Application of the Analytic Hierarchy Method to Setting Priorities on Bridge Replacement Projects

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The bridge rehabilitation and replacement project ranking procedures currently available can be grouped into three types: sufficiency rating, level-of-service deficiency rating, and cost-effectiveness rating. These procedures help, to some extent, to set priorities on bridges that may be eligible for funding and hence for implementation. However, most of the currently available procedures do not incorporate possible subjectivity, fuzziness, or personal preferences of the decision makers involved in the bridge programming process. The analytic hierarchy method, based on the eigenvalue approach, provides a decision-making method that allows transformation of subjective judgments into quantitative values for ranking alternatives. This method also provides an opportunity for decision makers to discuss the issue, clarify relationships among criteria, and reach a consensus about the resulting judgments. The procedure for using the analytic hierarchy method in decision making is described and illustrated in an example using a simple, three-strata hierarchy pertaining to the ranking of bridge replacement projects. In the example, the analytic hierarchy method was modified by incorporating utility curves so that the method could be applied to a large-scale problem. This example shows that the analytic hierarchy method can be effectively used for setting priorities on rehabilitation and replacement projects.

In recent years there has been a growing concern about the safety of existing bridges. This concern is shared by highway agencies at all levels of government *(1)*. The FHWA rated about 45 percent of the existing bridges in the United States as either functionally or structurally deficient *(1)*. In an effort to alleviate the nation's bridge safety problem, a federally mandated system for bridge inspection, evaluation, and reporting was established *(2)*. Data collected by this system became a valuable source for assessing levels of federal funding for deficient bridges.

As a bridge-ranking index, FHWA developed the sufficiency rating, which ranges from 0 to 100 points. This index is computed using structural condition ratings of bridge components and other information such as serviceability and essentiality of bridges *(2)*. A bridge is considered structurally deficient (SD) if its deck, superstructure, or substructure has weakened or deteriorated to the point that the bridge is inadequate to support all types of traffic *(1)*. A bridge is considered functionally obsolete (FO) if deck geometry, load-carrying capacity, clearance, or approach roadway alignment no longer meets the usual criteria for the system of which it is a part *(1)*. An SD or FO bridge with a sufficiency rating of less than 50 is eligible for federal bridge funds for replacement. An SD or FO bridge with a sufficiency rating between 50 and 80 is eligible for federal bridge funds for rehabilitation. FHWA, however, provides the states and other bridge owners flexibility in selecting bridges. Such procedures should reflect state needs and local input to ensure a fair and equitable distribution of funds throughout the state because these funds are limited, despite the growing need for bridge improvements.

Evaluating bridge rehabilitation and replacement alternatives is one of the major tasks in the field of highway improvement programming because bridges play a strategically important role for the well-being of the entire highway network. However, decision makers who decide on the allocation of funds must often rely on subjective judgments, namely condition ratings, to determine the comparative effectiveness of alternative bridge projects to meet the goals of bridge conditions in the state. Besides the structural condition, other factors such as traffic safety, average daily traffic (*ADT*), and costs need to be included for ranking consideration. Setting priorities on bridge-related projects can be a typical multiattribute decision-making problem that requires the decision maker to simultaneously evaluate several decision factors. Therefore, a systematic evaluation procedure is needed that can not only quantify subjective judgments, but also incorporate values of different units into a single decision-making scale. The procedure must also be a flexible one that reflects the opinions and the preferences of decision makers of the agencies involved.

Most priority-setting procedures available today for bridge project ranking do not have a mechanism to allow for a weighted consideration of many important measures of effectiveness that decision makers want to include. Therefore, there is a need for a methodology that can help decision makers reach the best trade-off solutions that will meet their desired goals.

In this paper, a multiattribute bridge evaluation methodology using the analytic hierarchy method developed by Saaty *(3)* is discussed and used to evaluate sample bridge replacement projects. Development of weight normalization methods, utility curves, and the use of weights to represent the relative importance of different criteria are illustrated. The result of this method is compared with the result of the successive subsetting method, which was originally used to solve this sample replacement problem *(4)*. The main objective of this paper is to develop and test a systematic methodology for evaluating bridge rehabilitation and replacement projects for the equitable allocation of available funds.

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LITERATURE

The bridge rehabilitation and replacement project ranking procedures currently available and known to the author can be grouped into three types: sufficiency rating, level-of-service (LOS) deficiency rating, and cost-effectiveness rating. The sufficiency rating approach *(2)* is often used as a reference at the state level of bridge management. The LOS approach was developed first in North Carolina *(5)*, based on an idea that priorities must be determined by the degree to which a bridge is deficient in meeting public needs. Major indices used by this method include single-vehicle load capacity, clear bridge deck width, vertical clearance, and remaining service life. In Pennsylvania, this LOS technique was modified so that structural condition elements were incorporated into the ranking process *(6)*. A type of bridge project ranking procedure based on life-cycle cost analysis was developed in Wisconsin and used in an actual highway programming process *(7)*. This procedure is based primarily on the cost-effectiveness approach that was also used as part of the bridge management system in Pennsylvania *(8)*.

These procedures become a stepping stone to advance techniques of bridge management systems. However, these procedures do not fully incorporate the subjective judgments or preferences of the decision makers, from inspectors to planners, into the priority setting process. An evaluation procedure needs to take into consideration the different perspectives of all the relevant decision makers at different levels of management so that final decisions can be consistent among the agencies.

Decision-making science has recently developed significantly, and techniques that deal with multiattribute problems have become widely accepted. Keeney and Raiffa's utility theory *(9)*, which has been used in transportation-related problems, has appeared to be effectively incorporated into decision making *(9, 10)*. This technique has been theoretically proven; however, it is considered to be the most complex among the multiattribute decision-making techniques available *(11)*.

Nijkamp's concordance analysis *(12)* is another technique that has been used to solve transportation problems. Janarthanan and Schneider *(13)* used it for selecting the best transit improvement alternative; Shiraishi, Furuta, and Hashimoto *(14)* used it in a bridge evaluation problem. This technique is based on a series of pairwise comparisons across a set of criteria. Concordance analysis seems to work for a small set of alternatives; however, it may be inefficient for a large-scale problem in which there are several hundred alternatives, because matrices of pairwise comparisons become extremely large and pairwise comparisons become time consuming.

Srinivasan and Shocker developed a multiattribute problem-solving process using linear programming techniques *(15)*. This method was also based on pairwise comparisons and was theoretically proven; however, like concordance analysis, the number of pairwise judgments increases as $n(n - 1)/2$, where n is the number of alternatives, when the number of alternatives increases. Moreover, the decision maker must consider all included criteria simultaneously when making pairwise judgments. The weights of the criteria are unknown to the decision maker by this method, but the decisions must be determined by paired alternatives. The outcome of this method is a set of weights for the alternatives.

After the flexibility in reflecting the decision maker's judgments at any level of the hierarchy of desired criteria and the applicability to a large-scale problem were considered, the analytic hierarchy (AH) method *(3)* was chosen for this paper to develop an effective bridge priority-setting procedure. This method has been used in many areas for which subjective judgments can be the only way to scale the importance of criteria and alternatives involved. It allows the decision maker to stratify criteria into several clusters. The essence of this method is discussed in the following section.

THE AH METHOD

The AH method was developed by Saaty *(3)* to solve a wide variety of allocation and strategic planning problems for corporate and international organizations. Its approach is to "systematize the assessment of judgments in complex situations in which an implicit objective criterion is multidimensional and perhaps only vaguely realized." The AH method reduces the study of intricate systems to a sequence of pairwise comparisons of properly identified components.

Hierarchies

Hierarchies are basic to the human way of breaking reality into clusters and subclusters. When priorities are set, first objects or ideas and relations among them are identified. That is, the complexity encountered is decomposed. Then, relations discovered among components are synthesized. This effort mentally simulates a decision-making system that is an abstract model for a real-life decision structure. A hierarchy is this abstraction of the structure of a system to study the functional interaction of its components and their impacts.

The goal of a hierarchical approach is to seek understanding of a decision problem at the highest level from interactions of the various levels of hierarchy rather than directly from the elements of the levels *(3)*. Two components must be considered in the hierarchical structuring of systems: structuring functions of a system hierarchically and measuring the impacts of any element in the hierarchy *(3)*. For the first component, a careful abstraction of the structure needs to be made so that the strata in the hierarchy can be as independent as possible. For the second component, a mathematical theory of hierarchies was developed for evaluating the impact of a level on an adjacent upper level from the composition of the relative contribution (priorities) of the elements in that level with respect to each element of the adjacent upper level. That is, elements within a stratum are evaluated by pairwise comparisons with respect to the characteristics in the immediate higher stratum. Saaty *(3)* includes a detailed description of the mathematical development of this method.

Measurement of Importance

A simple example of setting priorities on three bridges is used to describe how their importances, or weights, are measured. In this example, the ranking of three bridges *A*, *B*, and *C* was analyzed. Figure 1 shows the employment of a simple three-strata hierarchy system. The first stratum (highest level in the hierarchy) was the ranking of the three bridges. In the second

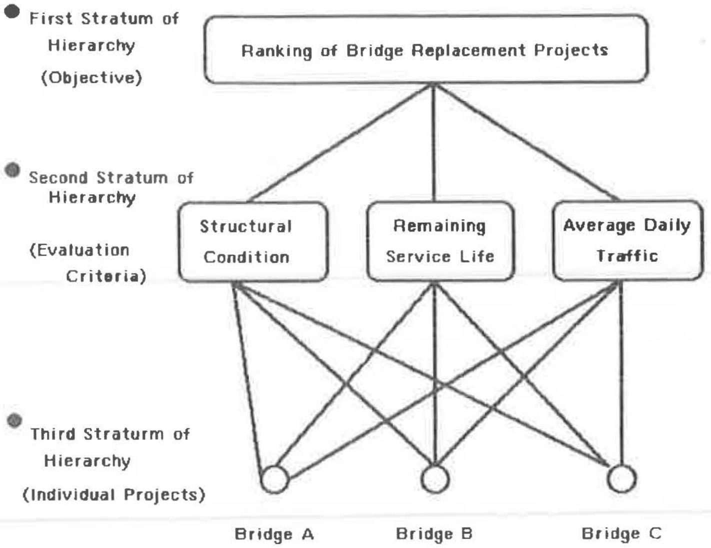

FIGURE 1 A sample hierarchy system for ranking three bridge replacement projects.

stratum, three evaluation criteria were used for comparison: structure rating, remaining service life, and *ADT*. The third stratum consisted of the three bridges. Data for these three bridges were as follows:

	Bridges		
Criterion	*A*	*B*	*C*
Structure rating	3	4	5
Remaining service life	15	15	20
ADT	2,000	3,000	10,000

Pairwise judgments were first made among individual projects with respect to each evaluation criterion in the next highest stratum by using a 1-to-9 scaling system, presented in Table 1. This scaling system is based on the psychological limit (7 ± 2) of humans in simultaneously comparing multiple alternatives *(3)*. Results of pairwise comparisons were entered into a reciprocal matrix, for which only the cells in the top half-triangle were filled, the cells in the lower half-triangle containing their reciprocals. Pairwise judgments were transformed into a set of scaling values by using the eigenvalue approach *(3)*. The eigenvalue approach for pairwise comparisons provides a way for calibrating a numerical scale for cases for which measurements and quantitative comparisons do not exist.

Pairwise comparisons of the three evaluation criteria with respect to the ranking of the bridges for $\lambda_{max} = 3.065$, $CI = 0.033$, $CR = 0.06$, and eigenvector = (0.73, 0.19, 0.08) follow:

Criterion	*Structure Rating*	*Remaining Service Life*	*ADT*
Structure rating	1	5	7
Remaining service life	1/5	1	3
ADT	1/7	1/3	1

Pairwise comparison tables for the three bridge projects with respect to the three evaluation criteria follow. For $\lambda_{max} = 3.094$, $CI = 0.047$, $CR = 0.08$, and eigenvector = (1.00, 0.27, 0.09), the comparison table is

	Structure Rating (S)		
Bridge	*A*	*B*	*C*
A	1	5	8
B	1/5	1	4
C	1/8	1/4	1

For $\lambda_{max} = 3.000$, $CI = 0.00$, $CR = 0.00$, and eigenvector = (1.00, 1.00, 0.25), the comparison table is

	Remaining Service Life (R)		
Bridge	*A*	*B*	*C*
A	1	1	4
B	1	1	4
C	1/4	1/4	1

For $\lambda_{max} = 3.065$, $CI = 0.03$, $CR = 0.06$, and eigenvector = (1.00, 2.33, 9.02), the comparison table is

	ADT (T)		
Bridge	*A*	*B*	*C*
A	1	1/3	1/7
B	3	1	1/5
C	7	5	1

Structure rating was believed to be strongly more important than remaining service life; therefore a scale value of 5 was entered. A reason for the difference was that structure rating reflected physical distresses observed by inspectors, whereas remaining service life was simply an estimate made by inspectors. Similarly, when structure rating was compared with *ADT*, the former was strongly more important than *ADT*; therefore, a scale value of 7 was inserted. A reason for this value was that deficient bridges should be repaired first and *ADT* should be a secondary factor. When remaining service life and *ADT* were compared, it was believed that remaining life was weakly more important than *ADT*; hence, a scale value of 3 was inserted. The reciprocal matrix was then constructed by setting $a_{ji} = 1/a_{ij}$. Similarly, reciprocal matrices for comparing the three bridge projects with respect to the evaluation criteria were

TABLE 1 IMPORTANCE OF ALTERNATIVE SCALE *(3)*

Intensity of Importance	Definition	Explanation
1	Equal Importance	Two activities contribute equally to the objective
3	Weak importance of one over another	Experience and judgment slightly favour one activity over another
5	Essential or strong importance	Experience and judgment strongly favor one activity over another
7	Very strong or demonstrated importance	An activity is favoured very strongly over another; its dominance demonstrated in practice
9	Absolute importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between adjacent scale values	When compromise is needed
Reciprocals of above nonzero	If activity i has one of the above nonzero numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i	A reasonable assumption
Rationals	Ratios arising from the scale	If consistency were to be forced by obtaining n numerical values to span the matrix

constructed. Attention should be paid to the orientation of each question. For instance, the traffic on Bridge A was less than that on Bridge C and was also less than the difference in traffic between the two bridges. In this comparison, Bridge C was demonstrably more important than Bridge A; therefore, a scale value of 1/7 was entered for Bridge A with a reciprocal value of 7.

After values of eigenvectors were normalized, a matrix for bridges versus criteria was constructed. When this matrix multiplied a transposed normalized column eigenvector of the criteria, the values in the product column vector became the weights of the three bridge projects.

$$\begin{vmatrix} 0.73 & 0.44 & 0.08 \\ 0.20 & 0.44 & 0.19 \\ 0.07 & 0.11 & 0.73 \end{vmatrix} \begin{vmatrix} 0.73\,(S) \\ 0.19\,(R) \\ 0.08\,(T) \end{vmatrix} = \begin{vmatrix} 0.62\,(A) \\ 0.27\,(B) \\ 0.13\,(C) \end{vmatrix}$$

Consistency Check

Consistency in the AH method means not only the traditional requirement of the transitivity of preferences, but the actual intensity with which the preference is expressed *(3)*. If a reciprocal matrix is perfectly consistent, its rank is unity and the sum of the eigenvalues is the trace $\sum a_{ii} = n$. The largest eigenvalue is $\lambda_{\max}$ and all other eigenvalues become zero. In general, however, a reciprocal pairwise comparison matrix does not yield a consistent matrix. However, it is known that the largest eigenvalue would remain near n and the remaining eigenvalues are near zero, although the consistency is perturbed *(3)*.

The results of weight determination become more consistent the closer $\lambda_{\max}$ is to n. Saaty *(3)* proposed that consistency of pairwise judgments be measured by the consistency index *CI*, defined as $(\lambda_{\max} - n)/(n - 1)$. The *CI* in question is compared with the consistency index of a randomly generated reciprocal matrix, on a scale of 1 to 9, called the random index *RI (3)*. The ratio of *CI* to average *RI* for the same order matrix is called the consistency ratio *CR*. A *CR* of 0.10 or less is considered acceptable and the corresponding matrix is considered to be consistent *(3)*.

In the simple example, pairwise judgments were all consistent, as indicated in the tables. When the ratio matrix (reciprocal matrix) is not consistent and the *CI* is sufficiently large, judgmental revision is warranted *(3)*. However, judgments should not be forced to be consistent, because such restrictions would distort results.

Setting Priorities on Bridge Replacement Projects

The AH method was used to set priorities on a set of 22 proposed bridge replacement projects used in a previous study *(4)*. The same sample set was used to compare the result by the AH method and the successive subsetting (SS) method used in the previous study *(4)*. The SS method is a subjective partitioning of candidate bridges into clusters according to a given set of criteria. No scaling is involved in the method. No numerical values are assigned to the alternatives.

Exactly the same criteria were used to make the decision under the same environment. These criteria as listed in Table 2 include physical condition of the bridge structure, remaining service life, curb-to-curb deck width, road narrowing, approach alignment, and the ratio between *ADT* and the state's share of construction cost. The ranking shown in Table 2 does not necessarily mean dominant preference of one criterion over another. A weak preference may exist between the adjacent two criteria.

In actual bridge improvement programming, many decision makers are usually involved. This group may include bridge inspectors, bridge designers, highway improvement planners, maintenance engineers, planners, and academicians. In this sample application, the author acted as the sole representative of the decision-making group. It is necessary that decision makers be familiar with bridges and their performance. The eigenvalues and eigenvectors of ratio matrices were obtained by using the EIGRF routine available in the IMSL library *(16)*. This routine provides eigenvalues and eigenvectors of a real general matrix.

Introduction of Utility Curves

First, a simple, three-strata hierarchy similar to the one shown in Figure 1 was considered. However, many bridges with the same condition ratings should be given the same weights. Also, filling a large reciprocal matrix is extremely tedious and may confuse decision makers. For instance, filling a 22 × 22 matrix required 231 pairwise comparisons. For six criteria, this meant 1,386 comparisons. Because eigenvalues exist to any *n*-rowed square matrix, regardless of whether or not the matrix is singular or nonsingular *(17)*, it would be necessary that a reciprocal matrix be checked carefully before eigenvalues are obtained. It is highly recommended that the size of a reciprocal matrix be small, say of dimension 10 × 10 to 15 × 15, to ensure accurate pairwise judgments.

Therefore, this three-strata hierarchy system was modified, as shown in Figure 2, and a concept of utility curve was introduced. The minimum and maximum values of each criterion were first set and the range between these two extreme points was divided into proper segments. For instance, if the maximum and minimum values of structure condition rating of candidate bridges were 7 and 3, respectively, the range was divided by ratings between the two values, that is, 4, 5, and 6. Instead of making pairwise comparisons of bridge candidates with respect to six criteria, the levels of each criterion measure were compared pairwise using the eigenvalue approach with respect to the objective, that is, ranking of bridge replacement projects. The utility curve for an evaluation criterion was drawn using the eigenvector corresponding to λ_{max}. Although the inclusion of utility curves in the algorithm deviates from Saaty's original method *(3)*, such modification would be more practical for a large-scale problem because the decision maker could spend more time evaluating the importance of the criteria themselves than simply comparing paired alternatives. When a reciprocal matrix became inconsistent, adjusting the values of entries of the matrix by trial and error was repeated until the consistency ratio of the matrix became less than 0.10. By this method, all pairwise comparisons were reviewed and

TABLE 2 PRIORITY EVALUATION CRITERIA FOR THE SELECTION OF BRIDGE REPLACEMENT PROJECTS *(4)*

Impact Category	Rank	Evaluation Criteria
Structural Condition	1	Minimum of Superstructure Condition and Substructure Condition
	2	Estimated Remaining Service Life in Years
Traffic Safety	3	Curb-to-Curb Deck Width
	4	Road Narrowing on Bridge
	6	Approach Alignment
Service and Highway Department Cost	5	ADT (Average Daily Traffic)/ State Share of Construction Cost

Note: The rank shown above does not necessarily mean a a dominant preference of one over another. A weak preference may exist between the adjacent two criteria.

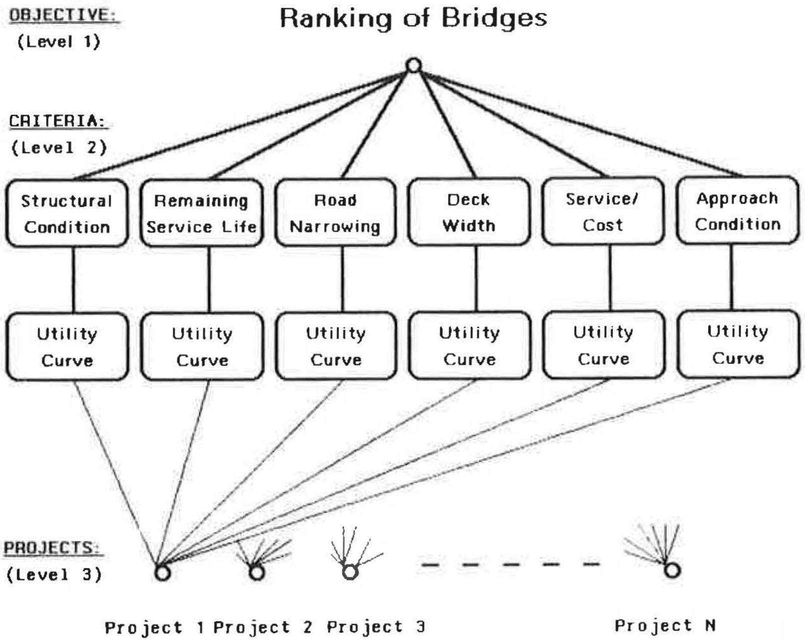

FIGURE 2 Hierarchy system for bridge replacement problem.

pairwise relationships were restructured. Saaty *(3)* provides alternative methods to review previously made judgments.

Weights of candidate bridges with respect to each evaluation criterion were computed by normalizing values obtained from its utility curve. Weights of the six evaluation criteria were determined by an ordinary eigenvalue computation method. After the weights of the elements of the second and the third strata were generated, they were synthesized for each alternative in the same manner as that used for the simple example, and final weights were obtained. Bridge projects were then sorted in descending order of synthesized final weights. The selection of projects for implementation was made using the final weights.

RESULTS

The six criteria were first compared pairwise according to their relative dominance in contributing to the overall priority of individual bridges. Table 3 presents the reciprocal matrix for the six criteria. Note that structural condition is strongly dominant over approach condition and therefore the latter cell received a 6. Another example is the deck width cell and the road narrowing cell. The latter criterion received a 2 compared with the former criterion, implying that the deck width was judged to be only slightly more important than the road narrowing.

The last column of Table 3 gives the values of the eigenvector. The normalized values of the eigenvector for the six criteria are also given in Table 3. They show that the structural condition was placed as most important, followed by the remaining service life. Criteria related to traffic safety received relatively large weights. However, the service/cost quotient criterion had a relatively insignificant weight.

In this pairwise comparison of the criteria, the judgments were highly consistent, as presented in Table 3. The consistency index *CI* became 0.024, which was small compared with its numerically determined expected value of 1.24 (*RI* in Table 3) from a randomly generated matrix of the same order *(3)*. The consistency ratio (*CR*) for this case was therefore 0.02, indicating the pairwise judgments were consistent.

Comparisons among the levels within each criterion were then made in a similar manner. Table 4 presents a pairwise comparison matrix in which the condition rating is defined as the minimum of the condition ratings for the superstructure and substructure. Utility curves of these criteria were drawn using their eigenvectors. Figure 3 shows a utility curve for condition rating that was developed based on the eigenvector of the matrix. The utility curve graphically shows how much utility would be assigned to a project when a bridge is replaced at a certain rating.

In this pairwise comparison, Condition Rating 3 was given the highest utility, three times higher than Condition Rating 4. In the condition rating scale, a bridge with Rating 3 is considered to be in poor condition, and would require immediate repair or rehabilitation *(2)*. However, at 4, this bridge is still at a marginal condition. The potential exists for major repair or rehabilitation, but it is not as serious as the bridge at Rating 3. Ratings 3 and 4 are actually key decision-making points for selecting bridges for rehabilitation based on condition rating. Therefore, it seems this utility curve translates closely the decision maker's judgment about the impact of structure rating on priority setting.

Another example of the utility curve for the service/cost quotient criterion is shown in Figure 4. This curve became S-shaped like the logistic curve or the choice probability curve, which are frequently used for modeling the consumer's choice behavior *(18)*. A utility curve of this shape implies that the decision maker is indifferent to a change in the level of cost-related evaluation measure near the upper and lower limits; however, between the limits the decision maker becomes sensitive. This tendency appears to reflect a reasonable attitude for making decisions on economic matters.

TABLE 3 RECIPROCAL MATRIX, EIGENVALUE, AND EIGENVECTOR FOR SIX ATTRIBUTES

	Attributes						Eigenvector
	Structural Condition	Remaining Service Life	Deck Width	Road Narrowing	Service/ Cost	Approach Condition	
Structural Condition	1	2	3	4	5	6	1.0000
Remaining Service Life	1/2	1	2	3	4	5	0.6546
Deck Width	1/3	1/2	1	2	3	4	0.4172
Road Narrowing	1/4	1/3	1/2	1	2	3	0.2631
Service/ Cost	1/5	1/4	1/3	1/2	1	2	0.1675
Approach Condition	1/6	1/5	1/4	1/3	1/2	1	0.1119

λ_{max} (Eigenvalue) = 6.12 C.I. = 0.024 R.I. = 1.24 C.R. = 0.02 < 0.10

Normalized Weights of Six Attributes

Structure Condition = 0.38251
Remaining Service Life = 0.25039
Bridge Deck Width = 0.15958
Road Narrowing = 0.10064
Service/Cost = 0.06417
Approach Condition = 0.04280

TABLE 4 PAIRWISE COMPARISON MATRIX FOR CONDITION RATING = MIN (SUPERSTRUCTURE, SUBSTRUCTURE)

Condition Rating	Condition Rating 3	4	5	6	7	Eigenvector
3	1	5	7	8	9	1.0000
4	1/5	1	3	4	5	0.3375
5	1/7	1/3	1	3	4	0.1850
6	1/8	1/4	1/3	1	3	0.1035
7	1/9	1/5	1/4	1/3	1	0.0597

NOTE: $\lambda_{max} = 5.35$, $CI = 0.09$, $RI = 1.12$, $CR = 0.08$ (<0.10).

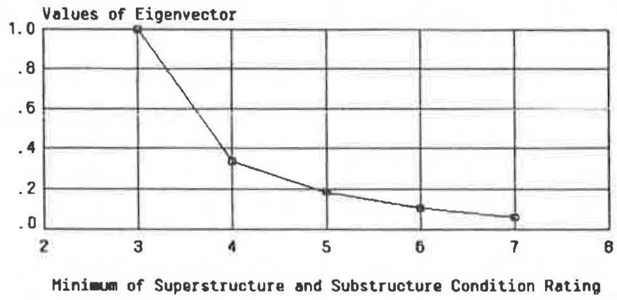

FIGURE 3 Utility curve for condition rating in terms of the eigenvector.

Using these and other utility curves, a matrix of normalized weights of bridge projects was generated for the six criteria. This matrix was then multiplied by a column vector of weights of the six criteria in a fashion similar to that described for the trivial problem to obtain the final weights of the 22 bridge replacement projects.

The final weights were then sorted in descending order and presented in Table 5. Project costs and the available budget presented in Table 5 were exactly the same as used in the sample problem of Harness and Sinha *(4)*. Table 4 shows how subjective judgments could be expressed quantitatively. According to this ranking, bridges were implemented up to the seventh rank. For the remaining $190,000, rather than simply following the original ranking, the rank could be reordered to effectively use the available funds. Because the final weights of Projects 143, 56, 2867, 888, 147, and 878 were close, switching ranks would not change the effectiveness of the overall program implementation. Further investigation could be made at the site and proper projects could be selected.

COMPARISON WITH THE SUCCESSIVE SUBSETTING METHOD

Results of the priority setting by the AH method were compared with the results of the successive subsetting (SS) method. The SS method is based on an assumption that impacts of highway improvements cannot be measured precisely, and if

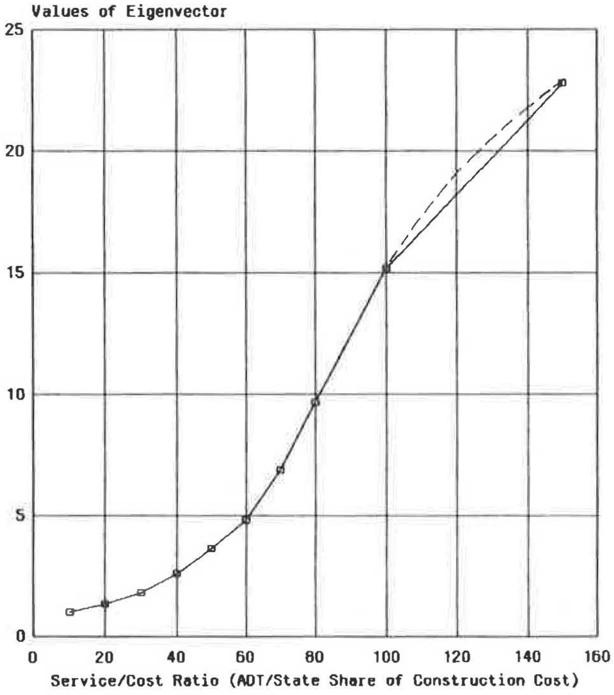

FIGURE 4 Utility curve for service/cost ratio.

they could be, their limits of accuracy would be quite large *(4)*. Projects are first grouped into the desired number of small groups, or subsets, using the criteria of highest hierarchy. Each subset of projects is then clustered into groups using criteria of the next important hierarchy. This process is repeated until each subset has only one project; that is, until it is ranked *(4)*. The SS method is basically a graphical approach to priority setting and no numerical values are generated for comparison.

Table 6 presents a comparison of priority setting of the sample projects by the AH and SS methods. The two methods produced similar rankings. However, the AH method provided several improvements to the SS method. First, the AH method allowed the incorporation of nonlinear utility functions to evaluate the levels of each criterion. It is difficult to incorporate nonlinearity of utility into the SS method because there can be no information to assume what type of utility curve can be appropriate. Therefore, in the SS method the utility functions of criteria were usually assumed to be linear.

Second, computerization of the SS method becomes extremely difficult, if not impossible, when there is more than one criterion at one stratum of hierarchy. This graphical method can be adequate for a small-scale problem, but it cannot be applied to a large-scale bridge priority-setting problem. By the AH

TABLE 5 FINAL RANKING AND PROJECT CHOICES FOR IMPLEMENTATION BY THE AH METHOD FOR THE SAMPLE BRIDGE REPLACEMENT PROBLEM

Rank	Project No.	Total Weight (Normalized)	Project Cost (1,000 dollars)	Available Budget (1,000 dollars)	Overall Condition Estimate
1	15	0.1139	136	1,025	(not done)
2	166	0.0936	166	889	very poor
3	8	0.0889	45	723	poor
4	1549	0.0887	19	678	poor
5	59	0.0685	302	659	poor
6	844	0.0561	57	357	poor
7	2862	0.0479	110	300	(not done)
8	143	0.0449	253	190	fair
9	56	0.0445	237		poor
10	2867	0.0445	39		(not done)
11	888	0.0435	73		poor
12	147	0.0426	57		fair
13	878	0.0423	122		poor
14	91	0.0328			fair
15	1	0.0321			fair
16	5	0.0263			fair
17	2860	0.0233			poor (Subjective rating error)
18	852	0.0232			fair
19	2861	0.0189			good
20	167	0.0177			good
21	2859	0.0114			good
22	889	0.0098			very good

(not done) - Field observation to determine overall condition estimate was not done for these bridges.

TABLE 6 COMPARISON OF RANKING BY THE AH AND SS METHODS

Rank	Project Number		
	AH Method	SS by Manual Technique	SS by K-Means Clustering
1	15	15	166
2	166	166	8
3	8	1549	15
4	1549	8	1549
5	59	59	56
6	844	844	844
7	2862	56	878
8	143	878	888
9	56	888	59
10	2867	147	147
11	888	1	91
12	147	91	1
13	878	5	5
14	91	2862	852
15	1	2867	2860
16	5	2860	2867
17	2860	143	143
18	852	852	2862
19	2861	167	2861
20	167	2861	2859
21	2859	2859	167
22	889	889	889

method, the computerization of the ranking process is straightforward as long as the weights of elements in each hierarchical stratum are established upon a consensus of a group of decision makers.

Third, the SS method provides ranking, but does not give the final weights to the projects. Therefore, when some projects have close relative weights, there is no way to logically compare them. The AH method, however, provides final weights and intermediate weights, if necessary, to find out what criteria are affecting the final weights. This information gives directions for further investigations in order to set the final ranking and effectively use available funds.

By introducing MacQueen's K-Means clustering method *(19)* the SS method was modified so that it could be used for a large-scale problem. The method minimizes the Euclidean distance between the cases and the centers of the clusters given the desired number of clusters *(19)*. This technique was used by Garber and Bayat-Mokhtari *(20)* for clustering highway links for traffic counting. The K-Means clustering routine available through the BMDP statistical analysis package *(19)* was used.

In the example used for the SS method by Harness and Sinha *(4)*, projects were clustered into eight groups. Therefore, the same number of groups was used for this modified SS method. From this point, whenever there were more than two projects within one group, the K-Means routine was run until each cluster had less than or equal to two bridges. In this example, cluster centers and distances were computed from the raw data and weights were not given to the criteria because criteria weights were not used in the Harness and Sinha *(4)* example.

The final ranking of projects by the modified SS method is presented in Table 5. Although there is a slight perturbation in the ranking, this ranking resembles the rankings produced by the other two methods. Note that this modified technique still requires manual operations at each level of hierarchy. Nevertheless, it is an improvement to the original SS method.

CONCLUSIONS AND RECOMMENDATIONS

Setting priorities on bridge rehabilitation and replacement projects is a typical multiattribute decision-making problem. In this paper, an application of the analytic hierarchy method to set priorities on bridges for replacement is discussed. This method reflects the decision maker's tendency to have relative pairwise judgments and their natures to organize complex goal structures in hierarchical clusters. The method is advantageous in cases for which subjective judgments can be the only way to solve problems and the evaluation process needs to be based on fuzzy and unstructured criteria measures. This type of evaluation often takes place in bridge project programming processes, because bridges are usually rehabilitated or replaced before they structurally fail.

The AH method can incorporate various groups of decision makers related to bridge improvement programming and can synthesize their judgments and preferences. The AH method also allows quantitative ranking of alternatives. Once weights are generated for the elements of each hierarchical stratum, the project-ranking process can be computerized for a large-scale problem. The eigenvector approach allows the comparison of different criteria to be measured in different units with different importance to decision makers. The example given here shows that the AH method can be effectively applied to bridge rehabilitation and replacement problems.

However, in order to apply this method to a large-scale programming process in a real situation, improvements are required. First, a method that aggregates judgments and preferences of several decision makers needs to be developed because a group of decision makers exists at several levels of highway agencies. The utility curves and weights given in this paper represent the judgment and preference of one decision maker. Second, utility curves were incorporated into the AH method. Such a modification was necessary in order to deal with actual bridge programming problems in which probably more than 100 bridges needed to be selected from each district in the state and assessed as to their eligibility for funding; however, this is not a feature of the AH method. Validity of this modification, therefore, needs to be tested.

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