Climate Change Influence on Priority Setting for Transportation Infrastructure Assets

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Abstract: Transportation infrastructure could be vulnerable to local manifestations of global climate change, such as storm frequencies and durations of seasons. To adapt, transportation agencies need methodologies for reprioritizing their assets subject to the new sources of vulnerability. Prioritizing assets is nontrivial when criteria assessments and owner/operator preferences are considered in conjunction with the possible climate scenarios. Few efforts to date have addressed these scenarios in a priority setting for infrastructure asset management in the literature. This paper extends a scenario-based multicriteria decision framework that can assist decision makers in effectively allocating limited resources to adapt transportation assets to a changing climate. The framework is demonstrated with one of the most susceptible metropolitan transportation systems in the United States, the Hampton Roads region in coastal southeastern Virginia. First, the high-level goals of a long-range transportation plans are used in a traditional multicriteria analysis to generate a baseline prioritization of assets. Next, several scenarios that incorporate and combine a variety of climate conditions are identified. Finally, the scenarios are used to adjust the initial criteria weighting, which results in several reprioritizations of the assets. The results help to identify the most influential scenarios and characterize the sensitivity of the baseline prioritization across multiple scenarios. With these results, additional scientific and investigative efforts can be focused effectively to study and understand the influential scenarios. **DOI: 10.1061/(ASCE)IS.1943-555X.0000094.** *© 2013 American Society of Civil Engineers.*

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Introduction

The effects of climate change on infrastructure systems could be realized in a variety of ways (Lambert et al. 2011). Climate-related physical-geographic changes, such as sea level rise, reduced snow cover, sea ice, and the increased frequency of extreme-heat days and changes in the hydrologic cycle have been observed globally (Karl et al. 2009). Global temperatures have been projected to rise between 1 and 6°C by 2100. Temperature increases can be associated with changes in seasonal duration and increased frequencies of extreme weather events with associated precipitation, runoff, and storm-surge impacts.

Transportation agencies have begun to consider how the impacts of climate change will affect their policies and programs for asset management [McFarlane and Walberg 2010; Transportation Research Board (TRB) 2008; Governor's Commission on Climate Change (GCCC) 2008]. An increase in temperature extremes would cause damage to pavement and railroad tracks (Karl et al. 2009; Meyer et al. 2010). Storm surge from hurricanes exacerbated by sea-level rise threatens coastal transportation assets. Bridges and tunnels, in particular, would be susceptible to extreme weather events and have the potential to be disruptive for regional transportation. System operations, such as evacuations, traffic management and monitoring, and other activities, could be impacted. Intermodal facilities, such as ports and airports, could be impaired with significant economic ramifications. These and other potential impacts of climate change on transportation have been enumerated in numerous studies, most notably the U.S. Global Change Research Program (USGCR) report (Karl et al. 2009).

If climate change is already underway and additional warming is expected, adaptation to these changes could be beneficial for ensuring the performance of particular transportation infrastructure systems into the future. A key challenge for adaptation is the variety of time horizons across the several factors of climate change. Although some regions may be experiencing a marked increase in climate change-related weather events over the past two decades,

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the effect is hardly uniform across regions, making it difficult to provide blanket guidelines for adaptation (TRB 2008). Some efforts, to date, have focused on predicting future climate change well enough to make decisions that are both economically viable and technically sound. For example, several research efforts have attempted to describe the impacts of climate change on transportation infrastructure (Lindquist 2009). The GeRiCi project in Europe focused on risk management related to climate change for infrastructures (Guerard and Ray 2006). Some relevant efforts in Europe include FUTURE-NET (Wilks 2010), WEATHER (Enei et al. 2011), and EWENT (Leviakangas et al. 2011). Similar work has been performed for infrastructure and climate change risk assessment in Victoria, Australia (CSIRO 2007). In the United States, considerable attention has been provided to the Gulf Coast region because of its susceptibility to extreme storms and sea level rise, whereas few efforts have explored the effects on other regions of the country.

In an effort to develop a more general framework for assessing the impacts of climate change on transportation infrastructure, the Federal Highway Administration (FHWA) of the United States proposed a conceptual model for understanding the risks of changing climate to transportation infrastructure (FHWA 2011). Fig. 1 describes the three elements of the model: (1) an inventory of critical assets, (2) climate forecasts, and (3) quantitative risk assessment. Taken individually, these are straightforward activities, but in practice, there are several key challenges to implementing the model. First, there are no universally accepted definitions for criticality that can be applied across classes of assets. Second, quantitative climate forecasts often focus too much on reducing uncertainty rather than exploring the ways in which changes to the climate might interact with other natural or anthropogenic phenomena, e.g., land subsidence or population growth. Third, for the transportation decision maker, quantitative risk assessment needs to be incorporated within a prioritization technique that would inform resource allocation and management.

Largely missing from the literature and from the FHWA model is a quantitative approach for carrying out priority setting across diverse transportation assets that are vulnerable to climate change. Vulnerability assessment is an important element of risk management that can categorize assets and enable the development of a risk management plan [U.S. Department of Energy (USDOE) 2001]. The results of such an assessment can support agencies in decision making under financially or politically constrained conditions (USDOE 2001). Asset prioritization is already an integral part of transportation assets management (TAM) systems, but it remains difficult to compare results across distinct classes of assets

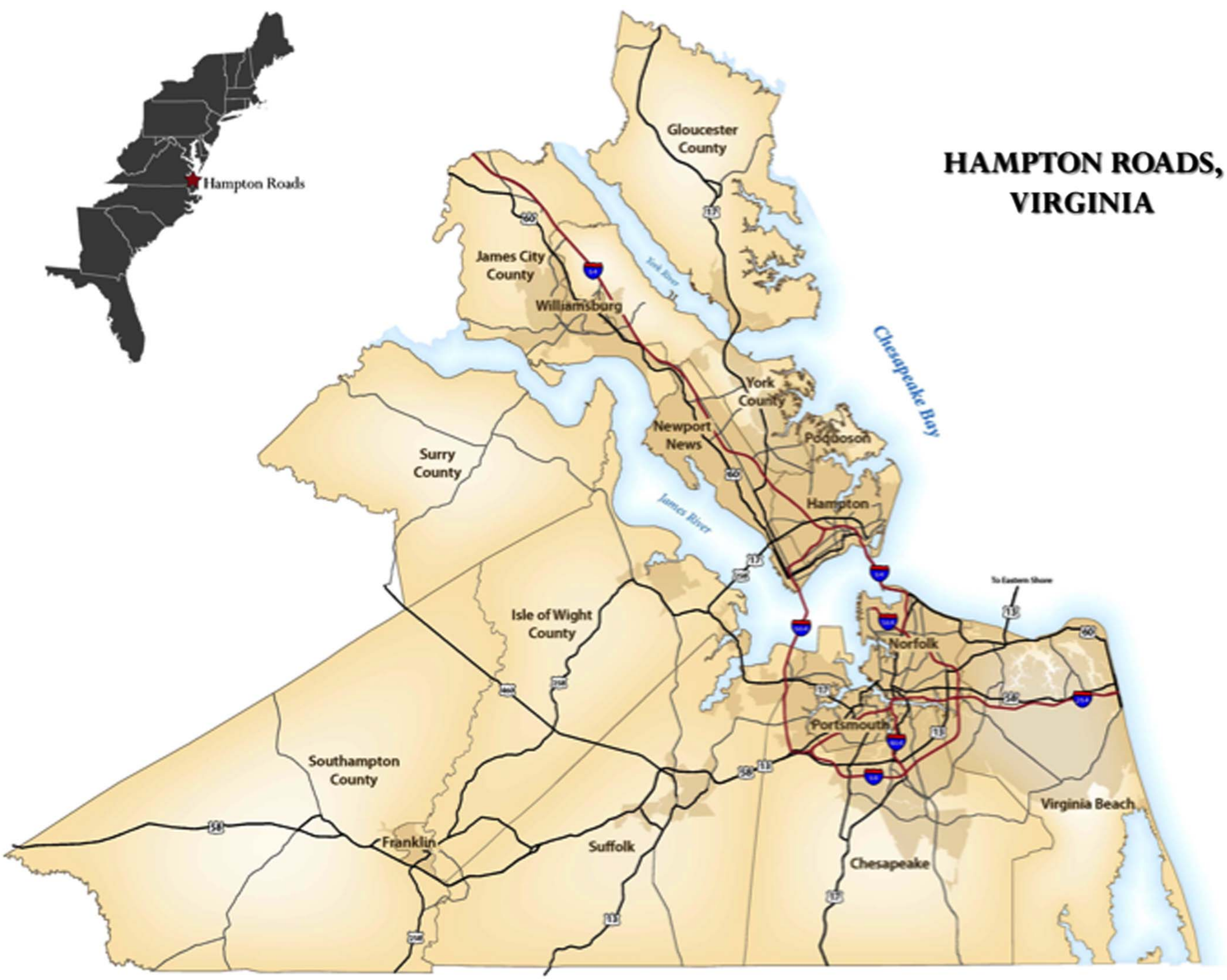

Fig. 1. Region of Hampton Roads, Virginia (McFarlane and Walberg 2010), used with permission from Hampton Roads Planning District Commission

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(Meyer et al. 2010). Because prioritization activities are already prevalent in infrastructure asset management, asset prioritization serves as an ideal platform for climate change-related decision making.

Incorporating climate stressors into asset prioritization is challenging in several respects. First, diverse criteria need to be considered and applied to assets that are not easily compared (e.g., a railway bridge and a highway winter-maintenance facility). The assessments across prioritization criteria require input from a variety of technical experts, and this introduces perceived subjectivity to the process. Second, climate change could be accelerating into the future, and thus, it is important to carry out vulnerability assessments that can evaluate assets and criteria over several time horizons. Third, climate change projections often take a global perspective and do not reliably identify the climate factors that will dominate in a particular region. Thus, the involvement of regional experts is essential. Fourth, traditional deterministic and uncertainty-based (e.g., probabilistic) asset prioritizations can overwhelm decision makers with lower-order concerns, making the key elements more difficult to identify.

Some examples of asset prioritization can be found in the literature. Rowshan et al. (2003) develop a six-step assessment tool for transportation planners to evaluate highway vulnerability. Baker (2005) develops a qualitative vulnerability assessment methodology for critical infrastructure sites. Erath et al. (2009) develop a methodology to assess transportation network vulnerability with a model to calculate failure consequences. None of the work to date has attempted to incorporate the effects of climate change in transportation asset management. Furthermore, the work does not yet address how transportation assets can be interdependent with utility assets, e.g., the electrical grid, which could also be affected by factors of climate change.

This paper develops a framework for prioritization in transportation asset management that is inclusive of the potential factors of climate change. The mathematical framework comes from a scenario-based multicriteria decision that was described for other applications, unrelated to asset management or climate change (Schroeder and Lambert 2011). The reinterpretation of the earlier published mathematics represents an innovative approach that should be useful for transportation decision makers broadly. For illustrative purposes, it is demonstrated here for the case of the Hampton Roads metropolitan area in southeast Virginia because it is one of the most vulnerable regions in the United States where the impacts of climate change on transportation infrastructure are only beginning to be studied.

Method

Scenario-Based Multicriteria Decision Analysis Framework

A framework for prioritizing a set of transportation assets under the influence of various climate scenarios was adopted in this paper. The prioritization was modified to consider climate scenarios, criteria, and assets. This was carried out by using selected mathematical elements of multicriteria decision analysis (MCDA) (Linkov et al. 2006), which has been used in various ways for portfolio selection for infrastructure investments. A scenario-informed MCDA can be effective in considering the criteria that vary in importance to stakeholders under the influence of scenarios. A scenario-informed MCDA has been applied in prioritizing infrastructure policies and investments (Karvetski et al. 2011). Scenario-informed MCDA has also been used for prioritizing transportation policies (Schroeder and Lambert 2011) and prioritizing environmental security investment alternatives for industrial and military installations (Karvetski et al. 2011). Selected elements of a scenario-informed multicriteria analysis method that was developed by (Karvetski et al. 2011; Schroeder and Lambert 2011) are adopted in this work.

Formulation of the Framework

The authors define a set of assets $A = \{a_i | i \le I, i \in N^+\}$ in which I is the total number of assets that are to be prioritized. Each asset a_i is evaluated across a set of criteria $C = \{c_j | j \le J, j \in N^+\}$ in which J is the total number of criteria. For transportation systems, these criteria might be evident from a long-range, unconstrained strategic plan. Each asset a_i is evaluated across the criteria c_j by experts to yield asset ratings z_{ij}, in which $0 \le z_{ij} \le 1$. This rating reflects an extent to which asset a_i addresses criterion c_j. The rating $z_{pj} > z_{qj}$, in which $p, q \le I$ and $p, q \in N^+$, represents that the asset a_p addresses criterion c_j more adequately than asset a_q. A vector $\mathbf{z}_i = (z_{i1}, z_{i2}, \ldots, z_{iJ})$ represents the assessments across all criteria for asset a_i.

To enable comparisons and prioritization of assets, a mapping from this vector to the real number set is constructed as follows. An additive value function $u{:}A \times C \to [0, 100]$ is defined as

$$u(a_i) = 100 \times \sum_{j=1}^{J} w_j z_{ij} \tag{1}$$

where the set $\{w_j\}$ = the normalized weights for criteria, such that

$$0 \le w_j \le 1 \tag{2}$$

and

$$\sum_{j=1}^{J} w_j = 1 \tag{3}$$

The weight w_j represents the relative significance of criterion c_j among other criteria. Then, the prioritization of assets can be determined by values of the function $u(\mathbf{z}_i)$.

Multicriteria decision analysis lacks a built-in capability to deal with the nonprobabilistic uncertainties of emergent and future conditions, particularly without consensus across experts. Scenario-informed analysis has proven to be an effective approach to confront such uncertainties (Montibeller et al. 2006). Thus, an integration of multicriteria decision analysis and scenario analysis is promising. By definition, a scenario is a plausible story about future conditions or circumstances (Peterson et al. 2003). Without assigning probability to future events as traditional forecast-based approaches, a scenario-informed analysis is not hindered by overprecision and/or lack of trustworthiness of forecasts.

A set of scenarios is defined as $E = \{e_k | k < K, k \in N\}$. Each scenario is a combination of emergent or future conditions. The set of conditions is $D = \{d_m | m \le M, m \in N^+\}$. Conditions are statements about a future climate change factor and can be either quantitative as global sea-level rise of 0.50 m or qualitative as an increase in the frequency of tropical storms. In practice, these conditions can be identified by expert and stakeholders of a large-scale system. A scenario is an element of the power set of the set of conditions $P(D)$. Mathematically, the relationships between the set of scenarios and conditions can be expressed as $e_k \in P(D)$ and $E \subseteq P(D)$.

Each scenario e_k will result in updating of criteria weights. To reflect this effect of scenarios, the additive value function defined in Eq. (2) becomes

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$$u_{e_k}(a_i) = 100 \times \sum_{j=1}^{J} w_{jk} z_{ijk} \quad (4)$$

where $u_{e_k}(a_i)$ = aggregated rating of asset i under scenario e_k.

This equation extends Eq. (1) to yield a vector of the form, $\mathbf{u}_{a_i} = [u_{e_1}(a_i), u_{e_2}(a_i), \ldots, u_{e_k}(a_i)]$ representing that the prioritization of assets differs across the several scenarios.

As the scenario analysis provides significant new factors to the original prioritization problem, it engages experts, decision makers, and stakeholders. According to the additive value function in Eq. (3), the number of variables that need to be elicited interactively from the experts is $(jk) + (ijk)$. To reduce the effort to elicit opinions from decision makers on the change of criteria relative importance, the authors consider the ratings, z_{ijk}, do not change across the scenarios. In this case, the expression of $u_{e_k}(a_i)$ is determined by the weights w_{jk} only. The fixing of the rating reduces the number of variables that are required to be provided by experts to $(jk) + (ij)$. This assumption is reasonable because the horizon for the policy making is most important in ascertaining whether scenarios most influence the criteria weights (as in this paper) or whether the scenarios most influence the ratings of the assets. The authors suggest that for a distant time horizon, the influence on the criteria weights is predominant over the influence on the ratings.

Removing the influence of scenarios on ratings, the additive value function in Eq. (3) can be revised as

$$u_{e_k}(a_i) = 100 \times \sum_{j=1}^{J} w_{jk} z_{ij} \quad (5)$$

The lower-order implications of varying the asset ratings with the scenarios could be considered in future effort.

Incremental Criteria Weights Adjustment for Scenarios

With the fixed ratings, the required level of interaction with decision-makers and stakeholders is significantly reduced. However, the experts still need to update the weights for each scenario. From a perspective of human-factors and cognition, repetitive tasks can lead to undesired effects, tending to yield output with poor quality. A method to adjust the criteria weights incrementally in the additive value function between scenarios has been introduced by Karvetski et al. (2011) and Schroeder and Lambert (2011).

For each scenario of e_k, one of five natural-language statements regarding the relative importance of a criterion can be made: major increase, minor increase, no change, minor decrease, or major decrease. Each statement will affect the criteria weights differently. The weight value of criteria c_j under a new scenario e_k is

$$w_{jk} \propto \left\{ \begin{array}{ll} (\delta) w_{j0} & \text{if statement “major increase” is made} \\ (\varepsilon) w_{j0} & \text{if statement “minor increase” is made} \\ w_{j0} & \text{if statement “no change” is made} \\ (1/\delta) w_{j0} & \text{if statement “major decrease” is made} \\ (1/\varepsilon) w_{j0} & \text{if statement “minor decrease” is made} \end{array} \right\} \quad (6)$$

such that

$$\sum_{j=1}^{J} w_{jk} = 1 \quad \text{and} \quad w_{jk} \in [0, 1] \quad (7)$$

where δ, ε $(\delta > \varepsilon)$ = coefficients assigned by decision makers or stakeholders, to define the significance of criteria importance change caused by natural-language statements. The recognition and argument that the previously mentioned mathematics can be adapted to climate change scenarios is the theme of the rest of the paper.

Model Application

To illustrate the potential of the modeling framework described previously, the model is applied to the Hampton Roads in southeastern Virginia (Fig. 2). Regional characteristics and the scenario development process are described in the following sections.

Regional Overview

The Hampton Roads regions, which includes Norfolk, Virginia Beach, and several other cities, is one of the most low-lying and vulnerable metropolitan areas in the United States. It has a total population of 1.7 million and is prominent for its year-round ice-free harbor. It is home to the largest naval base on the U.S. East Coast, and it has numerous other military facilities from agencies, such as U.S. Navy, Coast Guard, Air Force, NASA, Marines, and Army. The mission performance of these civil and military facilities and infrastructure could be vulnerable, over a horizon of decades, to manifestations of climate change, such as sea level and storm frequency. Among the other transportation assets of this region are two international airports, a number of major bridges and tunnels, and an extensive highway and secondary road network, much of which is maintained by the Virginia Department of Transportation (VDOT). The Virginia Governor's Commission on Climate Change (GCCC 2008) forecasts an average temperature increase of 3.1°C (5.6°F) for Virginia. The U.S. EPA's Chesapeake Bay Program (Pyke et al. 2008) estimates that the Chesapeake Bay will experience sea-level rise [approximately 0.7~1.6 m (2.3~5.2 ft) by 2100], water temperature rise [about 0.3°C (0.5°F) per decade] and increased precipitation intensity. According to (GCCC 2008), the Virginia Beach-Norfolk metropolitan statistical area ranks tenth in the world in values of assets exposed to flooding caused by sea-level rise.

The analysis framework of this paper has been implemented in a software workbook to facilitate real-time interaction and engagement with stakeholders. Applying the framework in a practical situation entails two phases: (1) baseline (no-scenario) analysis, and (2) scenario analysis. Each phase has several worksheets to provide for the transparency of inputs and intermediate and final results. In a single iteration, the workbook can address up to fifty criteria, forty assets, and five scenarios. Recognizing that analyzing more criteria, assets, or scenarios would increase the cognitive challenge and diminish the transparency of the procedures, thirteen criteria, twelve assets, and three scenarios are used in the demonstration to follow. The various natural-language statements related to the assessment of assets and to criteria importance are obtained and interpreted by conventional elicitation methods (e.g., Ayyub 2001).

Assets Identification

The number of assets owned by a transportation agency are typically large and diverse in nature. Here, the asset data were retrieved from the VDOT asset management system (AMS) (VDOT 2006) and Pontis database (Thompson et al. 1998), and a preliminary list includes thousands of assets. Four screening criteria are used to systematically reduce the scale of the problem to fewer than twenty major assets. These include: (1) those assets that are on Hurricane evacuation routes (VDOT 2011b), (2) those assets that carry high traffic volume (AADT > 10,000 vehicles/day), (3) those assets that represent a maintenance priority route (e.g., snow removal priority route), and (4) those that are at low elevation. These criteria are intended to focus the demonstration on a high-level policy

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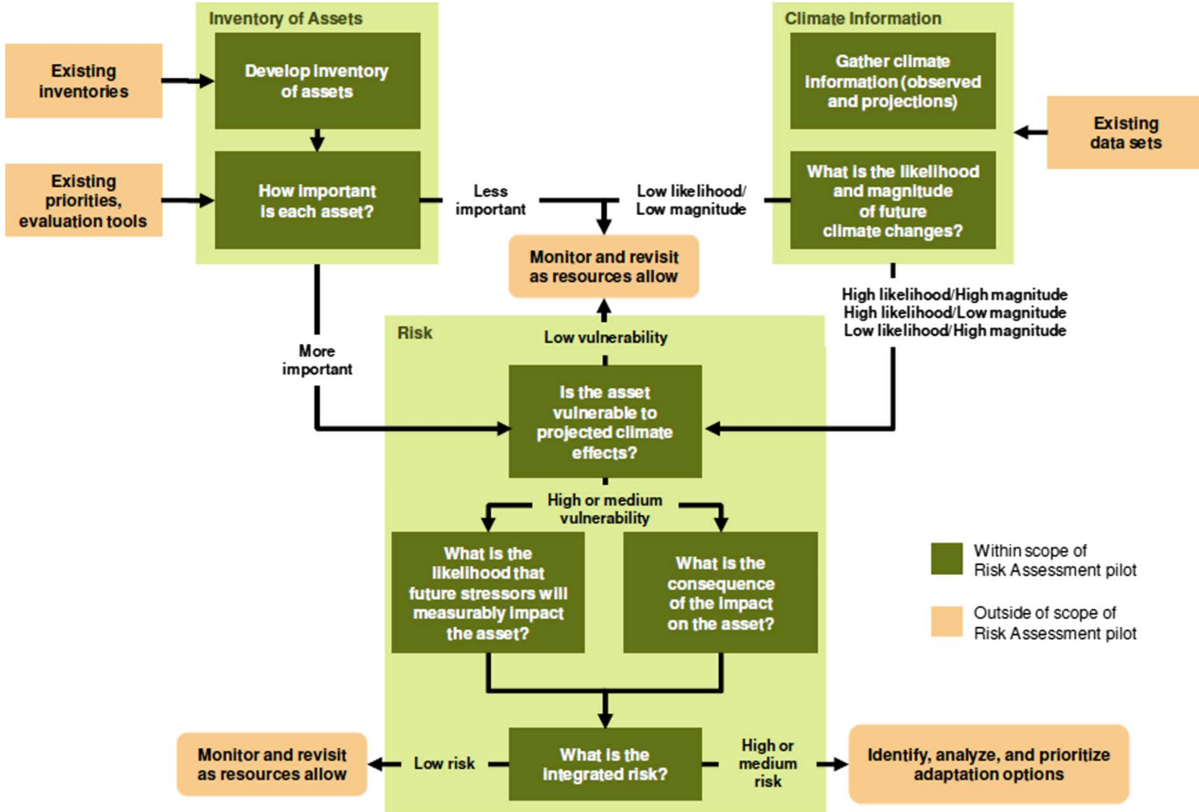

Fig. 2. Assets vulnerability assessment conceptual model proposed by FHWA (2011)

analysis on a manageable set of major assets. Three bridges—Chesapeake Bay Bridge-Tunnel, Berkley Bridge, and Gilmerton Bridge—are included because of their importance to transporting freight and people (VDOT 2011a). In addition to the bridges and tunnels, there is particular concern for two traffic management center facilities. Table 1 and Fig. 3 describe the assets that are selected for the demonstration.

Criteria Definition

Cost-related factors are usually not included in the criteria, because the analysis is supporting what the agency describes as an unconstrained long-range plan. An unconstrained plan is useful to focus high-level discussion on the needs of the region, without considering the uncertain costs of potential actions. Unconstrained planning is a common activity in large-scale systems. Cost-effectiveness, cost-benefit, and cost-efficiency analyses are typically performed in subsequent or parallel analysis.

Table 1. Set of Selected Transportation Assets for the Demonstration

ID	Assets
a_{01}	George P. Coleman Memorial Bridge
a_{02}	James River Bridge
a_{03}	Hampton Roads Bridge-Tunnel
a_{04}	Monitor Merrimac Memorial Bridge-Tunnel
a_{05}	Midtown Tunnel
a_{06}	High Rise Bridge
a_{07}	Downtown Tunnel
a_{08}	Hampton Roads Bridge Tunnel Administrative Building
a_{09}	Hampton Roads Transportation Operations Center
a_{10}	Chesapeake Bay Bridge-Tunnel
a_{11}	Berkley Bridge
a_{12}	Gilmerton Bridge

The criteria set C for prioritizing the assets were adapted from the working papers of the regional transportation planning organization (Hampton Roads Planning District Commission, in coordination with the regional Metropolitan Planning Organization) (Case et al. 2007). The criteria are harmonious with the planning factors of the FHWA and with goals of the Safe, Accountable, Flexible and Efficient Transportation Equity Act (SAFETEA).

Table 2 describes how the criteria appear in the workbook. For demonstration, the weights of criteria under the baseline scenario are set to be equal (Guiasu and Shenitzer 1985).

Baseline Scenario Multicriteria Analysis

With the criteria and assets already defined, the framework requires input of experts to complete the baseline scenario assessment. The baseline scenario aims to prioritize assets assuming no-scenario climate conditions (no climate change is yet considered). Table 3 describes the recording of expert inputs on the ratings across the set of criteria under the baseline scenario. The expert inputs are in terms of natural-language statements (strongly agree, agree, somewhat agree, indifferent, and disagree or not relevant). Across the criteria, c_{01}, c_{09}, and c_{13} are considered not relevant to the prioritization. The expert inputs were quantified and aggregated through a weighted sum to obtain scores and corresponding prioritization of assets under the baseline scenario. Table 4 shows the score and priorities resulting rank order of the assets under the baseline scenario.

Scenario Definition

Fig. 4 demonstrates that climate change scenarios were developed and incorporated to adjust the baseline prioritization of assets. The reader is referred to (Wu et al. 2013) for more details on

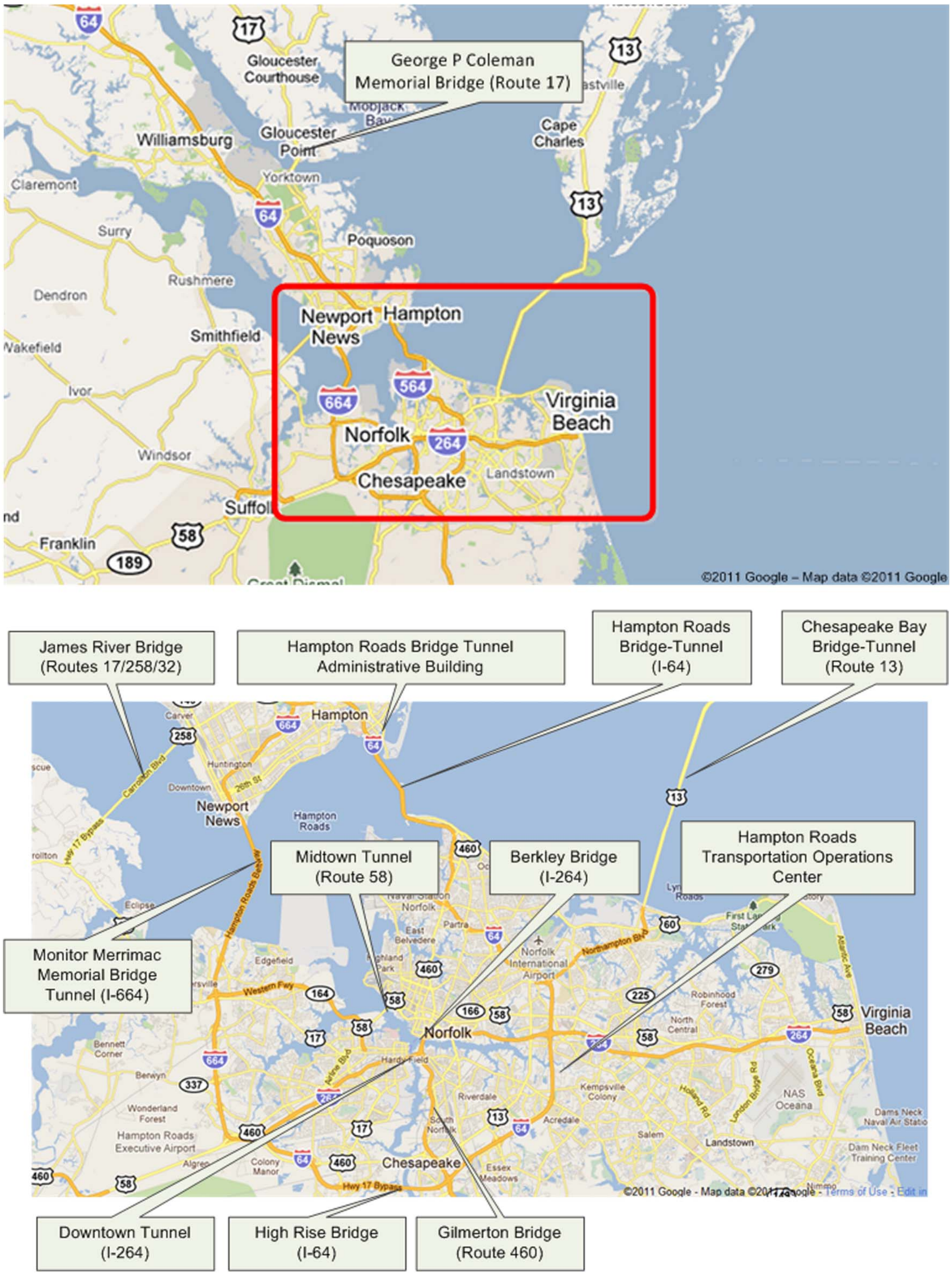

Fig. 3. (a) Selected infrastructure assets for the demonstration; (b) enlarged rectangular area from Fig. 3(a) (© 2011 Google)

scenario development. Experts and stakeholders were invited to adjust the criteria importance per scenario, as follows. Climate change scenarios are constructed by combining a variety of climate change conditions. These conditions describe climate change events that would be expected to influence the prioritization of the assets, such as sea-level rise, increase in storm surge, and increase in storm frequency. The demonstration addressed three scenarios. The first two scenarios consist of adverse-impact conditions, to capture the effects brought by plausible future climate change. The first scenario, e_{01}, is an extreme scenario, consisting of the most adverse conditions of climate change and natural disasters. The second scenario, e_{02}, is a milder scenario. This scenario considers climate change conditions—sea-level rise, land subsidence—are becoming worse, whereas other climate conditions are unchanged. The third scenario, e_{03}, a nonextreme scenario, represents a situation in which climate change would slow down. Table 5 describes the construction of the three scenarios through the software workbook.

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Table 2. Comprehensive Set of Performance Criteria Adapted from 2034 Hampton Roads Long-Range Transportation Plan (2011) for the Consideration of Infrastructure Policies and Investments

Criterion	Descriptions
c_{01}. Public involvement	Enhance public involvement in the development of the region's transportation system.
c_{02}. Regional perspective	Include a regional perspective among the transportation prioritization criteria.
c_{03}. Fiscal responsibility	Develop a long-range transportation plan that is fiscally constrained.
c_{04}. Economic vitality	Support the economic vitality of the region, emphasizing global competitiveness, productivity, and efficiency.
c_{05}. Safety	Increase the safety of the transportation system for motorized and nonmotorized users.
c_{06}. Security	Provide for the security of the regional system for motorized structure and its users.
c_{07}. Accessibility and mobility	Increase accessibility and mobility of people and goods.
c_{08}. Environment	Protect and enhance the environment, promote energy conservation, improve quality of life, and reduce greenhouse gas emissions.
c_{09}. Compatibility with land use and economic patterns	Obtain compatibility between transportation improvements and planned land use and economic development patterns.
c_{10}. Modal integration and connectivity	Enhance the integration and connectivity of the transportation system, across and between modes, for people and goods.
c_{11}. Management and operation	Optimize the efficient system management and operation of the regional transportation system.
c_{12}. Maintenance and replacement	Increase the optimization, maintenance, and replacement of the existing transportation system.
c_{13}. Revenue source	Work toward finding dedicated and sustainable revenue sources for transportation.

Table 3. Baseline Assessment of the Infrastructure Assets

	Asset											
Criterion	a_{01}	a_{02}	a_{03}	a_{04}	a_{05}	a_{06}	a_{07}	a_{08}	a_{09}	a_{10}	a_{11}	a_{12}
c_{01}	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
c_{02}	Agr	Agr	StrAgr	Agr	SomAgr	Agr	StrAgr	Agr	Agr	StrAgr	SomAgr	Agr
c_{03}	SomAgr	Agr	Agr	Agr	Agr	Agr	Agr	Agr	Agr	Agr	Agr	Agr
c_{04}	SomAgr	Agr	StrAgr	StrAgr	StrAgr	Agr	StrAgr	Agr	Agr	StrAgr	Agr	Agr
c_{05}	Agr	SomAgr	Agr	Agr	Agr	Agr	Agr	Agr	StrAgr	Agr	SomAgr	Agr
c_{06}	SomAgr	Agr	Agr	StrAgr	Agr	Agr	Agr	SomAgr	SomAgr	StrAgr	Agr	SomAgr
c_{07}	Agr	Agr	StrAgr	StrAgr	Agr	Agr	Agr	StrAgr	StrAgr	StrAgr	Agr	Agr
c_{08}	Agr	SomAgr	Agr	Agr	Agr	SomAgr	Agr	SomAgr	SomAgr	StrAgr	Agr	Agr
c_{09}	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
c_{10}	Agr	Agr	StrAgr	StrAgr	StrAgr	Agr	StrAgr	SomAgr	Agr	Agr	SomAgr	SomAgr
c_{11}	Agr	SomAgr	Agr	Agr	SomAgr	Agr	Agr	StrAgr	StrAgr	Agr	Agr	SomAgr
c_{12}	SomAgr	SomAgr	Agr	Agr	Agr	SomAgr	SomAgr	StrAgr	StrAgr	Agr	SomAgr	Agr
c_{13}	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Note: The twelve selected assets (top row) are assessed on thirteen criteria (left column). The assessment levels are: strongly agree (StrAgr), agree (Agr), somewhat agree (SomAgr), and disagree or not relevant (N/A).

Table 4. Baseline Scores and Rankings of Selected Assets in Demonstration; Scores are Obtained through the Weighted Sum Defined by Eq. (3)

	Baseline scenario e_{00}	
Assets	Score	Ranking
a_{01}	41	11th
a_{02}	41	10th
a_{03}	62	2nd
a_{04}	62	2nd
a_{05}	51	7th
a_{06}	46	8th
a_{07}	56	4th
a_{08}	51	6th
a_{09}	56	4th
a_{10}	64	1st
a_{11}	41	11th
a_{12}	44	9th

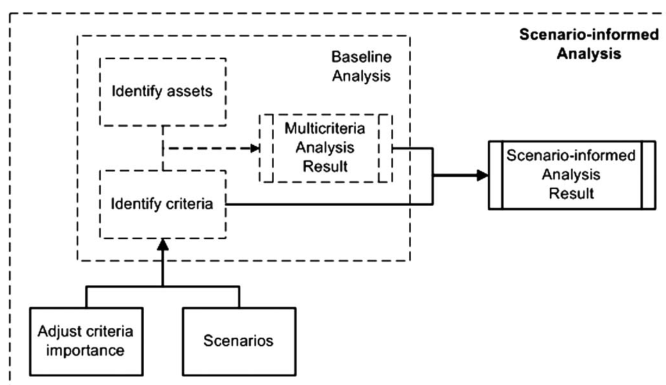

Fig. 4. Workflow of scenario-based multicriteria framework proposed in this paper; the dashed boxes and lines represent the traditional components of multicriteria analysis; and the solid boxes and lines represent how scenarios are integrated to the analysis

Criteria Importance Adjustment for New Scenarios

The adjustment of the relative criteria importance is a key innovation of this study. The weights of criteria were changed (reweighted) on the basis of each of the several climate scenarios. Table 6 shows a summary of how the criteria importance varied with the scenarios. The importance changes were accomplished by natural-language statements of major increase, major decrease, minor increase and minor decrease to the criteria. A blank cell means no change of relative importance. On the basis of these

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Table 5. Scenario Definitions Including Twenty- to Thirty-Year Horizon for Climate Change: Baseline Scenario (e_{00}), Extreme Climate Change Scenario (e_{01}), Sea-Level Rise Dominated Scenario (e_{02}), Mild Climate Change Scenario (e_{03})

Conditions	Scenarios e_{00}	e_{01}	e_{02}	e_{03}
Sea level rise <1 m				x
Sea level rise <1 m		x	x	
Increase in stormwater		x		
Decrease in stormwater				x
Increase in wave height		x		
Storm surges		x		
Subsidence		x	x	
Decreased erosion				x
Increased flooding		x		
Decreased flooding				x

statements, the incremental weights adjustment of a previous section was used to generate new weights for these criteria under each scenario.

Results

Table 7 shows the implications of considering climate scenarios in terms of the scores and the rankings of the assets. The result under baseline scenario e_{00} is described in the first two columns. The scores and rankings for scenarios from e_{01} to e_{03}, which are obtained through the reweighted additive value functions, reflect the effects of expert adjustments on the relative criteria importance under the scenarios of climate change. For example, asset a_{08}–Hampton Roads Bridge Tunnel Administrative Building scores a 51 in the baseline scenario e_{00}, a 65 in scenario e_{01}–extreme climate change scenario, a 60 in scenario e_{02}–sea-level rise only scenario, and a 62 in scenario e_{03}–mild climate change scenario.

Several implications can be identified from the corresponding rankings of assets. For example, asset a_{08}–Hampton Roads Bridge Tunnel Administrative Building is considered to be significantly more important in the scenarios of e_{03}–sea-level rise only scenario. For scenario e_{01}–extreme climate change scenario and e_{02}–sea-level rise only scenario, the priority of this asset among the set of selected assets was approximately constant. This interpretation provided insight to a shifting of asset-management priorities across scenarios. By investigating the source of these different results in criteria weights and assets ratings, the results also allow decision makers to understand how the priorities for asset management can vary with climate change scenarios that are special to the region.

Figure 5(a) illustrates the range of scores for the assets across the scenarios. The diamond represents the score of the asset in the baseline scenario. The maximum and minimum scores across the other scenarios are represented by the vertical bars extending from the

Table 6. Three Scenarios (Top Row) and Their Shift in Importance for the Thirteen Criteria (Left Column)

Criteria	Scenarios e_{01}	e_{02}	e_{03}
c_{01}. Public involvement			
c_{02}. Regional perspective	Major decrease	—	Minor increase
c_{03}. Fiscal responsibility	Minor decrease	—	Minor increase
c_{04}. Economic vitality	Major increase	Minor increase	—
c_{05}. Safety	Major increase	Minor increase	—
c_{06}. Security	Minor increase	—	—
c_{07}. Accessibility and mobility	—	—	Minor decrease
c_{08}. Environment	—	—	Minor increase
c_{09}. Compatibility with land use and economic patterns	—	—	—
c_{10}. Modal integration and connectivity	Minor increase	Minor increase	Major increase
c_{11}. Management and operation	Major increase	Minor increase	Minor decrease
c_{12}. Maintenance and replacement	Major decrease	—	Minor increase
c_{13}. Revenue source	—	—	—

Note: The levels of shift are marginal increase, marginal decrease, minor increase, minor decrease, and no change (—).

Table 7. Scores and Rankings of Selected Assets across the Baseline and Additional Three Climate Scenarios

Assets	e_{00} Scores	e_{00} Ranking	e_{01} Scores	e_{01} Ranking	e_{02} Scores	e_{02} Ranking	e_{03} Scores	e_{03} Ranking
a_{01}	41	11th	46	10th	44	10th	44	10th
a_{02}	41	10th	43	12th	41	12th	40	11th
a_{03}	62	2nd	66	4th	63	4th	61	4th
a_{04}	62	2nd	73	3rd	67	2nd	61	4th
a_{05}	51	7th	59	6th	54	7th	46	9th
a_{06}	46	8th	53	8th	51	8th	53	7th
a_{07}	56	4th	56	7th	57	6th	60	6th
a_{08}	51	6th	65	5th	60	5th	64	2nd
a_{09}	56	4th	73	2nd	67	2nd	67	1st
a_{10}	64	1st	74	1st	68	1st	62	3rd
a_{11}	41	11th	45	11th	44	10th	49	8th
a_{12}	44	9th	51	9th	46	9th	39	12th

Note: e_{00} = baseline scenario; e_{01} = extreme climate change scenario; e_{02} = sea-level-rise dominated scenario; and e_{03} = mild climate change scenario.

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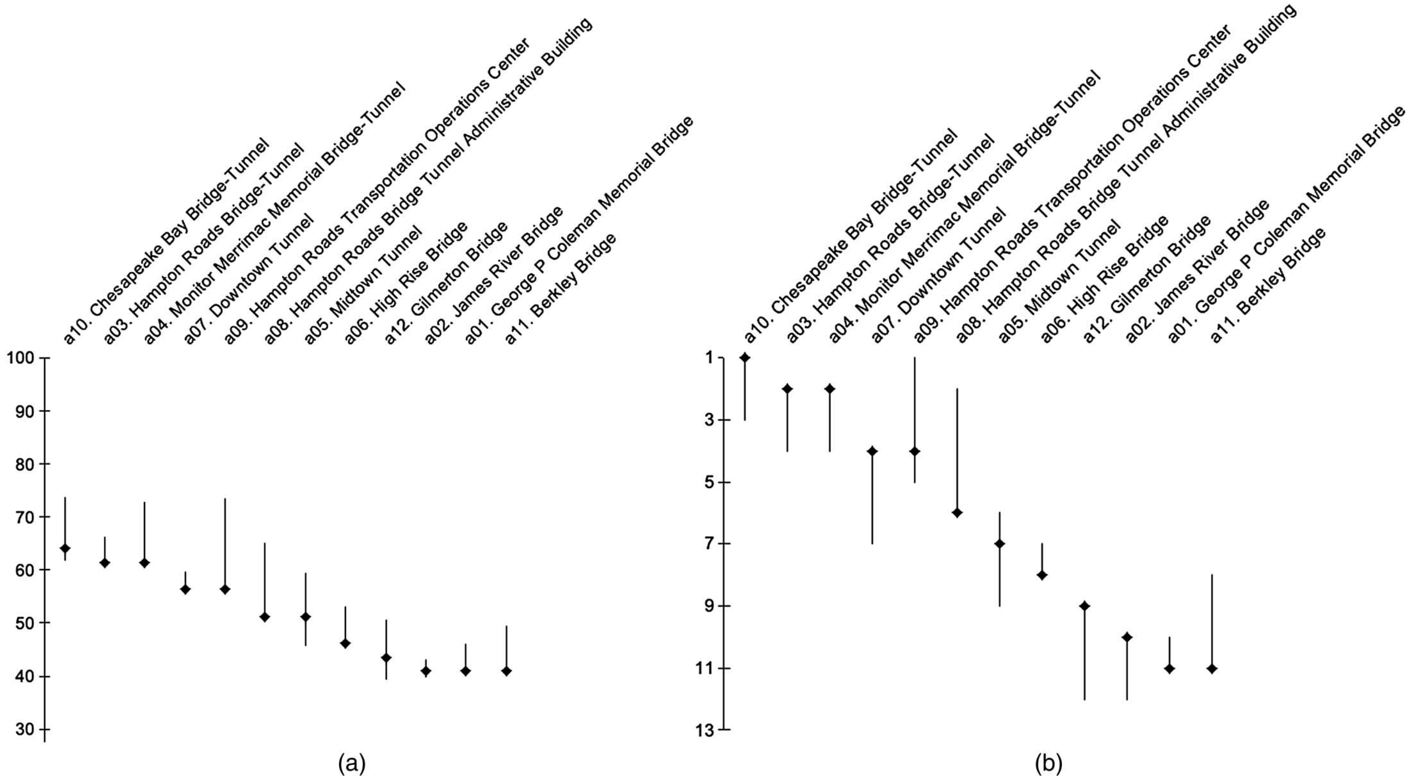

Fig. 5. (a) Baseline scores (diamonds) and the ranges (vertical bars) of scores associated to the three additional climate scenarios of the twelve infrastructure assets addressed in the demonstration; (b) baseline rankings (diamonds) and the ranges (vertical bars) of rankings associated to the three additional climate scenarios of the twelve infrastructure assets addressed in the demonstration

diamonds. A taller sensitivity bar suggests a greater influence of scenarios on the asset. The subbars extending from the baseline scenario also can be considered as representing the effect of the reweighting of the assets assessment criteria. Several of the criteria reweightings increase and decrease asset scores equally, for example asset a_{05}–Midtown Tunnel and asset a_{12}–Gilmerton Bridge. It indicates that the reweighting gives potential opportunity and risk to the baseline score. Most of the reweightings increase and decrease the baseline scores unequally. For example, the reweighting only results in the increase of aggregated score of asset a_{03}, a_{08}, and a_{09}. Other than the direction of the impact of reweighting brought by different scenarios, the magnitudes of the impacts of reweighting also differs. The score of asset a_{03} is less affected compared to a_{08} and a_{09}. The previous observations are potentially important to understand the degree of consensus for asset management priorities across the scenarios. Another important observation from Fig. 5(a) is that many of the vertical bars are overlapping. This indicates that there exist no assets that are dominant in the rankings across all scenarios.

Fig. 5(b) shows the fluctuation of the asset rankings (priority order) across the scenarios. The ordinal information is not a lossless summary of corresponding cardinal information, and rankings do not maintain the full information of the asset scores. However, rankings make assets more distinguishable from one another, relative to the cardinal scores. Moreover, from a requirement for prioritization, rankings are the preferred form of the output.

There are two important observations from Fig. 5(b). First, a majority of the assets only have either upside or downside deviation under multiple scenarios relative to their baseline ranking. For example, asset a_{10}–Chesapeake Bay Bridge-Tunnel, a_{03}–Hampton Roads Bridge-Tunnel, a_{04}–Monitor Merrimac Memorial Bridge-Tunnel, and a_{07}–Downtown Tunnel have downside sensitivity only. Assets such as a_{08}–Hampton Roads Bridge Tunnel Administrative Building and a_{06}–High Rise Bridge do not have downside sensitivity. Second, the assets can be divided into two tiers in the range of their rankings. The assets that rank from first to sixth, that is, assets a_{10}, a_{03}, a_{04}, a_{05}, a_{08}, and a_{09} are the first tier. The remaining assets, a_{02}, a_{06}, a_{07}, a_{10}, a_{11}, and a_{12}, comprise a second tier. The assets in the first tier rank between first and seventh under the baseline and the constructed climate change scenarios. The second tier assets all rank no higher than sixth. Identifying the tiers can potentially help decision makers to make robust allocations of resources to assets. With no additional information, a focus of resources on the first tier of assets might be reasonable.

Conclusions

The consideration of climate impact to prioritization of infrastructure assets should play an important role in transportation asset management and related planning. This paper has developed a framework for integrating multicriteria decision analysis and scenario-based analysis to assist priority-setting in infrastructure asset management influenced by several factors of climate change. This framework was demonstrated in the case study of the Hampton Roads Region in Virginia. Twelve selected critical transportation infrastructure assets were prioritized across thirteen long-range transportation planning criteria and under three synthetic scenarios of climate change. The results suggested that the priorities for the Hampton Roads Transportation Operations Center are significantly influenced by the extreme and mild climate change scenarios. The authors suggest the framework is practical for assisting decision makers in prioritizing transportation infrastructure assets for risk management and resource allocation. With real-time iteration and adjustment of the parameters of an automated version

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of the model, the stakeholders in the Hampton Roads region tested the sensitivity of the results to assumptions and inputs including the selection of criteria. Investigative resources can be focused to the scenarios that most matter to asset management.

The innovations of the paper relative to the literature have been: (1) to reappraise priorities for transportation asset management in the face of nonprobabilistic climate change and/or lack of expert consensus on the relevant factors of climate change; (2) to develop a modeling tool that can be broadly applied of climate-change factors/conditions that can be assembled for any number of scenarios; (3) demonstrate how climate change can manifest as a unique set of scenarios for a regional transportation system and how criteria importance is correspondingly influenced; (4) select and adopt existing calculation methods for strategic reweighting/updating of criteria weights according to the scenarios of climate change; (5) interpret results that relate climate change impact analysis to the perspectives of stakeholders in a large-scale transportation infrastructure system; and (6) recommend ways in which the developed methodological framework for climate change can assist to focus investigative resources and inform policy making for asset management in large-scale transportation systems.

Although this study has demonstrated the immediate effectiveness of a quantitative approach, the insights and results will surely evolve in the future, having shown the knowledge value of more precise information about climate change and the infrastructure assets. The model parameters can be adjusted on the basis of additional interaction with a panel of experts and stakeholders. Moreover, the model could be further exercised with historical records of past assets, criteria, and scenarios.

The framework does not require the construction of mutually exclusive scenarios for future climate change. Analytical model-based deterioration and impact analysis are not within the scope of this framework. However, the framework could make use of such analyses as inputs. The framework does not search or generate an optimum or robust prioritization of assets for a near time horizon. Rather, the framework has been shown to be useful in strategic priority setting, whether consensus does or does not exist about the possible scenarios of climate change. Future work in this direction will combine climate change with economic, regulatory, and other conditions including deterioration or wear and tear.

This framework is generally applicable to address scenarios of climate change in multicriteria prioritization of assets for transportation or other infrastructure agencies. The software workbook developed for the case study of Hampton Roads has been made available through the internet to other agencies. The workbook enables redefining the assets, the criteria, and the climate conditions. The method of analysis by another agency would be expected to be similar to and to benefit from the case study presented in this paper.

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