Modeling of Life Cycle Alternatives in the National Bridge Investment Analysis System

William Robert (corresponding author)
Spy Pond Partners, LLC
1165D Massachusetts Avenue
Arlington, MA 02476
617-500-4853
wrobert@spypondpartners.com

Stephen Sissel
Federal Highway Administration
1200 New Jersey Ave. SE, E83-448
Washington, DC 20590
202-366-5764
stephen.sissel@dot.gov

ABSTRACT

The Federal Highway Administration (FHWA) has developed the National Bridge Investment Analysis System (NBIAS) as a tool to analyze bridge investment needs and predict future bridge conditions and performance at a national level. NBIAS analyzes each bridge in the national inventory for each year in a multi-year analysis period through a program simulation model. In the model the system simulates deterioration, traffic, preservation needs, functional needs and costs.

The modeling approach used in prior versions of the system was initially based on that implemented in the Pontis Bridge Management System. Though the modeling approach has evolved over time, its fundamentals are well-established, and have been discussed previously in the literature. Recently FHWA developed Version 5.0 of NBIAS introducing fundamental changes in the NBIAS modeling approach. This paper details the revised modeling approach implemented in NBIAS 5.0, focusing on the modeling of multiple life cycle alternatives for each bridge.

In previous versions of NBIAS, the system prioritized bridge alternatives (allowing for the possibility there may be multiple alternatives on a bridge) using the Incremental Benefit Cost Ratio (IBCR) heuristic. This approach involves calculating the IBCR of each alternative relative to the next cheaper alternative, and prioritizing alternatives in order of decreasing IBCR. Funds are then allocated to the list of alternatives until they are expended. This approach is repeated for each year of the analysis period, which may be up to 50 years. The IBCR heuristic has been shown to yield a near-optimal solution for prioritizing capital projects given certain conditions. However, it is not designed to support multiple budget constraints. Also, because the system simulates in a year-by-year manner, it may produce a suboptimal result in some cases when results are viewed over multiple years, particularly if additional constraints are added to the system.

The basic approach implemented for NBIAS 5.0 was to shift from a simulation model that generates and prioritizes bridge alternatives year-by-year to one that generates and prioritizes multi-year alternatives. In this version the system first generates a set of 21 different life cycle alternatives for each bridge, reflecting different strategies concerning timing of preservation and functional improvement work. The system then uses a modified IBCR heuristic termed "MINCBEN" previously developed for the Virginia Department of Transportation to select life-cycle alternatives given a matrix of budget constraints specified by work type and year. This revised modeling approach provides improved modeling of trade-offs between bridge preservation and replacement, better optimizes resource allocation over time, and allows for flexibility in setting budget constraints by work type and year.

INTRODUCTION

The National Bridge Investment Analysis System (NBIAS) is the tool the Federal Highway Administration (FHWA) uses to analyze investment needs for U.S. highway bridges. FHWA's analyses appear in the U.S. Department of Transportation (USDOT) *Report on the Conditions and Performance of U.S. Highways, Bridges and Transit*, published biennially and termed the "C&P Report" *(1)*, as well as in other documents. Although it was designed for use by FHWA for its national-level analyses, NBIAS has been utilized extensively for other national, state and local bridge needs analysis, often in conjunction with FHWA's Highway Economics Requirements System (HERS) for highway investment needs analysis.

NBIAS was first introduced in the 1999 C&P Report *(2)*. The initial version of the system was based on the analytical framework similar to that used in the Pontis Bridge Management System developed by FHWA in 1992 and subsequently adopted by the American Association of State Highway and Transportation Officials (AASHTO). The basic input to the system is National Bridge Inventory (NBI) data, from which the system synthesizes data on representative structural elements. NBIAS models investment needs for element-level maintenance, repair and rehabilitation (MR&R, also termed "preservation"), and for functional needs such as widening existing lanes, raising, strengthening, and replacing bridges. The basic modeling approach used in NBIAS has been documented previously in the literature *(3, 4, 5)*.

Over time FHWA has implemented a number of enhancements to the NBIAS modeling approach to improve the quality of the system's projections and the overall usability of the system. In 2014 FHWA identified a need to enhance the system to allow the user to specify investment budgets by type of work and/or category of bridge to simulate targeting of investment to certain types of work (e.g., replacement of bridges classified as Structurally Deficient). Previously only one overall budget could be specified in the system. In conjunction with making this enhancement, FHWA sought to improve the functionality of the system for determining the funds required to achieve a targeted level of performance, and to better model tradeoffs between performing MR&R work and replacing bridges. Implementing this set of enhancements required both the addition of additional budget constraints to the system's program simulation, and addition of new logic forcing the system to consider additional alternatives for a bridge to better take advantage of available funds. The following sections summarize the NBIAS modeling approach, detail the above enhancements made to Version 5.0, discuss the impacts of the enhancements, and outline future improvements to NBIAS currently under development.

NBIAS MODELING APPROACH

NBIAS analyzes each bridge (excluding culverts) in the national inventory for each year in a multi-year analysis period through a program simulation model. In this model the system simulates deterioration, traffic, preservation needs, functional needs and costs.

An important input to the program simulation is the MR&R policy. MR&R needs are determined through a Markov modeling approach by first developing the MR&R policy, which specifies what actions to perform on individual bridge elements depending on their condition. The MR&R policy is determined using a linear optimization solved for each combination of structural element, condition state, operating environment, climate zone, and U.S. state. The output of the optimization is specification of what action to take in each condition state to minimize life cycle costs, and the savings in life cycle costs of performing the recommended work relative to deferring action for one year. The modeling approach is similar to that implemented initially in Pontis, but incorporates consideration of user costs (for decks) and includes a penalty function that varies based on condition.

Figure 1 outlines the steps in the program simulation for NBIAS versions prior to Version 5.0. As indicated in the figure, a series of steps is performed for each year of the analysis period. These include generating potential work, sorting the list of project alternatives, allocating the available budget, and simulating the results of the budget allocation. To generate project alternatives the system uses the MR&R policy to establish needed MR&R work, and applies a set of functional improvement criteria to determine the need for widening existing lanes, raising bridges and/or strengthening bridges. Replacement of a bridge may be triggered if functional improvements are needed but infeasible (e.g., widening a truss bridge), if a replacement rule is triggered based on consideration of bridge condition and age, or if replacement is more economically efficient than MR&R or other functional improvements.

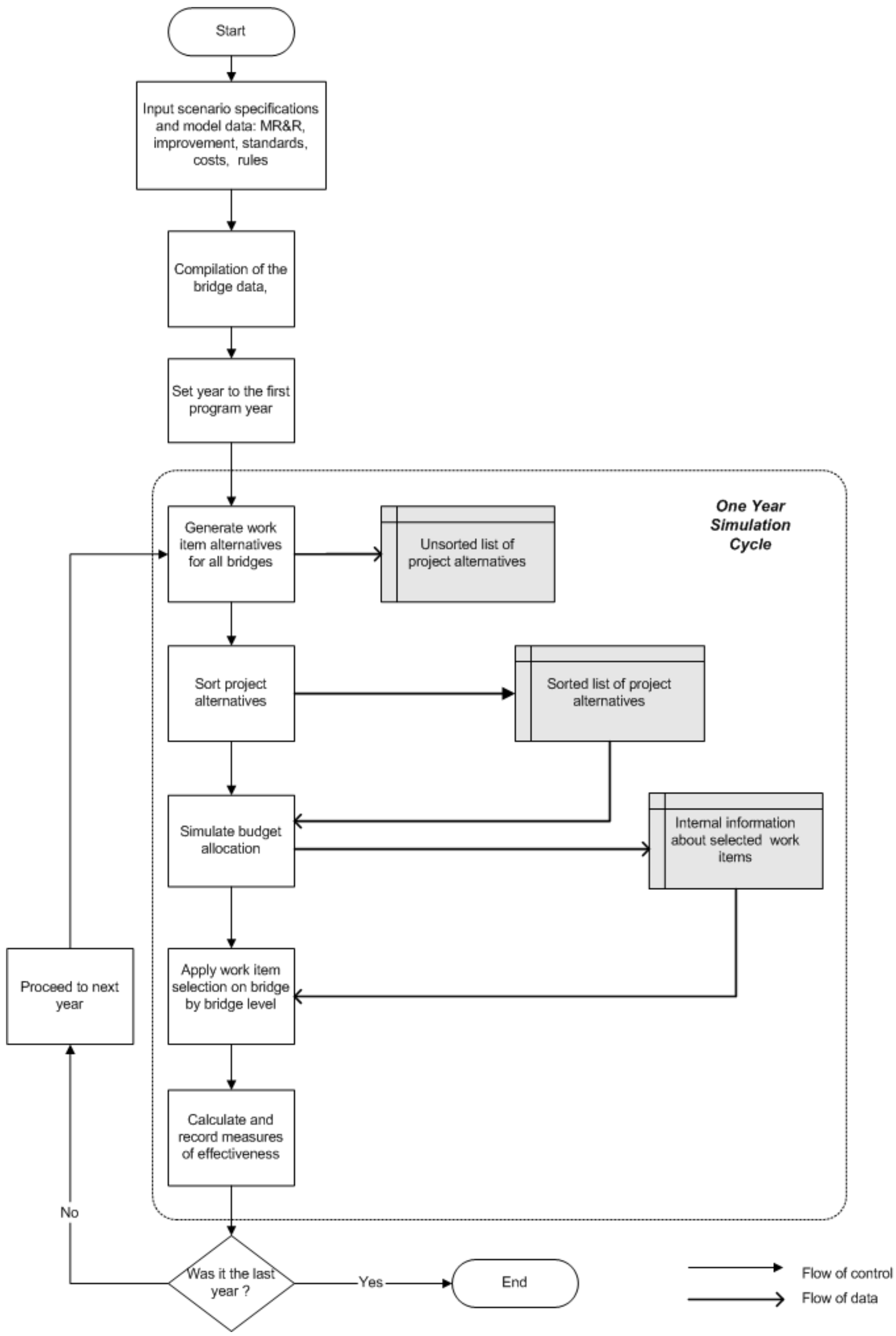
Once the set of needs is established, the list of needs is sorted in decreasing order of incremental benefit cost ratio (IBCR), and projects are selected from the list until the available budget has been expended. The approach of selecting projects in decreasing benefit/cost ratio (BCR) is a heuristic that provides a near-optimal solution to the Capital Budgeting Problem *(6)*. The additional step of using IBCR rather than BCR was recommended by McFarland, et. al. in their description of the INCBEN heuristic for solving the Capital Budgeting Problem for cases where one must select using multiple, mutually-exclusive project alternatives *(7)*.

The basic modeling approach is subject to several issues and limitations. These include the following:

- Generation of MR&R needs is strictly guided by application of the MR&R policy. The system will neither reconsider the policy if funding is chronically short, nor will it "up-scope" work to take advantage of available funds. On the other hand, MR&R needs, are typically accorded high priority, and almost inevitably funded in national-level simulations run with budget levels comparable to expected funding.
- Absent adjustment, the tendency of the system is to allow bridge elements to deteriorate to poor condition, then take action prior to element failure. This tends to result in poor overall conditions, and large numbers of bridges predicted to be Structurally Deficient. Note this behavior occurs only when allowing an element to deteriorate to poor condition is the lowest life cycle cost alternative. However, it does not account for agency performance standards and other factors that may result in a different element-level strategy in practice. Further, the tendency to allow elements to deteriorate to poor condition prior to taking action can be overcome to some degree by placing a penalty on poor conditions in solving for the MR&R policy.
- The system allows for specification of replacement rules forcing bridge replacement at specified minimum conditions. However, it can be difficult to predict the impact of adding replacement rules to the program simulation, particularly as the system will

recommend replacement only if the BCR of replacing a bridge exceeds a specified minimum threshold.

- Only one overall budget may be specified when performing a simulation.
- The system allocates funds one year at a time, and does not carry unspent funds from one year to the next. Thus, particularly if the budget is unbalanced there may potentially be unspent funds in one year, and/or unmet needs in others.



Source: Robert and Gurenich (5)

Figure 1. NBIAS Program Simulation Steps Prior to Version 5.0

NBIAS 5.0 MODELING ENHANCEMENTS

In designing NBIAS Version 5.0 FHWA sought to change the NBIAS program simulation to support multiple budgets by work type, and to make additional changes to support generation of project alternatives to leverage available funds and enable improved performance targeting. To implement this change FHWA made the following enhancements, detailed further in the following subsections:

- Implemented logic for generating a set of life cycle alternatives for each bridge, with each alternative specifying what action to be taken each five-year period for up to fifty years.
- Changed the MR&R policy from a one-year to five-year policy.
- Altered the program simulation to select project alternatives for each bridge across all periods considering a matrix of budget constraints.

Generation of Life Cycle Alternatives

The key change made to NBIAS Version 5.0 was to shift from selecting project alternatives on a year-by-year basis to making a single selection of bridge life cycle alternatives over all periods at once. In order to facilitate this change it was necessary to implement new logic for generating alternative bridge life cycles, with each life cycle describing what actions will be performed on the bridge over a period of up to 50 years.

In concept, generating a life cycle is straightforward – one simply need specify what action to perform each period. However, given there are conceivably three feasible actions for a bridge in any one period (do nothing, MR&R and functional improvement/replacement), one could in theory generate 3^{50} (approximately 7.18E+23) alternatives for each bridge. Managing this many alternatives can best be described as impractical. Thus, to reduce the number of alternatives generated for each bridge, the following rules were implemented in generating life cycle alternatives:

- The model was changed to consider 10 five-year periods rather than 50 one-year periods.
- A bridge can be replaced or improved only once every 50 years.
- After the first five-year period, the do nothing alternative is not generated. The "do minimum" option is thus to perform recommended MR&R work.

Based on these rules, in total 21 alternatives are defined for each bridge. These are illustrated in Table 1. This table includes one row for each life cycle alternative, with the columns of the table indicating the action performed in each five-year period for the specified alternative. In the table the do nothing action is indicated by "DN" and replacement or functional improvement (whichever is recommended) is indicated by "Improve." Each of the alternatives listed can be characterized by:

- Dollars spent by type of action each period.
- Discounted agency and user benefits obtained each period.
- Discounted future cost of maintaining the bridge following the end of the analysis period (calculated using the MR&R policy).

Table 1. Life Cycle Alternatives Generated for Each Bridge

Alt.	Action by Period 1	2	3	4	5	6	7	8	9	10
1	DN	MR&R	MR&R	MR&R	MR&R	MR&R	MR&R	MR&R	MR&R	MR&R
2	DN	Improve	MR&R	MR&R	MR&R	MR&R	MR&R	MR&R	MR&R	MR&R
3	DN	MR&R	Improve	MR&R	MR&R	MR&R	MR&R	MR&R	MR&R	MR&R
4	DN	MR&R	MR&R	Improve	MR&R	MR&R	MR&R	MR&R	MR&R	MR&R
5	DN	MR&R	MR&R	MR&R	Improve	MR&R	MR&R	MR&R	MR&R	MR&R
6	DN	MR&R	MR&R	MR&R	MR&R	Improve	MR&R	MR&R	MR&R	MR&R
7	DN	MR&R	MR&R	MR&R	MR&R	MR&R	Improve	MR&R	MR&R	MR&R
8	DN	MR&R	MR&R	MR&R	MR&R	MR&R	MR&R	Improve	MR&R	MR&R
9	DN	MR&R	MR&R	MR&R	MR&R	MR&R	MR&R	MR&R	Improve	MR&R
10	DN	MR&R	MR&R	MR&R	MR&R	MR&R	MR&R	MR&R	MR&R	Improve
11	MR&R	MR&R	MR&R	MR&R	MR&R	MR&R	MR&R	MR&R	MR&R	MR&R
12	MR&R	Improve	MR&R	MR&R	MR&R	MR&R	MR&R	MR&R	MR&R	MR&R
13	MR&R	MR&R	Improve	MR&R	MR&R	MR&R	MR&R	MR&R	MR&R	MR&R
14	MR&R	MR&R	MR&R	Improve	MR&R	MR&R	MR&R	MR&R	MR&R	MR&R
15	MR&R	MR&R	MR&R	MR&R	Improve	MR&R	MR&R	MR&R	MR&R	MR&R
16	MR&R	MR&R	MR&R	MR&R	MR&R	Improve	MR&R	MR&R	MR&R	MR&R
17	MR&R	MR&R	MR&R	MR&R	MR&R	MR&R	Improve	MR&R	MR&R	MR&R
18	MR&R	MR&R	MR&R	MR&R	MR&R	MR&R	MR&R	Improve	MR&R	MR&R
19	MR&R	MR&R	MR&R	MR&R	MR&R	MR&R	MR&R	MR&R	Improve	MR&R
20	MR&R	MR&R	MR&R	MR&R	MR&R	MR&R	MR&R	MR&R	MR&R	Improve
21	Improve	MR&R	MR&R	MR&R	MR&R	MR&R	MR&R	MR&R	MR&R	MR&R

Revised MR&R Policy

The second major enhancement was to change the MR&R optimization to solve for a five-year rather than a one-year period. This change was made without changing the underlying modeling approach of the system described in *(4)*, and instead required changing only the transition probabilities and discount factor used to account for the five-year period.

Tables 2 and 3 illustrate the impact of shifting from a one-year to five-year policy. In this case, the MR&R model is shown for Element 104, Prestressed Concrete Box Girder, Climate Zone 1 (Wet, Freeze/Thaw) with default costs. Further, the discount rate is 7% (resulting in a discount factor of 0.934) and the unit failure cost is $3,894.66. Four condition states are defined for this element. Actions other than do nothing are feasible in States 2, 3 and 4. In States 2 and 3 the feasible actions are to do nothing or clean and patch. In State 4 the feasible actions are to do nothing, rehabilitate, and replace. The table shows the probability of transition to each state given the indicated action is performed, the unit cost of the action (in this case in dollars per lineal meter of girder), and the long-term cost of performing the action. The long-term cost is the discounted future cost for the element, assuming the indicated action is performed in the current period, and the optimal policy is followed subsequently. The final column of the table indicates which action is optimal in each state (the action with the lowest long-term cost). Here the optimal policy is to clean and patch in State 3 and rehabilitate in State 4.

Table 3 shows a revised version of the model solved assuming a five-year period rather than a one-year period. In this version of the model the do-nothing transition probabilities have been revised to reflect the probability distribution resulting from five years of deterioration, and the problem is solved with a five-year discount factor of 0.713 rather than a one-year discount factor of 0.934. The unit costs and transition probabilities for clean and patch, rehabilitate and replace have been left unchanged. The resulting optimal policy is the same – clean and patch in State 3 and rehabilitate in State 4 – but the long-term costs are different, and the relative benefit of the clean and patch action is much greater in State 2 and 3 (the cost differential between do nothing and clean and patch), as this action is now considered once every five years rather than annually.

Comparing the long-term costs for State 3 in each table helps illustrate the differences. For State 3 the benefit of performing the Clean & Patch action in State 3 is $74.27 in Table 2 ($984.32 – $910.05), and $241.11 in Table 3 ($1,432.17 – $1,191.06). Though the optimal action is the same in both cases, the benefit of performing the action is substantially higher in Table 3. Had the unit cost of the action been $100 higher, the action would not have been recommended in the model solved for a one-year period, but would have remained the optimal action in the model solved for a five-year period. Note the long-term costs are higher for all actions and states in Table 3 than in Table 2 largely because in the case of the five-year model there is a small probability of element failure from State 2 (triggering the failure cost) even when the optimal policy is followed.

Table 2. Example MR&R Model with One-Year Periods

		Probability of Transition to State					Unit Cost	Long-Term	
State	**Action**	**1**	**2**	**3**	**4**	**Fail**	**($)**	**Cost ($)**	**Optimal?**
1	Do Nothing	92%	8%	0%	0%	0%	0.00	87.84	Y
2	Do Nothing	0%	98%	2%	0%	0%	0.00	161.48	Y
	Clean & Patch	86%	14%	0%	0%	0%	584.25	677.31	
3	Do Nothing	0%	0%	87%	13%	0%	0.00	984.32	
	Clean & Patch	53%	38%	10%	0%	0%	725.77	910.05	Y
4	Do Nothing	0%	0%	0%	87%	13%	0.00	2,127.88	
	Rehabilitate	33%	41%	17%	9%	0%	1,620.42	2,026.86	Y
	Replace	100%	0%	0%	0%	0%	3,953.51	4,035.60	

Table 3. Example MR&R Model with Five-Year Periods

		Probability of Transition to State					Unit Cost	Long-Term	
State	**Action**	**1**	**2**	**3**	**4**	**Fail**	**($)**	**Cost ($)**	**Optimal?**
1	Do Nothing	65%	28%	7%	1%	0%	0.00	435.74	Y
2	Do Nothing	0%	55%	33%	10%	2%	0.00	813.42	Y
	Clean & Patch	86%	14%	0%	0%	0%	584.25	933.12	
3	Do Nothing	0%	0%	50%	37%	13%	0.00	1,432.17	
	Clean & Patch	53%	38%	10%	0%	0%	725.77	1,191.06	Y
4	Do Nothing	0%	0%	0%	48%	52%	0.00	2,372.81	
	Rehabilitate	33%	41%	17%	9%	0%	1,620.42	2,259.49	Y
	Replace	100%	0%	0%	0%	0%	3,953.51	4,264.17	

As illustrated in this example, in general shifting to a five-year period for the MR&R policy results in projection of increased benefits for taking action. It also in some cases results in a more aggressive MR&R policy, with actions recommended sooner, and tends to reduce the effect of introducing penalties for poor condition.

Revised Program Simulation

The underlying problem the program simulation attempts to solve is a variant of the Capital Budgeting Program discussed above, and can be expressed as follows:

$$max \sum_i \sum_j \delta_{i,j} U_{i,j}$$

such that:

$$\forall_i \forall_j \delta_{i,j} = \begin{cases} 0 \\ 1 \end{cases}$$

$$\forall_j \sum_i \delta_{i,j} = 1$$

$$\forall_k \forall_t \sum_i \sum_j \delta_{i,j} C_{i,j,k,t} \leq K_{k,t}$$

where:

$\delta_{i,j}$	=	1 if alternative *i* for bridge *j* is programmed, 0 otherwise
$U_{i,j}$	=	benefit obtained from performing alternative *i* for bridge *j*
$C_{i,j,k,t}$	=	cost of performing alternative *i* for bridge *j* for action type *k* in period *t*
M_t	=	maximum budget for period *t*
$K_{k,t}$	=	maximum budget for action type *k,* period *t*

The problem can be solved exactly using optimization methods, but in practice it is often impractical to solve the problem using an exact approach given limitations in processing speed and memory. Further, the IBC approach used in previous versions of NBIAS has been demonstrated to provide a near optimal solution under certain circumstances, though it is designed to work with a single budget constraint. Thus, for NBIAS 5.0 a different heuristic was used for sorting project alternatives. Specifically, this version utilizes the MINCBEN heuristic documented previously by Robert, Gurenich and Thompson *(8)* and implemented in an analysis tool designed to work in conjunction with Pontis developed for the Virginia Department of Transportation.

To clarify how this heuristic works it is helpful to review the basic steps in the IBC approach originally defined by MacFarland, et. al. *(7)*. These are as follows:

- The set of mutually exclusive alternatives is defined for each asset.
- For each asset the alternatives are ordered by increasing cost.
- If a given alternative has benefit less than or equal to that of another alternative with the same or less cost, the alternative is discarded.
- The IBCR for each alternative is calculated as the difference in benefit divided by the difference in cost of the alternative compared to the next cheaper alternative. For the cheapest alternative the IBCR is equal to BCR.

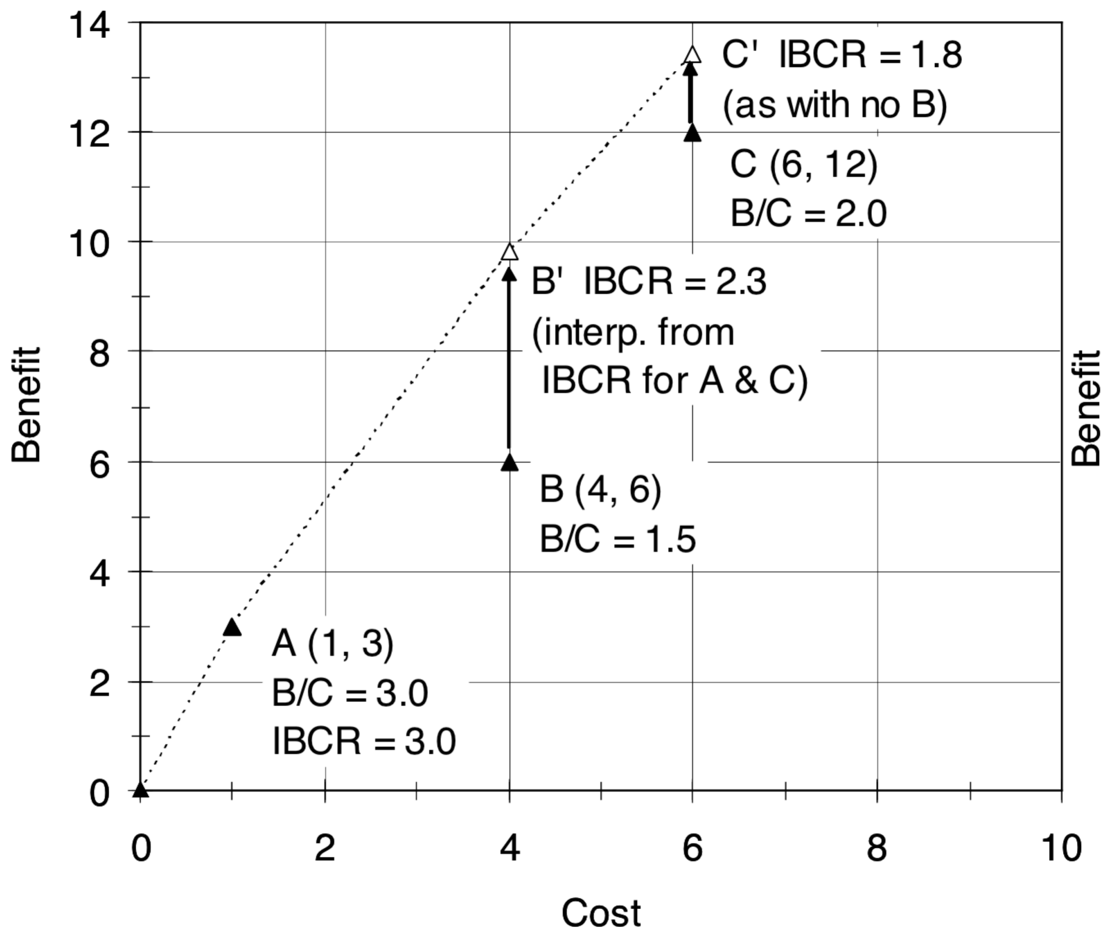
- The IBCR values are examined to verify that the benefit function is well-behaved (i.e. IBCR decreases as cost increases, which implies that the curve of benefits, plotted as a function of costs, is concave). In cases where a higher incremental benefit follows a smaller one, the two are averaged. This process is repeated until the benefit function is well-behaved. If the benefits measure is monetized consistently with costs, then incremental benefits should exceed incremental costs for each alternative, or the alternative should be discarded.
- The IBCR values for all assets are combined into a single list and sorted in decreasing order.
- Projects are selected from the list until the budget constraint is reached.

Figure 2, reproduced from *(8),* provides an example of the calculation of IBCR using this approach. In this case three mutually-exclusive alternatives are defined: A, B and C. If funding is sufficient then C is preferred as this alternative provides the greatest benefit (12 versus 6 for B and 3 for A). However, if funds are limited then C may not be affordable regardless of its greater benefit. Thus the heuristic first selects A, as it has the highest IBCR, then B, followed by C if funds are sufficient. Note MacFarland recommends adjusting IBCR values as needed to make sure IBCR decreases with increasing costs, hence the adjustment to Alternative B. In practice, in many implementations of the IBCR heuristic – including Pontis and NBIAS – alternatives such as B that fall below the benefit/cost curve are excluded along with any alternatives where benefits decrease with increasing cost.

As noted previously, the above heuristic is not designed to work with multiple budget constraints (e.g., for different work types or multiple periods). In these cases it becomes more important to consider how to handle alternatives such as B, and there may be cases where the optimal solution involves selecting an alternative that has less benefit than a cheaper alternative. For instance, if project C has greater benefit and is cheaper than a hypothetical project D then it is obviously preferred. However, project D may be the preferred alternative if it involves spending money in a year that is less constrained than required for C. The following variation on the IBCR heuristic (termed "MINCBEN") was proposed in *(8)* to address such cases:

- The set of mutually exclusive alternatives is defined for each asset.
- For each asset the alternatives are ordered by increasing cost.
- The IBCR for each alternative is calculated as the difference in benefit divided by the difference in benefit of the alternative compared to the next cheaper alternative. For cheapest alternative is compared to the "do nothing" alternative.
- The IBCR values are examined to verify that the benefit function is well-behaved (i.e. IBCR decreases as cost increases, which implies that the curve of benefits, plotted as a function of costs, is concave). In cases where a higher incremental benefit follows a smaller one, the alternative with the smaller IBCR value is removed from the set of alternatives, and reserved for further consideration. The IBCR is then recalculated for the remaining alternative.
- After the set of alternatives for the asset is examined, analysis proceeds to the reserved set.

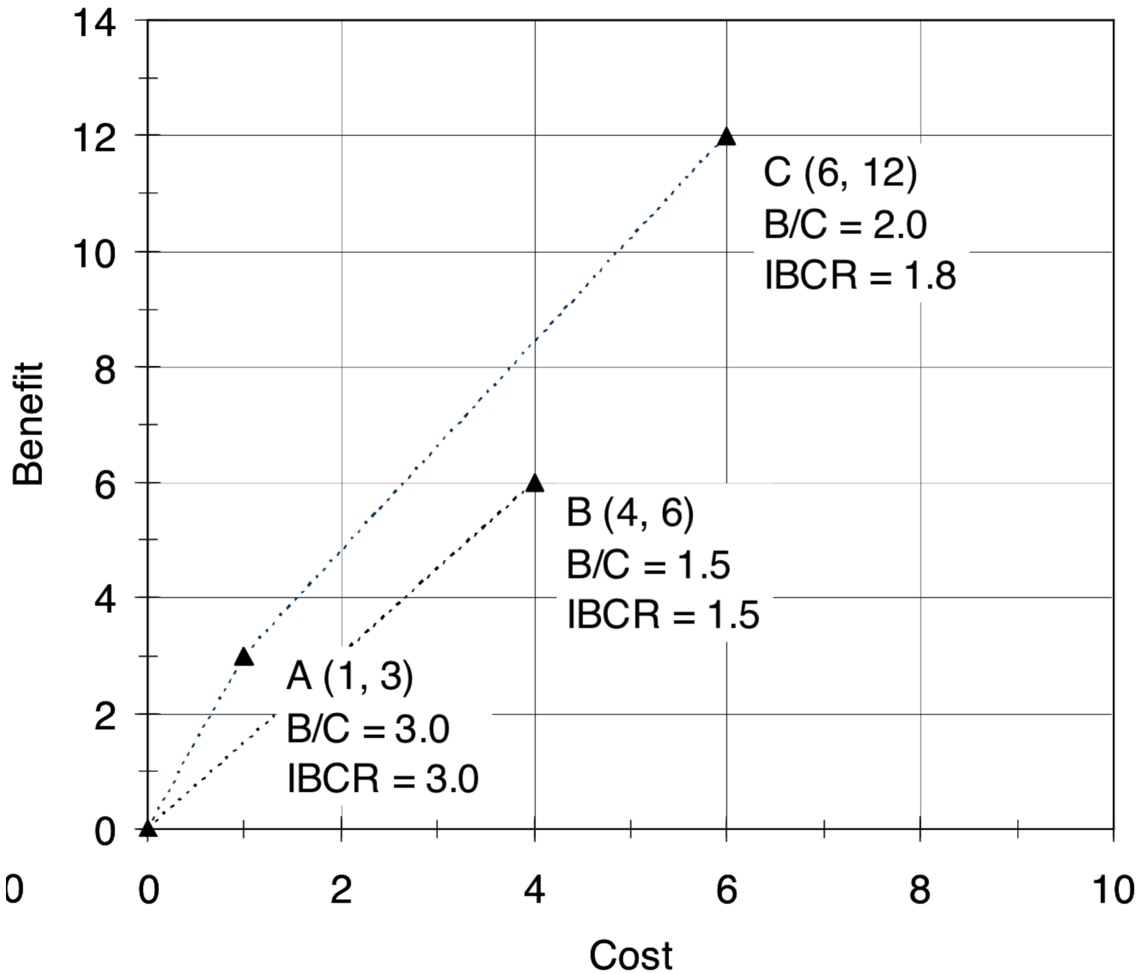
- The preceding three steps - recalculating IBCR, examining the benefit function, analyzing the new reserved set - are repeated until multiple sets of alternatives have been defined for each asset, each set having a well-behaved benefit function.
- The IBCR values for all assets and alternative sets are combined and sorted in decreasing order.
- Alternatives are selected from the list of alternatives until the budget constraints are met. An alternative is skipped if selecting the alternative would violate a budget constraint, or if a selection has been made from a different alternative set for the same asset.



Source: Robert, Gurenich and Thompson (8)

Figure 2. Example Calculation of IBCR using the INCBEN Heuristic

Figure 3, also reproduced *(8)*, illustrates how this heuristic functions. In this case, Alternative B is reserved. The heuristic first selects A, then C if funds are sufficient. Only if neither A nor B is selected will the heuristic consider C. For cases with a single budget constraint alternative C would never be selected, and the algorithm yields the same result as that of the current version of NBIAS. However, for complicated cases with budget constraints for multiple years and work types the modified heuristic “keeps all options on the table” and thus can provide a result that is closer to the optimal solution.



Source: Robert, Gurenich and Thompson (8)

Figure 3. Example Calculation of IBCR using the MINCBEN Heuristic

Figure 4 illustrates program simulation approach implemented in NBIAS 5.0, and shows how the generation and selection of life cycle alternatives described above fits into the overall process. In contrast to previous versions of NBIAS, alternatives are generated once for all periods rather than once each period, and the selection of alternatives is performed in a single step. Alternatives are selected subject to a matrix of budget constraints. The following constraints are specified by period, as well as for non-deficient, deficient and all bridges:

- MR&R (constrained for the first period only)
- Widening
- Raising
- Strengthening
- Replacement
- All Functional Improvements Except Replacement
- All Functional Improvements Including Replacement
- Total Budget

Once life cycle alternatives have been selected, the system simulates the application of each life-cycle alternative. The results are saved for viewing and reporting using the NBIAS What-If Module detailed in *(5)*.

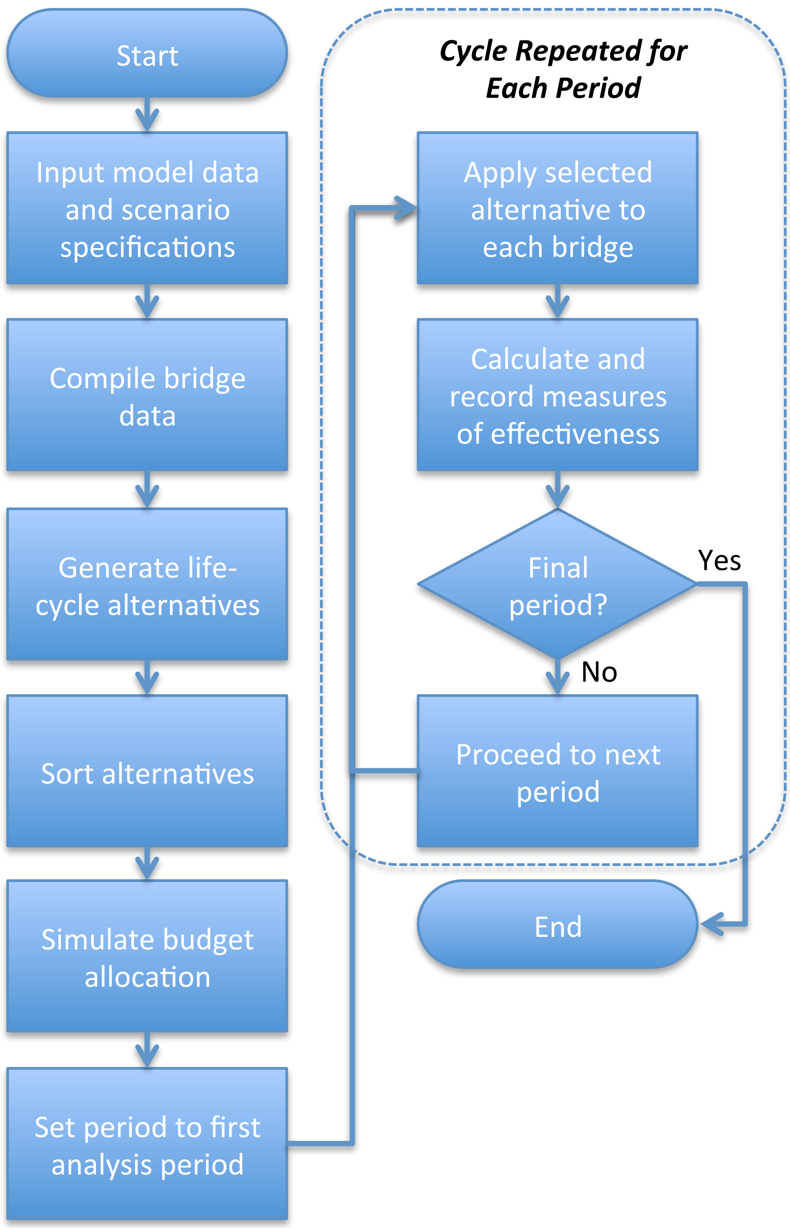


Figure 4. NBIAS 5.0 Program Simulation Steps

IMPACT OF MODELING ENHANCEMENTS

Initial testing of NBIAS 5.0 indicates that this version of the system does indeed generate different results from prior versions, particularly as budget constraints are introduced by work type. Consistent with its approach to introducing other major modeling enhancements in the tools used to support development of the C&P Report, FHWA is planning to run old and new versions of the system in parallel in developing the next C&P Report to document and clarify the differences. Pending results of this process, initial findings from early tests of the system are:

- The MR&R policy recommended by the system is more aggressive, recommending treatments sooner than that recommended previously. Previously FHWA used an MR&R policy with a penalty on poor conditions to yield better and more realistic results. Adding this penalty had a similar effect, in terms of generating a more aggressive policy. Further testing is needed to determine whether such a penalty is justified in running NBIAS 5.0, and if so how it should be set.
- Generally there is an additional benefit to be obtained by replacing or improving a bridge in addition to performing needed MR&R work, and the tendency of the system, absent budget constraints, is to schedule replacement or improvement at some point over a bridge's life cycle. This reduces – and may even eliminate – the need to create replacement rules to force realistic model behavior. However, if traffic is projected to increase and the accumulation of benefits is limited to a period of 20 years, one can observe cases where greatest benefits are achieved by deferring improvement/replacement as late as possible in the simulation. Further investigation is needed to determine to what extent this occurs in practice, and whether the benefits accrual period should be adjusted.
- Version 5.0 of the system runs somewhat faster than prior versions as a result of the fact that alternative generation and selection is a separate process and need not be repeated when changing budgets and various other scenario parameters. Further speed improvements are nonetheless feasible.

PLANNED NBIAS ENHANCEMENTS

A variety of other enhancements are planned for NBIAS 5.1, scheduled for release in Spring 2017. This version of the system will extend the enhancements detailed here, adding:

- **New element definitions.** Transition from use of the AASHTO Commonly-Recognized (CoRe) elements defined in *(9)* to the newer element specification detailed in *(10)*. Elements modeled by the system will include those defined in FHWA's *Specification for National Bridge Inventory Bridge Elements (11)*.
- **Support for culverts.** The National Bridge Inventory includes a number of bridge-length culverts, but these are screened from analysis in NBIAS. Beginning with NBIAS 5.1 these will be included in the analysis.
- **Support for good/fair/poor measures.** NBIAS predicts numbers of bridges with specific values for deck, superstructure, and substructure ratings, but provides few measures summarizing overall conditions across rating values. In Version 5.1 the system will calculate percentage of bridge area in good, fair and poor condition. Consistent with measures defined separately by FHWA, a bridge will be defined to be in good condition if the minimum value of its condition rating is 7 (on a scale from 0 to 9), in fair condition of the minimum is 5 or 6, and in poor condition if the minimum is 4 or less.

CONCLUSIONS

The modeling enhancements to NBIAS described in this paper offer the potential for FHWA to obtain more accurate and robust projections of highway bridge investment needs and future bridge conditions. However, the work described here raises a number of questions and potential topics for future research. These include:

- **Increasing the number of alternatives considered.** As detailed here, NBIAS 5.0 considers 21 life-cycle alternatives for each bridge over a 50 year period. In concept this number could be increased significantly, particularly in cases where one is analyzing a subset of the nation's bridges, or analyzing a period shorter than 50 years. In these cases it may be valuable to increase the number of periods with a do-nothing alternative defined, and/or allow for a variable analysis period – both of which would tend to increase the number of alternatives generated.
- **Exploring potential for using an exact optimization rather than a heuristic approach.** The heuristic approach used in NBIAS for selecting project alternatives is expected to yield near optimal results, but further research is warranted to evaluate how well the heuristic performs, and whether implementation of an optimization approach yielding an exact solution is warranted.
- **Implementing parallel processing.** NBIAS is architected as a client/server system and does not take advantage of parallel processing or other advanced computational features. However, the change in the program simulation approach of the system, to decouple generation of project alternatives from the year-by-year simulation, enables implementation of parallel processing at a later date to further speed the analysis.
- **Other modeling enhancements.** FHWA has considered a variety of other potential model enhancements, and may implement these in the future, to the extent they support improved results and can be implemented given available resources. These include but are not limited to modeling other bridge needs besides those triggered by physical condition, such as scour and seismic vulnerability, expanding modeling of widening to consider need for capacity improvements, further improving performance targeting, utilizing the element-level inspection data now being submitted for National Highway System bridges, and various other enhancements.

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