sociation of State Highway and Transportation Officials' (AASHTO) manual for maintenance and inspection of bridges.

For bridge-design-related information, refer to the PennDOT design manual, part IV, and the 1977 AASHTO standard specification for highway bridges and the interim specifications for the years 1978, 1979, 1980, and 1981.

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Computer Model for Life-Cycle Cost Analysis of Statewide Bridge Repair and Replacement Needs

WILLIAM A. HYMAN AND DENNIS J. HUGHES

The Wisconsin Department of Transportation (WisDOT) has developed a computer simulation model that uses life-cycle cost analysis, in addition to information on the structural adequacy and functional obsolescence of bridges, to determine the least-cost mix of bridge repair and replacement work for up to 25 000 bridges and up to 20 program periods. The mathematical structure underlying the replacement decision rule is partly based on the solution to an unconstrained cost-minimization problem suitable for assessing funding requirements for bridge work irrespective of budget constraints. The decision rule also depends on the condition, age, and life expectancy of each bridge. This paper presents a description of the computer model and the results of examining three policy directions for 4500 state-owned bridges for the program period 1982-1999. WisDOT is using these results for its State Highway Plan and to provide guidance in formulating its six-year highway investment program and its biennial budget proposal for bridge repair and replacement. The results indicate that WisDOT should probably replace between 27 and 38 bridges/year from 1982 through 1999, that the cost of repair work will increase more than 75 percent over the period, and that the average condition of the bridges will decline over the period if the Department minimizes the cost of repair and replacement work. The paper also discusses issues regarding implementation. One can learn to run the model with several days training, and in-house staff needed to maintain the model may be as little as one-quarter of a person-year annually.

It is estimated that 105 000 bridges nationwide require replacement; about one-third of them are on the federal-aid highway system (1, p. 4). Assuming an average replacement cost of $300 000/bridge, current bridge replacement needs throughout the country total $31.5 billion. These are enormous costs. Are they believable?

Estimates of bridge replacement needs on state and federal highway systems are usually based on the number of bridges that have become structurally deficient, functionally obsolete, or closed. A bridge is structurally deficient if the superstructure or substructure requires immediate repairs or rehabilitation or if the ability to carry normal live loads is severely impaired. A functionally obsolete bridge has a narrow deck, low vertical clearances, or poor alignment relative to the roadway (2).

Is structural adequacy or functional obsolescence a sufficient criterion to determine replacement needs? Clearly not. By definition, a structurally inadequate bridge is in immediate need of major repairs, rehabilitation, or replacement, but it does not require replacement. Moreover, a functionally obsolete bridge may be in excellent condition and have many additional years of useful life even if it is narrow, has substandard clearances, or has poor alignment. Thus, such criteria as structural adequacy and functional obsolescence are not sufficient to determine replacement needs by themselves.

A more germane issue is whether repair or rehabilitation is more cost effective than replacement at various times during the life cycle of a bridge.

This paper reports the development and application of a computer simulation model that supplements information on the structural adequacy and functional obsolescence of structures with life-cycle cost analysis in order to determine the number of state-owned bridges in Wisconsin that will require replacement in each period from 1983 to the year 2000.

The computer model also estimates the number of bridges that will require different repairs, including concrete overlays, new decks, painting, joint work, and other minor repairs. The model calculates the cost of replacement and each type of repair work in each period and forecasts bridge condition. Results may be summarized by type of structure.

The Wisconsin Department of Transportation (WisDOT) is currently using the model to evaluate long-term bridge repair and replacement needs for its State Highway Plan (3) and to provide estimates of required bridge funding levels for the Six Year Highway Improvement Program (4) and the Department's biennial budget proposals. Other states and the federal government may find the model useful for similar applications.

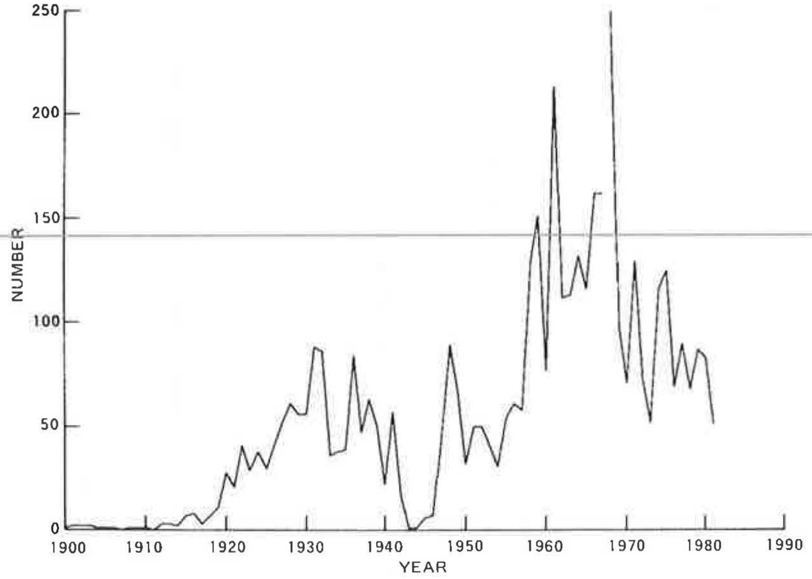
SCOPE OF PROBLEM IN WISCONSIN

In Wisconsin, there are close to 12 000 bridges. The state owns nearly 4300 bridges that carry traffic on or over the state trunk highway system. In addition, the state has both repair and replacement responsibility for an additional 200 bridges. The total of 4500 bridges under state responsibility has been the focus of this study.

The three most common structure types are steel deck girders, prestressed concrete, and concrete slabs. They represent 77 percent of all these bridges and 85 percent of the total deck area. The Department has ceased to build trusses and reinforced-concrete deck girders, which comprise most of the remaining bridges. Forty-eight percent of the 4500 bridges are on the highest functional systems: Interstates and principal arterials. Repair costs are concentrated on these structures, since they account for 57 percent of the deck area, and repair costs are proportional to deck size. The average size of bridges has been increasing over time as new bridges have been designed to constantly improve standards. Bridges on lower function and volume roads are more likely to be replaced in the next 20 years because they are generally much older than bridges that serve higher function and volume roads.

Indeed, structure age significantly influences system-level bridge needs. The average age of all

Figure 1. Number of bridges constructed each year.



bridges is 25.6 years. However, more than 500 bridges are at least 50 years old. Surges of building activity occurred during the Depression years of the 1930s and as the Interstate and other major highway improvements were made between 1960 and 1975. A lull in bridge construction occurred during World War II. Bridge replacement candidates come almost entirely from bridges built during or before the Depression. Figure 1 shows how many bridges were constructed each year.

Two well-known indices of the current state of bridges are condition appraisal and sufficiency rating. Condition appraisal is a combination of field ratings of superstructure, substructure, inventory rating, and, in some cases, deck condition (when the deck is a main load-bearing member). Bridges rated three or less on a nine-point scale are considered "deficient" and are in need of immediate major repairs, rehabilitation, or replacement. Eleven percent of these bridges, which represent 8 percent of the deck area, are rated three or less.

Sufficiency rating is another composite index based on structural adequacy, functional obsolescence, and essentiality for public use. More than half (55 percent) of the sufficiency rating is attributable to the condition appraisal. There are 283 bridges of state responsibility with a sufficiency rating below 40. An additional 235 bridges (5 percent) have a sufficiency rating of less than 50. In all, 12 percent of the bridges, which represent 11 percent of the deck area, have a sufficiency rating below 50 percent, the threshold to be eligible for federal bridge replacement funds.

PRECEPTS FOR MODEL DEVELOPMENT

We have tried to estimate the least-cost mix of bridge and repair work in Wisconsin over the next 20 years. This is an unconstrained optimization problem and thus allows us to address bridge needs irrespective of budget constraints. Four principles should govern the treatment of this problem:

1. A bridge whose condition is beyond repair and unsafe should be replaced.
2. If the cost to continue maintaining a bridge over its life and subsequently replacing it is greater than the sum of the cost of constructing and maintaining a new bridge over the same life-cycle analysis period, then the bridge should be replaced.
3. All costs must be treated in constant dollars so that cost estimates are not influenced by inflation.
4. All future costs must be discounted by the factor $1/(1 + r)^t$, where r is the discount rate and t is the year in which a cost is incurred. The failure to use a discount rate would seriously distort the determination of the optimal bridge replacement and repair program. The discount rate may reflect any reasonable opportunity cost for the use of bridge funds.

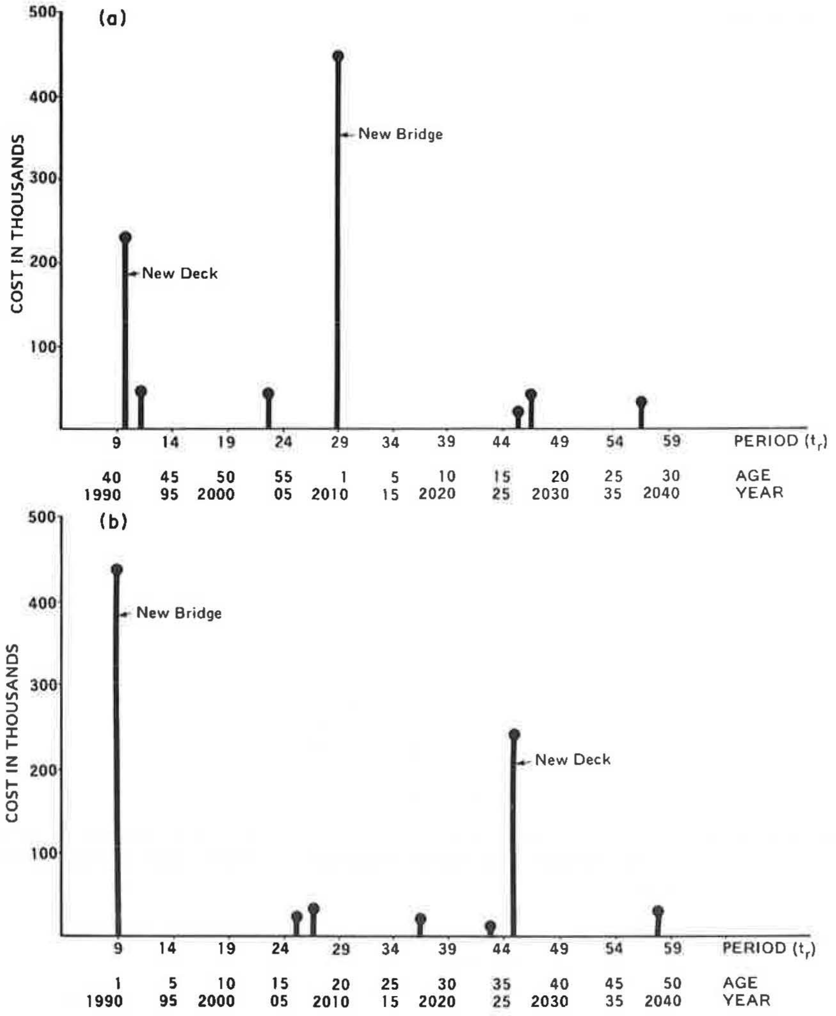
As a practical matter, several other precepts should govern the development of a model to estimate bridge needs. Ample allowance for engineering experience and judgment is necessary. Trends in the history and current practice of bridge repair and replacement are generally not well documented for meaningful analytical use in system simulation models. The extensive experience of a department's bridge engineering staff regarding the many types of structures, their costs, timing of repairs, as well as the maintenance options, must be input to the model.

Both "top-down" and "bottoms-up" perspectives are necessary. Optimal decisionmaking on a systemwide basis should take precedence over optimal decisionmaking for individual bridges. However, one should not forsake information regarding specific bridges in pursuit of a systemwide perspective. The model should make use of existing detailed data on specific bridges regarding their type, dimensions, condition, and function of the highway served.

A statistical approach is essential if an analysis of systemwide bridge needs is not to become obfuscated or distorted by analysis of individual bridges. The assignment of profiles of repair activities should be based on predetermined probabilities that reflect trends in bridge maintenance practices. In addition, a statistical approach should be used to estimate equations that simulate the change in bridge conditions over time.

Finally, the model should be flexible and issue oriented. It should permit the variation of the many important parameters and assumptions that influence bridge replacement needs and thus be able to evaluate a wide variety of bridge-related policy issues.

Figure 2. (a) Repair and (b) replace options.



MATHEMATICAL STATEMENT OF PROBLEM

To develop the mathematical structure of the model, it is helpful to perform a "thought experiment". Place yourself in the position of a time traveler and transport yourself to the foot of one of Wisconsin's state-owned bridges in the year Y = 1990. In 1990 you are faced with deciding whether to continue to repair the bridge or replace it, and you must report your decision to a person performing an analysis of future bridge needs who is working on the problem in the year 1982 (the base year), Y_o.

Let t be a period on an interval time scale beginning with the base program period (t_o) and extending in the future beyond the year (t_r) in which you are collecting data to make a replacement decision. Thus, $t = t_o = 0$ corresponds to 1982 and $t = t_r = 9$ corresponds to 1990.

Now suppose you, the time traveler, continue into the future on one of two paths. The first path represents the case of bridge repair and the second path represents the case of bridge replacement. On the first path you follow the life of the bridge, assuming it continues to be repaired to the end of its life; it is then replaced, and the new bridge is subsequently repaired as needed. Figure 2a shows the types, timing, and cost of repair and replacement activities you find on this bridge up to the end of the life-cycle analysis period, which is $t^* = 50$ years. Thus, the profile of work activities shown in Figure 2a covers the same period from $t_r = 9$ to $t_r + t^* = 59$ years. A new deck is put on the bridge in 1991 and the whole structure is replaced in 2010.

Figure 2b shows the types, timing, and cost of repairs you find occurring as you travel in time down the other path. On the second path, the bridge is replaced in 1990 and subsequently repaired.

Now that you know what future work will occur on this bridge if it is either repaired or replaced in 1990, you return to 1982 and report the information in Figures 2a and b to the analyst who is assessing future bridge replacement needs. The analyst then discounts each future year cost back to 1982 under both the replacement and repair cases by using the following formulas:

$$\text{Replacement case: } D^R_{ij}(t_r) = \sum_{t=t_r}^{t_r+t^*} [C^R_{ij}(t)/(1+r)^t] \qquad (1)$$

$$\text{Repair case: } D^M_{ij}(t_r) = \sum_{t=t_r}^{t_r+t^*} [C^M_{ij}(t)/(1+r)^t] \qquad (2)$$

where

$D^R_{ij}(t_r)$ = discounted present value of costs to replace the jth type i bridge in period t_r (which corresponds to the year $Y_o + t_r$) followed by repairs to the new bridge;

$D^M_{ij}(t_r)$ = discounted present value of the costs to continue repairing the jth type i bridge in period t_r (which corresponds to the year $Y_o + t_r$) until the end of its life, and subsequently replacing it and repairing the new bridge;

$C^R_{ij}(t)$ = cost in real (e.g., 1982) dollars for work performed on the jth type i bridge under the replacement case in period t;

$C^M_{ij}(t)$ = cost in real (e.g., 1982) dollars for work performed on the jth type i bridge under the repair (maintenance) case in period t;

t = interval index of time beginning at $t_o = 0$, which corresponds to the base year Y_o (= 1982, for example);

t_r = year within the planning/programming horizon ($\neq t^*$) in which a repair or replacement decision is made based on discounting the streams of future costs back to the base year (Y_o);

t^* = length of the life-cycle analysis period (e.g., $t^* = 50$ years); and

r = discount rate.

The decision rule for replacing the jth type i bridge in period t_r is as follows: Replace in period t_r if $D^R_{ij}(t_r) < D^M_{ij}(t_r)$.

The cost of work on the jth type i bridge in period t_r in real dollars will be

$$\mathrm{COST}_{ij}(t_r) = \begin{cases} C^R_{ij}(t_r) \text{ if } D^R_{ij} < D^M_{ij} \\ C^M_{ij}(t_r) \text{ if } D^R_{ij} \geqslant D^M_{ij} \end{cases} \tag{3}$$

Now suppose you begin time traveling in period $t_r = 0$, visit every state-owned bridge, examine each bridge under the repair and replacement case, and report the information to the analyst working in 1982. Next you travel to the following period ($t_r = 1$), examine every bridge again under the repair and replacement case, and continue doing so until the end of the planning/programming period, p (which may be 2 years for a biennial budget proposal, 6 years for a 6-year bridge program, 20 years for a state highway system plan, etc.). With the information you have gathered, the analyst could calculate the following costs:

1. The total of the least-cost repair and replacement work on all type i bridges in period t_r, i.e.,

$$\mathrm{TC}_i(t_r) = \sum_{j=1}^{J} \mathrm{COST}_{ij}(t_r) \tag{4}$$

2. The total of the least-cost repair and replacement work on all types of bridges in period t_r, i.e.,

$$\mathrm{TC}(t_r) = \sum_{i=1}^{I} \sum_{j=1}^{J} \mathrm{COST}_{ij}(t_r) \tag{5}$$

3. The total of the least-cost repair and replacement work on all bridges from the base year through the end of the planning/programming horizon (p), i.e.,

$$\mathrm{GTC} = \sum_{t_r=0}^{p} \sum_{i=1}^{I} \sum_{j=1}^{J} \mathrm{COST}_{ij}(t_r) \tag{6}$$

As a time traveler, one is able to collect perfectly accurate information about future cost under either a replacement or a repair scenario. However, in reality, one does not have perfect information about the future. Future costs are gross estimates and subject to considerable error. Thus it is necessary to supplement economic analyses with the results of engineering data from field inspections and historical construction and maintenance records. A bridge known to be in very poor condition now should be a strong candidate for replacement in a few years, especially if its useful or functional life will expire or it will become unsafe.

The version of the computer model described here uses a three-part decision rule for replacement. A bridge is replaced if

1. It is less costly to replace then to repair, taking into account discounted future life-cycle costs;
2. The age is greater than its life expectancy and the condition appraisal is less than some threshold (S_1), which indicates that the bridge is in immediate need of major repairs, rehabilitation, or replacement; or
3. The age is less than or equal to its life expectancy and the condition appraisal is less than some threshold $S_2 \leq S_1$ (S_2 is at least as stringent as S_1).

More formally stated, the replacement rule is as follows

$$\text{Replace in period } t_r \text{ if } \begin{cases} D^R_{ij}(t_r) < D^M_{ij}(t_r) \\ \text{or } S_{ij}(t_r) < S_1, \text{ and } a_{ij}(t_r) > L_i \\ \text{or } S_{ij}(t_r) < S_2, \text{ and } a_{ij}(t_r) \leqslant L_i \text{ and } S_2 \leqslant S_1 \end{cases}$$

where

$S_{ij}(t_r)$ = state of the jth type i bridge in period t_r measured by condition appraisal,

S_1 = condition appraisal threshold below which a bridge will be replaced if its age is greater than its life expectancy,

S_2 = condition appraisal threshold below which a bridge will be replaced if its age is less than or equal to its life expectancy,

$a_{ij}(t_r)$ = age of the jth type i bridge in period t_r, and

L_i = life expectancy of a type i bridge (may be based on useful or functional life).

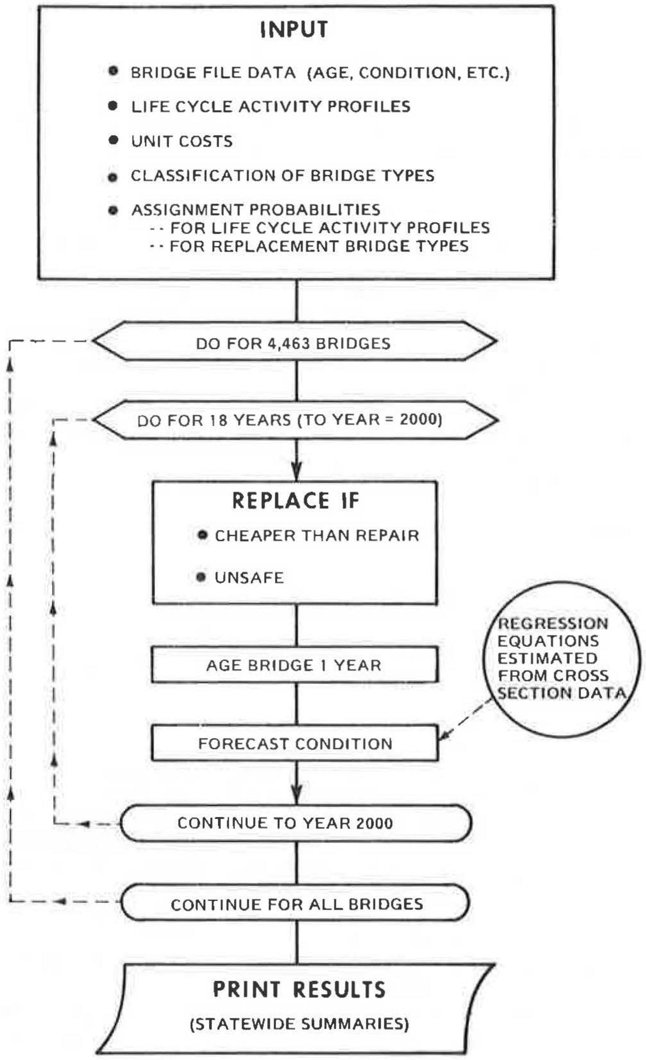
DESCRIPTION OF COMPUTER MODEL

Figure 3 is a flowchart for the computer model WisDOT developed to analyze systemwide bridge replacement and repair needs. The computer program incorporates the replacement decision rule presented above and is written in FORTRAN. The model can determine the least-cost mix of replacement and repair work for up to 25 000 bridges in 20 or less program periods. An analysis of 4500 bridges in 20 program periods required 3.53 min of central processing unit (CPU) time when running on an Amdahl 470V/6 computer.

Key input data are life-cycle activity profiles. These define tracks of future bridge repair activities common to particular structure types. Types of work are input into the model as two-digit codes, and the kind of work is later converted to costs given unit cost input data, the dimensions and type of a specific bridge, and the functional class of the highway it carries. Replacement and widening costs are calculated partly on the basis of the increase in bridge width necessary to meet minimum roadway width standards.

The model selects a life-cycle activity profile for the repair case that applies to an existing bridge. The computer also selects a second profile to represent the replacement case. The second profile pertains to a replacement bridge that may be the same or a different type than the bridge it replaces. The user must specify the percentage of

Figure 3. Flowchart of computer model.



time one type of bridge will be replaced with another type, which activity profiles apply to each kind of bridge, and the percentage of time the profiles apply. An algorithm uses a uniform random-number generator to assign life-cycle activity profiles to each bridge under the repair and replacement cases so that, on average, profiles are assigned in accordance with the predetermined probabilities of occurrence. Figure 4 shows an example of alternative life-cycle activity profiles for steel deck girders.

The replacement case is always represented by a single activity profile for a new bridge, such as STLA4501 shown in Figure 4. However, the repair case is a combination (a splicing) of two profiles. The first profile provides the sequence of repair work on an existing bridge from its current age to the end of its expected life, which can be based on its useful or functional life expectancy. The second profile, which is identical to the one selected under the replacement case, is spliced on following the first profile and shows what happens after an existing bridge's life ends; it is replaced and the new bridge is repaired when scheduled.

The computer model begins in the first program period (t_0) that corresponds to the base year and processes each bridge sequentially. The computer obtains data from WisDOT's Bridge Section data file on each bridge's type, age, condition, dimensions, and functional class of the road on the bridge. Then the model determines whether the bridge should be replaced or repaired by using the decision rule presented in the previous section. A bridge is aged one year if it is not replaced, otherwise its age is reset to zero and the replacement type of the new bridge is recorded for analysis in subsequent program periods.

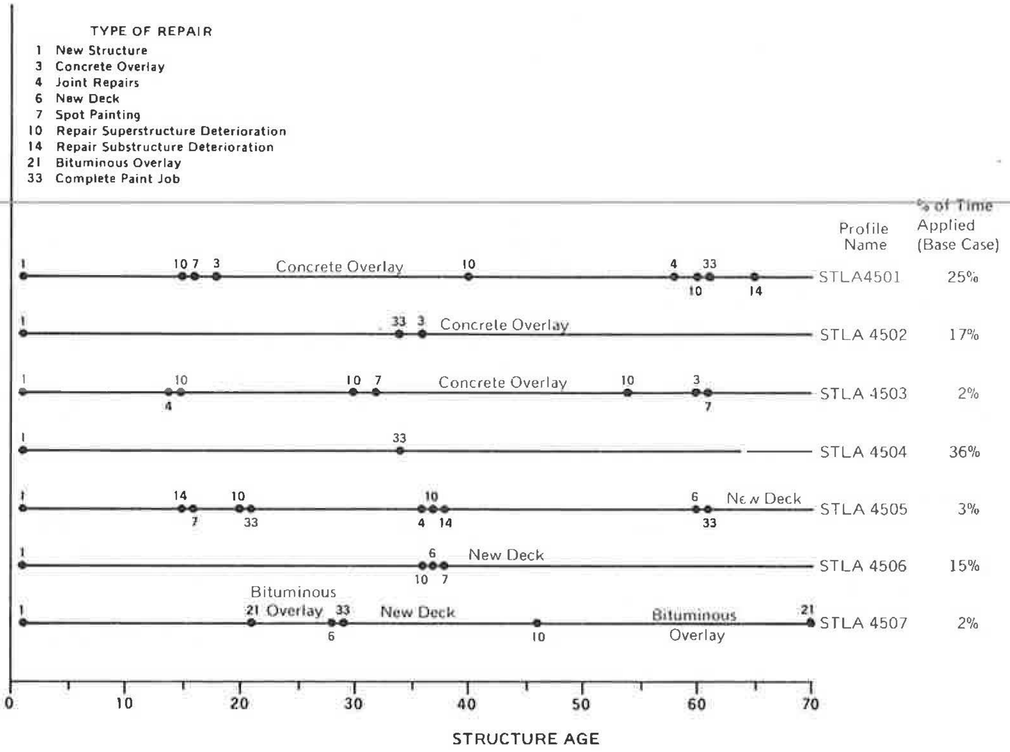
Forecasts of condition appraisal by bridge type are made by using the regressions given in Table 1 and the summary statistics in Table 2. Condition regressions are piecewise linear functions of age--the only independent variable. Equations are estimated from cross-section data, since no time-series data are available. Unfortunately, the estimated condition at any age not only reflects wear and tear but also the influence of maintenance in the midlife of bridges and the effects of changing design standards over time. These confounding effects can only be eliminated by estimating conditions from pooled time-series and cross-section data, which WisDOT will develop in the future. Also, heteroscedasticity is present for age in the range from 1 to 20 years. Regression analyses that use other specifications have shown that condition is significantly related to traffic levels and deck area, but no relation has been found between condition and the time since the last repairs were done, probably because of incomplete historical data in the Bridge Section data file. In future work on the model we will incorporate traffic levels and deck area into the piecewise linear functions for estimating condition appraisal.

The output includes the number of bridges replaced in each period and the corresponding costs broken down by structure, demolition, approach, engineering, and traffic-control costs. The increase in deck area over replaced bridges is also calculated. In addition, the model counts how many bridges get no attention in each period and the number that receive various types of repairs (concrete overlays, new decks, painting, patching, bearing work, joint repairs, and so forth--the model is quite flexible as to the types of repairs it can consider and can allow up to 50 different kinds, ranging from minor work to major rehabilitation). Corresponding costs are tallied. Finally, the model prints out the average condition of each type of bridge in each program year.

DATA COLLECTION TO DETERMINE LIFE-CYCLE ACTIVITY PROFILES

Few data have been available at WisDOT in a convenient form for life-cycle cost analysis. Data collection to determine life-cycle activity profiles proceeded in two steps. The first was to collect data for model testing and to produce initial results. This input was based entirely on the judgment of bridge maintenance and construction engineers regarding past and future bridge maintenance trends and practices. The second step consisted of a major effort to merge data from disparate sources and corroborate or modify the original input data. The second set of input data comes mainly from (a) the Bridge Section computer data file, which contains information on the construction year of bridges and high-type repair work (e.g., concrete overlays and new decks), generally since 1975, and (b) bridge maintenance records, which are not on a computer file but cover maintenance work dating back to 1960. The second data-collection step has consisted of identifying the sequence of repair work on each state-owned bridge. Then rough random samples (>100 bridges) for each combination of repair and

Figure 4. Life-cycle activity profiles: bridge maintenance and high-type repairs.



bridge type were taken to determine the frequency, timing, and costs of repairs. The results presented in the concluding sections reflect the more detailed and definitive data-collection effort. Although substantial progress has been made in identifying typical life-cycle activity profiles, we also relied on engineering judgment to fill in gaps, particularly for such types of structures as prestressed concrete, none of which are older than 30 years.

POLICY OPTIONS AND MODEL RESULTS

We analyzed three long-term policy directions for bridges in developing the State Highway Plan and to provide guidance for the Six-Year Highway Improvement Program and the biennial budget submittal. The outline below presents the main features and input parameters of the three policy directions: an austerity option, a preventive maintenance option, and a functional obsolescence option:

I. Austerity option
    A. Revenue shortage
    B. Maximize useful life
    C. Assumed life expectancy by bridge type in years (L_i)
        1. 60 years for slabs, reinforced-concrete deck girders, and culverts
        2. 75 years for some steel deck girders
        3. 80 years for other steel bridges and prestressed concrete.
    D. Sacrifice condition to obtain cost savings
    E. Types and rate of repairs in future similar to today
    F. Tolerate narrow bridges
II. Preventive maintenance option
    A. Adequate revenues
    B. Preventive maintenance to achieve longer life expectancies (L_i)
        1. 60 years for slabs and reinforced-concrete deck girders
        2. 80 years for all other bridges
    C. Frequent and periodic painting of steel structures and concrete overlays
    D. Minimum roadway width standards similar to today's
III. Functional obsolescence option
    A. Adequate revenue
    B. Bridges become functionally obsolete at 57 years on average; i.e., life expectancy for all bridge types (L_i) is 57 years
    C. Type and rate of repairs in future are similar to today
    D. Minimum roadway width standards greater than today's

Table 3 summarizes the estimated bridge repair and replacement needs under each policy direction through the year 1999. The results have been expressed in average annual levels of work by decade partly to smooth out the extreme peaking of the estimated annual replacement needs shown in Figure 5. The few discrete values that make up the scale for condition appraisal--the primary indicator of bridge deficiency--cause replacement estimates to be lumped together every few years.

The lower estimate of 27 new bridges per year during the 1980s for the austerity and preventive maintenance options equals the average number of bridges scheduled for replacement in the Department's independently developed highway program for the 1982-1987 period. Replacement needs will rise slightly from the 1980s to the 1990s as long as the Department does not pursue a policy to replace large numbers (38/year) of functionally obsolete and older bridges in this decade.

An analysis of the results revealed that virtually every bridge is cheaper to repair than to replace up to the end of its expected life. Nearly all estimated bridge replacement needs in any period occur because the age of a bridge exceeds its life expectancy and its condition appraisal has been forecast to fall below 2, which indicates that the bridge is unsafe.

Table 1. Piecewise linear regressions for condition appraisal.

	Bridge Type									
	All Bridges (n = 4372)		Steel Deck Girders (n = 1937)		Other Steel (n = 136)		Reinforced-Concrete Deck Girders (n = 427)		Concrete Slabs (n = 725)	
Variable	Coefficient	t-Statistic	Coefficient	t-Statistic	Coefficient	t-Statistic	Coefficient	t-Statistic	Coefficient	t-Statistic
INTERCEPT	+7.681 25		+7.501 60		+6.784 94		+7.772 46		+7.458 85	
AGE	−0.071 97	−16.782	−0.056 36	−7.966	NU		−0.120 80	−3.153	−0.097 77	−10.190
PIEC25[a]	+0.080 39	9.958	+0.062 30	4.991	−0.006 25	−0.201	+0.100 84	2.114	+0.044 19	1.834
PIEC45[c]	−0.186 59	−13.507	−0.196 58	−8.310	−0.241 21	−4.197	NU[b]		−0.041 99[b]	−0.712
PIEC60[d]	+0.195 90[e]	4.248	+0.149 85[e]	1.823	+0.137 09[e]	1.031	−0.074 09[e]	−0.582	+0.220 64[e]	1.314

Notes: For forecasting in this table, the residual in the base year (= actual − predicted condition) is added to the predicted condition in future years. If a bridge is replaced, the base year residual is set to zero. Note that the forecasted condition appraisal for the base year = predicted condition appraisal plus the base year residual = actual condition appraisal.
NU = not used. Tolerance exceeded when estimating regression equation.

[a] PIEC25 = AGE-25 if AGE >25, 0 otherwise.
[b] Corresponding coefficient for All Bridges used to forecast condition appraisal instead.
[c] PIEC45 = AGE-45 if AGE >45, 0 otherwise.
[d] PIEC60 = AGE-60 if AGE >60, 0 otherwise.
[e] Not used for forecasting. All coefficients for PIEC60 were dropped because of generally wrong sign, which occurred due to effects of repairs on very old bridges.

Table 2. Summary statistics for Table 1.

Statistic	All Bridges	Steel Deck Girders	Other Steel	Reinforced-Concrete Deck Girders	Concrete Slabs	Prestressed Concrete	Culverts
R^2	0.25	0.15	0.20	0.13	0.30	0.11	0.07
F-ratio	363.737	82.546	29.347	21.0045	76.489	32.274	6.965

Table 3. Bridge replacement and repair needs for state-owned and state responsibility bridges by decade.

	Total Effort				Avg Annual Effort			
	Replaced		Repaired		Replaced		Repaired	
Policy Direction	Number	Cost ($000 000s)	Number	Cost ($000 000s)	Number	Cost ($000 000s)	Number	Cost ($000 000s)
1982-1989								
Austerity	216	108.0	1519	46.0	27	13.5	190	5.8
Preventive maintenance	215	110.4	2205	78.7	27	13.8	276	9.8
Functional obsolescence	301	177.1	1488	44.5	38	22.1	186	5.6
1990-1999								
Austerity	315	171.3	2064	85.9	32	17.1	206	8.6
Preventive maintenance	314	189.9	2887	137.8	31	19.0	289	13.8
Functional obsolescence	291	162.5	1960	83.8	29	16.3	196	8.4

Note: All costs are in 1982 dollars.

Figure 5. Cost of replacements (millions of 1982 dollars).

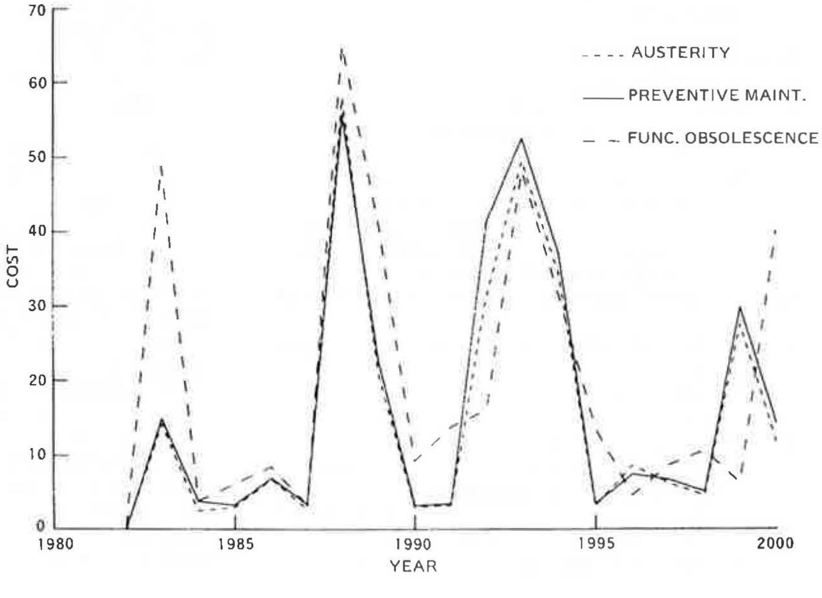


Table 1. Continued.

Prestressed Concrete (n = 753)		Culverts (n = 347)	
Coefficient	t-Statistic	Coefficient	t-Statistic
+7.751 84		+7.997 48	
-0.064 52	-9.772	-0.328 4	-3.661
+0.223 98[b]	1.128	+0.048 85	2.399
-0.300 11[b]	-0.480	-0.154 58	-2.635
NU[e]		+0.396 81[e]	2.637

Bridge widening and other types of repairs tantamount to a new bridge (e.g., a new superstructure) were not considered explicit alternatives to replacement in these runs. In other runs, consideration of the widening option resulted in a great many more bridges being replaced as the least-cost alternative.

The repairs we did consider were new decks, concrete and bituminous overlays, painting, joint repairs, and other routine repairs to the superstructure or substructure such as full-depth deck patching and bearing replacement. Figure 6 shows that the computer model projects bridge repair costs will be substantially greater under the preventive maintenance option than under the others. Also, total repair costs will rise noticeably from this decade to the next under all three policy directions. A large number of bridges built since 1955 will reach their midlife and require new decks and additional concrete overlays. Figure 7 presents

Figure 6. Cost of repairs (millions of 1982 dollars).

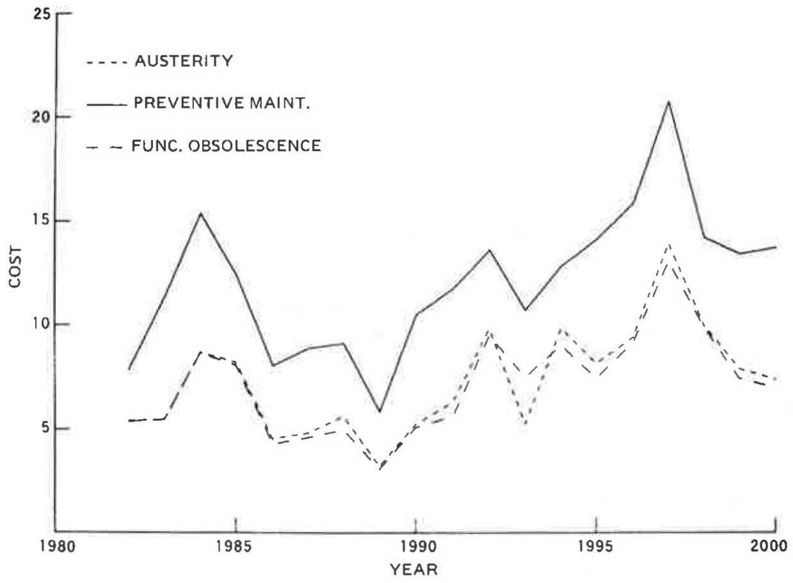


Figure 7. Cost of concrete overlays and new decks for austerity option (1982 dollars).

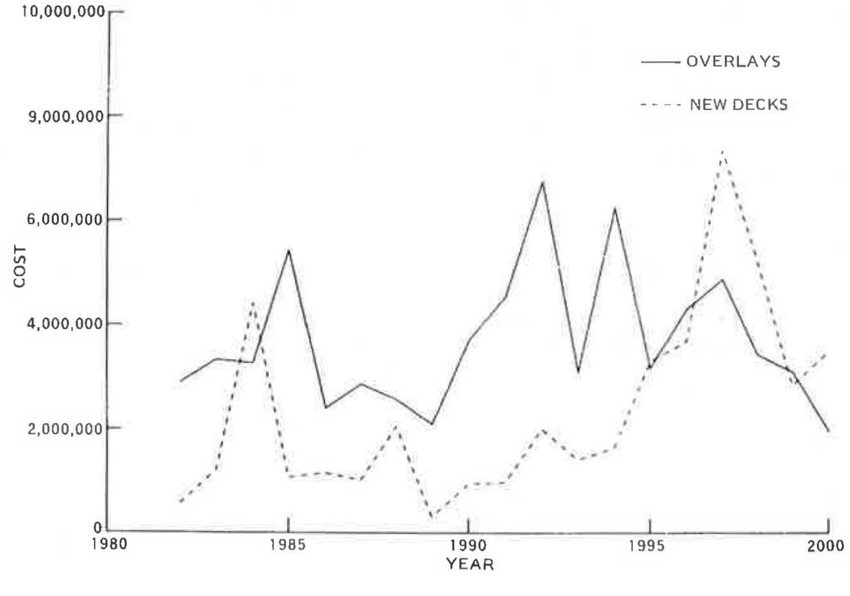
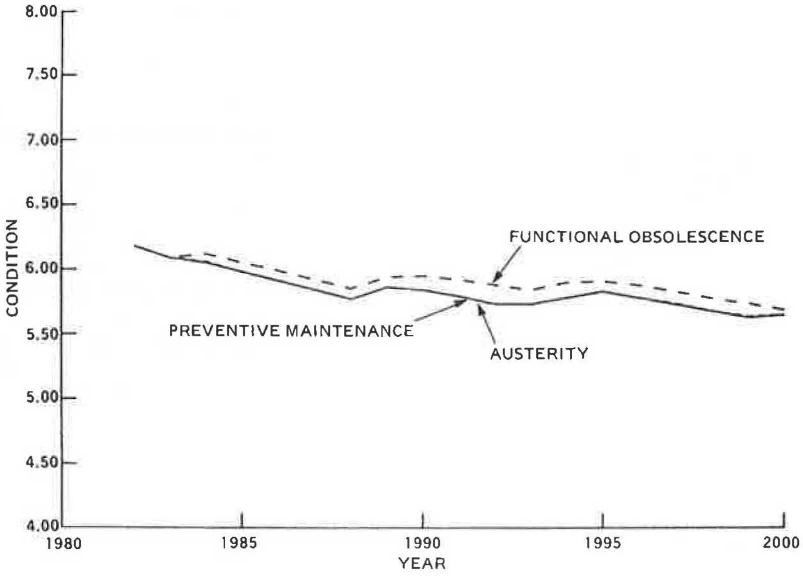


Figure 8. Change in condition over time.



these repair costs for the austerity option. Varying the discount rate from 4 to 10 percent showed virtually no change in the mix of replacement and repair work.

When one totals replacement and repair costs through 1999 in 1982 dollars, the austerity option ($371.3 million) proves to be the most inexpensive. The next most inexpensive is the functional obsolescence option ($476.3 million), and the preventive maintenance alternative ($484.0 million) is the most costly. However, by using real costs (1982 dollars) discounted at a 10 percent rate, the three options ranked from least to most expensive through 1999 are austerity ($168 million), preventive maintenance ($214 million), and functional obsolescence ($221 million).

Figure 8 shows that the functional obsolescence option would provide a small improvement in the average condition of the 4500 bridges compared with the austerity option. Both of these policy directions are represented by identical sets of life-cycle activity profiles. Changing condition is due to the changing age distribution and the number of bridges replaced in a year. The current version of the model does not revise condition appraisal when repairs occur, although deck replacement is the only kind of repair we considered that would actually increase condition appraisal given the way WisDOT revises condition ratings in the computer file on completion of work. Thus, it is not possible to assess the cost-effectiveness of different repair strategies in terms of their long-term effect on condition. In particular, one cannot compare the condition estimates for the preventive maintenance option, which had different life-cycle activity profiles (more frequent overlays and new decks), with the other two policy options.

Figure 8 also shows that the predicted average condition under each option declines over time. The decline is slightly overstated because deck replacement does not affect condition in the model. Nonetheless, the figure shows the approximate optimal path for this "state" variable for each option. Many analysts fallaciously believe that if the average condition appraisal of bridges is declining, then one should arrest the decline. If the repair and replacement mix has been determined by using a minimum-cost criterion, any attempt to increase the average condition by replacing or repairing more bridges would waste money; it would raise costs above the least-cost amount.

This model determines bridge replacement needs independently of highway improvements. In actual practice, many bridge replacement projects are tied to highway improvement projects. In these instances, bridge replacement needs should be examined in the context of a benefit-cost analysis of the entire highway project, including the bridge.

Finally, the model does not consider user benefits that would accrue if closed or posted bridges were replaced.

IMPLEMENTATION

Although the Department has historically been cost-conscious, it has applied life-cycle cost analysis to bridges only intuitively. To successfully implement the model, it was necessary to develop it under the auspices of the Bridge Committee, an in-house steering group. It included engineers from the Bridge Section (design and construction), the Bridge Maintenance Unit, the Highways Facilities Development Section, the Program Development Section, and the System Planning Section. Additional members represented policy planning and the budget shop. Many of the engineers accustomed to evaluating bridges from the facilities development perspective and relying on field inspections, input from district offices, and engineering judgment were uncomfortable with our approach at first but ultimately agreed the computer model was a useful tool for assessing midterm and long-term needs for the highway system plan. The model results, though considered tentative and subject to revision, are seen as providing part of the justification for the six-year bridge replacement program and the biennial budget submittal.

Continual improvements are planned for the model, including examining user benefits, adding budget constraints, and revising the forecast equations so that they capture the effects of repairs, traffic, and other factors. Although it was originally developed in the Division of Planning and Budget, the model is likely to be transferred to the Bridge Section. Then bridge engineers can use it themselves and more directly apply their skills and experience as we make enhancements. Future staff support for the model might require as little as one-quarter of a person-year annually. A person can learn to run the model with several days training, but some minor reprogramming is necessary if the list of repair types is changed.

CONCLUSIONS AND POLICY IMPLICATIONS

The model has revealed numerous important insights concerning bridge repair and replacement needs for state-owned bridges. These are as follows:

1. It is nearly always cheaper to repair than replace a bridge (except when widening is an option), provided a bridge has not become unsafe and beyond repair.
2. Wisconsin should replace between 27 and 38 bridges under state responsibility per year to the year 2000.
3. Wisconsin should let the average condition of bridges decline over the next two decades to take advantage of the remaining years of useful life in its bridges reflected in their age distribution. This conclusion assumes WisDOT always selects the least-cost option for repair and replacement work.
4. Major repair costs for concrete overlay work and new decks on steel deck girders and prestressed-concrete structures built after 1955 will increase substantially from the 1980s to the 1990s. The reason is that these bridges are reaching their midlife when significant repairs are typically required.
5. Implementation of the model has been achieved by involving key staff and decisionmakers in both the development and evaluation of the model as well as the results. Broad participation will be needed for both future applications and enhancements of the model.

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The results, views, conclusions, and recommendations are solely ours and not necessarily those of WisDOT.

REFERENCES

1. Special Bridge Replacement Program. U.S. Department of Transportation, Seventh Annual Report of the Secretary of the U.S. Department of Transportation to the Congress of the United States in Compliance with Section 144, Title 23, U.S. Code, Government Printing Office, Washington, DC, 1978.
2. Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges. FHWA, U.S. Department of Transportation, Jan. 1979.
3. State Highway Plan Special Report: Deficiency Analysis. Wisconsin Department of Transportation, Madison, Draft Rept., July 1982.
4. Six Year Highway Improvement Program, 1982-1987. Wisconsin Department of Transportation, Madison, Nov. 1, 1981.

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Performance Specification for Bridge Deck Joint-Sealing Systems

ARTHUR LINFANTE

A performance specification, although an unconventional approach, can be an effective way to ensure that only high-quality bridge deck joint-sealing systems are designed and selected for use. History of the past decade, when these systems were first used to seal the gap between moving bridge ends, has shown that the systems have not always been as durable as they need be to fulfill their intended function over the life span of the bridge. Disappointing results can be attributed in part to the relative newness of their application and unfamiliarity of the producers with the demands of the task. More important, shortcomings can be traced to a selection procedure that relies mainly on low initial cost rather than quality. Without the application of uniform standards by which to measure performance, there can be no means to judge the relative merits of candidate systems. A well-designed performance specification can meet this need. Although it would be desirable to force producers to guarantee their system's quality over the long term, the concept is contractually and practically untenable. A specification that embodies performance criteria for products to comply with prior to, and just after, installation can go a long way to ensuring that only systems that have a good chance of success are selected.

Two decades ago, the traditional approach to providing for bridge end movements greater than 1 in was to construct open joints. With the increasing use of salt compounds to maintain bridge decks free of ice, steelwork and concrete substructures in the vicinity of the joints suffered extensive deterioration as the waterborne corrosive agents spilled through and splashed on these surfaces. Oftentimes drainage troughs were constructed beneath the openings to collect deck runoff and direct it, via a plumbing system, to discharge away from the bridge. Usually these collection systems rapidly became clogged with accumulations of road debris. They soon became useless and, on occasion, broke away from their supports as the load carried within them increased and bridge vibrations caused their connections to fracture.

Clearly, the solution to the problem was to devise a joint seal capable of spanning a moving gap while remaining watertight.

For small movement ranges not exceeding 2.5 in, these needs were met with the development and widespread use of the compression seal. These seals, which can be as large as 6 in², are open-webbed neoprene products. Inserted within steel-armored joint edges, these seals have compiled an impressively successful record of accommodating bridge movements while maintaining watertight joints. The width of a properly selected model cycles between 20 percent (in warm temperatures) and 80 percent (in cold temperatures) of the unstressed width.

Unfortunately, manufactured products designed to