NATIONAL SUSTAINABLE PAVEMENT CONSORTIUM

TPF 5 (268)

Pre-Print

Dehghani, M., Giustozzi, F., Flintsch, G.W., Crispino, M., "Cross-asset Resource Allocation Framework for Achieving Performance Sustainability," Journal of the Transportation Research Board, 2013, vol. 2361, pp 16-24.

Cross-asset Resource Allocation Framework for Achieving Performance Sustainability

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Submission Date for Publication: 8 March 2013

1) Paper presented at the Annual Meeting of the Transportation Research Board and published by the *Journal of the Transportation Research Board*, 2013, vol. 2361, pp 16-24.

2) This paper was produced under partial sponsorship of the Transportation Pooled Fund 5-268 - National Sustainable Pavement Consortium. The authors thank the Mississippi, Pennsylvania, Virginia, and Wisconsin DOTs, as well as FHWA for support and guidance.

ABSTRACT

The resource allocation across multiple assets in transportation systems has gained significant attention over the past few years. In this context the present paper proposes a framework to help decision makers estimate the optimal resource allocation across multiple assets considering functional, structural, and environmental performance indicators. The CO_2-equivalent emissions are considered in the calculations along with condition measures to evaluate the optimal budget allotment scenario that will lead to structural and functional integrity as well as environmental sustainability. The application of the framework is demonstrated in a case study with pavement and bridge assets. The results show that the framework can be used as a supporting tool for decision makers and transportation agencies to estimate the optimal budget to invest on each asset. The paper also evaluates the impact of different parameters on the resource allocation policy with a sensitivity analysis. The findings show that the initial condition of assets, and the priority (weights) assigned to each indicator (functional, structural, and environmental) can change the optimal resource allocation scenarios. It was also found that the relative size of the assets has notable impact on the optimal budget share. Finally, the paper discusses the need for agencies to consider their own data inputs, and provides recommendations for future research.

INTRODUCTION

The financial crisis and the lack of sufficient funds and resources have affected the management of transportation infrastructure facilities (such as highways) and degraded their quality and level of service [1]. The importance of effective preservation and maintenance of infrastructure systems has become more evident than ever before. Agencies and engineers are demanding methods and frameworks that are able to optimally distribute the budget across multiple assets such as pavements, bridges, culverts, guardrails, and signals, and to promote the quality of service of the entire facility. However, cross-asset resource allocation is a complicated task. The complexity mainly arises with the heterogeneity of assets that are to be managed as well as the diversity of goals and objectives, and their unclear relative merit. In addition, the need for public awareness regarding the environment has forced transportation agencies to move from an efficient infrastructure system into a "sustainable and efficient" transportation infrastructure system. Therefore, the decision process of allocating resources and choosing between alternatives is no longer based only on cost evaluations and standard performance assessments. Environmental considerations as well as impact calculations in terms of land use, greenhouse gas emissions, recycling practices, and material consumption, for instance, have to be included into the overall decision framework. On one hand, accounting for a wide range of different parameters requires the cross-asset resource allocation process to be a comprehensive and adaptable optimization methodology. On the other hand, numerous variables and objectives increase the complexity of the problem. Multi-attribute optimization processes, already developed for transportation purposes, should now be enhanced by including environmental considerations to help create a sustainable transportation system.

Heterogeneity of Assets

In the resource allocation process, providing a procedure to compare the assets, their performance, and their relative importance is key. The comparison procedure should be able to identify why one asset should receive more funding than another. In roadway systems, measures such as the International Roughness Index (IRI) and Pavement Condition Index (PCI) for pavements, Health Index (HI) for bridges, and time-to-failure for signs and signals have been developed and are able to well explain the performance and condition of the corresponding assets. Nevertheless, these performance measures have a different methodology, scale, and nature which make the comparison of assets a difficult and challenging task [2]. One solution to understand the relative importance of assets is to look at the bigger picture and understand how different pieces (assets) contribute to the overall performance of the system. Since the assets within an infrastructure or a transportation system are interconnected and work together, an effective resource allocation should keep the entire system functional, not just the individual components.

Therefore, the overall system-level performance can be a reasonable indicator against which different resource allocation scenarios can be evaluated. Research studies started developing overall performance indicators for one asset (such as pavements) by combining and aggregating their performance measures[3, 4]. These studies were then further extended to develop overall system indicators for an infrastructure by aggregating and combining the performance measures of different assets within that infrastructure [5, 6].

Multi-Objectivity and Trade-Off Analysis

The unique set of performance measures for different assets and various agency goals emphasize on multi-attribute approaches that capture all measures and goals [5, 7]. Agencies are often more concerned with the functional and structural aspects of roadway systems. Safety is the major concern for politicians and strategic-level decision makers. In the face of the energy crisis and climate changes due to global warming, the environmental sustainability of preservation and maintenance policies, as well as reducing emissions related to the resulting asset conditions during the usage phase [8], are being increasingly emphasized. Therefore, transportation agencies are gradually incorporating the environmental impacts of maintenance and construction activities – such as carbon equivalent emissions (CO_{2e}) – in their calculations. Since a considerable amount of non-renewable resources (i.e.; virgin aggregates, bitumen, etc.) are used daily for constructing and maintaining transportation assets, a calculation of emissions produced and a comparison between design and maintenance strategies is thus significant. Emissions analysis represents a step forward for selecting the right design and maintenance alternative to be applied while preserving the environment.

An ideal infrastructure management system (IMS) should preserve all network sections at a high level of service, with adequate structural, functional, and safety conditions, within a minimum reasonable budget. The optimal maintenance strategy to be implemented into an IMS for assets preservation would be the one that maximizes performance over time, minimizes costs (both agency and user costs), and reduces the impacts on the environment over the life cycle of the asset.

Unfortunately, many of these goals are usually in conflict; e.g., more frequent maintenance interventions will provide higher traffic delays and congestion for users, increasing their relative costs. Frequent interventions due to a low performance of the assets will result in higher material consumption, increased use of equipment, and traffic disruptions, which results in higher environmental impacts.

OBJECTIVE

This paper proposes a framework to help agencies allocate the budget across their multiple assets while taking the structural and functional integrity of assets, as well as the environmental impacts of maintenance actions into account. The paper proposes a simple and practical procedure to assess the optimal strategy according to several objectives and illustrates its practicality with a case study example.

METHODOLOGY

This section presents the proposed sustainable cross-asset management framework. The framework, as shown in FIGURE 1, consists of four steps: resource allocation, treatment selection, performance prediction, and overall performance evaluation. The iterative framework presented here is generalized and includes main roadway assets and performance indicators that serve as a future reference for agencies. However, without loss of generality, the demonstration of the framework application will be focused on a smaller number of assets and performance measures for simplicity purposes.

Resource Allocation (Step 1)

The process begins with an initial resource allocation scenario. Each resource allocation scenario shows how much funding is allocated to each asset. The initial scenario is normally based on expert opinions, goals and objectives, and constraints within the agency. In the proposed framework the results and outcomes of each resource allocation scenario are compared with the goals and objectives and are used to update the scenario until the optimal resource allocation is reached.

Treatment Selection (Step 2)

When a resource allocation scenario is selected and the resources are distributed across assets, the best maintenance treatment alternatives are then selected for each asset based on the available budget. The treatments are selected from a range of alternatives that are classified under the main categories of preventive, corrective, restorative, and heavy rehabilitation. For simplicity, the maintenance categories were kept similar for all classes of assets, although the maintenance types under each category may be different for each asset. For example, preventive maintenance in bridges usually includes crack sealing, bridge painting, deck overlay, deck sealing, and joint projects, where preventive maintenance of pavements includes ultra-thin overlays, slurry seal, and microsurfacing applications, etc. [9].

Performance Prediction (Step 3)

After maintenance and rehabilitation (M&R) treatments are selected for each asset, the next step is to predict performance improvements due to maintenance applications. Modeling of asset performance is absolutely essential to infrastructure management on all levels. Performance models can be deterministic or probabilistic and rely or not rely on actual conditions of the asset; however, monitoring is an essential step to determine objectively the current condition of the asset and its historical deterioration trend so as to use that information in formulating a management plan of action for the future. An accurate and effective resource allocation can only be implemented if maintenance effectiveness is continuously monitored by agencies.

Performance of an asset defines how the asset condition changes over time or how well the asset serves its intended functions with accumulating usage. Several types of performance and, therefore, several types of performance models can be acknowledged. Functional performance represents an evaluation of the asset serviceability and superficial conditions (i.e.; roughness, surface friction, etc.); structural performance identifies asset distresses and structural deficiencies. These two types of performance can also be combined with other performance features such as safety or environmental evaluations for developing a comprehensive (or combined) performance.

In the proposed method several types of performance measures will be predicted after maintenance is applied on the assets. Examples are: IRI, cracking and rutting for pavements, and condition states for the elements of bridges. These measures are then aggregated into combined indicators for a comprehensive evaluation of the corridor. Further explanation on performance measures and indices used in the paper will be provided in the next sections.

Overall Performance Evaluation (Step 4)

In step 4, the performance measures predicted for each asset are aggregated via a framework into combined measures that explain the performance of the entire corridor or facility. As already discussed in the Introduction section, translating the performance of individual assets into indicators that describe the entire corridor performance can be a useful benchmarking measure for selecting optimal resource allocation policies. The performance aggregation framework used in this paper employs the concepts and methods proposed in [5]. The framework and the calculation steps are shown in FIGURE 2 and includes the following stages:

Stage 1: Quality measures are converted to performance indicators (PI) having a scale of 0-10 with 10 representing the best condition. For bridges, PIs are defined for each element of the bridge (say element type f); they are calculated based on the total quantity of element type f (TEQ_f) and the weighted quantity of that element (WEQ_f) in the bridge using the equations in Step 1 in FIGURE 2. The WEQ_f values are calculated based on quantities of element type f that are in state i (EQ_{fi}) where a_i is the weight associated with condition state i.

Stage 2: Performance indicators are converted to asset health indicators (AHI). The asset health indicator associated with asset type *i* (pavement or bridge) and health indicator type *j* (structural, functional, etc.), AHI_{ij}, is calculated using the equation in step 2 in FIGURE 2. The AHI_{ij} is a weighted average of PI_{ik} values across *k* different quality measures associated with asset type *i*, and p_{kj} denotes the weight of PI_{ik} in calculating health indicator type *j*.

Stage 3: The asset health indicators are aggregated into corridor health indicators (CHI). The calculation process is similar to stage 2. Corridor health indicator type *j*, CHI_j, is a weighted average of asset health indicator type *j* across all assets where the weight, w_{ij}, represents the importance of AHI_{ij} in computing corridor health indicator type *j*.

Stage 4: Corridor health indicators are aggregated into the overall corridor health rating (OCHR). Again, *OCHR* is a weighted average of CHI_j values where the weight z_j indicates the importance of corridor health indicator type *j* in the overall corridor health rating.

Once the overall performance measures are derived, they will be compared with the goals and objectives. The resource allocation will be updated in an iterative process through a feedback loop until the goals are met.

PERFORMANCE MEASURES

Without loss of generality, the application of the framework is demonstrated for pavements and bridges considering functional, structural and environmental performance. This section explains the data collected and analyzed to obtain the functional and structural properties of each maintenance action for pavements and bridges. The section also discusses how the environmental impacts of maintenance actions were assessed.

Functional and Structural Performance

Four types of maintenance actions were considered in this study as shown in List of **Tables and Figures**

TABLE 1. Maintenance Characteristics for Pavements and Bridges

: preventive, corrective, restorative, and heavy rehabilitation. Preventive maintenance (PM) was intended for both pavements and bridges as a way to act proactively for extending the asset service life, slowing down the deterioration. Preventive treatments were identified within the usual treatments conducted by the Virginia Department of Transportation (VDOT). Pavement preventive maintenance includes four treatments: microsurfacing, slurry seal, chip seal, and ultra-thin overlay. Bridge preventive maintenance mainly includes epoxy concrete overlay and cleaning and resealing expansion joints. Corrective maintenance (CM) was intended to be applied when the asset has already started to deteriorate but still retains a good level of service. CM on pavements includes milling and resurfacing (≤ 2 in) and moderate patching (less than 10% of the pavement area, 6-inch depth); CM on bridges addresses minor issues on deck and superstructure/substructure adopting concrete overlays (≈ 7 in) and minor repairs on the structure. Restorative maintenance (RM) was considered as a major rehabilitation method for addressing medium to severe issues on pavements and bridges. Restorative maintenance includes milling and resurfacing (≤ 4 in) and heavy patching (less than 20% of the pavement area, 12-inch depth); RM on bridges includes major interventions such as deck and superstructure replacement. Heavy rehabilitation includes treatments that significantly extend the asset life.

The functional and structural gains associated with each treatment action as well as their environmental impacts were assessed and are shown TABLE 1. The treatment costs were computed using the average price list for construction and maintenance activities in Virginia. The functional improvements were evaluated in terms of gains in associated performance measures after the maintenance activity. For instance, pavement functional gain after preventive maintenance was evaluated by analyzing data on PM effectiveness from real pavement sections throughout the state. The treatments effectiveness was analyzed over a time span of 10 years, evaluating trends of several common indices such as IRI and rutting – that contribute to functional performance of pavements – according to different traffic levels and pavement types [10]. It should be noted transportation agencies can use their own performance measures since deterioration trends and maintenance effectiveness significantly change depending on traffic levels, climate conditions, and current pavement structure.

Similarly, the structural evaluation was conducted by analyzing the improvements on the structure of the asset provided by the specific maintenance type or treatment. Several indices commonly used for evaluating the structural capacity of pavements and bridges were analyzed and an effectiveness value, on a 0-10 scale, was consequently derived. PM on road pavements, for instance, do not provide a significant change in the Structural Condition Index (SCI) [11]; the structural gain associated to the PM of pavements is therefore 0. Again, transportation agencies should use their own data to determine the structural gain values based on their know-how, typical maintenance type, experience, etc. Also note that the values for bridge treatments' characteristics were obtained from different resources and reports [9, 12] as well as from discussions with pavement engineers and VDOT managers.

Along with structural and functional measures considered in the framework, the innovative improvement presented in the paper includes the environmental impacts assessment in the resource allocation process as a step toward a *sustainable* cross-asset resource allocation. The current resource allocation process can represent a more sustainable way to manage the transportation infrastructure system. The final allocation of resources to multiple assets may also change based on weights that transportation agencies would assign to the environmental impacts; this, for example, would identify more sustainable maintenance strategies for managing assets. The methodology to assess the environmental impacts related to maintenance strategies is illustrated in the following section.

Environmental Performance

Environmental impacts are usually measured through the computation of the greenhouse gases (GHG) emitted in the atmosphere during the whole process over the life cycle of a product; this is usually known as the carbon footprint [13, 14]. The lower the amount of emissions produced, the more sustainable the material, process, or strategy. Carbon footprinting analyses are not straightforward to develop mainly because specific standards have not been set yet for road pavements and bridges. Different procedures and constraints can therefore be adopted, achieving different results depending upon the inputs. For this reason, every environmental analysis should initially state the constraints and the boundary conditions adopted (ISO-EN 14044, 2006). A carbon footprint is a measure of the impact a specific activity has on the environment and, in particular, climate change. Six GHGs, as identified by the Kyoto Protocol, form a carbon footprint. These gases absorb infrared radiation and can therefore affect the climate when they are released into the atmosphere [15].

Emissions from the manufacture of raw materials, and equipment utilized during the construction stage, maintenance practices, and rehabilitation/reconstruction procedures are then converted into carbon equivalent emissions to compute their carbon footprints. Indeed, in order to simplify the calculations, the six gases are combined together into the equivalent carbon dioxide (CO_{2e}). The conversion from a certain greenhouse gas into a unit of equivalent carbon dioxide is conducted by multiplying the amount of that GHG by its Global Warming Potential (GWP) on a specific time interval, usually 100 years. The GWP is the measure of the global warming produced by a GHG trapped in the atmosphere for a specific time interval (20, 100, or 500 years) [16].

A specific methodology [17], to which the reader is referred, was developed for computing environmental impacts related to maintenance treatments of the assets. Processes, and their related emissions, involved in manufacturing the initial raw material up to the final product as ready-to-use, have been considered in the carbon footprint assessment. Different literature data available were averaged to compute a reasonable value of emissions due to the manufacture of raw materials [18]. Furthermore, emissions related to machines and on-site mobile plants were also computed, analyzing the equivalent amount of carbon dioxide coming from the engine exhaust systems. Boundaries were set in the case study to only include emissions related to materials and equipment; however, the framework presented in the paper can be easily adjusted to involve other phases (hauling, usage-phase, disposal, landfilling, etc.) in the analysis.

TABLE 1 reports the assessed values obtained from the environmental analysis of the different types of maintenance activity on pavements and bridges. PM treatments were analyzed according to the procedure reported in [17]; in particular, four PM treatments were evaluated for pavements and the outcoming emissions were then averaged to obtain a final impact value related to PM on pavements. Other treatments were further simplified to compute environmental impacts and emissions; i.e., environmental impacts of epoxy overlays were only taken into account when computing emissions related to PM on bridges. However, the present paper does not aim to exactly assess a unique and general value for environmental impacts related to maintenance activities; rather, it proposes a methodology for including environmental burdens into cross-asset resource allocation. Transportation agencies can then modify the input parameters according to their needs, software, data, and expertise.

The following assumptions were made for conducting the environmental impact assessment of maintenance strategies:

- PM on pavements included materials and equipment emissions of microsurfacing, slurry seal, chip seal, and ultra-thin overlay [19]; PM on bridges included emissions computation for the epoxy overlay, a standard maintenance practice in Virginia.
- CM on pavements took into account emissions related to mill and resurface treatments and a 7-inch concrete overlay on bridges.
- Restorative maintenance on pavements considered a 4-inch milling and a 4-inch resurfacing treatment, and a 15-inch concrete overlay for bridges.
- Heavy rehabilitations include actions such as heavy milling and thick overlay that extends the service life significantly and restores functional performance and structural capacity of the assets.

As an explanatory example, calculations for the epoxy overlay are reported in TABLE 2. Data from the European Association of Plastic Manufacturers [20] were assumed as key values for the environmental assessment of the raw production of 1 kg of epoxy resin. A two-coat epoxy application was chosen for being applied; a first coat of 40 ft^2 per gallon (application rate) followed by 3 lbs of crushed aggregates was placed, and a second coat of 20 ft^2 per gallon followed by 4 lbs of crushed aggregates was finally applied for completing the epoxy maintenance treatment. Emissions from epoxy and aggregates were then summed up according to their relative quantities; the final quantity of emissions was then computed for a square foot of bridge, providing the results expressed in TABLE 1Case Study

In order to show the application of the proposed framework, a roadway section with a 2000 sf^2 bridge segment and a 3 lane-mile pavement segment was considered. For simplicity in results analysis, only two asset segments (pavement and bridge), and three performance indicators (functional, structural, and environmental) were considered. However, multiple pavement segments or bridges can be considered, each as an individual asset and can be input into the framework. The information about the initial structural (SI_0) and functional (FI_0) indicators of the bridge and pavement section as well as the available budget are shown in FIGURE 3.

In order to find the optimal resource allocation scenario – or, in other words, the optimal treatment strategy for each asset – several scenarios were examined. For each resource allocation scenario the calculation process was as follows:

- The best treatment option was selected for the pavement and bridge segments based on the allocated budget. Then, the functional and structural gains as well as the environmental impacts of the selected treatments were calculated using TABLE 1.
- For simplicity and without loss of generality, a 6-year analysis period was considered with no additional maintenance actions during the analysis period. In each year of the six-year period, the functional and structural indicators of the pavement and bridge segments were predicted via MATLAB simulation. It was assumed that the pavement and bridge segments will deteriorate linearly over their extended life, as provided in TABLE 1.
- The structural indicator of the pavement was combined with the structural indicator of the bridge to calculate the structural indicator of the entire corridor using the formulas in Step 3 in FIGURE 2. The aggregation weights (w_{ij}) were calculated based on the relative construction cost of the pavement and bridge segments in the corridor. Similarly, by using the formula in Step 3 of FIGURE 2, the functional indicators of the pavement and bridge segments were aggregated. The weights were calculated based on the relative surface areas of the pavement and bridge segments in the corridor. The assumption was that users are exposed to the surface condition of pavements and bridges, which affects their perception of the functional performance of these assets [5]. However, agencies may use other approaches to select the weights based on their objectives and the feedback from travelers. The environmental indicator of the corridor was calculated simply by summing up the environmental impacts of the treatments selected for bridge and pavement segments. The environmental impact was then normalized in a 0-10 scale, with 10 representing the state with the lowest CO_{2e} emission (best environmental condition).
- The structural indicator of the corridor was averaged over the analysis period and, similarly, the average functional indicator of the corridor was calculated. Note that the corridor environmental indicator is a fixed value that is associated with the treatment type applied at the beginning of the analysis period. The environmental impacts of the usage phase were not considered.
- The overall corridor health rating for the 6-year period was then calculated by aggregating the average structural indicator with the average functional indicator and the environmental indicator using the Step 4 formula in FIGURE 2. The weights (z_j) for structural, functional, and environmental aspects were selected to be 0.45, 0.40, and 0.15, respectively. Again, these values were selected for the demonstration purposes and transportation agencies can select their own values based on their priorities.

Results

The results for different resource allocation scenarios are shown in FIGURE 3. In the first scenario, 95% of the available budget ($1.2M) was given to the bridge section. Therefore, heavy rehabilitation was selected for the bridge and PM was applied to the pavement based on its lower amount of budget. The corridor environmental indicator as a result of this treatment policy was 5.4. The policy resulted in an average structural health of 6 and an average functional health of 4.5 for the corridor over the analysis period (6 years). The overall health of the corridor (taking functional, environmental, and structural aspects into account) was 5.3.

The pavement budget share was raised to 20% of the total budget in the second policy, which increased the structural, functional, and overall health indicators of the corridor. However, the environmental indicator was reduced from 5.4 to 2.7 since the corrective maintenance policy selected for pavement produced more CO_{2e} emission. The pavement budget share was further increased in the third policy to around 50% of the budget. The structural and functional indicators were increased significantly while the environmental indicator had a marginal improvement of 0.2. This is because of a lighter bridge treatment as a result of a lower budget for the bridge. The overall health indicator was improved significantly with this policy.

However, further increase in the pavement budget share to over 90% did not improve the corridor functionality, while the structural integrity of the corridor decreased around 2 units. This is because the pavement segment in this case study has a greater contribution to the corridor functional indicator due to its significantly larger surface area compared to the bridge (190,000 ft^2 vs. 2000 ft^2). However, since the pavement and bridge segments in the corridor have relatively close construction costs ($3M vs. $2M), they both make considerable contributions to the structural indicator. Therefore, when the bridge resource share is decreased further from 50%, the structural indicator drops significantly and reduces the overall corridor health. The environmental indicator was significantly improved from 2.9 to 5.4 because the bridge received lighter treatments. Note that bridge treatments, mostly concrete overlays, had higher impacts on CO_{2e} emission. The increase in pavement share from 50% also decreased the overall corridor health by 0.15. As shown in FIGURE 3, when the pavement budget share is between 50%-60% the overall corridor health condition is maximized.

Note that the optimal resource allocation found here is specific to the presented case study. Factors such as such as initial condition of the pavements and bridges, treatment characteristics (TABLE 1**List of Tables and Figures**

TABLE 1. Maintenance Characteristics for Pavements and Bridges

), size of the assets, and the weights given to each health indicator (functional, structural, etc.) can result in different optimal resource allocation policies. Agencies can use the proposed methodology with more accurate data and information associated with each asset and maintenance type to select appropriate decision policies. In the next section, the paper briefly discusses how the resource allocation approach is sensitive to different levels of input parameters.

SENSITIVITY ANALYSIS

This section discusses how the proposed approach and the resulting optimal policies are sensitive to parameters such as the relative size of the assets in the corridor, and their initial condition. Several experiments were designed and analyzed. In the first experiment, the impact of the initial conditions of the assets on the optimal scenario was evaluated. The analysis shows that if the condition of the pavement and bridge in the corridor are not significantly different, then the optimal policy does not change notably. However, if the asset conditions are significantly different, then the optimal resource allocation policy will be changed. For example, in the case shown in FIGURE 4a, where the bridge had a more critical condition compared to the pavement, the bridge segment received a notable portion of the budget (80%) in the optimal scenario.

In the second experiment, the impact of the relative size of the assets on the resource allocation was analyzed. A bridge segment with a higher surface area (3000 ft^2 instead of 2000 ft^2) in the corridor was considered and the total budget was increased to \$1.5M (FIGURE 4b). In this case, although both assets have similar construction costs (equal to \$3M) and the pavement has a more critical condition, the optimal policy allocates 60% of the budget to the bridge, as shown in FIGURE 4b. This is because, with similar construction costs, the pavement and bridge segments have equal contributions to the structural integrity of the corridor (regarding the proposed method). Therefore, a notable drop in the bridge structural indicator will drop the corridor structural indicator and, consequently, the overall health rating. Note that since the bridge area has increased, the CO_{2e} emission from maintenance actions on the bridge has increased as well, which decreased the environmental indicator compared to the original example.

The resource allocation process also depends on the weights assigned to functional, structural, and environmental indicators. For example, in the case study discussed in this paper, a higher weight of environmental indicator results in selecting optimal policies that favor pavement segment. This is because the concrete material in the bridge produces significant CO_{2e} emission for raw material manufacturing. Also, and with respect to the proposed method, giving higher weights to the structural indicator would favor assets that have higher construction costs. Similarly, higher weights for the functional indicators will favor assets that have larger surface areas.

In general, the analysis of the example case study shows that significant difference in the initial condition of the assets, the relative size of the assets, and the weights assigned to each indicator can result in different optimal resource allocation policies. The assets' relative size seemed to have the most notable impact on the optimal budget share. Nevertheless, it was found that the budget is not allocated only based on the relative size (construction cost or the surface areas) of the assets in the corridor.

DISCUSSION AND RECOMMENDATIONS

This paper proposes a framework for resource allocation across multiple roadway assets. The framework is a multi-attribute decision making model that captures the structural and functional integrity of the assets and the corridor, as well as the environmental impacts of maintenance activities on the assets. Without loss of generality, and for simplicity in the analysis, the application of the framework was demonstrated in a simple case study with one pavement segment and one bridge segment. The results showed that the proposed method can be used as a helpful supporting tool to assist decision makers in selecting the optimal budget allocation. It was also shown that parameters such as initial condition of the assets, their relative size, and the weights given to each indicator (structural, functional, environment) can result in different optimal policies.

The information used in the case study was based on mathematical calculations (for environmental impacts), VDOT reports, and expert opinions and was merely intended for demonstrating the application of the framework. Agencies are encouraged to use more accurate information from actual data for the assets they manage (such as asset performance prediction models, maintenance characteristics, asset specifications etc.) to obtain more reliable and accurate results. While the agencies are encouraged to use their own information, further research is needed for defining the accurate relationship between different maintenance activities (preventive, corrective, etc.) and the associated improvements in the performance measures (IRI, cracking, rutting) of each asset.

As for future, the current research will incorporate other roadway assets (e.g. culverts, sign and signals, guardrails) into the framework and considers other important indicators such as safety in the decision making process. The focus of this study was on maintenance aspects of activities and capturing the environmental effects associated with material production and installation phase of treatments. Considering maintenance and operations more broadly would allow capturing mobility and safety as additional consequences of maintenance and a broader set of environmental impacts to analyze. Research is also needed to translate agency policy directives and priorities to an appropriate set of analytic weights. Since factors such as road classification, traffic volume, and network topography are important in the resource allocation, the values of weights needs to be sensitive to such factors.

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List of Tables and Figures

TABLE 1. Maintenance Characteristics for Pavements and Bridges

	Treatment type	Cost*		Extended life *(years)*	Functional gain *0-10 scale*	Structural gain *0-10 scale*	Environmental impact *kg of CO_2e/ft^2*
		$/ft²	*$/lane mile*	average			
Pavements	**Preventive** (chip seal, slurry, microsurf, ultra-thin ov.)	0.27	20000	4	2	0	0.187
	corrective (≤ 2" Milling and ≤ 2" AC Overlay, moderate patching - less than 10% of pav. area, depth 6")	0.68	80000	9	5	2	0.497
	Restorative (≤4" Milling and Replace with ≤4" AC Overlay, heavy patching - less than 20% of pav. area, full depth 12")	1.13	200000	13	8	6	0.710
	Heavy rehab.		400000	18	10	10	1
Bridges	**Preventive** (epoxy overlay ($/m2), clean and reseal expansion joints ($/m))	40.00		8	2	0	4.146
	Corrective (rigid deck overlay, superstructure/substructure repairs)	100.00		15	4	2	36.306
	Restorative (superstructure replacement, deck replacement)	300.00		25	8	6	77.798
	Heavy rehab	500.00		40	10	10	100
*: Pavement construction cost ≈ $1,000,000/lane-mile, Bridge construction cost ≈ $1000/ft²							

TABLE 2 Emissions for Epoxy Overlay

AIR EMISSIONS							
Emission	**From fuel prod'n (mg)**	**From fuel use (mg)**	**From transport (mg)**	**From process (mg)**	**From biomass (mg)**	**From fugitive (mg)**	**Totals (mg)**
dust (PM10)	1.304E+03	5.071E+02	1.688E+01	6.807E+03	0.000E+00	0.000E+00	8.635E+03
CO	2.556E+03	1.550E+03	1.953E+02	3.930E+02	0.000E+00	0.000E+00	4.695E+03
CO_2	1.306E+06	4.053E+06	2.708E+04	3.239E+05	2.245E+03	0.000E+00	5.708E+06
SOX as SO_2	4.963E+03	6.094E+03	0.000E+00	6.577E+02	0.000E+00	0.000E+00	1.191E+04
NOX as NO_2	3.620E+03	8.659E+03	2.597E+02	8.756E+02	0.000E+00	0.000E+00	1.341E+04
HF	5.785E+00	1.587E+00	9.533E-04	2.153E-04	0.000E+00	0.000E+00	7.373E+00
N_2O	5.391E-06	2.966E-09	7.306E-08	3.151E-03	0.000E+00	0.000E+00	3.156E-03
H_2	7.104E+01	5.600E-06	5.784E-03	4.396E+03	0.000E+00	0.000E+00	4.467E+03
CFC/HCFC/HFC not specified elsewhere	3.770E-06	0.000E+00	1.844E-05	9.089E+00	0.000E+00	0.000E+00	9.089E+00
CH_4	9.771E+04	2.162E+03	9.121E-02	1.756E+03	0.000E+00	7.800E-02	1.016E+05
CO_2 EQUIVALENTS*							
Type	**From fuel prod'n (mg)**	**From fuel use (mg)**	**From transport (mg)**	**From process (mg)**	**From biomass (mg)**	**From fugitive (mg)**	**Totals (mg)**
20 year equiv	7.374E+06	4.191E+06	2.770E+04	4.389E+05	2.245E+03	5.808E+00	1.203E+07
100 year equiv	3.563E+06	4.107E+06	2.769E+04	3.704E+05	2.245E+03	2.766E+00	8.066E+06
500 year equiv	2.000E+06	4.072E+06	2.769E+04	3.423E+05	2.245E+03	1.518E+00	6.440E+06

**CO_{2e} values are referred to a time horizon of 100 years in the analysis*

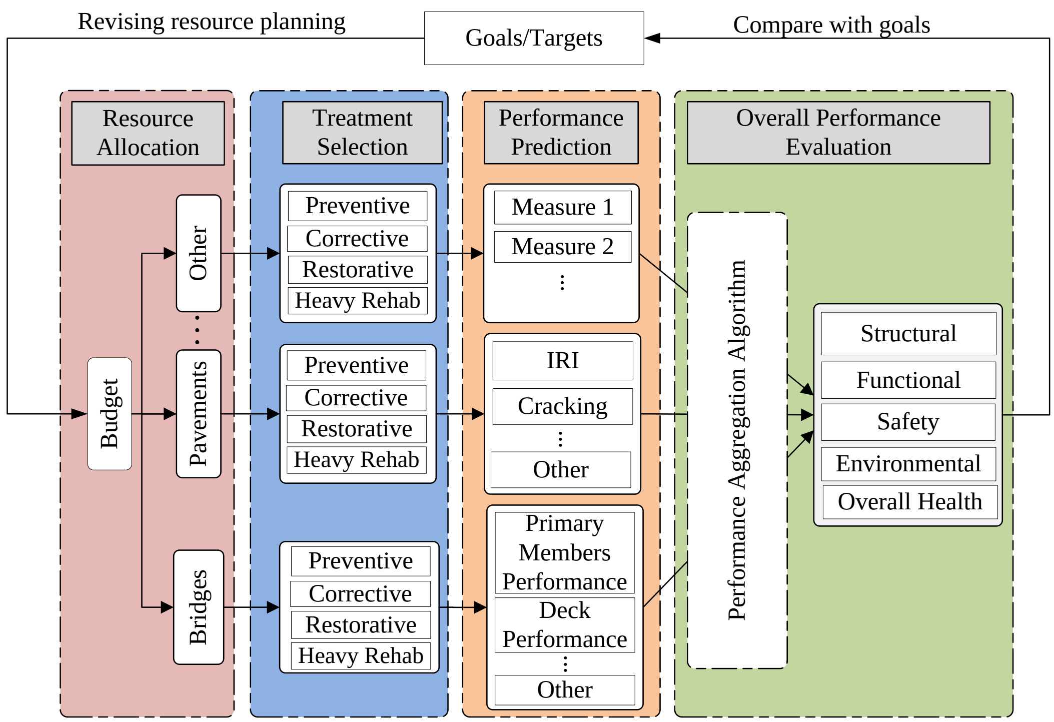


FIGURE 1 Cross-asset resource allocation framework.

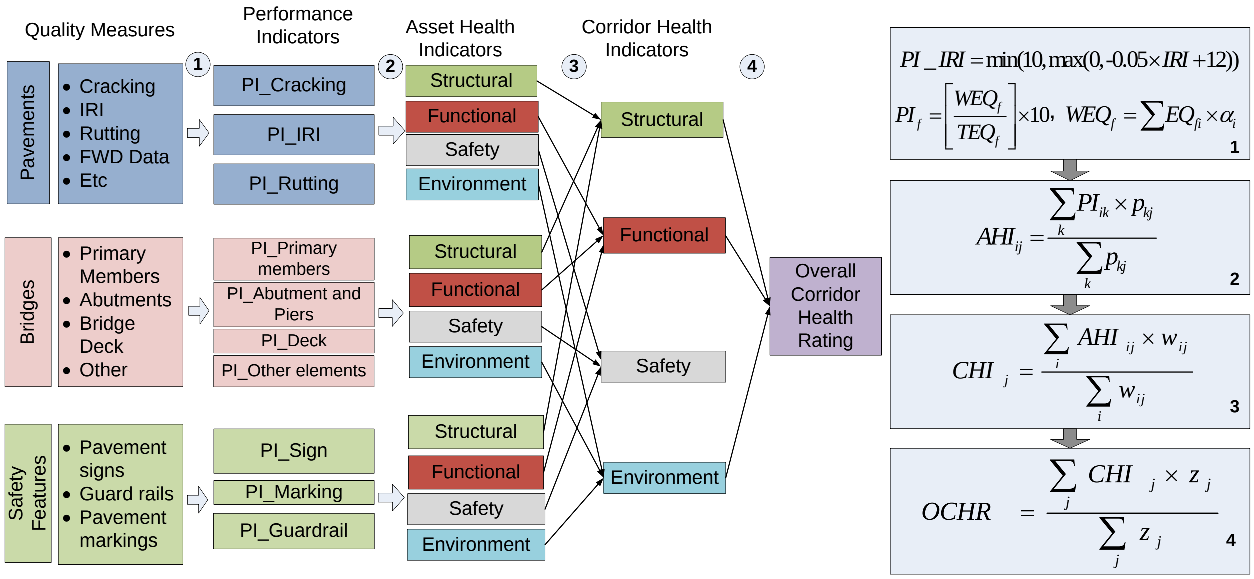


FIGURE 2 Performance aggregation framework and computation steps.

	Pavement	Bridge
Lane. Mile	3	-
Area (ft^2)	190,000	2,000
FI_0	4	5
SI_0	6	7
Available Budget ($)	1,200,000	

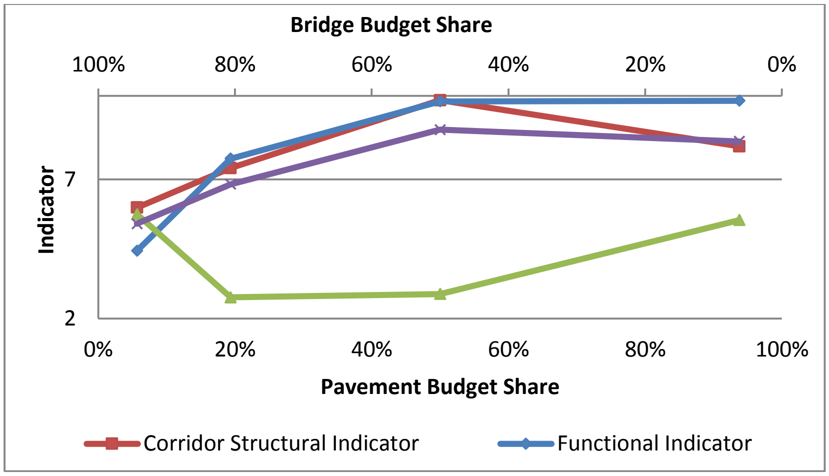
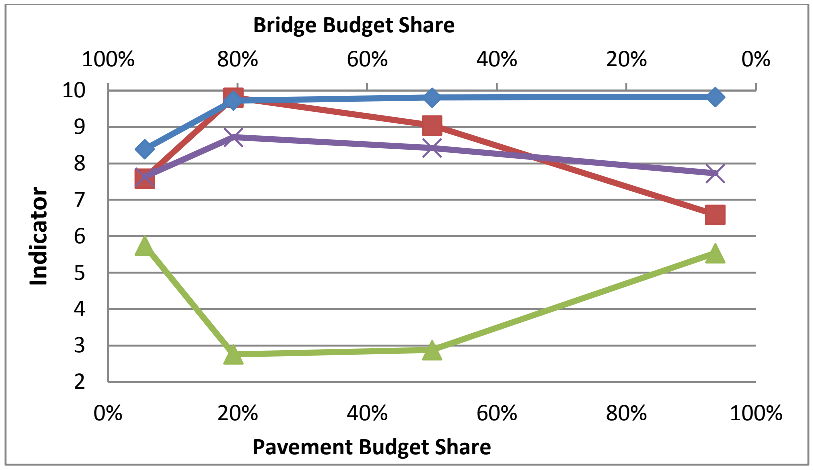


FIGURE 3 Resource allocation policies and the resulting performance measures

a)

	Pavement	Bridge
Lane. Mile	3	-
Area (ft^2)	190,000	2,000
FI_0	**7**	**3**
SI_0	**8**	**2**
Available Budget ($)	1,200,000	



b)

	Pavement	Bridge
Lane. Mile	3	-
Area (ft^2)	190,000	**3,000**
FI_0	4	5
SI_0	6	7
Available Budget ($)	**1,500,000**	

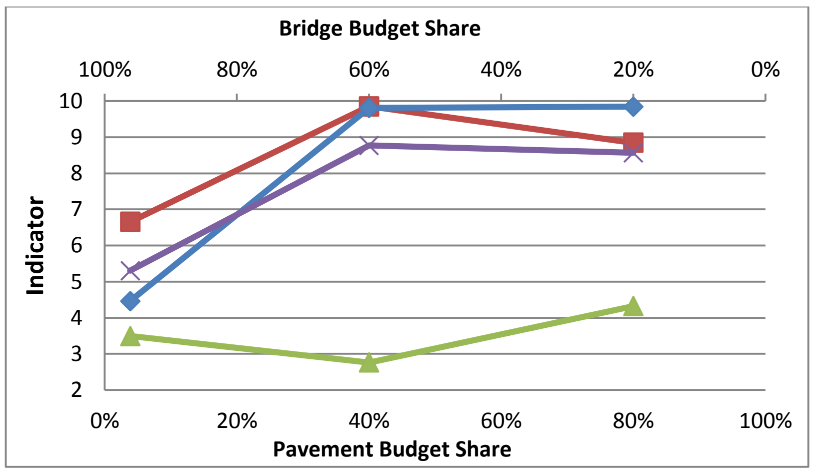


FIGURE 4 Examples of the impact of initial condition (a), and asset size (b), on resource allocation.