Analysis of Past NBI Ratings for Predicting Future Bridge System Preservation Needs

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ABSTRACT

A Bridge Management System (BMS) needs an analytical tool that can predict preservation needs based on the deterioration process of bridges, and answer what-if questions. Pontis was developed to serve this purpose. Because of its intensive data requirement, Pontis has not been fully utilized by the Louisiana Department of Transportation and Development (LaDOTD). Although a project has been initiated by LaDOTD to collect the Pontis element data, it will take several years to complete due to the large numbers of bridges in Louisiana.

An innovative approach was developed in this project: using readily available NBI data in Pontis to evaluate the long-term performance of the bridge system under various BMS alternatives. The deterioration process of three NBI elements was studied, based on which element deterioration models were developed. The bridge preservation plans and the associated cost schemes were also defined according to the current LaDOTD's practice and available information.

This paper demonstrates that it is not only feasible but also practical to utilize NBI data for BMS analysis with Pontis. While waiting for the completion of Pontis database, LaDOTD can use its readily-available rich NBI data to conduct analysis and evaluate long-term performance of the bridge system under various budgetary and operating scenarios. The initial results indicate that the current LaDOTD's $70 million annual budget is only sufficient to meet the bridges' preservation needs, but not adequate to satisfy the needs of bridges' functional improvement. The bridge preservation plan, if implemented successfully, can maintain the system in good operation conditions for a long time under limited annual budget.

BACKGROUND

There are more than 8,000 bridges on the Louisiana state highway system. To maintain these bridges in acceptable operating conditions, limited funds are allocated to the system annually. To effectively utilize the resources, the Louisiana Department of Transportation and Development (LaDOTD) needs a procedure that can optimize the long-term system performance under the budgetary constraints. The ability to predict future bridge preservation needs is critical to the 2001 LaDOTD Strategic Plan and to the update of the Statewide Transportation Plan. At the present time, LaDOTD is contributing $25,000 annually in license fees to the American Association of State Highway and Transportation Officials (AASHTO) to maintain a comprehensive bridge management software called Pontis for this purpose. Pontis requires extensive data on bridge inventory and condition ratings at the very detailed bridge element level, i.e., the Commonly Recognized (CoRe) Elements. Mainly due to the large amount of work required, LaDOTD had never collected this type of data until very recently. The newly initiated data collection project will take years to complete (with both CoRe elements inventory details and condition ratings).

While there are no data available for utilizing the Pontis program, LaDOTD has collected the extensive National Bridge Inventory (NBI) data for the past two decades. The NBI data are not at the detailed CoRe element level; therefore, they cannot be directly used as input to the program for analysis. Pontis, a result of many years of research and development, is a complex program for bridge system's optimization and simulation. Despite its powerful modeling capability, only a very few state DOTs in this country have fully utilized Pontis for their bridge management systems.

To solve this problem, an innovative approach was developed in this study: using readily available NBI data in Pontis to evaluate the long-term performance of the bridge system under various alternatives of BMS. The results from this project have demonstrated that it is feasible and practical to use the rich historical NBI data for BMS analysis. The preliminary results show that the preservation plan, if implemented successfully, can maintain the bridge system in good operation conditions perpetually under a limited annual budget.

METHODOLOGY

Louisiana Bridge Deterioration Model

One important task of this study is to develop a Louisiana bridge element deterioration model that can be used to predict future bridge system performance. Although Pontis has the default element deterioration models for the CoRe elements based on the Markovian Chain Theory, it cannot be applied to the NBI elements. Three steps involved in developing the deterioration models are described below.

Step 1. Developing the Historical NBI Rating Charts for the Four Aggregated Bridge Groups

There are 30 different types of bridges according to the NBI bridge categories on the LaDOTD bridge system. Considering their similarities in deterioration behavior and construction material, four major bridge groups are defined. They are concrete, steel, prestressed concrete, and timber bridges. Each type of bridges has three NBI elements: deck, superstructure, and substructure as shown in Table 1. To examine how the NBI ratings vary during the past 20 years for each of these 12 elements, 108 NBI rating transition charts were created that clearly illustrate the changes of the ratings over time due to deterioration and maintenance actions. As shown in Figure 1, the majority of concrete deck stays in the original rating of *eight* while some elements deteriorate to ratings *seven* and *six*. Not a single element of concrete deck experiences a rating increase after five years since, at the original condition state of *eight,* there is no need for any rehabilitation actions. The same cannot be said if the previous rating is *one* as show in Figure 2, on which some type of actions (maintenance or placement) must have been conducted to improve the bridge conditions. It is clear that based on all 108 element rating transition charts (12 elements multiplied by 9 ratings), the NBI rating of *six* represents the most stable condition state since it has the highest retaining rate after five years comparing with other condition states.

Step 2. Transferring NBI Ratings to Pontis Condition Ratings

In order to use the Pontis program, the NBI ratings must be converted to Pontis ratings. Although the two systems have the same objectives, the NBI ratings differ from Pontis ratings in a number of ways. The three most significant differences, for the purposes of this study, are: (1) There are nine rating classes in the NBI ratings (*nine* as the best and *one* as the worst), but only five or four rating scales in Pontis (*one* as the best and *four* or *five* as the worst); (2) the NBI rating is set for a whole element (deck, superstructure, or substructure) while the Pontis rating is typically expressed as the distribution of a CoRe element between different condition states; and (3) Since a NBI element is generally larger in size, an NBI rating may capture the ratings of multiple CoRe elements. Referring to the definitions of the two rating systems, the rating conversion scheme is determined as shown in Table 2.

After rating conversion, the 5-year transition matrix of Pontis rating for concrete deck is shown in Table 3. The upper triangle of the matrix indicates element deterioration (the condition state getting worse), while the lower part of the matrix reflects the maintenance actions (the condition state getting better). The diagonal numbers can be interpreted as the probability of an element staying at the same condition rating after five years. The transition matrices for all elements are given in reference [1].

Step 3. Development of Deterioration Matrices

The development of a pure deterioration matrix is based on the assumption that there were no maintenance actions during the five years. That is, the numbers in the lower triangle of Table 3 should be zero. The final deterioration matrix, D, is computed by the transition matrix P as shown below:

$$D = \begin{bmatrix} p_{11} & p_{12} & p_{13} & p_{14} & p_{15} \\ 0 & p_{22} + \frac{1}{2} p_{21} & p_{23} + \frac{1}{6} p_{21} & p_{24} + \frac{1}{6} p_{21} & p_{25} + \frac{1}{6} p_{21} \\ 0 & 0 & p_{33} + \frac{3}{5} \sum_{1}^{2} p_{3j} & p_{34} + \frac{1}{5} \sum_{1}^{2} p_{3j} & p_{35} + \frac{1}{5} \sum_{1}^{2} p_{3j} \\ 0 & 0 & 0 & p_{44} + \frac{7}{10} \sum_{1}^{3} p_{4j} & p_{45} + \frac{3}{10} \sum_{1}^{3} p_{4j} \\ 0 & 0 & 0 & 0 & p_{55} + \frac{8}{10} \sum_{1}^{4} p_{5j} \end{bmatrix}_t$$

where $\boldsymbol{P}_{ij}$ represents the transition probability based on the Markovian Chain Theory with which the rating of a bridge element changes from i to j on a t-year interval. The diagonal probabilities $\boldsymbol{P}_{ij}$ (i=j) are the probability of bridge components staying with the same ratings after the t-year interval. This is an empirical formula, whose justification is based upon the considerations discussed in detail in reference [2].

Step 4. Model Calibration

The deterioration matrices developed at this point are based on a five-year interval. During this period, it is possible that an element could have been subjected to some types of maintenance actions first and then experienced deterioration. Therefore, it is possible that the rating of an element does not always change monotonously during the time period. To avoid this situation, one-year interval should be used. However, state bridge inspection cycle is two years as mandated by FHWA. Considering these potential drawbacks with each time interval, the final element deterioration model D is calibrated by two matrices developed with the same historical data but at two different time intervals, *t=1*, and *t=5,* as shown below:

$$
\begin{aligned}
D_2 &= D_1^{\ 1} \times D_1^{\ 1} \\
D_3 &= D_2 \times D_1^{\ 1} \\
D_4 &= D_3 \ \times D_1^{\ 1} \\
D_5 &= D_4 \ \times D_1^{\ 1} = (D_1)^5 \\
D_5^{\ 1} &= \sqrt[5]{D_5}
\end{aligned}
$$

where D_n is the Markovian Chain deterioration matrix developed in an n-year interval, and $D_m^{\ n}$ is the m^{th} year deterioration matrix developed in an n-year interval. The combination of the two one-year matrices developed at one- and five-year intervals leads to the final one-year deterioration matrices for all 12 elements as typically shown in Table 4 for concrete deck.

Bridge System Analysis with Pontis

There are two types of modeling programs in Pontis: bridge preservation and bridge improvement. Preservation projects consist of bridge maintenance, repair, and rehabilitation

(MRR) actions. Bridge improvement projects enhance functional aspects of bridges, i.e., to address bridges' functional shortcomings. To develop improvement projects, Pontis identifies those instances where adequate design standards are not met, develops strategies to meet them, and prioritizes candidate improvements. Example improvement projects include widening a deck, raising a bridge to gain added vertical clearance, or strengthening a bridge to support heavier loads.

The preservation and improvement actions are identified through optimization and simulation models. Pontis simulation model predicts how MRR actions improve element conditions, and how bridge elements deteriorate over time in the absence of MRR actions. The objective of optimization model is to prioritize the projects by minimizing long-term costs, while maintaining the system in steady operating conditions. The applications of Pontis are summarized below:

1. Define the Preservation Actions, Corresponding Costs, and Condition States

Considering the aggregated nature of NBI elements, the preservation action plans defined in this study are not as detailed as Pontis default action plans. Basically, there are four actions: do-nothing, minor maintenance, major maintenance, and replacement. Because of the inconsistent practices of LaDOTD project contracts in the bidding calculations, it is infeasible to collect and apply the detailed unit cost data for this study. The estimated unit costs for element replacement in this study are based on: (a) Louisiana Standard Specifications, which gives the general information on pay items and items identification; (b) the average unit cost of $90 per square foot of deck area from an overall estimation of LaDOTD projects; and (c) an approximate 50-50 cost distribution between upper (deck and superstructure) and lower parts (substructure) of a bridge. The minor and major maintenance costs are estimated as a fraction of the replacement costs as shown in Tables 5 and 6.

2. Define the Input Parameters

In Pontis, there are 1,109 configuration parameters, 170 configuration options, 324 scenario parameters, 88 input/output tables, and the newly added simulation rules [3]. Understanding these settings are very important as having been proved in this study.

To investigate the impact of various BMS options on the long-term performance of the LaDOTD bridge system, nine scenarios were defined based on the three key settings: annual budget, preservation action cost, and modeling functions as shown in Table 7. The zero budget (do-nothing) scenarios were designed to evaluate the deterioration process as well as to validate the program. The separation and combination of MRR and Functional Improvement (Func.) scenarios show the needed work for the two different purposes.

RESULTS

The results of the analysis over a period of 30 simulated years (2002-2032) are organized and presented at both the general and detailed levels in this paper. The results at the detailed level include selected work from the identified needs and three performance measurements for the bridge system.

1. Summary

The last year's needs, health index, and the total spending for each action are given in Table 8. The identified needs at the simulation year under the do-nothing scenario is more than 20 times higher than the one under a $70 million annual budget scenario when only MRR projects are considered. The difference in the identified needs between the annual budget of $70 million and $140 million is only $2 million, which indicates that doubling the annual budget is not necessary if only the MRR needs are considered. With no investment to the bridge system, the health index (HI) of the system is under 60 at the last simulated year, which is not acceptable for BMS. The HI increases about 14 percent as the annual budget increases from $0 to $70 million, which shows the effect of the preservation actions. The results from the $140 million scenario, however, do not show significant difference from the scenario with the annual budget of $70 million. Thus, it is reasonable to assume that the annual budget of $70 million is sufficient for the bridge preservation needs.

The results displayed at Table 8 indicate that the majority of bridge replacement needs come from functional improvement projects in Louisiana. With an annual budget of $70 million, the total replacement cost over 30 years increases from $16 million to $797 million when the scenario changes from MRR only to the combination of MRR and Functional improvement; this indicates a great deal of bridge replacement needs due to functional obsolescence or structural deficiency. In that sense, $70 million is not sufficient to meet the needs of preservation and improvement for the current Louisiana highway bridge system.

2. Predicted Needs vs. Work

Given the deterioration models and all the required settings and rules, Pontis program simulates the system and identifies the needs. If the assigned budget cannot meet all the needs, Pontis prioritizes the needs and produces a list of selected work on a yearly basis. The results in terms of annual needs and work for the three budgetary scenarios (S-0-1, S-70-1, and S-140-1 as defined in Table 7) are presented in Figures 3, 4, and 5. Under the do-nothing scenario, the need increases rapidly and reaches $140 million at the end of the 30th year. Although the $70 million annual budget cannot meet all the needs initially, it reduces the needs in the first few years quickly; and by the end of the10th year, the $70 million annual budget satisfies all the predicted needs. The only difference between the two budgetary scenarios of $70 million and $140 million is the number of years required to meet the needs of the bridge system.

3. Pontis Condition Ratings

In addition to the predicted needs and selected work, the next three sections show the conditions of the system. First, the Pontis condition ratings for the deck under scenarios of S-0-1 and S-70-1 are shown in Figures 6 and 7. Although under both budgetary situations the deck areas with the average condition state rating *one* decrease with time, the amount of deck areas with the condition rating *one* at the end of the 30th year is very different. Most importantly, under an annual budget of $70 million, much higher percentages of deck areas stay in the condition rating *two*, and lower percentages of deck areas in condition ratings *four* and *five*. The annual budget of $70 million has greatly constrained deck elements from deteriorating into the worse condition states. The distributions of condition state rating for superstructure and substructure show very similar trends.

It is clear that with an annual budget of $70 million, most of the elements with lower condition ratings (*four* or *five*) are subjected to either major and minor maintenance actions or element replacement. With a sufficient budget, the numbers of elements with low condition ratings can be controlled to fewer than 5%.

4. Health Index

Unlike Pontis condition ratings, health index is a combined measurement of bridge condition. It is mainly a function of the ratings for defined bridge elements. California Department of Transportation has used health index calculated by CoRe elements to evaluate its bridge system performance (5). The HI from this study is calculated by the ratings of deck, superstructure, and substructure. Figures 8 and 9 display the distribution of HI of the system under two budgetary scenarios.

Again, it is demonstrated that, with an annual budget of $70 million, most bridges or high percentages of deck areas have an HI higher than 75; with no annual budget, the process of deterioration puts many bridges falling into poor and unacceptable HI states. The numbers of bridges with the unacceptable HI (less than 25) are almost eliminated with a $70 million annual budget.

5. Sufficiency Rating

Sufficiency rating is another combined condition indicator, which is a function of NBI ratings for the three elements, structural adequacy, serviceability and functional obsolescence, and essentiality for public use. The distribution of SR under the two budgetary situations is illustrated in Figures 10 and 11.

According to the FHWA guidelines, bridges with an SR greater than 80 are considered in excellent conditions; between 50 and 80, in fair conditions subject to certain type of maintenance; under 50, need to be replaced. Again, Figures 10 and 11 demonstrate that the differences in bridge SR between the two budgetary scenarios are significant. With an annual budget of $70 million, there are more bridges with an SR greater than 80, and the numbers of bridges with an SR less than 50 are greatly reduced. The results under all other scenarios show similar patterns.

DISCUSSION

This study has demonstrated that, while waiting for a complete set of database containing Pontis elements' inventory and condition ratings and paying an annual maintenance fee of $25,000 to FJWA, the state DOTs can utilize readily available NBI data to evaluate bridge system performance under various strategies for their bridge management systems. Based on the past experiences at DOTs across the country, it is clear that going from the system of NBI element to the system of CoRe element takes considerable transition time. This innovative method can provide much needed information for DOTs in making cost-effective funding decisions for the highway bridge management system during this transition time period.

The results of the analysis indicate that the current $70 million annual budget for the LaDOTD bridge system is only sufficient for bridge preservation needs. It is, however, not sufficient to satisfy both preservation and improvement needs of the Louisiana highway bridge system. Based on the preliminary results, it is clear that bridge preservation actions do have an impact on the long-term system performance. Therefore, identifying effective and efficient bridge management strategies is crucial to the LaDOTD's bridge management system.

As illustrated in this paper, the methodology can answer various what-if questions that are crucial to long-term planning and budgeting of a bridge management system. The quantitative results can help to investigate the impact of maintenance actions, costs, and element deterioration rate on the bridge system's long-term performance. LaDOTD is currently planning to conduct more analyses along this direction.

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TABLE 1 Four Major Groups of Bridges

	Deck (ft^2)	Super (ft)	Sub (Item)
Concrete	22,074,867	2,857,781	59,841
Steel	54,326,379	6,492,388	180,990
Prestressed Concrete	53,863,558	6,264,197	162,487
Timber	1,650,716	252,527	5,059
Total	131,915,520	15,866,893	408,377

TABLE 2 Condition Rating Conversion Scheme

NBI Rating	Pontis Condition State		
	Deck	Superstructure	Substructure
7-9	1	1	1
6	2	2	2
5	3	3	3
3-4	4	4	4
1-2	5		

TABLE 3 Transition Matrix in Pontis Rating for Concrete Deck

Original State	New State				
	1	2	3	4	5
1	82.43	15.59	0.84	1.09	0.06
2	4.35	90.52	2.51	2.53	0.09
3	3.90	19.84	59.19	14.58	2.49
4	2.55	2.49	6.80	87.05	1.10
5	67.65	14.36	12.87	3.20	1.91

TABLE 4 Deterioration Matrix for Concrete Deck

Original Rating	Pontis Rating After One Year				
	1	2	3	4	5
1	95.78	3.82	0.19	0.15	0.06
2	0	97.24	1.20	1.18	0.39
3	0	0	94.97	4.32	0.71
4	0	0	0	98.24	1.76
5	0	0	0	0	88.28

TABLE 5 Pontis Action Plans for Deck

Current Rating	Actions	Rating Change Due to the action	Cost ($ per ft^2)
1	Do Nothing	None	$0
2	Do Nothing	None	$0
3	Do Nothing Minor Maintenance	None Up to 2	$0 10% of replacement
4	Do Nothing Major Maintenance	None Up to 3	$0 60% of replacement
5	Do Nothing Major Maintenance Replace Element	None Up to 4 Up to 1	$0 60% of replacement $28

TABLE 6 Pontis Action Plans for Superstructure and Substructure

Current Rating	Actions	Rating Change Due to the action	Cost ($ per ft)
1	Do Nothing	None	$0
2	Do Nothing	None	$0
3	Do Nothing Minor Maintenance	None Up to 2	$0 10% of replacement
4	Do Nothing Major Maintenance Replace Element	None Up to 3 Up to 1	$0 60% of replacement $210 (superstructure) $1,200 for substructure

TABLE 7 List of Scenarios

Modeling Plan / **Annual Budget**	MRR (60%,30%)	MRR (10%,5%)	MRR (30%,15%)	MRR (60%,30%)
$0	S-0-1	S-0-2 (Same as S-0-1)	---	S-0-4
$7M	S-70-1	S-70-2	S-70-3	S-70-4
$140M	S-140-1	S-140-2	---	---

TABLE 8 Summary of Results

Budget		MRR (30%, 60%)*	MRR (10%, 60%)	MRR (5%, 15%)	MRR+Func. (10%, 60%)
$0	Needs From Last year	$1,457M	$1,185M	-	$4,404M
	HI	59.4	59.4		59.4
	Total** spending	0	0	-	0
$70M	Needs From Last Year	$66M	$109M	$107M	$2,165M
	HI	73.5	72.8	74.3	75.4
	Total spending	Rep.=$85M Elem.=$659M Major =$793M Minor =$343M	Rep.=$16M Major=$974M Minor=$340M	Rep.=$17M Major=$934M Minor=$372M	Rep.=$797M Major=$927M Minor=$326M Wid.=$47M Str.=$2.4M
$140M	Needs From Last year	$64M	$45M	-	-
	HI	73.5	73.3		
	Total spending	Rep.=$85M Elem.=$663M Major =$799M	Minor =$349M Rep.=$81M	Major=$981M Minor=$341M	- -

** Minor and major maintenance costs as the percentage of the element replacement cost*
***Rep. = bridge replacement, Elem..= element replacement, Major = major maintenance, Minor = minor maintenance, Wid. = widening bridge, Str. = bridge strengthen*

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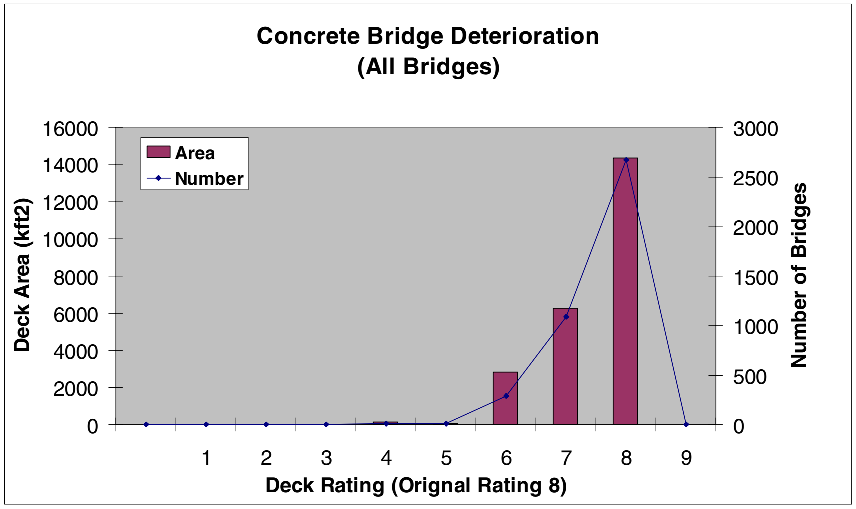

FIGURE 1 Example of NBI Rating Transition Chart for Original Rating Eight.

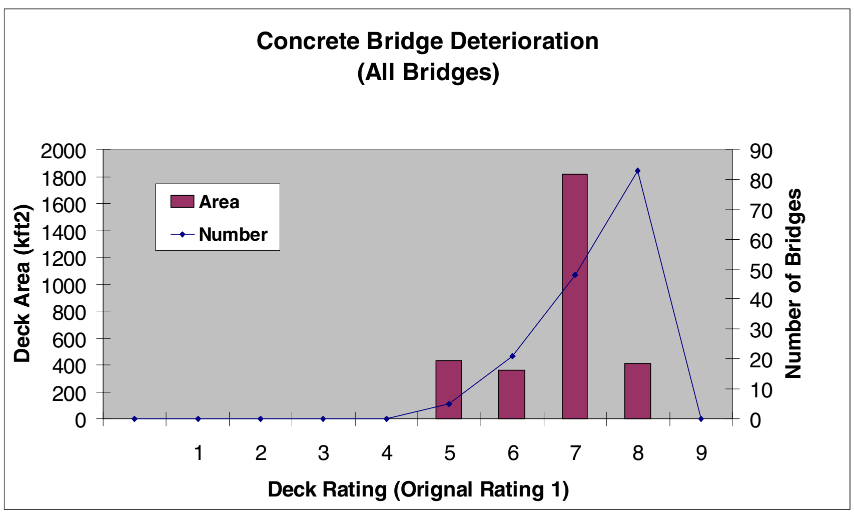

FIGURE 2 Example of NBI Rating Transition Chart for Original Rating One.

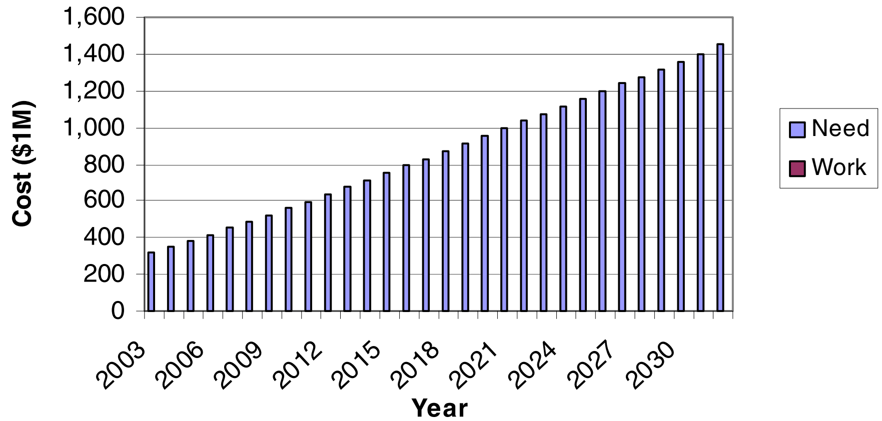

FIGURE 3 Annual Needs vs. Work with S-0-1.

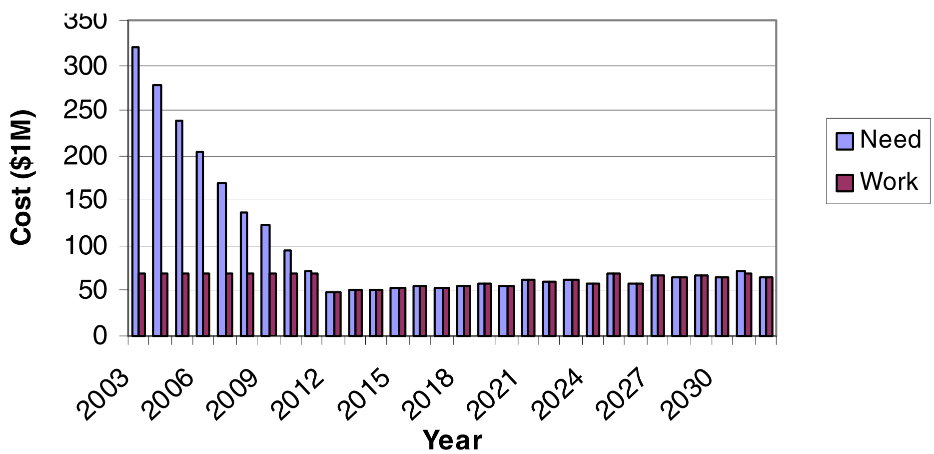

FIGURE 4 Annual Needs vs. Work with S-70-1.

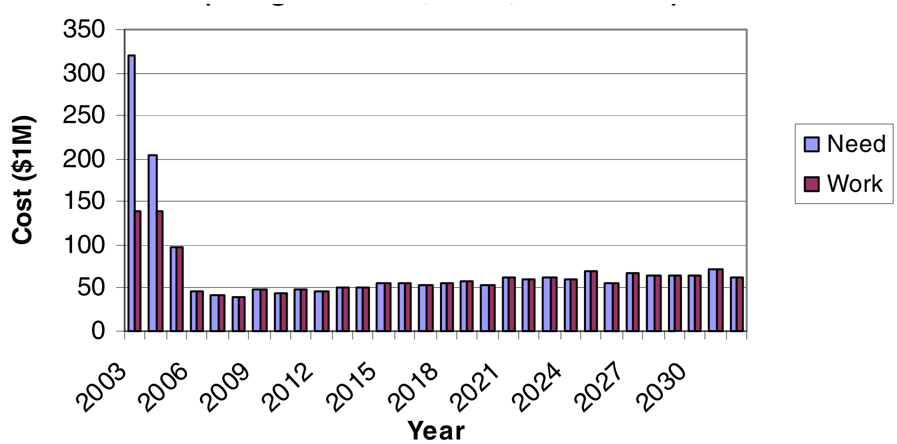

FIGURE 5 Annual Needs vs. Work with S-140-1.

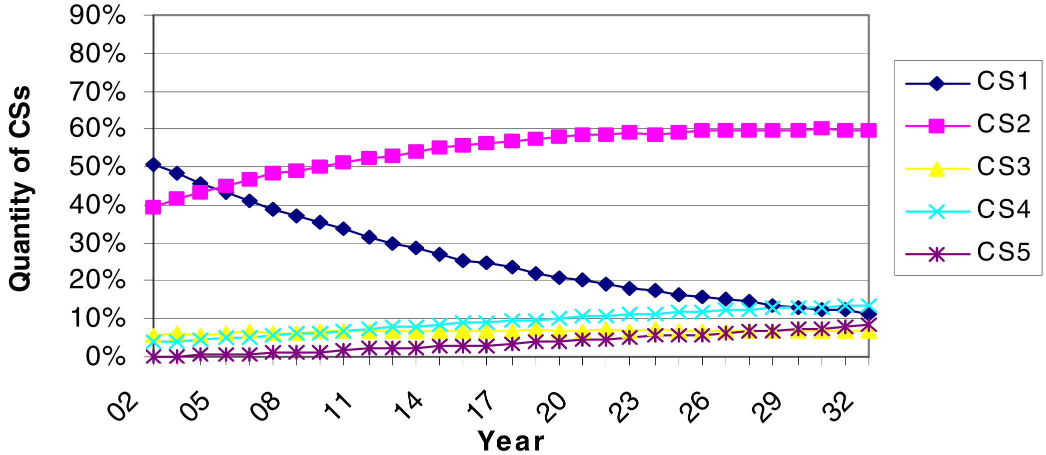

FIGURE 6 Pontis Condition State Rating for Deck with S-0-1.

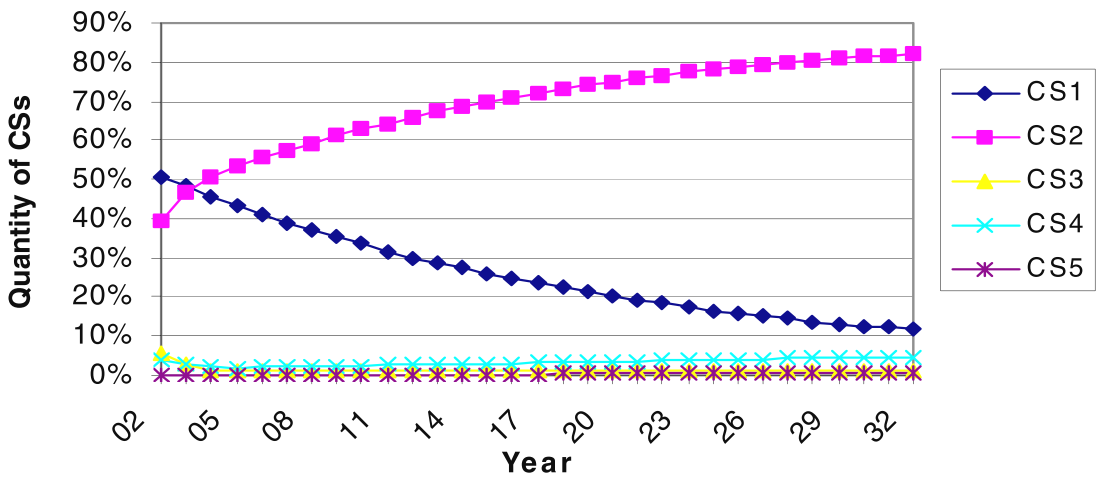

FIGURE 7 Pontis Condition State Rating for Deck with S-70-1.

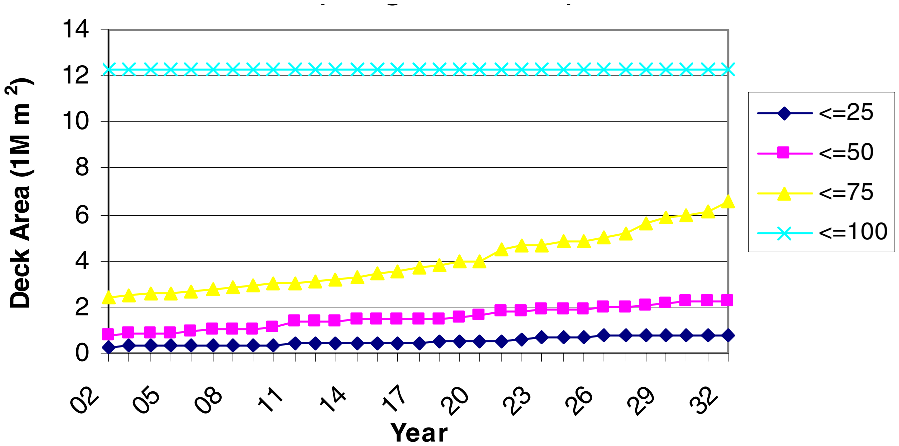

FIGURE 8 Accumulated HI Distribution by Deck Area with S-0-1.

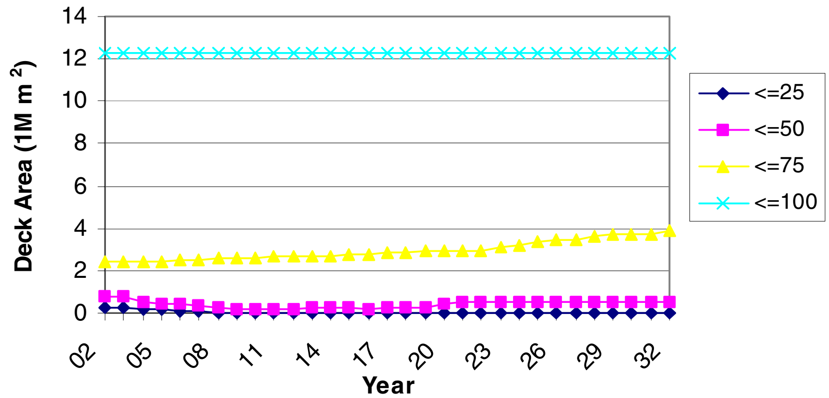

FIGURE 9 Accumulated HI Distribution by Deck Area with S-70-0.

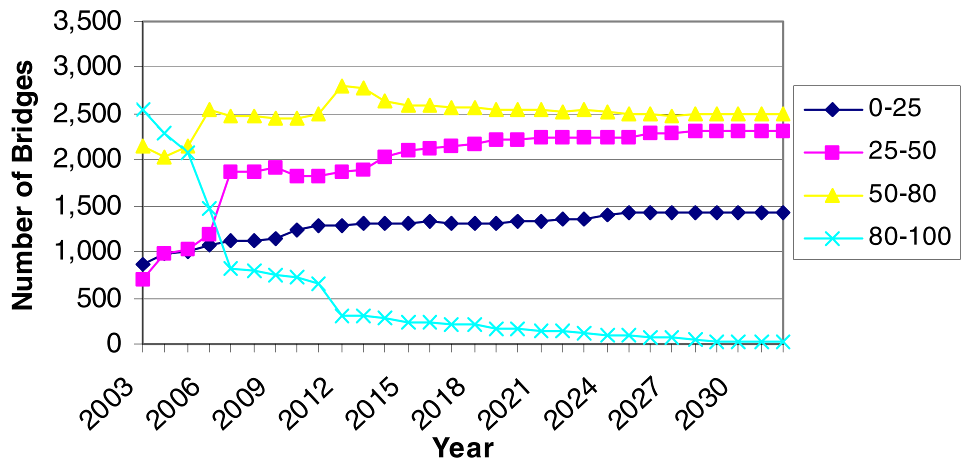

FIGURE 10 Distribution of Sufficiency Rating with S-0-1.

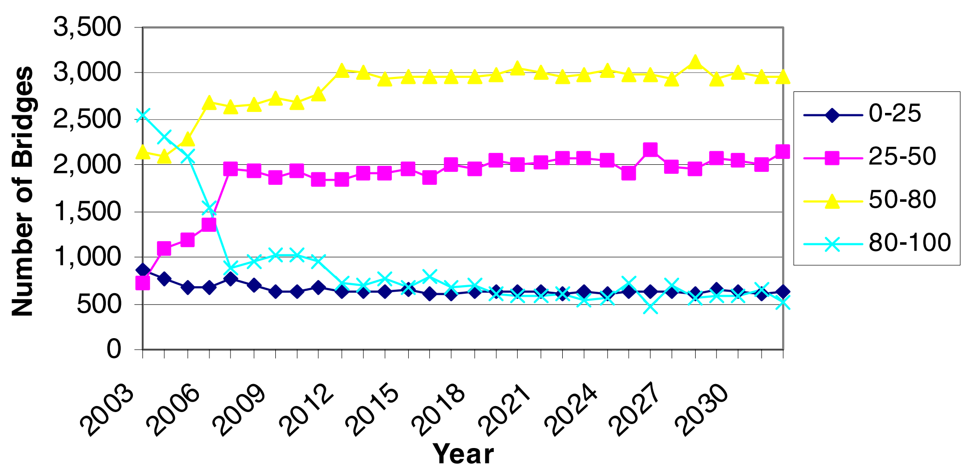

FIGURE 11 Distribution of Sufficiency Rating with S-70-1.