PONTIS-BASED HEALTH INDICES FOR BRIDGE PRIORITY EVALUATION

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ABSTRACT

This paper describes the use of PONTIS-based health indices, in place of NBI ratings, of bridge deck and structural conditions to evaluate bridge priorities for major rehabilitation or replacement projects. This paper describes how the health indices were calculated for the conditions specific to Kansas, evaluates the statistical correlation between the NBI ratings and the health indices, explains the reasons for the major differences between the two sets of numbers, and compares the bridge priorities using the two methods. Decisions made by KDOT based on the results of these analyses are also discussed.

INTRODUCTION

The Kansas Department of Transportation (KDOT) has been using priority formulas over the past 20 years to select roadway and bridge projects for major rehabilitation, modification, or replacement. The current bridge priority formula uses National Bridge Inventory (NBI) ratings for the deck and structural conditions. Since 1994, KDOT has also been conducting element level inspections for use in the Pontis Bridge Management System (BMS).

In order to avoid duplication of data collection and to better utilize the detailed element-level data from PONTIS, KDOT was interested in evaluating whether the PONTIS inspection data could replace the NBI ratings in the bridge priority formula. Another issue KDOT wanted to explore was whether the PONTIS system should replace the bridge priority formula as the basis for evaluating bridge improvement priorities and selecting bridges for major rehabilitation or replacement. If replacing the priority formula with PONTIS made sense, this would eliminate the need to maintain the bridge priority formula.

This paper describes the various approaches KDOT explored to integrate PONTIS into the evaluation of bridge priorities. The final approach selected for implementation was based on using health indices that could be derived using PONTIS analysis. The development of this approach and its impact on the evaluation of bridge priorities are discussed in detail.

The current bridge priority formula and the role of the NBI ratings in the formula are described in the next section. Next, the alternative approaches to integrate PONTIS data and/or output into the evaluation of bridge priorities are explored. The basis of each

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approach is presented, bridge priorities using the alternative approaches are compared with those obtained from the current formula, and the choice of the approach selected for implementation is described. The final section contains a summary and conclusions.

CURRENT BRIDGE PRIORITY FORMULA

Background

KDOT is charged with providing a safe and efficient transportation system for the citizens of Kansas. State transportation projects are funded through the Comprehensive Transportation Program (CTP). While KDOT also has responsibilities for airport, freight, and transit services, its primary responsibility is to preserve, modernize, and expand the state highway system as needed. In total, KDOT is responsible for maintaining approximately 10,000 miles of roads and 5,000 bridges.

The State Highway Program consists of four parts:

Routine maintenance – The objective of this part is to correct highway deficiencies on a temporary basis through minor maintenance until a more permanent action can be applied. These actions are generally performed by KDOT maintenance personnel.

Substantial Maintenance Program – The objective of this part is to protect the state's investment by preserving the "as built" condition of roads and bridges as long as possible. This category covers everything from pavement patching and overlays to bridge painting and repair. These actions are performed by private contractors.

Major Modification/Priority Bridge Program – The objective of this part is to improve capacity and enhance safety. The projects could include everything from completely replacing the pavement to adding lanes. Also, the most deficient bridges are targeted for replacement or modernization under this program.

System Enhancement Program – The objective of this part is to substantially improve safety, relieve congestion, improve access, or enhance economic development. Examples of these projects include new bypasses or four-lane improvements.

This paper deals with the selection of projects under the Priority Bridge Program. KDOT's 10-year budget for the Priority Bridge Program is of the order of 300 million dollars.

Over 20 years ago, the Kansas Legislature had the foresight to start the state of Kansas down the path of developing an objective, data-based method of project selection under the Major Modification/Priority Bridge Program. In 1979, the Legislature directed KDOT to develop a method of project selection that:

- Was clearly defined and used documented criteria;
- Was systematic and consistent;
- Was reproducible; and
- Used quantitative and verifiable factors in determining relative priorities.

Out of that directive, KDOT's priority formulas were developed. Originally, two formulas were developed – one for roadways and one for bridges. In the mid-1980s, the single roadway formula was split into separate formulas for Interstate and Non-Interstate roadways. These three formulas are used to select the Interstate Roadway, Non-Interstate Roadway, and Priority Bridge projects.

A need-based approach was used to develop each of the three formulas. The fundamental principle of the need-based prioritization system is that the priorities of alternative roadway and bridge projects to receive capital funding should be based on the overall need for improvement. The need for improvement exists because over time different deficiencies develop that adversely impact a roadway segment's or bridge's operation. Such deficiencies can develop for a variety of reasons. The bridge structure may become weaker after being subjected to traffic loading and environmental exposure. An old bridge that was designed with past design standards may not have appropriate physical features (e.g., bridge width) consistent with modern design standards.

Different roadway or bridge deficiencies may not have the same degree of impact on the driving public. Structural deficiencies that could cause a bridge failure would be more critical than, say, a rough deck surface that may impact driver's comfort. Consequently, different deficiencies may have to be weighted differently in calculating the overall weighted need of each roadway segment or bridge. Roadway segments and bridges are then ranked in a descending order of the overall weighted need, and those that are ranked higher would be selected for funding ahead of those ranked lower. This is a need-based priority system ("highest need first"), which is quite different from an optimization approach based on, for example, benefit/cost ratio.

Over the past 20 years, the three priority formulas have been fine-tuned to some extent. In 1999, KDOT and its consultants conducted a comprehensive review of the formulas and found that the formulas were fundamentally sound, but could be enhanced by taking advantage of newly available technology and better data collection and reporting methods (HNTB and URS Greiner Woodward Clyde, 2000).

Details of the current bridge priority formula are provided below.

Overview of Current Bridge Priority Formula

To ensure that the priority formulas were based on what is important to the people of Kansas, the KDOT project team began by identifying why a road or bridge should be improved. This was expressed as objectives of a quality highway network. The bridge objectives were defined to be:

- Maximize user safety
- Maximize preservation of investment
- Minimize user travel time and vehicle operating cost

Each objective was then related to one or more *attributes*, which are physical features of a roadway or bridge that could be measured and corrected or improved. Figure 1 shows the objectives and attributes included in the bridge priority formula.

A need function was developed for each attribute to convert the raw data levels of the attribute into a need score; that is, a relative measure of the need to improve, on a scale of 0 to 1. Figure 2 illustrates the need function for the attribute of "NBI deck condition rating". For example, the need score of two bridges with NBI deck condition ratings of 4 and 7 are 0.8 and 0.2, respectively.

Certain *adjustment factors* may be applied to some of the attributes. An adjustment factor in itself is not a deficiency and hence does not create a need for improvement. But it may change the degree of concern related to a specific deficiency. For example, the traffic volume may be used as an adjustment factor for an attribute such as bridge width. The traffic volume in itself does not represent any deficiency, but the need to improve a bridge with substandard width may be assessed to be less if the traffic volume on the bridge is low.

The project team identified several potential improvements to the current bridge priority formula. One key recommendation was to explore approaches to revise, or completely replace, the current formula using PONTIS data and analysis. The following section describes the different approaches that were explored.

APPROACHES TO INCORPORATING PONTIS INTO BRIDGE PRIORITY EVALUATION

Motivation for Incorporating PONTIS into Bridge Priority Evaluation

The NBI records the structural condition of a bridge primarily through three items that represent major bridge components – the deck, the superstructure, and the substructure. The condition of these components is assessed on a rating scale of 0 to 9. These ratings provide information on the severity of a condition, but do not identify or quantify the extent of the problem. The failure to quantify the extent of a deficiency minimizes the effectiveness of the NBI condition ratings in determining bridge maintenance and rehabilitation needs. Relating the NBI ratings to specific needs requires a subjective interpretation by bridge inspection staff.

PONTIS is a comprehensive Bridge Management System (BMS) developed as a tool to assist in the challenging task of Bridge Management. PONTIS uses element-level inspection techniques as described in the AASHTO Guide for Commonly Recognized (CoRe) Structural Elements. This element level inspection technique provides a more detailed breakdown of the bridge components. Instead of the NBI's single superstructure rating, the element-level inspection of PONTIS requires individual condition assessments for girders, floor beams, pins, hangers, and so on. The element-level inspection data define each element's condition state in precise engineering terms, i.e., in terms of severity and extent of critical deficiencies. Thus, the element level inspection data in Pontis provides a more objective assessment of relative needs to improve different bridges.

Because of the PONTIS's superior conceptual framework, KDOT (and many other states) decided to use this approach to perform the regular bridge inspection. If the PONTIS inspection data could be incorporated in the bridge priority formula in place of the NBI ratings, this would avoid the duplication of the data collection effort and provide substantial cost savings to KDOT. Furthermore, the PONTIS system itself provides an evaluation of bridge improvement priorities and selection of bridges for major rehabilitation or replacement. KDOT, therefore, was also interested in evaluating PONTIS in order to determine whether it should replace the bridge priority formula.

Approaches Explored for Use of PONTIS in Priority Formula

Three alternative approaches were explored to incorporate the PONTIS inspection data and the results of its analysis into the bridge priority formula:

1. Use translated NBI ratings.
2. Use health indices.
3. Replace the bridge priority formula with PONTIS.

Each approach was tested using the NBI and PONTIS ratings of bridges maintained by KDOT, and the resulting bridge priorities were compared to those obtained from the current priority formula. Results of testing each approach and its implications for KDOT are presented below.

1. Use Translated NBI Ratings

In this approach, the PONTIS inspection ratings are translated into NBI ratings using the computer program developed for the Federal Highway Administration (FHWA) by University of Colorado. The translator program determines NBI condition ratings for deck, superstructure, substructure, and culverts using a table-driven procedure. The condition state quantities of "CoRe" elements recorded in PONTIS inspection are compared to criteria for NBI rating assignment in determining the equivalent NBI ratings. The translated NBI ratings could then be used in the priority formula in place of the field NBI ratings.

The reliability of this approach was tested by evaluating the correlation between the field and translated NBI ratings. Note that for the priority formula, the structural condition rating is defined to be the lower of the super- and sub-structure condition ratings. The correlation between the two sets of ratings is very poor. The square of the correlation coefficient (r^2) is 0.117 for structural condition ratings. This means that only 11.7% of the data variability in the translated NBI ratings is "explained" by the field NBI ratings. Many bridges that have a low field NBI structural condition rating have a high translated NBI structural condition rating. Conversely, many bridges that have a high field NBI structural condition rating have a low translated NBI structural condition rating. The square of the correlation coefficient between the field and translated NBI deck condition ratings is only 0.249. This apparent lack of correlation between the two sets of ratings was not surprising given the difficulty one would expect in converting the multi-dimensional PONTIS ratings into the one-dimensional NBI ratings.

Based on the correlation results, the project team concluded that the translated NBI ratings, calculated using the PONTIS inspection data, would not provide a reliable assessment of the bridges with relatively high deficiencies and hence with a greater need to improve. This approach of using the translated NBI ratings, therefore, was considered to be ineffective and was not pursued further.

2. Use Health Indices.

Overview of Approach

In this approach, "health indices" for deck and structure are calculated using PONTIS inspection data. These health indices are then used in the priority formula in place of the NBI field ratings.

The concept of "health index," as used in PONTIS, is described in (Shepard and Johnson (2001)). Basically, the health index is a single number assessment of a bridge's condition based on the bridge's element value, determined from an element-level inspection. The health index can be calculated for any given group of bridge elements. It is defined as the ratio of current element values, summed over all elements, to the initial element values, summed over all elements. The current element value takes into account the quantity in each of several possible condition states and the value of the quantity in each condition state. Similarly, the initial element value is calculated using the total element quantity and the value of the quantity in its initial condition state.

There are a total of 4911 bridges in the Kansas State Highway System, and the deck health index was calculated for 4762 bridges in using the PONTIS inspection data for deck elements. Additionally, separate health indices were calculated for the super- and sub-structure using the appropriate elements in each group. As was done with NBI ratings, the lesser of these two indices was taken as the structure health index.

To understand the characteristics of the statewide distribution of health indices, histograms and summary statistics were prepared. The range of the deck health index is from 0 to 100, with an average of 84. The range of the structure health index is from 11 to 100, with an average of 91. The range of the NBI deck rating is from 3 to 8, with an average of 6.9. The range of NBI structure rating is from 5 to 8, with an average of 6.9.

Because of the significant differences between the procedures used in NBI and PONTIS inspections, one would not expect a perfect match between the two sets of ratings. NBI inspections are made for three major components of a bridge (the deck, the superstructure, and the substructure) and the ratings are discrete numbers on a scale of 0 to 9. On the other hand, the PONTIS inspections are made for the many elements of a bridge and the health indices are evaluated on a continuous scale of 0 to 100.

In spite of the fact that significant differences may exist between NBI ratings and PONTIS health indices for individual bridges, one would expect that a group of bridges with low NBI ratings should, on the average, have a low health index. Conversely, a group of bridges with high NBI ratings should, on the average, have a high health index. To check whether these conditions are met, graphs of NBI ratings versus PONTIS health indices were prepared. The graphs showed a fairly strong relationship between the two variables, with lower NBI ratings being associated with lower health indices and vice versa. The square of the correlation coefficient (r^2) between the two variables is 0.66 for deck and 0.96 for structure.

These results confirm that there is a reasonable agreement between the two methods in identifying groups of bridges generally in good versus poor condition. However, for individual bridges which display varying conditions among different elements, the PONTIS health indices may provide very different relative ratings compared to the NBI ratings. Additionally, the health indices are evaluated on a continuous scale, while NBI ratings are evaluated on a discrete scale. Therefore, health indices provide better discrimination among individual bridges in terms of their rehabilitation need. For these reasons, this approach based on health indices was considered to be promising and was pursued further in evaluating bridge priorities. Bridge priorities under the two approaches -- PONTIS-based health indices versus NBI ratings -- were compared; the results are presented next.

Bridge Priorities Using Health Indices versus NBI ratings

The Kansas State Highway System consists of approximately 5000 bridges. The relative priorities of this entire set of bridges were evaluated using the bridge priority formula under two alternative approaches. One approach was the current bridge priority formula that uses NBI ratings for deck and structure conditions. The other approach replaced the NBI ratings with the corresponding PONTIS-based health indices. Based on available funding levels for bridge rehabilitation projects, no more than 10% of bridges can be considered for a 10-year bridge rehabilitation program. The distribution of the top 10% of the bridges in the priority-ranked lists was analyzed.

Replacing the NBI ratings with PONTIS health indices significantly affected the priority ranking of bridges. The analysis of the priority rankings of bridges showed that about 40% of the bridges that were in the top 10% when using the NBI ratings remained in the top 10% when using the PONTIS health indices. However, about 60% of the bridges ranked in the top 10% were different for the two cases. About 30% of the bridges that were in the top 10% when using the NBI ratings dropped below the top 10% when using the PONTIS health indices. Conversely, about 30% of the bridges that were not in the top 10% when using the NBI ratings moved into the top 10% when using the PONTIS health indices.

The resulting discrepancy of priority rankings when using NBI ratings versus PONTIS health indices can be attributed to a number of causes. PONTIS health indices provide better distinction among bridges based on their structural and deck conditions. This is because the PONTIS health indices are expressed on a nearly continuous scale, while the NBI ratings are expressed on a discrete scale with a limited number of levels. Thus, for example, bridges having the same NBI rating may have different PONTIS health indices, thus separating them with regard to the need for improvement.

3. Replace the Priority Formula with PONTIS.

Overview of Approach

In this approach, the priority ranks of individual bridges for rehabilitation would be based on the results of the PONTIS application rather than on those of KDOT's current Bridge Priority Formula. The fundamental difference between PONTIS and the Bridge Priority Formula is that PONTIS employs a cost-benefit analysis, while the Bridge Priority Formula uses a need-based methodology. For a fixed amount of budget, PONTIS will select the bridges for improvement that return the highest amount of dollar benefits per unit cost. On the other hand, the Bridge Priority Formula will select the bridges in the order of their need scores/deficiencies (need-based approach, i.e., "highest need first"). As a result, the priority ranked lists derived from these two methods are likely to be different. This section analyzes the differences in the lists of high-ranked bridges developed using the two methods.

Method of Analysis

A priority ranked list of bridge projects was developed using PONTIS and separately using the current Bridge Priority Formula. When using PONTIS, we retained the default input parameters, such as cost matrix settings, policy settings matrix, and improvement parameters. These parameters address such issues as unit construction costs for different actions on given types of bridges, the improvement in bridge condition following an action, and the minimum serviceability life required for each action. KDOT bridge engineers used the default parameters for the base case PONTIS runs to determine bridge improvement priorities. Only replacement or major rehabilitation actions were considered; substantial maintenance actions were excluded. These choices were consistent with the typical scopes selected for Priority Bridge projects. A budget of 286 million dollars was used, which was equal to the budgeted dollars for KDOT's 10-year highway program for bridge replacement/rehabilitation projects currently in the Priority Bridge Program. Other factors for this PONTIS optimization run included a minimum cost threshold for a project of $50,000 and a minimum life of 10 years for the bridge rehabilitation action.

The resulting list of projects consisted of 361 bridges when all budget dollars were exhausted, and the list was sorted in a descending order of the benefit/cost ratio. Projects with higher benefit/cost ratios would be selected ahead of those with lower benefit/cost ratios. The calculation of the benefit/cost ratio incorporated both the actual construction costs (agency costs) as well as user benefits and user costs, and the choice of rehabilitation actions was generated based on PONTIS-specified criteria.

The ranked list of projects from PONTIS was compared with the list generated from the current Bridge Priority Formula. The results of comparing the two lists of projects are described below.

Results and Discussion

Of the 361 bridges selected by PONTIS, 34 bridges were not found in the current pool of bridges using the Priority Formula (a total of 4911 bridges). This is primarily because these 34 bridges were outside KDOT's jurisdiction (e.g., Kansas Turnpike Authority bridges). Consequently, these bridges were excluded and the remaining 327 bridges were further analyzed. To compare the two methods, the top 327 ranked bridges (approximately top 6.7 percent of bridges) from the current Bridge Priority Formula were selected.

Of the top 6.7 percent of bridges, only 1.5 percent (74 bridges) appeared in both lists of top 327 ranked bridges. The majority of the bridges (253 out of 327 bridges) did not overlap between the two lists, indicating that the project selection between PONTIS and the Bridge Priority Formula was substantially different from each other. The top 327 ranked bridges were further subdivided into two groups, the top 1 to 163 ranked bridges were labeled as "high" priority in each list, and 164 to 327 ranked bridges were labeled as "medium" priority. Bridges ranked below 327 were defined to be "low" priority.

There is a very low match between the project selections of PONTIS and the Bridge Priority Formula. The primary reason for the differences in project selection is that PONTIS uses the benefit/cost ratio as the ranking criterion, whereas the Bridge Priority Formula uses the need score. PONTIS, in general, selects projects with lower costs so that the fixed budget allows more work to be done. The Bridge Priority Formula does not consider user costs and benefits in ranking projects.

Further breakdown of the top 327 ranked bridges selected by PONTIS and the Bridge Priority Formula shows the following:

- The Kansas state highway system is divided into five Route Classes based on their strategic importance and the amount of total and commercial traffic carried. These Route Classes in descending order of importance are A, B, C, D, and E. PONTIS selected more bridges in Route Classes A, B, and C, whereas the Priority Formula selected more bridges in Route Classes D and E. This was likely due to the inclusion of user benefit as a project selection criterion in PONTIS, for which higher traffic volumes in Route Classes A, B, and C would generate higher user benefits from bridge improvements. The current priority formula does include an adjustment factor for traffic. However, the range of this adjustment factor is limited to 0.85 to 1.0. In contrast, the PONTIS user benefits would be proportional to traffic; that is, the user benefits would double when the traffic doubles. Therefore, traffic has much greater effect on the PONTIS results than the priority formula results.

- For the same reasons discussed above, PONTIS selected significantly more bridges for eastern Kansas than for western Kansas, as well as more bridges in the urban area or with higher traffic (AADT) volumes.

- The analysis of deficiencies in the bridges selected indicated that PONTIS would select some bridges with primary concerns on geometric and deck condition. In contrast, the top 327 ranked bridges selected by the Priority Formula were all driven by structural condition because it carried the most weight in the Priority Formula.

- The average structure length of bridges selected by PONTIS appeared to be longer than those selected by the Priority Formula, and similarly for the surface area. This finding may be explained by the fact that urban bridges carrying higher traffic generally are longer/wider and PONTIS selected more bridges in urban area and with higher traffic.

- Other bridge parameters, including the type of bridge, number of lanes carried by structure, and roadway width did not appear to be significantly different among the two sets of bridges selected.

Choosing between PONTIS and Bridge Priority Formula

Because of the fundamentally different project selection strategies used by PONTIS and the Bridge Priority Formula, the priority lists based on the two methods were substantially different. PONTIS employed a benefit-cost analysis in project selection, while the Priority Formula used the "highest need" approach. PONTIS selects bridge projects in ascending order by benefit/cost ratio. The Priority Formula, however, selects projects with the most severe bridge deficiencies. Thus, for example, a bridge in poor structural condition would be ranked high in the Priority Formula list, but low in the PONTIS list if its unit cost of improvement was relatively high. KDOT's philosophy over the years has been to select projects (roadway or bridges) based on their need without regard to the unit cost of the improvement needed. KDOT places even greater emphasis on maintaining functional bridges, because unlike roads, when a bridge fails, motorists simply cannot travel on that route and a very lengthy detour may be needed to go past the feature that has to be crossed.

The PONTIS method appears to select a very different set of bridges from those based on the need alone. Specifically, PONTIS would select a bridge with a lower need and lower cost ahead of one with a higher need and higher cost if the cost difference is greater than the benefit difference.

Project selection based on cost and benefit, although accepted by the user community, would be harder to explain to the public. However, the project team did believe that incorporating PONTIS Health Indices into the Bridge Priority Formula allowed KDOT to take advantage of the element inspection level techniques, while still utilizing KDOT's long-standing philosophy of fixing bridges with the most severe deficiencies first.

SUMMARY AND CONCLUSIONS

KDOT wanted to explore ways in which PONTIS inspection data could be incorporated in the Bridge Priority Formula in place of NBI ratings. The motivation for this change was to avoid duplication of bridge inspections and data collection/recording by dropping NBI inspections, and at the same time, to take advantage of the superior element-level PONTIS inspection methodology. Three alternative approaches were evaluated for incorporating PONTIS data into the Bridge Priority Formula. These approaches were to: (1) convert PONTIS data into equivalent NBI ratings, which then would be used in the Bridge Priority Formula in place of the direct NBI ratings; (2) use health indices calculated based on the PONTIS inspection data; and (3) replace the Bridge Priority Formula completely with PONTIS analysis.

Conversion of PONTIS data into equivalent NBI ratings using FHWA's translator computer program produced inconsistent results and hence was dropped from further consideration.

Using PONTIS in place of the Bridge Priority Formula was not considered to be an acceptable option, because it was inconsistent with KDOT's long-standing philosophy of fixing bridges with the most severe deficiencies first (i.e., highest-need first). A detailed examination of the bridges selected using the two alternative approaches confirmed that the distribution of bridges selected using PONTIS results was significantly different from that of bridges selected using the Bridge Priority Formula. Furthermore, the portfolio of bridges selected using the Bridge Priority Formula was more consistent with the preferences of KDOT's management than the portfolio of bridges selected using PONTIS. For example, PONTIS selected a number of bridges with geometric or deck deficiencies ahead of bridges with structural deficiencies. This appeared to be a result of lower costs of fixing geometric or deck problems than fixing structural problems. On the other hand, the Bridge Priority Formula almost always selected bridges with structural deficiencies ahead of those with geometric or deck problems. Again, the bridge selection based on the Bridge Priority Formula better reflected KDOT's policies and philosophy.

The third method of using health indices proved to be most effective for incorporating PONTIS data into the Bridge Priority Formula. The calculation of the health indices is able to utilize the element-level PONTIS inspection, a strong advantage of the PONTIS inspection method over the NBI method. Furthermore, there was a reasonable agreement between the NBI ratings and the average PONTIS health indices for each group of bridges with same NBI rating. This agreement provided a validation of the health index approach. KDOT is currently revising the Bridge Priority Formula to replace the NBI ratings for deck and structural conditions with the corresponding PONTIS-based health indices.

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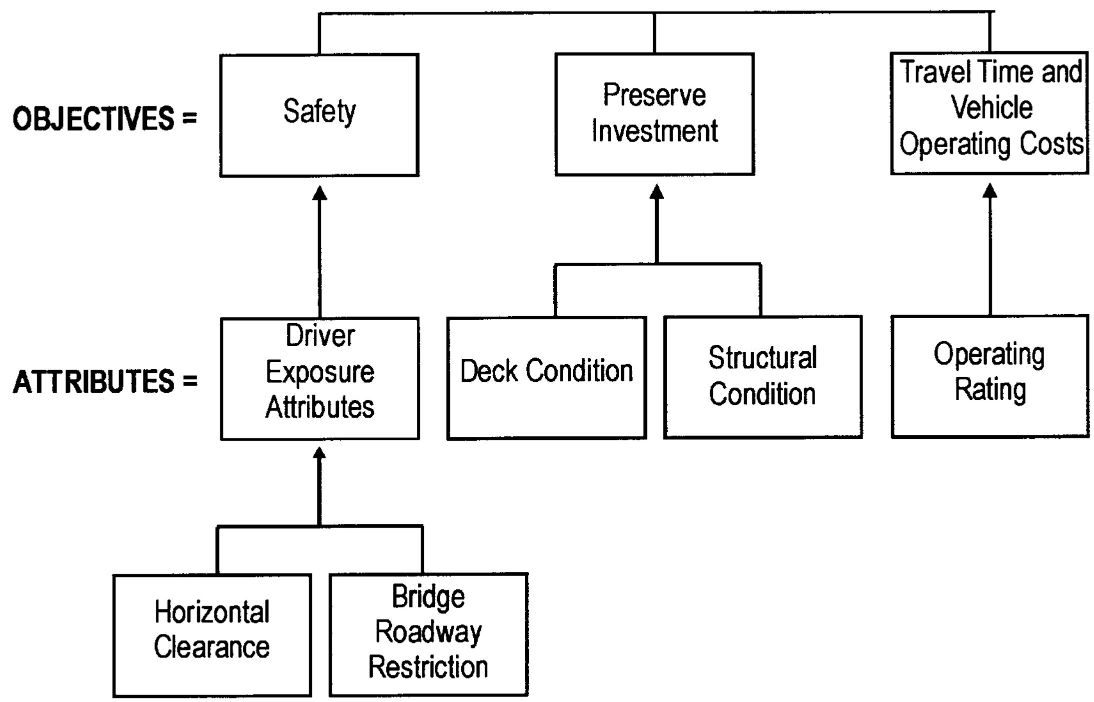

Figure 1. Objectives and Attributes in the Bridge Priority Formula

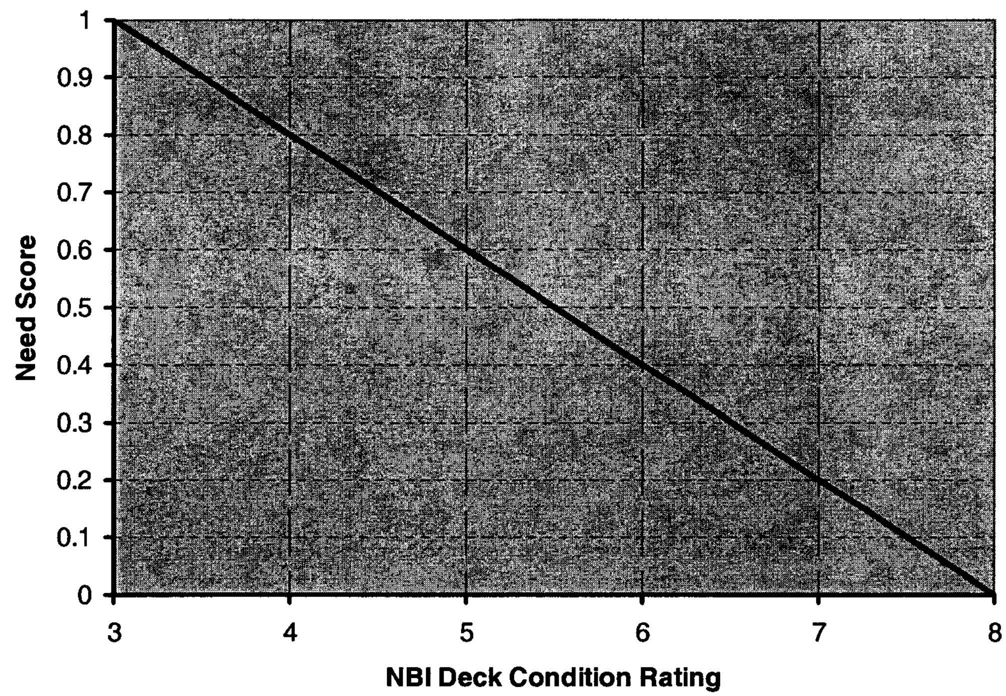

Figure 2. Need Function of NBI Deck Condition Rating