Life Cycle Performance of Bridge Components in New York City

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ABSTRACT

Bridge conditions in New York City are examined from an engineering management viewpoint. The objective is to optimize maintenance, repair and reconstruction expenditures over the structural life-cycle. Inspection records for the bridges and their components are reviewed. An attempt is made to develop relationships between the rate of bridge component deterioration in time and the maintenance operations. The most significant bridge components to emerge as targets of intensified maintenance are joints, bearings, wearing surface and paint. The article presents the current results of the continuing study conducted at the Bridge Management Unit of the New York City Department of Transportation.

BRIDGE MANAGEMENT PROBLEM

There were 770 bridges under the purview of the New York City Department of Transportation in 1998 and their average age was 72 years. (Roughly 100 culverts were eliminated from the total count reported in previous years and earlier publications.) Typical recent annual expenditures are approximately $450 to $500 million for bridge rehabilitation, $20 to 30 million for component rehabilitation, $20 million for maintenance and $25 million for repairs and hazard mitigation. The average bridge condition over the last 10 years has remained at a rating of approximately 4.5 on the New York State Department of Transportation scale. This state of bridge management equilibrium was described and analyzed in (*1*).

The City bridge managers must determine whether these annual expenditures of over $0.5 billion could be more effectively distributed among the above (or other) bridge related operations in order to achieve better bridge performance at lower costs. To this end the life cycle performance of bridge components has been continually studied. Yanev's model (*1*) divides bridges into groups and assign to these groups average condition ratings. If the overall average bridge condition rating is to remain constant over 2 consecutive years, Eq. (1) should be satisfied.

$$NR = \left[(N_1R_1 + N_2R_2)(N - N_3) - rN_0^2 \right] / (N_1 + N_2) + R_3N_3 \qquad (1)$$

Where: N - total number of bridges with overall average bridge condition rating R,
N_0 - bridges under regular maintenance with average condition rating R_0,
N_1 - bridges completing full rehabilitation with average condition rating R_1,

N_2 - bridges completing component rehabilitation, average condition rating R_2,
N_3 - closed bridges with average condition rating R_3
r - average annual deterioration rate of bridges N_0.

Yanev (*1*) demonstrates that the average bridge deterioration annual rate r is by far the dominant factor determining the overall average bridge condition rating in the model of Eq. (1). It is commonly assumed that bridge deterioration rates (in a relatively stable environment) are directly related to bridge maintenance. There is no known relationship, however, between specific maintenance operations and rates of bridge or bridge component deterioration. This is the main difficulty in estimating the cost and the exact type of the maintenance capable of reducing the rate of bridge deterioration r and consequently raising the overall bridge condition rating R of a large group of bridges, such as those in New York City. As part of a project for updating the New York City bridge Maintenance Manual (*2*), currently underway, a procedure is proposed for obtaining the required relationship between bridge maintenance and condition ratings. A description of the basic steps in resolving this fundamental bridge management problem follows.

AVAILABLE DATA

The available data consist of the following.

Bridge inspection condition ratings according to New York State Department of Transportation. Inspection reports are consistently available since 1982 for the bridges and all their components. Conditions are graded as follows: 7 - new, 1 - failed and 3 - not functioning as designed. Limitations of such condition ratings have been discussed at length, for instance in (*1*). Beyond their subjective and non-homogeneous nature, the ratings mostly indicate differences between inspected and as-built conditions. Thus, the inspector directly evaluates not the bridge capacity but, rather, its maintenance. This does not imply that a brand new structure with a potential instability should be rated 7 nor that an extremely deteriorated one, overdesigned by a factor of 10, should be rated 1. However, less extreme cases of the above paradoxical example have occurred. Despite this limitation, inspections of this type provide useful data, particularly for a large body of bridges, as long as it can be assumed that bridge design and construction have been generally adequate. Such inspections cannot provide estimates for a bridge rehabilitation scope of work.

Emergency reports of potentially hazardous conditions. These reports are termed "Flags." They can be structural or safety related; their priority varies from requiring prompt interim action to not requiring intervention prior to the next inspection. Flag incidence in New York City has escalated from 20 in 1983 to 3000 in 1996. It is estimated that currently one flag repair which mitigates the potential hazard but does not necessarily improve the structural condition (and its rating) costs the City approximately $15,000, not including user costs due to traffic delays. Flags were crucial for bridge inspections on the onset of the program, 20 years ago. At that time the occurrence of lifethreatening accidents had a much higher (and unknown) probability. As such conditions were steadily eliminated, "flag" report numbers escalated due to numerous subjective factors, but their hazard potential substantially declined. Yanev (*3*) demonstrated a successful empirical procedure for linking flag incidence to component condition rating.

Bridge design, construction and maintenance cost and performance information. The records of this essential information are neither complete nor entirely consistent but still provide important guidelines for estimating future construction and maintenance costs.

Engineering experience. It is essential to recognize that all inspection data is generated and evaluated by bridge engineers. Just the opposite of attempting to create a new "knowledge based system," this implies that such a system has been under development over the centuries. The first New York City Bridge Commission Report dates back to 1906. It is impossible to quantify the contribution of engineering knowledge to bridge management decision making but its presence is fundamental. Problems in bridge management typically arise as a result of ignoring engineering knowledge rather than due to its insufficiency. While future attempts to discretize engineering knowledge and build systems based on it can serve a positive role, the competent engineer should remain the leading factor.

DATA ASSESSMENT

An appropriate first step in the data assessment is to determine whether a deterministic or a probabilistic approach should be taken. The bridge management data of the above type could be modeled by fuzzy sets. Hence, recent publications, such as (*4*), point out that ". . . Many of these actions are highly uncertain, and therefore can be defined only in probabilistic terms . . ." (p. 934). Significantly, the same approach is implemented in bridge design with the replacement of the old Allowable Stress and Load Factor AASHTO Design code by the probability based Load and Resistance Factor Design (LRFD) code. The shift towards the probabilistic type of analysis is among the most significant recent developments in engineering practice. It points to the fact that uncertainties, inherent to structural engineering, are becoming more manageable. An attempt to describe some of the more obvious difficulties to be resolved in this process follows.

Parameters. Bridge design and bridge management both deal with structural capacity, structural condition, reserve and redundancy, but the terms are not identically defined in the two fields. Structural analysis, for instance, identifies the degree of redundancy with the degree of statical determinacy. Bridge inspection, on the other hand, identifies redundancy with the existence of alternate load path.

Scope. Strength of materials and structural analysis is highly advanced and the information they provide is of excellent quality, lending itself to a refined probabilistic treatment. Traffic data is less reliable, but still relatively comprehensive. Data on structural deterioration and consequent capacity loss, on the other hand, are much less reliable. Attention should be given to the superposition of parameters obtained probabilistically in domains with widely diverse order of reliability.

Fracture critical structural members (FCM), for instance, are defined in (*5*), p. 1, as "tension members, or tension components of members, whose failure *would be expected to result in collapse of the bridge.*" In (*6*), p. 18-1 the wording is ". . .*would probably cause a portion of or the entire bridge to collapse.*" The scope has been expanded in (*6*), but it would be hard to assign a numerical value to the increase in probability of taking partial failure into account due to the modified definition.

Constraints. The objective of any analytical method in engineering practice is to accurately model actual phenomena. Thus the probabilistic approach has a strong claim, since the phenomena under consideration are indeed of uncertain nature. Engineering practice, however, requires procedures which are highly probable to produce conservative, i.e., safe, results both by virtue of their analytic accuracy and their practical applicability. Practical guides, such as design or maintenance manuals, regardless of their theoretical basis, are applied in a deterministic procedure. Civil engineers take professional actions to ensure that structures are designed and managed in a manner safe for public use. Because of the high degree of reliability involved, cost and reliability are not commonly associated during design and maintenance of civil engineering projects. The position is tacitly taken that no cost should be spared to make a structure safe. Further optimization requires the same result at a lower cost. The engineering process often begins with deterministic analysis, provides empirical data, refines them in a probabilistic assessment and ends with an application, which, in hindsight, appears deterministic.

Beyond actual engineering, bridge management has to contend with political and social constraints as well. These constraints are uncertain to a degree that renders all engineering analysis axiomatic in comparison.

Objectives. In (*7*) the authors argue that ". . .The current deterministic and load factor methodologies for evaluation and design of highway bridges may lead to a considerable waste of resources because of overconservatism." It is pertinent, although beyond the scope of this article, that bridges were most frequently "overdesigned" by underestimating the torsional strength of the deck structure. Taking that strength into account has involved important empirical and deterministic analysis as well as the probabilistic one.

Relevant to bridge management is the example of the Williamsburg Bridge, which opened to traffic in New York City in 1903. In as-built condition, the bridge suspension cables should have had a strength reserve factor greater than 4 under today's live loads (based on certain assumptions). After years of deferred or inadequate maintenance, however, various studies (and divergent sets of assumptions) evaluated that reserve at a magnitude between 2.0 and 3.6. Clearly the original "overdesign" (which by today's standards may have been arrived at merely by ignorance) was the one engineering decision that saved the bridge. As ever the classic, John Roebling overdesigned the Brooklyn bridge by providing suspenders, stays and a stiffening truss. He argued that if either one of these systems should fail, the bridge would sag but not collapse. As it turned out, a hundred years later both diagonal stays and suspenders were near (and some beyond) failure due to an unforeseen factor—corrosion. The redundancy of the design rendered the repairs relatively easy.

While conservatism is definitely a feature of civil engineering practice, it is extremely difficult to establish to what extent and under what conditions it can be termed as "over." While ignorant overdesign is gradually eliminated from engineering analysis, it is essential to retain the wisdom that overdesigned all the great ancient structures still standing. Economy of material does not drive the economics of bridges. The currently achieved shortening of bridge life-cycles benefits neither users nor owners .

DATA FOR THIS STUDY

Based on the considerations stated above, the position is taken that the available data is too incomplete and non-homogeneous to be treated probabilistically. The approach taken is empirical. At any later stage a degree of probability can be assigned to each of the considered parameters and to the outcome of the analysis. The parameters used in the proposed procedure are contained in Tables 1 and 2. Relationships between them are assumed as follows:

The 13 bridge components of Tables 1 and 2 are used to determine the "Bridge Condition" rating by the New York State Department of Transportation formula. The lowest rating for each of the 13 components over all spans of a multi-span bridge is multiplied by the respective weight wi (Table 2). The resulting weighted average is the "Bridge Condition" rating (Eq. 2 below).

Table 1 also lists the fifteen maintenance activities j recommended for the New York City bridges in (*2*). Finally, the table contains importance factors Iij, ranging from 0 to 1, indicating the estimated effect of the 15 maintenance activities *(j)* on the 13 components *(i)*. Dual values of Iij are listed for items related to painting of steel but irrelevant to concrete. It is assumed that the following are given:

1. "Bridge Condition" rating based on the 13 essential lowest rated bridge components. The formula was established by New York State Department of Transportation on the onset of the inspection program, along with the weight factors wi. The latter were prescribed by the New York State Department of Transportation in the early stages of the bridge inspection program and have come under scrutiny for possible revision, yet they determine the "bridge condition" ratings, which drive the capital rehabilitation program. "Span Condition" ratings were later developed as well. A different "Bridge Condition" formula, with a stronger bias towards maintenance, rather than rehabilitation, is also under consideration.
2. Deterioration rates of the 13 bridge components at no maintenance. One approach is to examine the 13 components as they appear in all 4700 City bridge spans, review all known ratings and obtain average ones for every age. Such deterioration curves were generated and presented, for instance in (*1*). Usually, they yield a rate of deterioration about half as fast as the one indicated by reconstruction and replacement needs. The average ratings usually approach the rating of "3" (not functioning as designed) asymptotically and, contrary to practical knowledge, rarely decline below that rating. This is attributed to the effect of the intensified but highly uneven and poorly documented

Table 1: Importance Factors Iij, *Relating Maintenance Activities to Bridge Component Ratings*

	i	1	2	3	4	5	6	7	8	9	10	11	12	13
	BR. COMPONENTS / **Maint. Activity**	**Bear.**	**Bwall**	**Abut.**	**Wwall**	**Seats**	**Prim. Mem.**	**Secon. Mem.**	**Curbs**	**Side Walk**	**Deck**	**Wear. Surf.**	**Piers**	**Joints**
	DEBRIS REMOVAL	0.7	0.5	0.2	0.1	0.8	0.5	0.5	0.8	0.8	0.8	0.9	0.1	0.8
	SWEEPING	0.2	0.1	0.1	0	0.5	0.5	0.5	1	0.8	0.9	1	0.1	1
	CLEAN DRAIN	0.9	0.9	0.9	0.8	1	1	1	1	1	1	1	0.5	1
4	**CLEAN ABUT./PIERS**	1	1	1	0.9	1	0.8	0.8	0	0	0.5	0.5	1	0.5
5	**CLEAN GRATINGS**	1	0.5	0.7	0.1	1	1	1	0.1	0.1	0.8	1	1	0.9
6	**CLEAN EXP. JOINTS**	1	0.8	1	0.5	1	1	0.8	0.5	0.5	0.9	0.9	0.9	1
7	**WASH DECK ETC.**	0.5	0.3	0.2	0	0.6	0.4	0.4	1	0	1	1	0.4	1
8	**PAINT**	1 / 0[a]	0.5	0	0	1	1 / 0[a]	1 / 0[a]	0	0	0.4	0	1/.1 [a]	0.5
9	**SPOT PAINT**	1 / 0[a]	0.5	0	0	1 / 0[a]	1 / 0[a]	1 / 0[a]	0	0	0	0	1 /.1[a]	0
10	**PATCH WALKS**	0	0	0	0	0	0	0	1	1	0.1	0.1	0	0.5
11	**PAVT & CURB SEAL**	1	1	1	0.5	1	1	1	1	1	1	1	0.5	0.5
12	**ELEC. DVC MAIN.**	0	0	0	0	0	0	0	0	0	0	0	0	0
13	**OIL MECH. COMPS**	1	0.5	0.5	0.2	1	1	1	1	0	0.5	0	1	1
14	**REPL. WEAR. SURF.**	0	0.1	0	0	0.1	0.1	0.1	0.5	0.5	1	1	0.1	1
15	**WASH UNDERSIDE**	1	1	1	0.5	1	1	1	0	0	0.8	0	1	0.9

[a] Steel / Concrete.

Table 2: Shortest Life (L_{i0}) and Weights (w_i) of Bridge Components

Component i	Lio [years]	w_i
Bearings	20	6
Backwalls	35	5
Abutments	35	8
Wingwalls	50	5
Bridge Seats		6
Primary Member	30/35[a]	10
Secondary Member	35	5
Curbs	15	1
Sidewalks	15	2
Deck	20/35[a]	8
Wearing Surface	15/20/30/35[a,b]	4
Piers	30	8
Joints	10	4

[a] Values correspond to with/without joint.
[b] Values correspond to thin bonded overlay/separate wearing surface.

maintenance and repair work, which has had a pronounced but unquantifiable effect on the condition ratings over the 18 years of bridge inspection records. On the contrary, this study needs the fastest known rates of deterioration, corresponding to the "no maintenance," for the 13 components and for the overall bridge condition ratings. Examples of results closer to satisfying this requirement have been presented in (*8*). These results were obtained by reviewing all available records of component deterioration and selecting the ones with the fastest rate. The shortest observed component life at no maintenance is shown in Table 2. Other components, such as scuppers and paint, were investigated because they are addressed by some of the 15 maintenance activities, even if they do not appear explicitly in the bridge condition formula. While it is impossible to assert that the component life-spans thus obtained contain no maintenance and repair effect at all, they are the shortest on record. It is known that during the 1970's bridge maintenance in New York City, if any, was minimal. It is also possible that a bridge component early failure was caused by accident or atypical malfunction. This conjecture, however, is refuted by the systematic recurrence of the shortest life-cycles and by the type of failure involved. The steepest deterioration rates are typically linear or bi-linear. Linear deterioration is the first approximation taken herein. Condition ratings of "1" or "2" are assumed as the lowest under which the bridge can safely operate. In this case, the conservatism of the method providing the data is essential. It is known that bridges rated 1 do not fail, although they are load-posted and receive emergency repairs. Nonetheless, a rating of "2" should be the minimum for primary members, decks and piers in a procedure such as this one.

3. Deterioration rates of the 13 bridge components at "full" maintenance. This is a far-fetched assumption. There is no "hard" data on structural performance under "full" maintenance. The concept of "full maintenance" will change with new designs or policies,

most importantly those related to painting of structural steel, elimination of salt for roadway de-icing, new types of concrete, joints, bearings, etc. It is necessary to assume a "maximum" component and, consequently, bridge life in order to assess the benefits of "full" maintenance. It is due to the low reliability of such an assumption that the entire concept of "full" maintenance is always questioned by budget authorities and never fully funded. Work on the optimal maintenance needs for the City bridges is in progress.

4. Maintenance and replacement activities j and their unit costs. Unit costs are available from the Bridge Maintenance Unit. The report (*2*) has investigated maintenance policies of a large number of bridge owners and the 15 maintenance activities listed in Table 1 are recommended as a result.

5. Bridge replacement costs. These are available from the Bridge Design/Construction Units. Typically, full bridge rehabilitation or reconstruction is expected to cost approximately $4840/sq. meter ($450/sq. ft.) of bridge deck.

6. Maintenance importance factors Iij as defined above. Iij are based on the experience of bridge engineers in charge of maintenace and inspection, e.g., they have a subjective nature akin to the one of the weights wi. Iij are a priori different for concrete and steel bridges, but further differences depending on the age of a bridge, the detailing of the structure, etc. will always exist. In a refined application of this approach, Table 1 would have to be prepared for each bridge and revised as experience is gained.

7. User costs due to traffic delays caused by bridge structural accidents, repairs and rehabilitation. These can be assumed on the basis of traffic data and economic indicators, but their assessment remains speculative. Costs incurred by the vehicle operators due to time lost and by the City due to lost business should be considered separately.

THE MODEL

The overall bridge condition rating *R* can be expressed as a function of the condition ratings *Ri* of the 13 bridge components of Table 1 as follows:

$$R = \sum_{i=1}^{13} kei\ Ri \tag{2}$$

where: *kei* are the normalized values of the weight factors *wi*, shown in Table 1,

Ri are the condition ratings of the 13 bridge components listed in Table 1.

If bridge component deterioration patterns at no maintenance and at "full maintenance" are known and if there is a direct linear relationship between intermediate maintenance levels and component condition ratings *Ri*, any level of maintenance *Mij* can be related to the condition rating of a bridge component deterioration rate *ri* by the importance factors *Iij* as follows:

$$ri = (ri_1 - ri_0)\sum_{j=1}^{15} kij\ Mij + rio \tag{3}$$

where: ri_1 and ri_0 are the deterioration rates at "full" and at no maintenance,

Mij are the maintenance levels for the 15 maintenance operations of Table 1,

kij are the normalized values of the influence factors *Iij* listed in Table 1.

From Eq. (2), the overall bridge deterioration rate *r* is:

$$r = \sum_{i=1}^{13} kei\ ri \tag{4}$$

Annualized costs can be computed and compared for different levels of maintenance M and respective bridge life-cycles, as defined by the deterioration rate r. Eq. (1) can then show the estimated average overall bridge condition rating, given known costs. The expected bridge life L can be expressed in terms of the known bridge life at no maintenance L_0 and the expected bridge life at "full" maintenance L_1 as follows:

$$L = (L_1 - L_0)M + L_0 \tag{5}$$

Assuming average distribution of bridges along the rating scale, the number of bridges entering or completing full and component rehabilitation (N_1, N_2 and N_3 in Eq. 1) can be expressed as a function of L. It is well known that such an assumption is currently not realistic. As shown in (*1*), the distribution of New York City bridge condition ratings is normal, and peaks around 4.5 with a standard deviation of 0.9. A considerable concentrated investment would be required before the above assumptions could become representative of the bridge maintenance needs.

WORK IN PROGRESS

Work is currently in progress at New York City Department of Transportation, Bureau of Bridges, and at Columbia University to broaden the scope of the study, imposed by the simplifying assumptions introduced herein. Most significant are the following subjects under consideration:

The "levels of maintenance *Mij*." It is realized that the "level of maintenance" is typically discontinuous and frequently consists of either performing a certain operation or not, although cycles of varying length are also possible, for instance in painting and washing of bridges. The continuous "level of maintenance" will eventually be replaced by discrete maintenance levels known to be of practical significance.

Bridges in different condition. As presented here the work truly applies to new bridges. Increasing the level of maintenance for a bridge well down on the deterioration path does not change the deterioration rate according to this model. The concept of component rehabilitation which is already applied to the City bridges will be incorporated in the maintenance strategies.

Structural diversity. Not only concrete versus steel but also different structures within those larger categories will be distinguished.

Types of maintenance. The effectiveness of the 15 maintenance operations is subject to review and optimization. Other maintenance operations may be considered as well. Extending the results reported in (*8*), bridge components with a significant contribution to the overall bridge condition and a consistent history of early failure, such as joints and scuppers, are identified as targets for more intensive maintenance or, depending on the cost analysis, early replacement. It is noted that some of these components, paint, scuppers and wearing surface in particular, do not appear explicitly in the bridge condition formula (Eq. 2 herein). Implicitly they are represented by the influence coefficients *Iij*, which are established in a highly subjective manner. The next step is to better quantify these factors. Particularly significant are the current developments in bridge painting strategies.

User costs to the community and the City can be incorporated in the annualized bridge maintenance and reconstruction costs.

The proposed method is a first step in establishing a more rigorous relationship between bridge maintenance expenditures and bridge conditions. It provides a flexible relationship, which can be the subject of continuing refinement and optimization.

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DISCLAIMER

The views stated in this article are those of the authors and do not represent the position of any organization or agency.

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