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Optimal transportation and shoreline infrastructure investment planning under a stochastic climate future

Ali Asadabadi, Elise Miller-Hooks*

Sid and Reva Dewberry Department of Civil, Environmental and Infrastructure Engineering, George Mason University, Fairfax, VA, USA

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ABSTRACT

This paper studies the problem of optimal long-term transportation investment planning to protect from and mitigate impacts of climate change on roadway performance. The problem of choosing the extent, specific system components, and timing of these investments over a long time horizon (e.g., 40–60 years) is modeled as a multi-stage, stochastic, bilevel, mixed-integer program wherein cost-effective investment decisions are taken in the upper level. The effects of possible episodic precipitation events on experienced travel delays are estimated from solution of a lower-level, traffic equilibrium problem. The episodic events and longer-term sea level changes exist on different time scales, making their integration a crucial element in model development. The optimal investment strategy is obtained at a Stackelberg equilibrium that is reached upon solution to the bilevel program. A recursive noisy genetic algorithm (rNGA), designed to address large-scale applications, is proposed for this purpose. The rNGA seeks the optimal combination of investment decisions to take now given only probabilistic information on the predicted sea level rise trend for a long planning horizon and associated likely extreme climatic events (in terms of their frequencies and intensities) that might arise over that planning period. The proposed solution method enables the evaluation of decisions concerning where, when and to what level to make infrastructure investments. The proposed rNGA has broad applicability to more general multi-stage, stochastic, bilevel, nonconvex, mixed integer programs that arise in many applications. The proposed solution methodology is demonstrated on an example representing a portion of the Washington, D.C. Greater Metropolitan area adjacent to the Potomac River.

1. Introduction

Increased storm frequency and intensity, increased total precipitation, sea level rise (SLR) and tides as high as 20 feet or more are among the concerns associated with climate change. More frequent temporary or permanent inundation of transportation elements are expected as a consequence. This paper proposes optimization-based solution techniques for long-term transportation investment planning in protection and mitigation strategies that aim to safeguard performance of our roadway networks.

SLR is perhaps the best documented and most accepted impact of climate change. SLR projections, however, require analysis of complex processes, including glacial melting and thermal expansion of the oceans. Thus, these predictions are at best

* Corresponding author.
E-mail address: miller@gmu.edu (E. Miller-Hooks).

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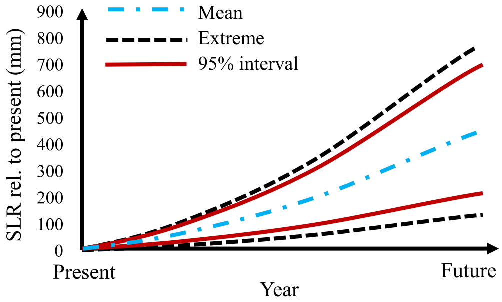

Fig. 1. Schematic range of SLR projections.

uncertain. SLR projections for year 2100 range, for example, from several centimeters to more than a meter (Powell, 2009). Thus, they are typically given in terms of trajectories (e.g. best, worst and average cases) as depicted in Fig. 1, where best and worst-case estimates have low occurrence probabilities. They can also be described in terms of probability distributions. Similar uncertainty exists in storm-event occurrence and resulting storm surges.

Increases in the frequency and extent of coastal flooding events due to storm surges in recent years are noted by Reuters (2014). They point out that for five coastal cities along the East Coast of the U.S. since 2001 there has been an average of 20–25 days at which water levels exceeded flood thresholds. Comparatively, before 1971, an average of only 5 days at such water levels occurred in the same cities. This increase arose with an estimated SLR during that 30-year period of approximately 0.1 m (NOAA, 2016). Predictions of future SLR range from as little as one foot to as high as 6.6 feet in the next 85 years (Walsh et al., 2014).

Flooding events can affect components of the transportation network from all modes. Examples include: roadway links, transit stations, subway tunnels, airports, ports and rail lines. Loss of components will impact the network topology and connectivity and therefore system-level performance (i.e. throughput, travel time, fuel consumption, pollution). These events can lead to very significant monetary losses, whether due to direct losses (e.g. loss of use of a roadway link) or indirect effects (e.g. requiring a mode change from rail to road). Consider only the five coastal cities of Baltimore, Boston, New York, Philadelphia and Providence. A SLR of 0.66 m by 2050, if correctly projected (Powell, 2009), would potentially impact $7.4 trillion worth (unadjusted for inflation) of civil infrastructure assets in these cities. On a global scale, it is estimated that $28 trillion (unadjusted) in world-wide assets associated with 136 “port megacities” would be at risk given a SLR of 0.5 m by 2050 (Powell, 2009).

Flood predictions on the order of several feet for four of the five Boroughs of New York City during severe storms are projected under predicted SLR rates 0.24 to 1.08 m (Jacob et al., 2007). Several works predict traffic disruptions and weakened infrastructure as a result of increased storm intensity and higher sea levels (Peterson et al., 2008; Savonis et al., 2008). The impact of even less extraordinary weather events on ground-based transportation systems will be intensified under higher sea levels (Council, 2010). In fact, approximately 60,000 miles of coastal roads in the United States are already exposed to flooding from coastal storms and high waves (TRB, 2008). Exposure of road infrastructure in coastal areas to SLR and storm surges shortens the life expectancy of highways and roads, requiring more frequent maintenance, repairs, and rebuilding. More than two billion people live within 60 miles of a coastline (Powell, 2009). Moreover, roadways in such coastal areas serve as critical evacuation routes that must be protected from flooding and damage for use in emergencies (TRB, 2008).

Actions or interventions can be taken to prevent or mitigate the effects of SLR and related increases in storm surges on the civil infrastructure. Actions may also be required in a flood event to reduce water levels and restore services. In support of response (or recovery) actions, preparatory acts, such as acquiring and prepositioning of resources, may be required. In determining which preparatory actions to take, trade-offs between mitigation efforts requiring significant capital investment and coping with post-event damage must be considered. Mitigation efforts hedge against effects that would be possible under future predictions of SLR levels and storm frequency increases that may not be realized; however, if realized their impacts can be tremendous and response capabilities may be limited or costly. In fact, the impacts may include permanent inundation and destruction of assets. In many cases, one can justify the costs of mitigation through savings due to their effectiveness in increasing network resilience to SLR and storm surge and recognizing that the costs incurred as a consequence of inaction would surpass the costs of implementing mitigation options (Lu et al., 2012).

Although the effectiveness of investments in combating the impacts of SLR and storm surge have been quantified (Lu et al., 2012), a virtually unlimited budget would be required to implement all mitigative actions that would be needed to prevent damage in a worst-case or other more extreme scenarios. Given budgetary limitations, the number of actions that can be implemented at a given point in time is restricted in practice and, therefore, optimal investment decisions over a time horizon are required. Such decisions require an ability to quantify the impact of combinations of investments in the infrastructure along with monetary costs due to post-event system-level performance losses. Furthermore, they must be taken under uncertainty in event and impact prediction, which makes the planning process for combatting climate-change impacts an even more complicated task.