported as a unit cost in a contract document. Unfortunately, for the present research the contractor is only required to reveal the unit cost and not the components of this cost. For example, for an LMC overlay the cost associated with calibrating mixers, engineering any necessary formwork, inspection and testing, and salvage values are not detailed in the bid price. Without this itemized description it is difficult to project historical costs to determine future costs because of the variability associated with these unreported components. Other problems arise when insufficient historical data on which to base a cost estimate are available. Regional variations in costs due to economic conditions and the frequency of applications can also be significant both within a particular SHA and among them. To use historical data as a basis for future costs it is necessary to establish an extensive data base of costs from carefully selected states across the country.

The strategy used to determine which states to visit was based on geographic location, which SHAs used the systems under consideration, and the ability and willingness of the SHA to provide the needed historical data. A total of 15 SHAs were visited.

Several guidelines were developed to aid in the determination of the costs. Road user costs, economic effects, and environmental impact were ignored since these costs are approximately equal for all alternative methods for each system. It was necessary to determine whether the system was more likely to be performed by contract or by departmental forces because the components of cost differ between the two. For contract work the components include preliminary engineering costs, maintenance and protection of traffic costs, inspection, testing and construction engineering costs, and salvage values. For systems applied by maintenance forces the cost components include materials, equipment, labor and supervision, preliminary engineering, inspection, testing, construction engineering, and salvage values.

Contract Work

The information available from the highway agencies for contract work was in the form of bid tabulations, standard specifications, and special provisions.

A total of 829 bid tabulations were obtained from the SHAs. The contracts obtained from the SHAs were for rehabilitation projects involving the treatments and systems previously discussed. Each SHA provided access to historical data. Although all contracts were generally available in an archival form (microfilm or computer tapes), only data for a limited number of years were in readily accessible form (paper copies). The years for which data were available was limited by the available storage space at the SHA and ranged from 1981 to 1991.

Of critical importance to the project was the ability to use the cost information obtained from each SHA to determine a national average cost for the specified repairs. To develop these national trends it is necessary to compare and analyze similar treatments. To ensure that similar materials, methods, and procedures were being compared, standard specifications and contract special provisions were obtained for all of the applicable treatments used by all SHAs. These documents played an important role in allowing comparisons for a given treatment among the different SHAs when the pay quantity or work description for that treatment differed.

Maintenance Force Work

Along with contract work consideration was also being given to analyzing the costs associated with repairs performed by state highway maintenance forces. When the SHAs were visited interviews were conducted with the administrative maintenance engineers and, when time permitted, with district maintenance engineers.

Only eight states that were visited have operational maintenance management systems which can provide detailed data on maintenance force repair costs. These systems provide the maintenance engineer with a good basis for tracking costs and predicting future needs. However, the information generated by these systems is inadequate for use in analyzing costs. The cost centers used are not specific enough or do not contain enough information to provide the required insight into the types of work performed. Thus, it was not possible to obtain accurate costs of maintenance force repairs. Further work on this task was terminated.

Engineering Costs

When developing life-cycle cost models for use in comparing various alternatives for bridge rehabilitation, it is desirable to include the cost of any engineering involved in the alternatives. The methods under consideration are generally accepted as being standard repair techniques. A great deal of effort is being spent on developing these standard repairs, and much time is being spent analyzing methods and materials, but once the standard has been developed, little engineering is required. This is especially true of deck repairs.

This assumption of little engineering cost associated with repairs may not be true for super- or substructure repairs. These types of repairs are usually not as generic as deck repairs and often require additional engineering to design formwork and provide necessary details. A considerable amount of engineering effort is also expended on developing MPT plans.

Because insufficient specific data were available and the costs will generally affect all treatments in about the same fashion, no further consideration was given to engineering costs. The exception to this is the more experimental and new treatment techniques, for which the costs were estimated because of a lack of empirical data.

Salvage Values

The salvage value remaining when the end of the service life is reached is an important factor in life-cycle cost modeling. Salvage value can affect the decision of which method to use. The salvage value is most often thought to be a positive value, such as trade-in allowance or resale; however, in the construction industry the salvage value can be an expense. It may be necessary to dispose of construction materials off-site, in a landfill, and the cost can be high, especially if hazardous materials are salvaged.

After interviewing design engineers, estimators, and construction personnel it was evident that little consideration is given to salvage costs in either contract or maintenance force work. Only in rare cases is salvage material ever considered on bridge rehabilitation work. When salvaging does occur it is usually for readily reusable items, such as guide rail, steel and prestressed beams, and highway lighting fixtures. It is expected that for contractors to remain competitive they will seek the lowest cost for disposal or the highest price for resale. This is then passed on to the SHA in the bid price. For this reason salvage value was not considered.

DATA ANALYSIS

Cost Data Adjustment Factors

On completion of the data acquisition phase, 829 contracts from 13 SHAs from 1981 to 1991 were used for data analysis. To pool information from different geographic regions and different years it was necessary to develop both geographic and inflation factors to adjust the data.

Cost and price indexes are composite costs or prices for given quantities of specified goods or services (*1–8*). They are usually compiled as a function of time and location and are thus indicators of inflation or deflation in a specific area. After a review of available cost indexes related to the present research, the following four were selected for more detailed consideration:

- FHWA Federal-Aid Highway Construction Price Index (*7*),
- FHWA Highway Maintenance and Operating Cost Index (*7*),
- *Engineering News Record* Construction Cost Index (*6*), and
- R.S. Means City Construction Cost Index (*8*).

These four indexes were analyzed for the period covering the past three decades, with 1977 chosen as the base year. Although there were various differences among the indexes, there were also some obvious differences. These are evident in Figure 1, in which the analysis is presented graphically for the period since 1970.

The reason for the divergent behavior of the FHWA Maintenance and Operating Cost Index is not clearly evident. However, it includes traffic service items such as snow and ice control, which not only may account for the behavioral differences but also raises the question of its relevance to the application at hand. Thus, the FHWA Maintenance and Operating Cost Index was judged to be too highly influenced by activities outside the scope of bridge protection, repair, and rehabilitation to warrant further consideration.

The inclination at this point leans heavily toward the FHWA Construction Price Index. This is reinforced by the availability of a geographical breakdown of cost indexes by state, which are published annually by *Engineering News Record* (*6*) in the 2nd

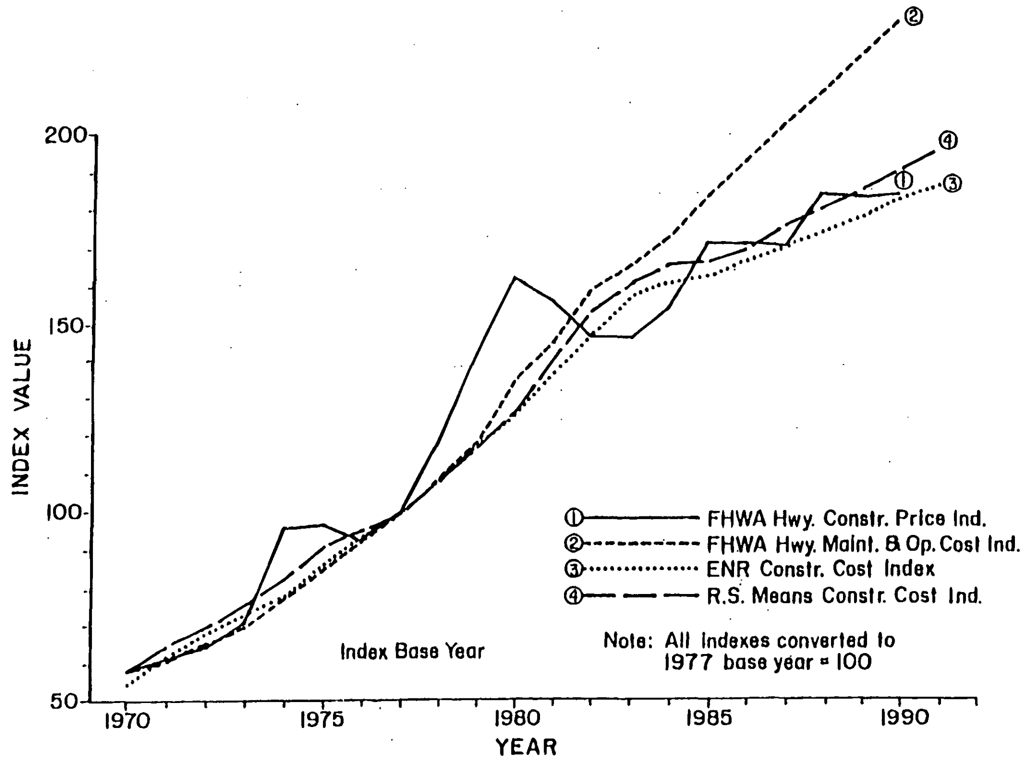

FIGURE 1 Cost indexes as function of time.

"Quarterly Cost Roundup" issues. These are generally published in the fourth weekly issues of the months of March, June, September, and December. However, for many of the states there are large, irrational variations in the index values from year to year that suggest random changes in the index bases or reporting procedures. Since the FHWA Federal-Aid Highway Construction Cost Index has a significant deficiency in this matter, it is prudent to consider using a different index.

It is clear that the R.S. Means City Construction Cost Index is more suitable. First, it is much more comprehensive and detailed than the *Engineering News Record* index. This permits the selection of a more specific subarea index to more nearly match the nature of the construction activities covered by this research. Only one combined index is available with the *Engineering News Record* index. Notice that in this regard the R.S. Means City Construction Cost Index also has the same advantage over the FHWA Federal-Aid Construction Cost Index. Second, it is based on a larger geographical data base than the *Engineering News Record* Construction Cost Index.

Accordingly, the R.S. Means City Construction Cost Index was used to prepare procedures and factors for adjusting archival cost data from SHAs for geographical and time effects. An important extra benefit results from this decision. The R.S. Means City Construction Cost Index is an integral part of the Means cost-estimating system. This naturally leads to procedures that will be used to provide engineering estimates for those activities for which insufficient cost data exist and for experimental and new procedures that have little or no prior history.

Procedures

The R.S. Means City Construction Cost Index was used as the basis for developing a system to convert archival cost data from local jurisdictions into mid-1991 national average values. The purpose is to produce cost figures with defined base to permit valid economic analysis comparisons of alternatives for the protection, repair, and rehabilitation of concrete bridge components. The collateral capability of the developed system to provide estimates of cost for a specific activity at a given geographical location and time by using archival data from a different time and place for the same activity will also be demonstrated.

Functional Relationships

The functional relationships on which the developed system is based are presented in algebraic form below. The general relationship for determining national average cost values is

$$N_n = C_{a,m} \times L_a \times (T_m/T_n) \quad (1)$$

where

N = national average cost,
C = cost in a particular city (or state),
L = geographical conversion factor for particular city (or state),
T = time conversion factor to convert to mid-1991 value,
a, b = particular cities (or states), and
m, n = particular years.

For the usual case that represents the primary purpose of this effort (converting local archival costs to 1991 national average costs) note that T_n is equal to 1.000 and Equation 1 becomes

$$N = C_{a,m} \times L_a \times T_m \quad (2)$$

where N is the 1991 national average cost.

If the national average cost for 1991 is known or has been calculated from Equation 2 the present (1991) cost in a particular city (or state), C_a, can be calculated from Equation 3 because T_m is equal to 1.000.

$$C_a = N/L_a \quad (3)$$

The general equation for estimating the cost in a particular city (or state) in a given year, $C_{a,m}$, from cost data for another city (or state) in a different year, $C_{b,n}$, is

$$C_{a,m} = C_{b,n} \times (L_b/L_a) \times (T_n/T_m) \quad (4)$$

If the national average cost in 1991, N, is known, the cost in a particular city (or state) in a given year, $C_{a,m}$, can be estimated from

$$C_{a,m} = N/L_a \times T_m \quad (5)$$

Location and Time Factors

The location and time factors are derived from the R.S. Means City and Historical Cost Indexes, respectively, as presented in the 1992 Means Concrete Cost Data (*8*). The location (L) factors were calculated from the Means Index Values by the following relationship:

$$L = 100/I_c \quad (6)$$

where I_c is the Means City Index Value. State L values were computed as the arithmetic means of the calculated city L values for each state. Only Division 3 (concrete construction) index values were used. The calculated L values covering the materials, installation, and total aspects of concrete construction can be determined for each city and state.

The time (T) factors were calculated by using the Historical Cost Index from the 1992 Means Concrete Cost Data (*8*) and the following relationship:

$$T = 221.6/I_T \quad (7)$$

where I_T is the Means Historical Cost Index Value for year T. The resulting time factors can be calculated.

Data Set Development

To better analyze the data to be collected a literature search and interviews with SHA maintenance engineers were performed to develop a more detailed list of work items. The original, very general list of seven repair and protection systems, was expanded to 44 specific work items. These treatment items are listed in Table 1.

Each of the 829 contract bid tabulations obtained from the SHAs was analyzed to obtain information regarding any of the subject treatment items used. Bid tabulations list all work items in the con-

TABLE 1 Specific Treatment Items To Be Costed for Identified Treatment Areas

- 100 Deck Patching
  - 110 Portland Cement Concrete Patches
    - 111 Partial Depth Repairs (square yard)
    - 112 Full Depth Repairs (square yard)
  - 120 Quick-Set Hydraulic Mortar/Concrete Patches
    - 121 Partial Depth Repairs (square yard)
    - 122 Full Depth Repairs (square yard)
  - 130 Polymer Mortar/Concrete Repairs
    - 131 Partial Depth Repairs (square yard)
    - 132 Full Depth Repairs (square yard)

- 200 Deck Protection Systems
  - 210 Latex Modified Concrete Overlay (square yard)
  - 220 Membrane and Asphalt Cement Concrete Overlay (square yard)
  - 230 Low Slump Densified Concrete Overlay (square yard)
  - 240 Sealers
    - 241 Boiled linseed oil (square yard)
    - 242 Silane, Siloxane (square yard)
    - 243 High Molecular Weight Methacrylate Deck Sealer (square yard)
  - 250 Scarification of Concrete Deck Surface
    - 251 Milling or Unspecified Method (square yard)
    - 252 Hydrodemolition (square yard)
  - 260 Removal of Asphalt from Deck Surface (square yard)

- 300 Experimental Deck Protection Systems
  - 310 Thin Polymer Overlay (square yard)
  - 320 Micro-Silica Concrete Overlay (square yard)
  - 330 Polyester Overlay (square yard)

- 400 Structural Patching
  - 410 Portland Cement Concrete Patches
    - 411 Shallow Repairs (square yard)
    - 412 Deep Repairs (square yard)
  - 420 Quick-Set Hydraulic Mortar/Concrete Patches
    - 421 Shallow Repairs (square yard)
    - 422 Deep Repairs (square yard)
  - 430 Polymer Mortar/Concrete Repairs
    - 431 Shallow Repairs (square yard)
    - 432 Deep Repairs (square yard)

tract for each bidder on the project. The number of bidders on any given project ranged from 1 to as many as 15. For each treatment item used in the contract the quantity and each contractor's bid price were recorded. This resulted in a series of data observations for each item. The total number of data observations for all techniques is 10,820. Each observation represents one bid price on a treatment item from one contract by one bidder.

The data obtained from each state were sorted by item numbers and were merged with those for the other states, resulting in individual data bases for each item. Since the items were normalized by modifying the pay units to be consistent and adjusting the unit costs for inflation and location, it was possible to merge all like treatment items. These are the data that were analyzed to produce the cost models.

In statistical modeling it is necessary to have a sufficiently large data set so that the resulting models provide significant estimations. Neter et al. (*9*) suggest that the number of observations should be at least 6 to 10 times the number of the variables in the independent variable pool. There were four independent variables (quantity, number of bidders, contract amount, and MPT amount), with the adjusted national price being the dependent variable. Therefore, the model-building data sets should contain between 24 and 40 observations. This criterion eliminated statistical analysis as a modeling tool for several treatment items. The newly developed treatments along with those with few observations were modeled by using classical estimating techniques. A discussion of the techniques used to determine the cost models for these is not included in this paper. Standard engineering estimation techniques were used and are fully discussed in the SHRP C103 project report (*10*).

Computer Models

In general, the extensive amount of data obtained from the various SHAs provided a sufficient number of observations with which to develop statistical models. Several problems may result from the use of only observational or historical data. The primary concern is

TABLE 1 (*continued*)

- 500 Structural Protection Systems
  - 510 Encase with Portland Cement Concrete (square yard)
  - 520 Sealers
    - 521 Boiled Linseed Oil (square yard)
    - 522 Silane, Siloxane (square yard)
  - 530 Shotcrete (cubic yard)
  - 540 Coatings
    - 541 Epoxy (square yard)
    - 542 Others (square yard)
- 600 New Deck Protection Systems
  - 610 Deep Impregnation, Grooving Technique
    - 611 Monomer, Methyl Methacrylate
    - 612 Corrosion Inhibitor, Postrite
    - 613 Corrosion Inhibitor, Cortec 2020
  - 620 Spray-on Corrosion Inhibitor, Inhibitor Modified Overlay System
    - 621 Non-Dried, Postrite
    - 622 Non-Dried, Cortec 2020
    - 623 Non-Dried, Alox 901
    - 624 Dried, Postrite
    - 625 Dried, Cortec 2020
    - 626 Dried, Alox 910

- 700 New Structural Patching
  - 710 Type I Concrete Removal, Patch with Corrosion Inhibitor Concrete
    - 711 DCI
    - 712 Cortec 2000
  - 720 Type II Concrete Removal, Spray-On Inhibitor, Patch with Corrosion Inhibitor Concrete
    - 721 Postrite, DCI Concrete
    - 722 Cortec 2020, Cortec 2000 Concrete
    - 723 Alox 901, PCC

that historical data do not result from a controlled experiment. Therefore, the data may not provide adequate information on cause and effect. Without a carefully controlled experiment all of the controlling independent variables may not be observed. Another aspect of this problem is that although an apparent statistical relationship is found to exist, this does not necessarily indicate that there is a causal relationship. If there is a causal relationship at present or in the past, there is no guarantee that this relationship will hold in the future.

After the data were obtained and processed into subsets containing similar work items from each state, model development procedures were instigated. Preliminary work was initiated into determining the possible factors that would affect the model. The only variables available from the bid tabulations that might have an effect on the adjusted national cost were quantity of work, the number of bids, the total contract cost, and the MPT cost. No other factors were available without extensive research of the project contract documents, which was infeasible for the more than 800 contracts used in the study.

With only these four variables used in the model, it was necessary to develop an understanding of how these variables affect the bid price. Cost has two components: fixed cost and variable cost. It is evident that there is a relationship between quantity and cost: as quantity increases, the unit cost decreases.

The state of the economy plays a role in determining the costs of repairs. As the economy worsens, more contractors begin to rely on public projects and the number of bidders on the projects increase. Knowing that competition has increased the contractors must cut costs to a minimum to be competitive. Although simply observing the number of bidders on a specific contract may be a crude indicator, it may provide additional insight and improve the model.

Another factor that has an effect on cost is the difficulty of the work. This difficulty may be the result of poor access to the repair area, remote location of the job site, and so forth. One variable available on the bid tabulations that may provide some information regarding the difficulties on the construction site is the cost of MPT items. Even more is revealed if the ratio of MPT costs to total contract cost is observed. An increase in this ratio indicates that more effort is being expended on job site activities rather than actual rehabilitation work.

The total construction costs should also be considered as a possible factor influencing costs. As the size of a contract increases it allows the contractor to spread overhead and profit over more items and quantities. Although the savings in this case may not be as significant as with other factors, some savings may be realized and this will be considered in the model.

The relationship between the four variables and unit cost can be simplified as follows:

- As quantity increases, cost decreases,
- As the ratio of MPT cost to total contract amount increases, cost increases,
- As the number of bids increases, the cost decreases, and
- As the total contracts amount increases, the cost decreases.

It is desired that these variables be combined into a series of factors that can be modeled to provide cost information. Since the quantity of work is probably the best indicator of cost, it was decided that this variable should be present in all factors. This results in the following eight factors that were used for model development:

Factor 1 = quantity,
Factor 2 = (quantity · contract amount)/MPT amount,
Factor 3 = quantity · contract amount,
Factor 4 = quantity · number of bidders,
Factor 5 = [(quantity) · (contract amount)^2]/MPT amount,
Factor 6 = (quantity · number of bidders · contract amount)/MPT amount,
Factor 7 = quantity · contract amount · number of bidders, and
Factor 8 = (quantity · number of bidders)/MPT amount.

Model Description

It was decided that on the basis of the shapes of the curves produced by plotting each factor with the cost for each item that a nonlinear decay model should be used to fit the data. Four models were proposed:

- an exponential decay model

$$y = b_1x + b_2\exp(-x/b_3) \tag{8}$$

- an inverse power model

$$y = b_1 + b_2x + b_3/x^{b4} \tag{9}$$

- an hyperbolic model

$$y = b_1x + (b_2 + b_3x)/(1 + b_4x) \tag{10}$$

- a logarithmic model

$$y = b_1 + b_2x - b_3\log_{10}(x) \tag{11}$$

These four models are capable of fitting the types of curves produced when each factor is plotted against cost.

The most commonly used measure of a regression model's fit is the coefficient of multiple regression, R^2. It measures the proportionate reduction of total variation in the dependent variable associated with the set of independent variables. The value of R^2 is between 0 and 1 inclusive. The closer that the R^2 value is to 1, the better the model takes into account the variability in the data. Generally, the model is considered a good fit for the data if the R^2 values are greater than 0.80. This type of agreement is usually the result of carefully controlled laboratory experiments in which all causal relationships are known.

It is not expected that the data available for analysis in this task will provide R^2 values in the range of what is normally considered acceptable in controlled laboratory testing. The use of observation data generally produces poor models since all of the causal variables may not be known. This scatter is particularly obvious at the lower ranges of the independent variables. To increase the R^2 value it is necessary to have less scatter and a smoother fit. Although this is desirable, caution must be used so that the true variability is not lost in attempts to improve the model.

In the analysis of the bid tabulations it is obvious that there can be, and very often are, large discrepancies between the bids offered by different contractors for the same item on the same contract. This wild variation can be attributed to several causes, including the following:

- A new contractor may not have the benefit of experience and will not be able to competitively perform certain types of work.
- Some contractors may place a higher profit margin on certain items of work.
- Some items may be subcontracted resulting in higher prices.

SHAs can expect that the price paid for a particular quantity of work will typically be somewhere around the midpoint between the highest and lowest bid for that item. Most states recognize this, and during the interviews with estimators it was revealed that most states keep a running average for use in developing the engineers' estimates. Very few states acknowledge the role that quantity or other factors have on the cost function, however. Most often the SHAs keep track of only the low bidder's cost, but some also track the low bid for the item as well.

Given that the bid price for a particular item may vary widely and that the SHA can expect to pay between the high and the low

TABLE 2 Sensitivity Analysis for Rounding of Factor 1 for Item 111, Partial-Depth PCC Deck Patching

Rounding Level	R^2
none	0.118
5	0.242
10	0.353
15	0.394
20	0.447
25	0
30	0

TABLE 3 Regression Parameters for Item 210, Latex-Modified Concrete Overlay

Factor	Rounding Level	Parameters				R^2
		b_1	b_2	b_3	b_4	
1	100	34.05	0.000147	1682.33	0.8389	0.640
2	10,000	36.21	0	913,880	1.3588	0.697
4	500	32.79	2.6×10^{-5}	2246.05	0.6961	0.807
6	50,000	34.60	2.98×10^{-6}	83,298.0	0.8952	0.727
8	0.01	37.87	-0.00123	0.02809	1.4360	0.899

bids for that item, it is suggested that the median value be used to predict the SHA's cost. The benefit in using the median to describe the data set is that the median is insensitive to a number of extremely small or large datum values. Since it is possible that there will be a large variation in the adjusted national cost for any value of the independent variables, the median of the cost will be used.

To enhance the model further a lumped mass approach will be used. This will be accomplished by taking all observations within a specified area of the plot and applying those observations at the center of this area. The procedure will be to round the independent variables and then find the median cost of all of the resulting observations.

The point that represents the median cost at the rounded value of the independent value will then be weighted by the number of observations. The effect of this approach will be to remove some scatter from the plots, yet weight the statistical analysis in the same manner as the original data.

When using this lumped mass approach to reduce the clutter of data, it is important to carefully select the value to which the independent variable is rounded. If too high a rounded value is used, the trends may be altered. If too small of a value is used, the clutter is not sufficiently removed and the trends may remain hidden.

To obtain the optimum rounding value a sensitivity analysis was performed. This sensitivity analysis was accomplished by starting with no rounding and gradually increasing the amount of rounding. For each rounding level a cost equation was generated and the R^2 value was recorded. The optimum rounding level was determined to be the level that produced the greatest R^2 value. This process is illustrated in Table 2 for Item 111—partial-depth PCC deck patching. As can be seen in Table 2 as the rounding level increases there is an increase in the R^2 value. This is attributed to the lumping and weighting of the data.

By this procedure the outliers are removed from the regression, thus increasing the R^2 value. However, the influence of agglomeration of points is maintained by the weighting. The more data observations that make up a lumped point, the more influence this point has on the regressed model. As mentioned previously if too large a rounded value is used the trend for the data is destroyed. This can be seen in Table 2 for rounding value levels of 25 and 30. When these values are used the trends are destroyed, and a seemingly random pattern of datum points is produced. This is verified by an R^2 value of zero, which indicates no relationship between the independent and dependent variables. For Item 111 this occurred rather quickly between rounding levels of 20 and 25. For most items, however, there was a gradual reduction in the R^2 value before the R^2 value reached zero.

RESULTS AND DISCUSSION OF RESULTS

Detailed descriptions are presented for one item, latex-modified overlays. A generic description of each item is provided so that the cost model can be adapted by any SHA by modifying it for its standard specification. Along with the description is a discussion of the pay quantity for each item. For most items the pay quantity varies from state to state, so this will aid in conversion of the model.

The information tabulated for each item includes the rounding level proposed to lump the data for regression, the values obtained for the four regression parameters (b_1 through b_4), and the R^2 value obtained for the regression. This information is provided for each for the eight factors (independent variables) previously described except when the R^2 value is so low that it indicates that no relationship is exhibited.

Latex-modified concrete overlay (Item 210) consists of all labor, material, and equipment required to furnish and place a latex-modified concrete overlay. The specifications for this work are usually quite lengthy and are very similar for each state. However, there are some differences in the thickness of the overlays. For the purpose of the equation derived here, all LMC overlays were assumed to be 31.8 to 38.1 mm (1.25 to 1.5 in.) in depth. These are the most typical depths specified by SHAs. The pay quantity used for this model is per square yard.

The results of the regression model are given in Table 3. Cost equations were not generated for Factors 3, 5, and 7 because of a lack of fit. All models reported in Table 3 will provide a sufficient accuracy for cost estimation purposes. The best model is based on Factor 8 [(quantity · number of bidders)/MPT amount], which has an R^2 value of 0.899. This value is very high, and it is recommended that it be used as the model for this item.

SUMMARY AND RECOMMENDATIONS

Based on the statistical analyses and engineering estimation described earlier equations were developed to predict the cost of the

TABLE 4 Recommended Price Equations

Item No.	Price Equation
111	$C = 133 + \frac{1{,}382{,}600}{(\text{Factor } 4)^{2.38}}$, \$/SY
112	$C = 214 + 0.01 \cdot (\text{Factor } 4) + \frac{361{,}990}{(\text{Factor } 4)^{2.11}}$, \$/SY
121	$C = 236 - 0.037 \cdot (\text{Factor } 1) + \frac{1408}{(\text{Factor } 1)^{0.50}}$, \$/SY
131	$C = 267 + 0.029 \cdot (\text{Factor } 2) + \frac{83{,}400}{(\text{Factor } 2)^{1.22}}$, \$/SY
210	$C = 38 - 0.0012 \cdot (\text{Factor } 8) + \frac{0.028}{(\text{Factor } 8)^{1.44}}$, \$/SY
220	$C = 9.8 - 0.00017 \cdot (\text{Factor } 1) + \frac{3{,}978{,}400}{(\text{Factor } 1)^{3.10}}$, \$/SY
230	$C = 32 + 8.82 \times 10^{-5} \cdot (\text{Factor } 4) + \frac{22{,}200}{(\text{Factor } 4)^{0.98}}$, \$/SY
241	$C = 1.4 - 3.0 \times 10^{-5} \cdot (\text{Factor } 1) + \frac{10.9}{(\text{Factor } 1)^{1.01}}$, \$/SY
242	$C = 8.7 + 7.04 \times 10^{-5} \cdot (\text{Factor } 1) + \frac{56.1}{(\text{Factor } 1)^{1.24}}$, \$/SY
243	$C = 9 - 2.69 \times 10^{-6} \cdot (\text{Factor } 2)$, \$/SY
251	$C = 7 + 2.38 \times 10^{-5} \cdot (\text{Factor } 1) + \frac{68{,}770}{(\text{Factor } 1)^{1.83}}$, \$/SY
252	use price equation for Item 251
260	$C = 6.4 - 2.5 \times 10^{-5} \cdot (\text{Factor } 4) + \frac{5{,}594}{(\text{Factor } 4)^{1.33}}$, \$/SY

rehabilitation treatments previously listed (Table 4). Although the models are useful in predicting costs, caution should be exercised when using them. Since most equations have an inverse term these models will result in a very high price for very small quantities. For this reason judgment should be used before applying the costs to a life-cycle cost model.

The most commonly used independent variable in the cost models was Factor 1, which represents the quantity of the item. As discussed previously most SHAs base their existing cost models solely on quantity. These cost equations will provide more accurate models while maintaining relative simplicity. The other factors that were used are Factors 2, 4, and 8. These three factors are not as simple as

TABLE 4 (*continued*)

Item No.	Price Equation
310	$C = 56 - 0.00036 \cdot (\text{Factor } 4)$, \$/SY
320	$C = 42 - 8.2 \times 10^{-5} \cdot (\text{Factor } 2) + \frac{67{,}470}{(\text{Factor } 2)^{1.01}}$, \$/SY
330	$C = 22 + 0.0012 \cdot (\text{Factor } 1) + \frac{42{,}250}{(\text{Factor } 1)^{0.92}}$, \$/SY
411	$C = 487 - 0.367 \cdot (\text{Factor } 1) + \frac{291}{(\text{Factor } 1)^{0.81}}$, \$/SY
412	$C = 613 - 0.027 \cdot (\text{Factor } 1) + \frac{3{,}328}{(\text{Factor } 1)^{2.92}}$, \$/SY
421	$C = 104 + \frac{1{,}485}{(\text{Factor } 1)}$ (see note 1), \$/SY
422	$C = 204 + \frac{1{,}435}{(\text{Factor } 1)}$ (see note 1), \$/SY
431	$C = 137 + \frac{1{,}476}{(\text{Factor } 1)}$ (see note 1), \$/SY
432	$C = 314 + \frac{1{,}468}{(\text{Factor } 1)}$ (see note 3), \$/SY
510	C = \$354/SY (encasing bridge piers)
521	use price equation for Item 241
522	use price equation for Item 242
530	$C = 3{,}610 - 6.11 \cdot (\text{Factor } 1) + \frac{18{,}820}{(\text{Factor } 1)^{1.85}}$, \$/CY

(*Continued on next page*)

Factor 1 and require some a priori knowledge about the entire construction project. The additional information required for these factors should be readily available by comparing the project with other similar projects and will provide more accurate models. The degree of accuracy to which this information is estimated may have a significant impact on the resulting cost, and as such a sensitivity analysis should be performed and judgment should be used in deciding on the values for these factors.

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TABLE 4 (*continued*)

Item No.	Price Equation
541	$C = -10 + 7.24 \times 10^{-5} * (\text{Factor } 4) + \dfrac{150}{(\text{Factor } 4)^{0.21}}$, $/SY
542	$C = 18 - 0.0035 * (\text{Factor } 1)$, $/SY

where:

C = price per unit measurement
Factor 1 = quantity
Factor 2 = (quantity * contract amount)/MPT amount
Factor 4 = quantity * number of bidders
Factor 8 = (quantity * number of bidders)/MPT amount

Note 1: For Items 421, 422, 431, and 432 unit prices vary significantly with the locations of the repair. Therefore, for specific bridge members, use the regression coefficients tabulated below for the equation $C = F * Q^{-1} + a$.

Concrete Bridge Member	Treatment #421		Treatment #422		Treatment #431		Treatment #432	
	F	a	F	a	F	a	F	a
Beams	1,226	65	1,226	123	1,226	97	1,415	251
Diaphragms	1,111	175	1,105	238	1,111	207	1,110	371
Piers	1,670	66	1,522	174	1,541	97	1,671	261
Pier Caps	1,398	112	886	263	1,537	97	1,393	308
Backwalls	1,977	65	1,887	174	1,975	98	1,977	261
Abutments	2,016	66	1,886	220	2,018	97	2,017	261
Wingwalls	1,461	65	1,461	123	1,447	102	1,461	261

Note 2: $\$/m^2 = (\$/SY) * 1.196$
$\$/m^3 = (\$/CY) * 1.308$

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REFERENCES

1. Jelen, F. C., and J. H. Black. *Cost Optimization and Engineering,* 2nd ed., McGraw-Hill, Inc., New York, 1983.
2. Humphreys, K. K. *Project and Cost Engineers Handbook.* Marcel Dekker, Inc., New York, 1984.
3. Barrie, D. S., and B. C. Paulson. *Professional Construction Management,* 3rd ed. McGraw-Hill, Inc., New York, 1992.
4. Gainsburgh, M. R., and J. Backman. Inflation and the Price Indexes. *Studies in Business Economics, No. 94.* National Industrial Conference Board. U.S. Government Printing Office, Washington, D.C., 1990.
5. Grant, E. L., W. G. Ireson, and R. S. Leavenworth. *Principles of Engineering Economy,* 8th ed. John Wiley and Sons, Inc., New York, 1990.
6. Quarterly Cost Roundup. *Engineering News Record.* McGraw-Hill, Inc., New York, various years.
7. Price Trends for Federal-Aid Highway Construction and Cost Trends—Highway Maintenance and Operations. In *Highway Statistics*—1990. U.S. Government Printing Office, Washington, D.C., 1991.
8. Smit, K. (senior editor). *Means Concrete Cost Data—1992,* 10th Annual Edition. R. S. Means Company, Inc., Kingston, Mass., 1991.
9. Neter, J., W. Wasserman, and M. H. Kutner. *Applied Linear Regression Models,* 2nd ed. Irwin Publishing Company, Boston, Mass., 1989.
10. Gannon, E. J., P. D. Cady, and R. E. Weyers. *Price and Cost Information.* Report SHRP-S-664. Strategic Highway Research Program, National Research Council, Washington, D.C., 1992.

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