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Public policy implications of harmonizing engineering technology with socio-economic modeling: Application to transportation infrastructure management

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ABSTRACT

The persistent infrastructure underinvestment coupled with a significant growth in commercial and non-commercial transportation demand has rendered the US transportation infrastructure unprepared for current and future demands. A significant improvement in the condition of the US transportation infrastructure must be grounded on a more sustainable and proactive approach to address the existing gap between short-term commitments and long-term needs. This paper demonstrates in quantitative terms the value of long-term investments to overcome the historical impediments to infrastructure rehabilitation, including the need for a proactive political structure that compensates for the apparent lack of public accountability, and for the poor understanding of the socio-economic effects caused by transportation infrastructure failures. Such a process could avoid impending catastrophes. This paper presents a modeling paradigm that accounts for multiple stakeholder perspectives and relates the formulation of public policy to a long-term horizon through the modeling of the transportation infrastructure as a system of systems. The methodology enables involved stakeholders and decision makers to visualize their shared interests and to promote coordinated individual decisions in order to achieve a more acceptable level of the overall system of systems objectives. To illustrate the relevance of the proposed modeling approach, we apply it to a bridge maintenance problem and we discuss the synthesis of existing engineering practice with socio-economic factors that aids in streamlining long-term infrastructure goals with immediate short-term needs. The insights obtained from the proposed system of systems methodological approach point to the need to adopt a more forward-looking and collaborative public policy for infrastructure maintenance.

1. Introduction

The United States' transportation infrastructure has been deteriorating for decades. Yet, the deterioration process is slow and its broader impacts are not always immediately evident. Today, the impacts of this deterioration process are more obvious and ominous than ever before, and numerous reports indicate a wide variety of consequences that the failing transportation infrastructure will cause. These include, among others, increased economic costs of freight congestion, decreased global competitiveness of the US, increased travel costs and reduced safety of travelers. The American Society of Civil Engineers (ASCE) suggests that the existing US transportation infrastructure is failing to sustain the economy, and that a variety

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of solutions will be needed at all levels of government to ensure the appropriate functioning of this infrastructure in the future (ASCE, 2011). In response to this challenge President Obama has asked the lawmakers to create a National Infrastructure Bank and approve a $50 billion national transportation infrastructure improvement budget. The failure to implement infrastructure improvement options will result in very significant costs to America's businesses and households.

The need to better understand and prioritize the current maintenance needs of the US transportation infrastructure is evidenced in reports spanning the last two and a half decades. As early as 1988, a national commission issued a report titled "Fragile Foundations," citing over 100,000 bridges that were not meeting safety and capacity standards (National Council on Public Works Improvement, 1988). This sentiment was recently revisited in reports issued by ASCE, including a report titled "Can We Come Back From the Brink" which concludes that certain components of the US public infrastructures are "on the brink of collapse" (ASCE, 2009b). In another report, ASCE (2011) estimates that approximately 18% of all vehicle miles of travel in the US occur on roads with inadequate capacity, and Caldwell (2011) further emphasizes the need to improve the quality of America's infrastructures to meet the increasing future demand. In a series of ongoing reports ASCE presents a sober picture of the nation's infrastructures, highlighting the "fragile foundations" of the infrastructures as evidence that citizens and governing bodies are increasingly recognizing the desperate state of our nation's infrastructure systems (ASCE, 1998, 2003, 2005, 2009a,b). A recent issue of the ASCE Infrastructure Report Card (ASCE, 2009a) gives America's infrastructure a grade D, and estimates that $2.2 trillion will be required over a 5-year horizon to bring US infrastructure systems to an acceptable condition.

Building America's future report (Building America's Future Educational Fund, 2011) suggests that the federal investment in US transportation infrastructure as a percentage of GDP has been continually shrinking over the last few decades, and that today's level of investment is approximately the same as it was in 1968 when the US economy was considerably smaller. The practice of persistent infrastructure underinvestment coupled with a significant growth in commercial and non-commercial transportation demand has left US transportation infrastructure "*stuck in the last century and ill-equipped for the demands of a churning global economy* [emphasis added]" and has caused the US's infrastructure to fall from the 1st place in the World-Economic Forum's 2005 economic competitiveness ranking to number 15 in 2011 (Building America's Future Educational Fund, 2011). ASCE estimates that given the existing transportation infrastructure conditions and investment patterns, by 2040: (i) US's infrastructure deficiencies will cost the national economy over 400,000 jobs, (ii) American firms will be generating $232 billion less in value added than they would have if supporting infrastructure had been adequate, and (iii) Americans will be earning $252 billion less than would have been possible if supporting infrastructure had been adequate.

Business sectors that will be most affected by the deterioration of the transportation infrastructure will include high-value knowledge-based professions, business and medical sectors, and restaurant and entertainment sectors (ASCE, 2011).

In order to improve the existing condition of the transportation infrastructure and ensure its viability under increased future demand, bigger maintenance budgets alone will not suffice. What is needed is a more sustainable and proactive approach that better addresses the existing gap between short-term commitments and long-term needs, and that overcomes the historical impediments to infrastructure condition improvements, including political structure and influences, the lack of public accountability, and a poor understanding of the causal socio-economic effects caused by transportation infrastructure failures. A significant improvement in the condition of the US transportation infrastructure will have to be grounded on a major paradigm shift. Decision- and policy-makers will have to approach the problem of deteriorating infrastructures from a system of systems perspective, understanding that any viable and sustainable solution must be grounded on engineering, scientific, social, economic and normative factors. This paradigm shift needs to happen now rather than later, because "although repairing and modernizing the country's infrastructure may seem daunting in lean times, the cost of doing nothing will be exponentially greater" (Caldwell, 2011).

In response to these needs, we suggest that the US transportation infrastructure should be modeled and managed as a system of systems, composed of numerous engineered, natural, human and organizational sub-systems. Based on characteristics that have been defined in the system of systems literature (Maier, 1998), we define a system of systems as an interdependent collection of sub-systems, each of which can be managerially and operationally independent with its own set of objectives, decision makers, and stakeholders, but which collectively fulfill a role that cannot be achieved by any of the individual sub-systems. The heterogeneous nature of the sub-systems and their underlying dynamic processes indicate that a single model is insufficient to model all aspects of a system of systems problem. Furthermore, the inherent sub-system interdependencies suggest that although decisions are made independently in a sub-system, these decisions have an effect (often unanticipated) on other interconnected sub-systems. Thus, we argue that systems of systems must be modeled through multiple models that account for these sub-system interdependencies.

With this in mind, this paper makes several contributions within the context of literature on policy and practice related to transportation research. This paper presents a system of systems modeling paradigm that: (i) enables a consideration of interdisciplinary models and multiple stakeholder perspectives in the process of creating public policy related to transportation infrastructure, and (ii) enables a more transparent evaluation of interdependencies between the different levels of the system and stakeholders. The paper introduces an example in which we illustrate in quantitative terms the value of long-term investment to avoid infrastructure failures. In this example, the system of systems modeling paradigm synthesizes (harmonizes) existing engineering practice with socio-economic factors and aids in streamlining long-term infrastructure goals with immediate short-term needs. By bringing the engineering evidence to the political arena, the discussed methodology provides a justification for action, and illustrates the need to account for the varying and often conflicting stakeholder perspectives. Moreover, the insights obtained from the system of systems methodological approach point to the need to