Agent-Based Simulation Model for Assessment of Financing Scenarios in Highway Transportation Infrastructure Systems

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Abstract: There is an urgent need for policies to close the existing financing gap for civil infrastructure. However, identification of the desired scenarios for the closure of the financing gap is complex because there are many factors that affect investment in infrastructure. Thus, comprehensive models are required to (1) simulate the impacts of policies, and (2) identify the highly likely scenarios for desired policy outcomes. The objective of this paper is to create a simulation model for ex-ante analysis of financing policies in highway transportation infrastructure in the United States. Using the agent-based technique, this model simulates the microbehaviors of state Departments of Transportation, private institutional investors, and the public. Using the output of the simulation model, financing landscapes of the U.S. transportation infrastructure are developed. The simulated landscape is shown to be helpful in identifying the highly likely scenarios leading to a high level of investment in highway transportation infrastructure under the existing infrastructure investment structures and budget constraints in the United States. The study presented in this paper is novel with respect to (1) the application of the system-of-systems modeling in the analysis of transportation infrastructure financing policies, (2) identification of the desired policy scenarios and their likelihoods for closure of the financing gap in the presence of uncertainties and adaptive behaviors, and (3) simulation and visualization of the impacts of financing policies at the state and national levels. The model promotes a data-driven policy analysis and provides policymakers with a tool to simultaneously account for the impacts of several factors and uncertainties. **DOI: 10.1061/(ASCE)CP.1943-5487.0000482.**

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Introduction

The objective of this paper is to describe the creation of a model for the ex-ante simulation and visualization of the impacts of financing policies in the highway transportation infrastructure in the United States. According to ASCE and the National Academy of Engineering (NAE), one of the greatest challenges for infrastructure renewal is the insufficiency of available financing sources (NAE 2008). There is an investment need of $3.6 trillion to enhance the close to failing condition of infrastructure in the United States (ASCE 2013). However, the available funding sources only account for approximately 40% of the need, and innovative policies are required to close the financing gap (ASCE 2013). There are different methods for financing, funding, and delivering infrastructure projects. Financing helps to bridge the time gap between the need for funds and their generation by the project or other fund providers, whereas funding generates the financial resources to cover the expenditures and amortize the financing, and delivery includes the construction and operation of the infrastructure. Infrastructure is financed either on a pay-as-you-go (PAYG) basis, i.e., earmarking funding revenues to infrastructure projects, by borrowing or equity investments. Taxation and user pay are the major methods of funding. These serve as the sources of funds for debt amortization and interest repayment in the borrowing method and the sources of returns on investment in equity investment. Infrastructure is delivered either publicly or privately or through varying combinations of public/private partnerships [please refer to the glossary of the Federal Highway Administration (FHWA) Office of Innovative Program Delivery (FHWA 2014) for a more detailed explanation of the terminologies].

Infrastructure system of systems (SOS) are complex in nature because of the existence of various components, organizations, activities, and interactions (Mishra et al. 2013). Factors, such as economic conditions, public attitudes, political priorities, and business and market dynamics, affect investment in infrastructure. While formulating policies related to infrastructure financing, policymakers often overestimate some factors and underestimate others.

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Thus, there is a need for a model that facilitates consideration of the complexities of infrastructure systems while analyzing financing policies (van der Mandele et al. 2006). Such a policy analysis model is missing in the existing body of knowledge related to infrastructure financing.

The key to successful analysis of financing policies in infrastructure SOS is the creation of appropriate analysis tools. Policy analysis tools can be divided into two categories: ex-post and ex-ante. Ex-post analysis tools consider the previously observed system behavior and identify the significant underlying factors that trigger the search for a best solution for a specific scenario (Mostafavi et al. 2011a, 2014a). Despite their robustness in static policy analysis, ex-post analysis tools, such as computable general equilibrium, statistical decision theory, and operations research, have not been successful for problems "where complexity and adaptation are central" (Bankes 2002).

The objective of this paper is to describe the model that was created on the basis of a SOS framework (Mostafavi et al. 2011c, 2014a) and using agent-based modeling to (1) capture the dynamics of investment in the highway transportation infrastructure in the United States and (2) identify the financing scenarios that can lead to closure of the financing gap. This paper proceeds as follows. First, the components of the model related to the analysis of different scenarios related to highway infrastructure financing are discussed. The ex-ante analysis of financing policies related to highway transportation infrastructure includes (1) a simulation/visualization model and (2) a metamodel for simulation of the policy landscape. Second, the simulated policy landscape is evaluated to identify scenarios for closure of the financing gap. Finally, the significance and potential future applications of the proposed framework for the ex-ante analysis of policies related to infrastructure are presented.

Background

This study contributes to two streams of research: (1) infrastructure financing, and (2) agent-based modeling in construction and infrastructure management. There are several studies related to infrastructure financing in the literature, ranging from qualitative evaluations and case studies to statistical assessments. Different studies have evaluated the dynamics of different infrastructure financing methods to close America's infrastructure gap. Eggers and Dovey (2007) evaluated the benefits and implications of using different public-private partnership (PPP) schemes in infrastructure financing. Vega (1997), Grimsey and Lewis (2002), and Griffith-Jones and De Lima (2004) evaluated risk mitigation strategies in PPP projects. Engel et al. (1997), Ashley et al. (1998), Miller et al. (2000), Williams et al. (2001), Yescombe (2007), and Garvin (2007) evaluated key success factors and determinants of infrastructure development using PPP. Schaufelberger and Wipadapisut (2003) and Grimsey and Lewis (2005) evaluated different infrastructure financing strategies. Although these studies are important in understanding different financing schemes and highlighting the factors affecting the success of different financing policies, the majority of these studies are on the basis of ex-post evaluations and do not provide a basis for the analysis of different scenarios. The majority of the existing studies related to infrastructure financing are on the basis of case study and statistical analysis approaches that do not capture the dynamic behaviors and interactions affecting the investment in infrastructure. Hence, the ex-post studies pertaining to infrastructure financing suffer from two major drawbacks: (1) the dynamics of investment in infrastructure systems changes over time because of the adaptive activities and interactions of different players, e.g., private institutional investors, federal agencies, and state agencies. However, the complex-adaptive behaviors of the players cannot be captured using ex-post evaluations; thus, ex-post studies pertaining to the policy analysis of infrastructure financing could not provide insights regarding the impacts of policies on the microbehaviors of the players. (2) The ex-post studies do not provide a tool for considering the impacts of uncertainties pertaining to infrastructure financing; hence, they cannot be used for evaluation of the likelihood of desired policy landscapes for the closure of the gap related to infrastructure financing. These drawbacks can be addressed using ex-ante evaluation of financing policies in infrastructure systems.

The investment in transportation infrastructure systems is affected by the behaviors and decision-making processes of different players, such as public transportation agencies, private institutional investors, and the general public. The behaviors and decision-making processes of the players evolve over time on the basis of their learning from the previous decisions, changes in the economic conditions, and interactions with other players in the system. Hence, capturing the dynamic adaptive behaviors of players is a critical step in long-term ex-ante analysis of financing scenarios in transportation infrastructure systems. An appropriate technique for ex-ante analysis of complex settings composed of adaptive entities is agent-based modeling. Agent-based modeling has been adopted in the assessment of various problems in the context of civil infrastructure and construction projects. Rojas and Mukherjee (2006) proposed a general purpose multiagent framework for situational simulations in the construction management domain; Taylor et al. (2009) developed an ex-ante analysis framework for simulating learning dynamics in project networks; and El-Adaway and Kandil (2009) proposed a multiagent framework for ex-ante analysis of construction dispute resolution. Azar and Menassa (2011) developed an agent-based based approach in the assessment of the impacts of occupants' behaviors on the energy performance of commercial buildings. Du and El-Gay (2012) utilized agent-based modeling in the human and organizational dynamics of construction projects. Taghaddos et al. (2014) proposed a multiagent simulation approach for scheduling modular construction. Despite these studies, the use of agent-based modeling in the assessment of infrastructure policies at state and national levels has been rather limited. The study presented in this paper aims to fill this gap.

Infrastructure Financing Policy Analysis Model

The authors presented the framework, proof of concept, and data collection in their previous study (Mostafavi et al. 2012a, c, 2014a). The objective of this paper is to present the creation of the agent-based model for the simulation of financing scenarios in transportation infrastructure. In addition, this paper presents a detailed scenario analysis using the agent-based model to explore and visualize the effects of different highway transportation infrastructure financing policies in the United States. The objective of the analysis is to identify the highly likely scenarios, which will lead to closure of the financing gap.

Overview of Data Collection

To abstract the components of the system, two sets of data were used. Set 1 includes identification of the activities and institutions of the different players in infrastructure financing, which was extracted from interviews with 15 subject matter experts (SMEs) in the area of infrastructure financing from different organizations. These experts included personnel from state Departments of Transportation (DOTs), FHWA, private institutional investors, and

Table 1. Data Used in Set 2

Data	Source
State Departments of Transportation debt obligations for highway	USDOT
Level of funding for debt repayment by Departments of Transportation	USDOT
Pay-as-you-go capital outlay for roads and bridges	USDOT
Level of investment need for highways, roads, and bridges in the states	ASCE
Debt ratio of state Departments of Transportation	FHWA
The existence and background of implementing PPP in various states	FHWA

private infrastructure operators and owners. Set 2 includes data regarding the current financing needs, level of public and private investment, and level of funding available for investment in highways. The data include the current debt level of the state DOTs; the level of funding available for debt repayment by DOTs; the level of need for highways, roads, and bridges in the states; and the existence and background of implementing PPPs or P3 in various states. Table 1 summarizes the data included in Set 2. The second set of data was obtained from the U.S. Department of Transportation (USDOT), FHWA, and AASHTO. Mostafavi et al. (2012c, 2014b) and Mostafavi (2013) provide more details related to the data used in the abstraction phase of the analysis.

Agent-Based Model

To simulate the dynamics of investment in highway transportation infrastructure, an agent-based model is created. The scope of this study is focused on assessment of the effects of the microbehaviors of state DOTs, private institutional investors, and the public on three broad infrastructure financing methods: pay as you go, debt financing, and private equity. The level of contribution of each of these sources of financing to the infrastructure is affected by the microbehaviors of different players. Fig. 1 shows the components of the model. The agent-based component of the model captures the complex microdynamics of investment in U.S. highway transportation infrastructure by simulating (1) the debt-related decisions of state DOTs, (2) equity investment decisions of private institutional investors, and (3) investment support/opposition of the general public. As shown in Fig. 1, the microbehaviors of private institutional investors determine the number of projects and amount of projects financed using private equity. The microbehaviors of state DOTs determine the amount of debt used for financing infrastructure projects. The level of the pay-as-you-go capacity is determined on the basis of the availability of state and federal grants that are affected by economic conditions. The microbehaviors of the public affect the level of public support of infrastructure investments, which ultimately affects the microbehaviors of private institutional investors and state DOTs (Mostafavi et al. 2011b). The section related to the computational model explains further details pertaining to the interactions among the players, parameters, and variables in the system. The agent-based model also captures the independent microbehaviors of the agents and incorporates the interdependencies of the players. The outcomes of the agent-based model are aggregated to determine the amounts of equity investment, debt financing, and pay-as-you-go financing and evaluate the amount of the annual total investment and financing gap at the state and national level. The values aggregated at the macrolevel affect the parameters at the microlevel. For example, the debt-related decisions made by state DOTs and the equity investment decisions made by the private investors are affected by the level of support and opposition of the public. These decisions affect the level of the

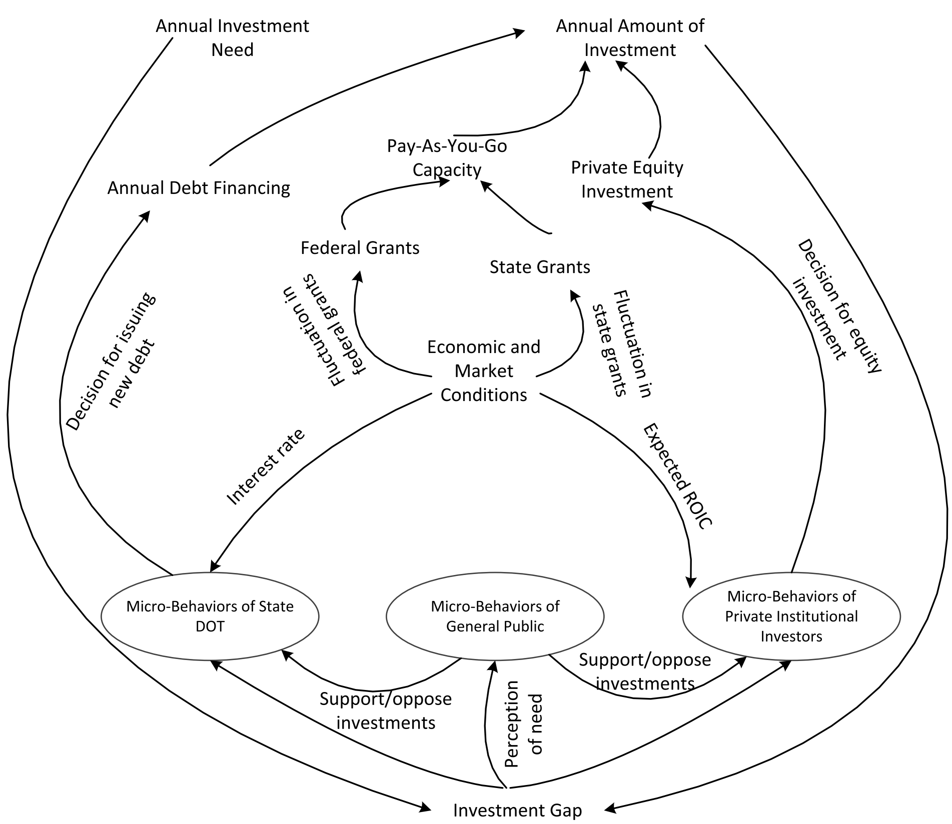

Fig. 1. Components of the agent-based model

financing gap in infrastructure, which would impact the level of public support or opposition.

Components of Computational Model

The agent-based model was created by capturing and simulating the microbehaviors of different players in the systems. The microbehaviors of the players were modeled on the basis of a set of rules related to the belief-knowledge-information (BKI) of the players. The BKI includes the rules used for modeling the microbehaviors of the players. These rules were extracted on the basis of the interviews conducted with SMEs from different agencies (see "Overview of Data Collection" for further details). Then, the rules pertaining to the microbehaviors of different players were converted into mathematical representations. The mathematical representations and logics were then verified through face validity (see "Verification and Validation") to ensure that they reasonably reflect the rules. Fig. 2 summarizes the process for creation and verification of the rules pertaining to the microbehaviors of the players.

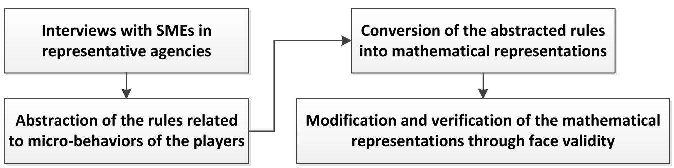

Fig. 2. Process for abstraction of BKI rules

Object-oriented programming and *ANYLOGIC 6.6.0* were used to create the model. In this paper, the term *agent* refers to an autonomous player in the system and the term *object* refers to a function, variable, or data structure that has memory in the computational model. Different studies (Richiardi et al. 2006; Grimm et al. 2010; Bersini 2012) have proposed protocols for the visual representation of agent-based models. In this study, the protocol proposed by Bersini (2012) is used because it is a unified modeling language (UML) capable of providing graphical visualization for simulation models. Fig. 3 shows the class diagram related to the model using UML protocol proposed by Bersini (2012) (not all the attributes and operators are presented in Fig. 3).

The classes of agents in the model include private investors, state DOTs, and general public, each of which is simulated in the model as an object. The private investors, state DOTs, and general public classes of objects were defined to represent the properties of the agents. The model also includes another active object class called infrastructure, which is not an agent, but which has a mathematical model related to each state in the United States. The purpose for considering an infrastructure object class is to facilitate

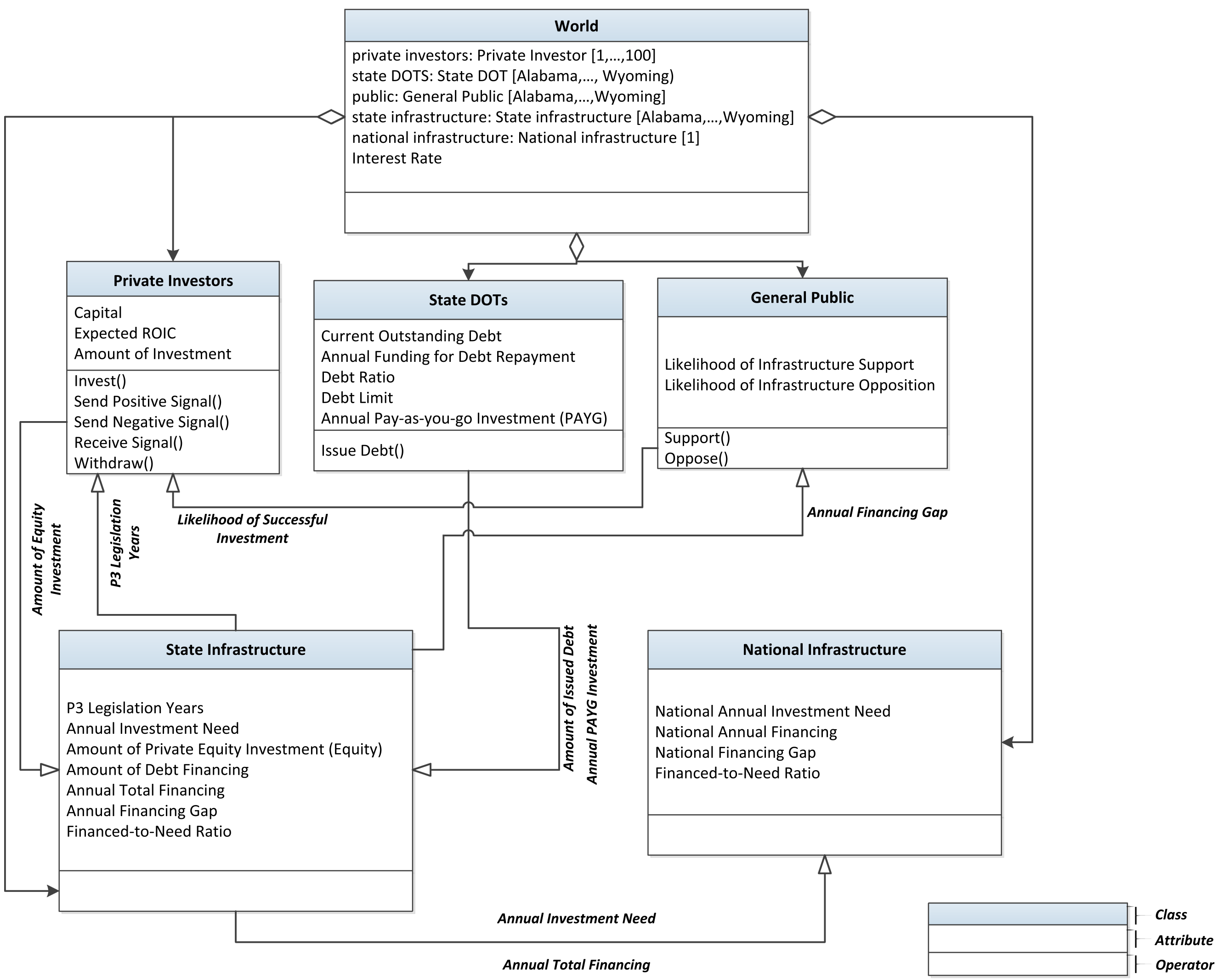

Fig. 3. Class diagram of model

the aggregation of the outcomes of other object classes at the state and national levels. A total of 50 objects of the infrastructure class were modeled to aggregate the dynamics of highway transportation infrastructure financing at the state level, and one object of the infrastructure class was defined to aggregate the dynamics of highway transportation infrastructure financing at the national level. In the remainder of this section, the traits of each object class are described in detail.

Private Investors Object Class

Fig. 4(a) shows a preview of the conceptual model used for this class. This active object class encompasses a state chart and the parameters and variables structured to define the BKI of the object in this class. There are four states for this object class: potential, motivated, active, and withdrawn. Initially, all objects of this class are in the potential investor state. Some objects change their states directly to the active investor state, whereas others require a signal of successful investments to become a motivated investor. The difference between potential investors and motivated investors is as follows: potential investors are those equity investment institutions that invest in markets other than the infrastructure sector. If they receive signals regarding the profitability of investments in the infrastructure sector, they become motivated investors. Objects whose active state is active investor may experience unsuccessful investments and may withdraw. In such situations, the object investor, whose state is withdrawn from investing in infrastructure, sends a signal to potential investors not to invest in infrastructure. In this model, it is assumed that all of the actions of different classes of agents are observable by the other agents. This assumption is consistent with the theory of open market valuation in financial markets. According to the theory of open market valuation, the participants in financial markets are informed about one another's actions. Second, the participants in the data collection interviews indicated that they observe the actions of other players in the system. For example, one of the participants in the data collection interviews mentioned that they monitor the activities of other private institutional investors and if they invest in infrastructure projects in new markets, they consider opportunities in the new markets too.

The object investor can only invest in highway transportation infrastructure projects in states that have P3 programs. The objective of private investors for investing in the infrastructure sector is to make a return on invested capital (ROIC). The expected value of ROIC for private investors in the transportation sector is 10–15% according to Newell et al. (2011). It is also assumed that the ROIC will not change under different economic conditions. Investors tend to have a greater probability of experiencing a successful

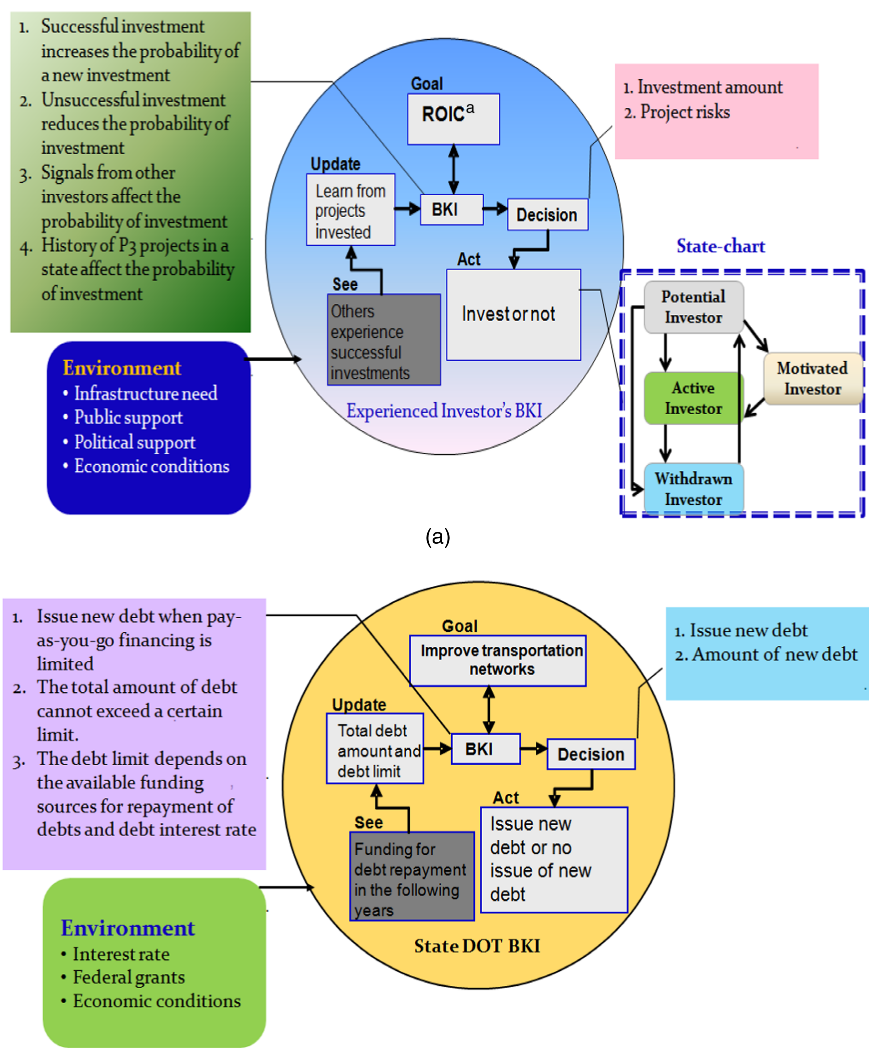

Fig. 4. Diagram to model microbehaviors of (a) private institutional investors; (b) state DOT

zinvestment in states with a longer history of practicing P3 because of the experience curve effect (Newell et al. 2011). This phenomenon is incorporated into the model using Eq. (1)

$$p_t(i) = \mathrm{Min}[p_t(\mathrm{U.S.\ Market}) \times x_i^{\log_2^b}], \quad 0.95 \tag{1}$$

where $p_t(i)$ = probability of successful equity investment in highway transportation infrastructure in state i at time t; $p_t(\mathrm{U.S.\ Market})$ = probability of successful equity investment in highway transportation infrastructure in the United States; x_i = cumulative number of years of practicing P3 in state i; and b = learning percentage. Eq. (1) is on the basis of the premise that investors tend to have a greater probability of experiencing a successful investment in states with a longer history of practicing P3 (Newell et al. 2011). This phenomena is consistent with the experience curve effect. According to the experience curve effect, there is a direct correlation between the level of experience and process outcome and efficiency. Hence, the experience curve effect formula (Chase 2001) is used to adjust the probability of experiencing a successful investment in states on the basis of their history of practicing P3. In addition, the probability of successful equity investment in state i is bounded to 95% because it is very unlikely to have zero investment risks. The ROIC of investors could vary with the probability of successful investment under different economic conditions. However, in this model, it is assumed that ROIC is a function of the expectations of private investors and will not change with the probability of successful investment. This assumption is on the basis of the information abstracted from interviews with private institutional investors regarding their decision-making rules. According to the SMEs that participated in the interviews, their expected ROIC is contingent on their business strategies and does not vary on the basis of the probability of successful investment under different economic conditions. Private institutional investors have the same expected ROIC from investing in infrastructure projects under an economic boom and downturn. The value of the learning percentage is determined to be uniformly distributed between 70 and 90%, as suggested by Yelle (1979) on the basis of his comprehensive survey of the learning curve in different organizations. Thus, the value of the learning percentage b would be different for each state. In modeling the equity investment decision of private investors, it is assumed that other factors, such as the opportunity cost of investment, does not affect the expected ROIC of the private investors. The state of the object changes on the basis of the equations, parameters, and variables defined in the transition between the states. Transitions between states are triggered by the rate of investment, message between different players, or condition of the object. Transitions to become an active investor in a state that has a P3 program are triggered by the investment rate, which is a function of the capacity of the transportation P3 market in the state per year. An example of a transition triggered by the condition is as follows: establishing a P3 program in a state creates a condition in which a potential investor could become an active investor in a state with a newly established P3 program. State DOTs with P3 programs have a limited capacity for procuring P3 projects each year. On the basis of the evaluation of the existing institutional competencies of the state DOTs, the SMEs stated that procurement of more than five P3 projects on average (annually per state) is very unlikely. While evaluating the highway transportation infrastructure market of the states for equity investment, investors tend to become active investors in states with a greater likelihood of successful investment. An example of a message-triggered transition is when a message is sent by active investors who experience unsuccessful investment. The message is received by potential investors and reduces the probability that they invest in highway transportation infrastructure in the state. This message-triggered transition is incorporated into the model using Eq. (2)

$$P[\text{successful investment in state } i | \text{signal of unsuccessful investment in the previous period}] = p_{t-1}(i) \times (1 - \beta) \tag{2}$$

where β = extent of the effect of unsuccessful investment and is assumed to be uniformly distributed between 5 and 25% on the basis of the input from SMEs from different organizations involved in infrastructure financing. Similarly, successful investment entails a positive signal to the market, thereby increasing the probability of successful investment. This successful investment signal effect is incorporated into the model using Eq. (3)

$$P[\text{successful investment in state } i | \text{signal of successful investment in the previous period}] = \mathrm{Min}[p_{t-1}(i) \times (1 + \gamma), 0.95] \tag{3}$$

where γ = extent of the effect of successful investment and is assumed to be uniformly distributed between 5 and 25% on the basis of the input from SMEs from different organizations involved in infrastructure financing. The probability of successful equity investment in state i is bounded to 95% because it is very unlikely to have zero investment risks.

The other parameter affecting the level of private equity investment is the size of the P3 market in the U.S. highway transportation sector. Although each state has a capacity for implementing P3 projects, the total number of P3 projects at the national level is limited by the size of the national market. This constraint has been incorporated into the model using Eq. (4)

$$\sum_{i=1}^{50} N_t(i) < \text{U.S. P3 market size} \tag{4}$$

where $N_t(i)$ = number of projects financed by private equity investors in state i at time t.

State DOT Object Class

Fig. 4(b) shows the conceptual model of this class. This active object class encompasses an action chart that includes a decision that determines whether a state DOT issues debt at the beginning of each year. The condition that leads to the decision is whether the current level of debt in the state DOT is less than the debt limit. This condition is incorporated into the model using Eq. (5)

$$D_t(i) < DL_t(i) \tag{5}$$

where $D_t(i)$ = current level of debt related to transportation financing in state i at time t; and $DL_t(i)$ = debt limit related to transportation financing in state i at time t. The debt limit for a state DOT is a function of the available funding for debt repayment and economic and market conditions. The debt limit is calculated using Eq. (6)

$$DL_t(i) = DR_t \times DF_t(i) \tag{6}$$

where $DL_t(i)$ = debt limit of state DOT i at time t; DR_t = debt ratio at the national level at time t; and $DF_t(i)$ = funding available for debt repayment related to highway financing in state DOT i at time t. The economic and market conditions are reflected in the model using the debt ratio (DR_t), which is a function of the bond market interest rates. The debt ratio is a dimensionless parameter defined as a uniform distribution ranging between 15 and 30. The estimated distribution of the debt ratio is on the basis of data related to the outstanding debt of state DOTs in 2009. Greater values of debt ratio imply lower interest rates and vice versa. The debt limit of state DOTs is a function of the funding made available by the federal government and other factors, such as the bond market conditions and the interest rates. Hence, this limit is tied to the federal ceiling for infrastructure financing.

If the level of debt at the end of each year during the policy horizon is greater than the debt limit, the decision leads to the no issue of new debt action. Otherwise, it leads to the issue of new debt action, in which case the amount of the new debt issued for the specific year would be equal to the median of the amount of debt issued by the state DOT during the last 5 years. Because the state DOTs issue new debt in a consistent manner over a number of years, using a 5-year median value would be a reasonable assumption. This debt-related decision made by state DOTs is modeled using Eqs. (7)–(9)

$$\text{If } D_t(i) < DL_t(i) \tag{7}$$

$$\text{Then } dD_t(i) = \min\{DL_t(i) - D_t(i), \text{median}[dD_{t-5}(i), dD_{t-4}(i), \ldots, dD_{t-1}(i)]\} \tag{8}$$

$$\text{Otherwise } dD_t(i) = 0 \tag{9}$$

where $dD_t(i)$ = amount of new debt issued by state DOT i at time t. Then, using Eq. (10), the current level of debt related to transportation financing in state i at time t will be modified

$$D_t(i) = D_{t-1}(i) + dD_{t-1}(i) \tag{10}$$

Public Object Class

Similar to the object class related to the state DOTs, the public object class encompasses an action chart (Fig. 5). The condition that leads to public support is whether the level of the investment gap for infrastructure investment is greater than the threshold value. The threshold value is a function of public perceptions of infrastructure financing. To identify the determinants of public perceptions of infrastructure financing, a survey was conducted by the authors in Summer 2011 to assess the determinants of public perceptions of infrastructure financing in the United States. The survey included at least 10 responses from each state. Mostafavi et al. (2012b) present the details related to the survey and findings. On the basis of this survey, the threshold value was estimated to be 50% (financed-to-need ratio) in the model. If the investment gap is greater than the threshold value, the decision leads to an increase in the probability of public support for infrastructure investment. This decision is modeled using Eqs. (11) and (12)

$$\text{If } G_t(i) > 50\%$$

$$\text{Then } p_t^s(i) = \min[1, p_{t-1}^s(i) \times (1+\varepsilon)] \tag{11}$$

$$\text{Otherwise } p_t^s(i) = p_{t-1}^s(i) \tag{12}$$

where $G_t(i)$ = investment gap in state i at time t; $p_t^s(i)$ = probability of public support in state i at time t; and ε = extent of the effect of public support and is assumed to be uniformly distributed between 20 and 40% on the basis of the input from the SMEs. The extent of the effect of public support determines how public support enhances the likelihood of successful investment in infrastructure.

Public support of infrastructure investments could increase the probability of successful investment by private investors. The effect of public support is incorporated into the model using Eq. (13)

$$P(\text{successful investment in state } i|\text{public support}) = \min[p_{t-1}(i) \times (1+\varepsilon), 0.95] \tag{13}$$

where ε = extent of the effect of public support and is assumed to be uniformly distributed between 20 and 40% on the basis of input provided by SMEs from different organizations involved in infrastructure financing. Conversely, public opposition would decrease the probability of successful investment by private investors. The probability of public opposition to an infrastructure investment is calculated using Eq. (14)

$$p_t^o(i) = 1 - p_t^s(i) \tag{14}$$

where $p_t^o(i)$ = probability of public opposition in state i at time t. The effect of public opposition is incorporated into the model using Eq. (15)

$$P(\text{successful investment in state } i|\text{public opposition}) = p_{t-1}(i) \times (1-\rho) \tag{15}$$

where ρ = extent of the effect of public opposition and is assumed to be uniformly distributed between 20 and 40%.

In the case of highway transportation infrastructure, the public priorities of neighboring states may affect the infrastructure investment decisions made by a state. However, in this model, the links between public opinions of neighboring states have been neglected to simplify the model.

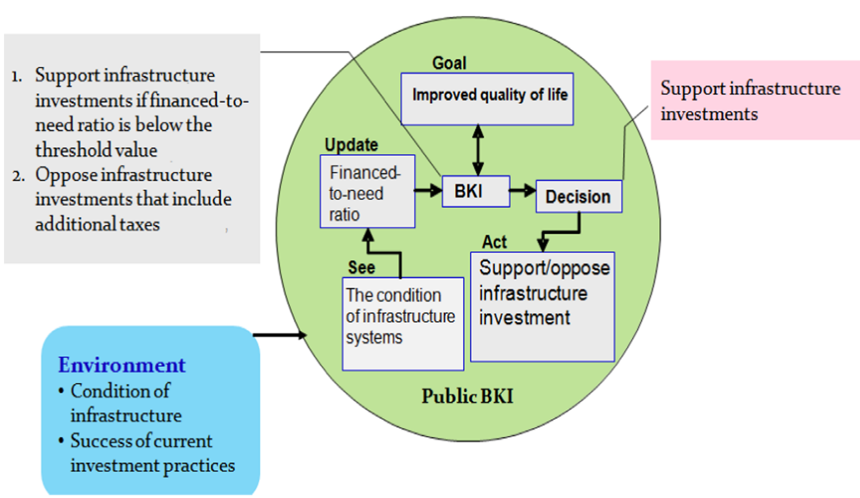

Fig. 5. Diagram to model microbehaviors of public

State Infrastructure Object Class

Fig. 5 shows the conceptual model for this class. The variables in the object include

- Pay-as-you-go financing, which is a function of the available state and federal grants. The pay-as-you-go capacity for financing infrastructure in a state is a function of the previous year's pay-as-you-go financing and the current volatility of pay-as-you-go financing. The volatility is an uncertain parameter and is defined using probability distributions. The pay-as-you-go capacity of state DOTs is calculated using Eq. (16)

$$\mathrm{pay}g_t(i) = \mathrm{pay}g_{t-1}(i) \times (1 + r_{\mathrm{pay}g}) \tag{16}$$

  where $\mathrm{pay}g_t(i)$ = pay-as-you-go capacity of state i at time t; and $r_{\mathrm{pay}g}$ = volatility rate of the pay-as-you-go capacity growth and is assumed to be uniformly distributed between −10 and 10%. The SMEs interviewed in this study indicated that the probability that the decline or growth rate of the pay-as-you-go capacity of state DOTs would be greater than 10% is unlikely.
- Debt (bonding) financing, which is a function of the decision regarding the issuance of new debt made by the objects representing the state DOT. The value of this variable would be equal to the debt issued by the state DOT objects, i.e., $dD_t(i)$, at a specific time during the policy horizon.
- Private investment, which is a function of the decision made by the private investor objects regarding investment in infrastructure projects in a state. The value of this variable would be equal to the number of projects financed by the private investors in a state multiplied by the average dollar value of the P3 projects at a specific time during the policy horizon. The amount of private investment is calculated using Eq. (17)

$$E_t(i) = N_t(i) \times V_t \tag{17}$$

  where $E_t(i)$ = amount of private equity investment in state i at time t; and V_t = average dollar value of the P3 projects at time t and is estimated to be uniformly distributed between \$200 million and \$700 million on the basis of the data obtained from USDOT related to the size of previous P3 transportation projects in the United States (USDOT 2011). Thus, the total amount of private equity investment in the U.S. P3 market is calculated using Eq. (18)

$$E_t(\text{U.S. transportation}) = \sum_{i=1}^{50} E_t(i) \tag{18}$$

  where $E_t(\text{U.S. transportation})$ = total amount of private equity investment in the U.S. P3 market.

  The other variables in the state infrastructure object class include the annual amount of investment in infrastructure per year $[I_t(i)]$, annual need for investment in infrastructure $[IN_t(i)]$, investment gap $[G_t(i)]$, and financed-to-need ratio $[\mathrm{FNR}_t(i)]$, which are calculated using Eqs. (19)–(25)

$$I_t(i) = E_t(i) + \mathrm{pay}g_t(i) + dD_t(i) \tag{19}$$

where $I_t(i)$ = total amount of infrastructure investment in state i at time t. Thus, the total amount of investment at the national level at time t would be equal to

$$I_t(\text{U.S. transportation sector}) = \sum_{i=1}^{50} I_t(i) \tag{20}$$

$$IN_t(\text{U.S. transportation sector}) = \sum_{i=1}^{50} IN_t(i) \tag{21}$$

where $IN_t(i)$ = amount of infrastructure investment need in state i at time t. Thus, the level of the investment gap in a state DOT i at time t is

$$G_t(i) = IN_t(i) - I_t(i) \tag{22}$$

$$G_t(\text{U.S. transportation sector}) = \sum_{i=1}^{50} G_t(i) \tag{23}$$

Consequently, the financed-to-need ratio at the state and national level will be calculated as follows:

$$\mathrm{FNR}_t(i) = \frac{I_t(i)}{IN_t(i)} \tag{24}$$

$$\mathrm{FNR}_t(\text{U.S. transportation sector}) = \frac{I_t(\text{U.S. transportation sector})}{IN_t(\text{U.S. transportation sector})} \tag{25}$$

where $\mathrm{FNR}_t(i)$ = financed-to-need ratio in state i at time t; and the initial values for $IN_t(i)$ for each state were obtained from the data collected from the USDOT. In addition, one object from the infrastructure class was defined and called the U.S. infrastructure object. The purpose of the object is to perform an aggregation of the dynamics of highway transportation infrastructure financing at the state level and reflect it at the national level. In the model, it is possible that the financed-to-need ratio could exceed one in some scenarios. In such cases, it is expected that the states would find appropriate avenues for investing the additional capital in new infrastructure projects. Thus, it is expected that (1) an increase in private investment in a state does not cause the state to give up its share from the federal grants; and (2) there will be no economic bubble as a result of a financed-to-need ratio exceeding one. Table 2 summarizes the rationale related to the assumptions made in the model.

Simulation Analysis

The simulation model includes a visualization component, which helps in visualizing the effects of policies on the level of investment in highway transportation infrastructure at the state and national levels. The simulation/visualization component of the model provides the following benefits for policy analysis purposes:

- Evaluation of the effects of policies over time in different states; and
- Assessment of the effects of financing policies at the national level over time.

The level of the financing gap, i.e., financed-to-need ratio, is visualized using colors that facilitate communication of the outcomes of the analysis with diverse groups of stakeholders in a more effective fashion. To evaluate the outcomes of policies using the model, three states, Arizona, California, and Texas, are selected for a closer assessment because these states have significant annual needs for investment in highway transportation infrastructure (Arizona = \$3.04 billion; California = \$14.62 billion; and Texas = \$13.4 billion).

Evaluation of the Effects of Policies over Time in Different States

Different financing policies would have different effects on the level of investment in highway transportation infrastructure in

Table 2. Assumptions Related to Distributions and Values of the Parameters

Parameter	Object	Assumed distribution/value	Basis of the assumption
Maximum capacity of each state to procure P3 projects	Private investors	5	On the basis of input provided by SMEs, state Departments of Transportations, which have P3 programs, would have limited capacity for procuring P3 projects each year
Extent of the effect of unsuccessful investment	Private investors	Uniform (0.05, 0.25)	On the basis of input provided by SMEs, a signal of unsuccessful investment would not significantly reduce the probability of successful investment in the subsequent period
Extent of the effect of successful investment	Private investors	Uniform (0.05, 0.25)	According to the input from SMEs, a signal of successful investment would not significantly enhance the probability of successful investment in the subsequent period
Expected ROIC	Private investors	Uniform (0.1, 0.15)	Newell et al. (2011) states that the expected return on investment in the infrastructure sector is between 10 and 15%
Debt ratio	State DOT	Uniform (15, 30)	Historical data (2007–2011)
Threshold value of financed-to-need ratio for public support of infrastructure investment	Public	50%	A survey of public perceptions implemented by the authors in Summer 2011 (Mostafavi et al. 2012b)
Effect of infrastructure need on the probability of public support	Public	Uniform (0.2, 0.4)	On the basis of input provided by SMEs, increased need for infrastructure investment would increase the probability of public support by 20–40%
Extent of the effect of public support on probability of successful investment	Public	Uniform (0.2, 0.4)	On the basis of input provided by SMEs, public support of infrastructure investment would enhance the probability of successful investment in the subsequent period by 20–40%
Annual growth of pay-as-you-go capacity of the states	State infrastructure	Uniform (−0.1, 0.1)	On the basis of input provided by SMEs, an annual decline or growth in the pay-as-you-go capacity of state Departments of Transportation is less than 10%
Average dollar value of the P3 projects	State infrastructure	Uniform ($200 million, $700 million)	Historical data related to the previous P3 projects in the U.S. transportation infrastructure indicated that the assumption related to the average dollar value of the P3 projects is valid

different states. Also, the time that it takes to close the financing gap in different states varies because of the differing characteristics of the states, e.g., financing needs, legislative structures, and budget priorities.

Fig. 6(a) demonstrates the effects of a policy that tends to increase the funding for debt repayment by 10%. Keeping all of the other policy target parameters constant, this policy would not lead to the closure of the financing gap in the states over a 10-year policy

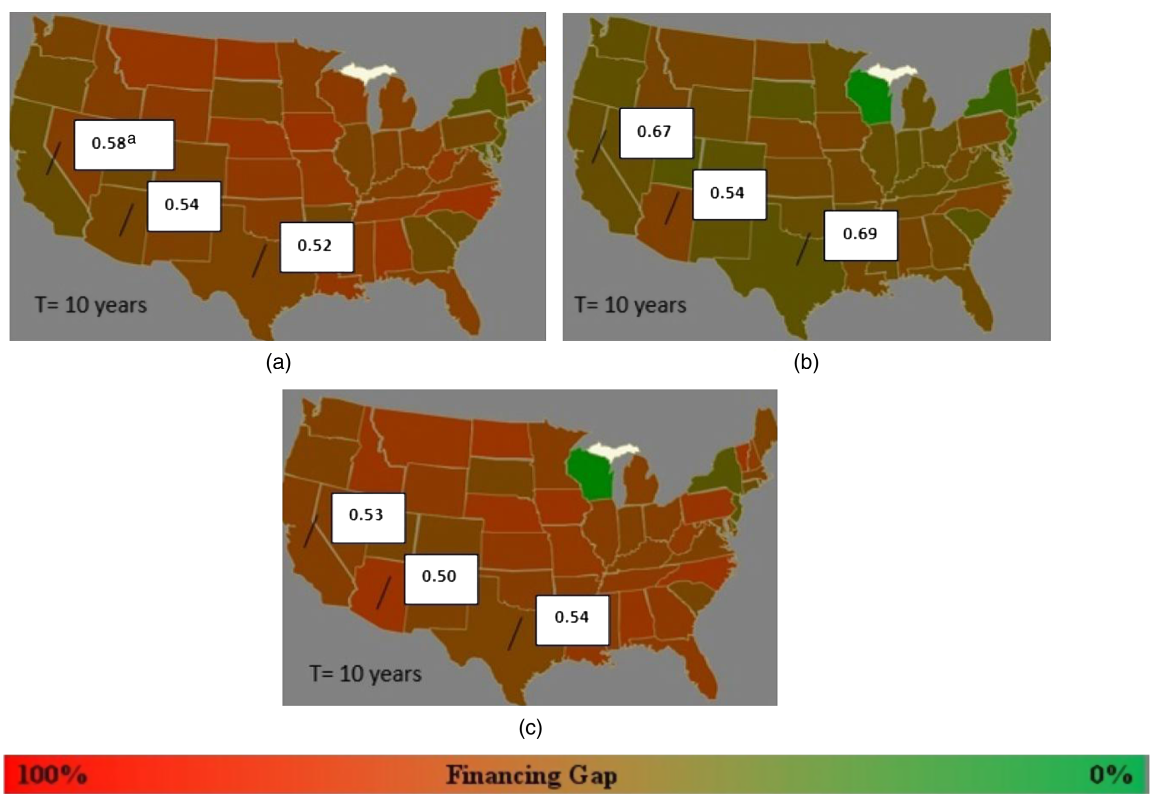

Fig. 6. Visualization and comparison of policy outcomes: (a) 10% increase in funding for debt repayment; (b) 3% increase in pay-as-you-go capacity; (c) P3 market size = 25 projects per year; average dollar value of P3 projects = $500 million

horizon. For example, as a result of this financing policy, the states of Arizona, California, and Texas would have a financed-to-need ratio of 0.54, 0.58, and 0.52, respectively, at the end of the 10-year horizon for the following two main reasons:

1. The debt capacity of the state DOTs is affected by available funding and market conditions. During the times of unfavorable bond market conditions, i.e., high interest yields, the tendency towards issuing new debt for infrastructure financing is unlikely.
2. These state DOTs have outstanding debt obligations related to highway transportation infrastructure investments that are close to their debt capacity. Most of the bonds, e.g., municipal, Build America, and GARVEE, issued by state DOTs have a long term to maturity, typically, 20–30 years. Thus, an increase in the funding for debt repayment would not lead to a significant increase in the bonding capacity of state DOTs.

Fig. 6(b) demonstrates the effect of a policy related to increasing the pay-as-you go financing of the state DOTs by 3%, which could lead to gradual closure of the financing gap at the state level. In the medium term, e.g., 10 years, Arizona, California, and Texas will have financed-to-need ratios of 0.54, 0.67, and 0.69, respectively, from the time when an increase in pay-as-you-go financing takes place. These results imply that states, such as Arizona, California, and Texas, which have a significant need for highway transportation infrastructure investment, would not be able to close the financing gap with a 3% annual increase in the pay-as-you-go capacity in a 10-year policy horizon. According to Fig. 6(c), expansion of the P3 market size (P3 market size = 25 projects per year; average dollar value of P3 projects = $500 million) would not lead to a significant increase in the financed-to-need ratio values across the states over a 10-year policy horizon.

Assessment of the Outcomes of Policies at the National Level over Time

The model enables aggregation of the outcomes of different policies at the national level and assessment of the changes in the financed-to-need ratio at the national level over time. Fig. 7 shows the outcomes of the following four policies at the national level and over time: (1) base case scenario; (2) 10% increase in the funding for debt repayment; (3) 3% increase in the pay-as-you-go capacity; and (4) increase in the size of the P3 market (25 projects annually—average dollar value of the projects = $500 million).

As shown in Fig. 7, pursuing the base case scenario would lead to a decline in the financed-to-need ratio at the national level over 20 years of the policy horizon. The financed-to-need ratio at the national level pursuing the base case scenario would be 0.47 at the end of 20 years.

Increasing the funding for debt repayment would not increase the financed-to-need ratio at the national level (Fig. 7). There would be a number of increases in the financed-to-need ratio during 20 years of the policy horizon; however, because of the high level of the current outstanding debt of the state DOTs, the increases in the financed-to-need ratio values will be cyclic. Therefore, each period of increased financed-to-need ratio would be followed by a period of decreased financed-to-need ratio. Although the 10% increase in funding for debt repayment does not increase the financed-to-need ratio above 0.7, this policy reduces the volatility of financed-to-need ratio values over 20 years. The financed-to-need ratio values show a mean-reversion behavior.

The policy involving a 3% increase (Fig. 7) in the pay-as-you-go capacity will lead to a sustained increase, i.e., one that builds on previous increases, in the financed-to-need ratio values at the national level over time. Unlike the other three policies analyzed using this model, the increase of the pay-as-you-go capacity is the only policy that leads to a sustained increase in the financed-to-need ratio values.

The policy related to the increase of the P3 market size has the greatest volatility. As shown in Fig. 7, the volatility of the outcomes of this policy is greater than those of the other policy scenarios. This implies that pursuing a policy on the basis of expansion of the P3 market size, without a sustained increase of pay-as-you-go capacity, would not lead to closure of the financing gap. Also, there would be significant uncertainties regarding the increase of the financed-to-need ratio as a result of policies involving an expansion of the P3 market size.

Verification and Validation

Verification and validation of ex-ante simulation models using historical data is not feasible because of the dynamic and evolving nature of complex systems. Sargent (1999) provided a guideline

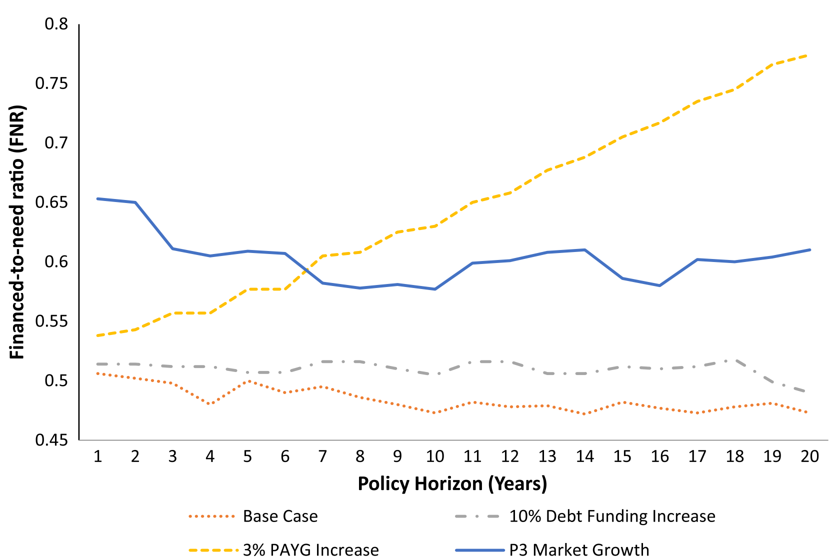

Fig. 7. Outcomes of financing policies at national level over time

for comprehensive verification and validation of ex-ante simulation models, which includes the following steps to ensure the quality of simulation models: data validity, conceptual model validity, computerized model validity, and operational validity. More than one approach was used to facilitate triangulation and thus the validation and testing process (Love et al. 2002). For instance, one of the approaches included face validity. According to Carson (2002), a model that has face validity appears to be a "reasonable imitation of a real-world system to people who are knowledgeable of the real world system." Face validity is conducted by having users and people knowledgeable with the system examine the model logic and output for reasonableness. In this research, face validity was conducted in two phases. In the first phase, the conceptual and computational models were evaluated by five verified SMEs from four different organizations involved in infrastructure financing, e.g., FHWA, AASHTO, the World Bank, and Inter-American Development Bank (IADB). The average experience of the SMEs involved in the verification and validation process was 18 years. The validation process included several face-to-face meetings, during which all the components of the model, i.e., conceptual model, logics, rules, data, assumptions, and results, were demonstrated to the SMEs in detail and modifications were made on the basis of input from the SMEs. The first phase of the face validation was completed when all the SMEs asserted that all the components, i.e., conceptual model, logics, rules, data, assumptions, and results, of the simulation model were reasonable and correct. Table 3 shows the results of the evaluation of the model by the SMEs in the first phase. The SMEs evaluated 12 features related to four components of the model, i.e., conceptual model, computational model, data, and results, during the face validation, as shown in Table 3. In the validation of the conceptual model, three features were evaluated to ensure that the conceptual model was complete in terms of capturing the important components and processes. In the validation of the computational model, three features were evaluated to ensure that the mathematical equations and logics used for capturing the dynamics of the system were reasonable and correct. In the validation of the data, two features were evaluated to confirm that the assumptions related to different parameters and variables in the model were reasonable. Finally, in the validation of the results, i.e., operational validity, four features were evaluated to ensure that the simulated behavior of the system and the results of the model were reasonable.

In the second phase of the face validation, the simulation model, its components, and the results were presented to two panels of experts in the area of transportation infrastructure financing. The panels took place as part of the Let's Rebuild America Leadership Council of the U.S. Chamber of Commerce and the Finance and Revenue Committee of the Transportation Research Board in 2012. The panels included more than 20 experts in total. The panels assessed whether the simulation results were reasonable and indicated that the outcomes of the model are reasonable for the evaluation of financing scenarios in the following aspects: (1) the behaviors of different players in the model are consistent with the real world; (2) the relationships between different components of the model are realistic and capture the most significant factors and players; (3) the identified highly likely scenarios for closing the financing gap are realistic; (4) the significant factors identified on the basis of the model outcomes are valid; and (5) the simulation and visualization component of the model provides a useful tool for scenario analysis and decision making.

The other method used for validation of the model was internal validation (Sargent 2013). Several replications of the stochastic model were made to determine the amount of stochastic variability in the model. The results of internal validation showed that the model results were consistent and did not show significant variations across the stochastic replications. External validity was also pursued and included comparison of the outcomes with the findings of other models/studies in the area of infrastructure financing. As shown in Table 4, the results of the model reinforce what other studies [e.g., Grimsey and Lewis 2005; Kwak et al. 2009; National Conference of State Legislatures (NCSL) 2011; Levinson 2001; M. Dailami and R. Hauswald, "The emerging project bond market: Covenant provisions and credit spreads," working paper, World Bank Policy Research, Washington, District of Columbia] have already noted. As shown in Table 4, the result of the model pertaining to the significance of pay-as-you-go financing in closing the existing financing gap is consistent with the findings of the study conducted by Levinson (2001). In addition, the results of the model highlighted that PPP is not a panacea for closing the existing financing gap; this outcome is consistent with the findings of other studies, such as those of Grimsey and Lewis (2005) and Kwak et al. (2009). Finally, the results of the model related to the use of debt financing in conjunction with pay-as-you-go financing for closure of the existing gap are consistent with the findings of other studies, such as that of Dailami and Hauswald ("The emerging project bond market: Covenant provisions and credit spreads," working paper, World Bank Policy Research, Washington, District of Columbia).

Table 3. Validation Scores on the Basis of Assessment by SMEs

Verification and validation (V&V) components	Identifier	Validation features	Average score[a] (standard deviation)
Conceptual model validity	1	The components of the model represent the most important features of the system	4.2 (0.45)
	2	The abstraction of the components and interactions in the model are complete	4.2 (0.45)
	3	The model explains the dynamics of the system	4.6 (0.55)
Computational model validity	4	The behavior of the components of the model is reasonable	4.6 (0.55)
	5	The theories and assumptions underlying the model are correct	4 (0.00)
	6	The model's representation of the system and the model's structure, logic, and mathematical and causal relationships are reasonable	4.6 (0.55)
Data validity	7	The assumptions regarding the model's parameters, variables, interactions, and decision rules are reasonable	4.6 (0.55)
	8	The level of detail and relationships used for the model are appropriate for the intended purpose	4.6 (0.55)
Operational validity	9	The output of the simulation model has the accuracy required for the model's intended purpose	4.2 (0.45)
	10	The graphical/animation output of the model is appropriate for the intended audiences	5 (0.00)
	11	The simulated behavior of the model is reasonable	4.6 (0.55)
	12	The model could be helpful in the domain of its applicability	4.6 (0.55)

[a]1 = poor; 2 = needs significant improvement; 3 = needs modifications to be useful; 4 = good enough; 5 = excellent.

Table 4. External Validity of the Model

Aspect of policy analysis	Findings of the model	Examples of other studies with similar findings
Effect of pay-as-you-growth	Growth of pay-as-you-go capacity is the most significant component for closure of the financing gap	Levinson (2001)
Effect of expansion of P3 market	P3 is not a panacea for closing the financing gap	Grimsey and Lewis (2005) and Kwak et al. (2009)
Effect of increase of funding for debt repayment	Increasing the funding for debt repayment would help in closing the financing gap in the long term if it is used as a complement to pay-as-you-go financing	Dailami and Hauswald ("The emerging project bond market: Covenant provisions and credit spreads," working paper, World Bank Policy Research, Washington, District of Columbia), Levinson (2001), and NCSL (2011)

Table 5. Assessment of Modeling Quality

Features of modeling quality	Explanation of assessment
Completeness	The results of the face validation (Validation Feature 1–6) of the conceptual and computational models by the SMEs confirmed that the most significant entities, behaviors, and processes pertaining to the dynamics of infrastructure investment were captured in the model
Consistency	The results of the face validation (Validation Feature 4) confirmed that the behaviors of different components in the conceptual and computational model were consistent with reality. In addition, the internal validation confirmed that the computational model generated consistent results across the stochastic replications
Coherence	The computational model codes were evaluated twice to ensure that all the components and elements in the model had functions
Correctness	The results of the face validation (Validation Features 9–12) confirmed that the model was appropriate for its intended application

The outcomes of the validation process ensured the four features (4Cs) of modeling quality: completeness, consistency, coherence, and correctness (Pace 2000; Kleijnen et al. 2005). The model completeness ensured that the conceptual representation identifies all representational entities and processes of the problem domain. The model consistency ensured that representational processes and processes within the conceptual model were addressed from compatible perspectives. The model coherence ensured that all the elements in the model had functions. The model correctness ensured that the model was appropriate for the intended application. Table 5 summarizes how the results of the validation features and processes were used to ensure that the model has the required 4Cs of modeling quality.

Metamodeling

The ultimate goal of policy analysis is to simulate the policy landscape rather than produce point predictions. Policy analysis of complex systems will not be effective if agent-based models are used to produce point predictions (Bankes 2002). The results of simulation models should be processed to generate the policy landscape and identify the decision factors affecting the outcomes (Kleijnen et al. 2005). To this end, metamodeling could be used for exploring the variation of output variables as functions of different input variables in the simulation model (Staum 2009). Different data-mining methodologies, such as regression, clustering, classification model, and neural networks, could be used for creation of the metamodel.

In this study, data from 2,000 runs of the Monte Carlo simulation of the policy analysis model were used in the classification and regression tree (CART) analysis to create the policy landscape of highway transportation infrastructure financing (Fig. 8). The CART is a nonparametric technique that can select, from among a large number of variables, the most important variables in determining the outcome variable to be explained and their interactions (Breiman et al. 1984). A regression tree is a tree-structured representation in which a regression model is fitted to the data in each partition. An advantage of CART analysis is that it facilitates identification of significant factors affecting the policy outcomes and scenarios leading to the desired policy outcomes. Beiman et al. (1984) explain CART analysis in detail.

In the simulated policy landscape, each path, which consists of a number of branches, leads to a terminal node. Each path represents a policy scenario, and each terminal node represents a policy outcome. Each branch of a policy scenario represents specific values of policy target parameters. Policy target parameters that are located in higher branches of the landscape are of more significance in affecting policy outcome. The simulated landscape could be used for the identification of (1) the significant factors affecting the level of investment in infrastructure, and (2) the policies that would lead to desirable scenarios. In the simulated policy landscape, each path, which consists of a number of branches, leads to a terminal node. Each path represents a policy scenario, and each terminal node represents a policy outcome. Each branch of a policy scenario represents specific values of policy target parameters. Policy target parameters that are located in higher branches of the landscape are of more significance in affecting the policy outcome. As an example, Fig. 9 shows a policy scenario that would lead to a financed-to-need ratio of 0.408. The policy scenario is related to Terminal Node 1. The target parameters, i.e., branches, of this policy scenario include the volatility of the pay-as-you-go capacity, U.S. P3 market size, and volatility of funding for debt repayment. The most significant policy parameter in this scenario is the volatility of the pay-as-you-go capacity, which is located in the highest branch. This policy scenario implies that if there is a greater than 3.2% annual decline in the pay-as-you-go capacity, the size of the P3 market is less than 20 projects per year, and if the increase of funding for debt repayment is less than 5%, the financed-to-need ratio at the end of the 20-year policy horizon will be 0.408. However, in this scenario, if the increase in funding for debt repayment is greater than 5%, Terminal Node 2 will be reached with a financed-to-need ratio of 0.511. The simulated landscape could be used for the identification of (1) the policies that would lead to desirable scenarios, and (2) the significant factors affecting the level of investment in infrastructure.

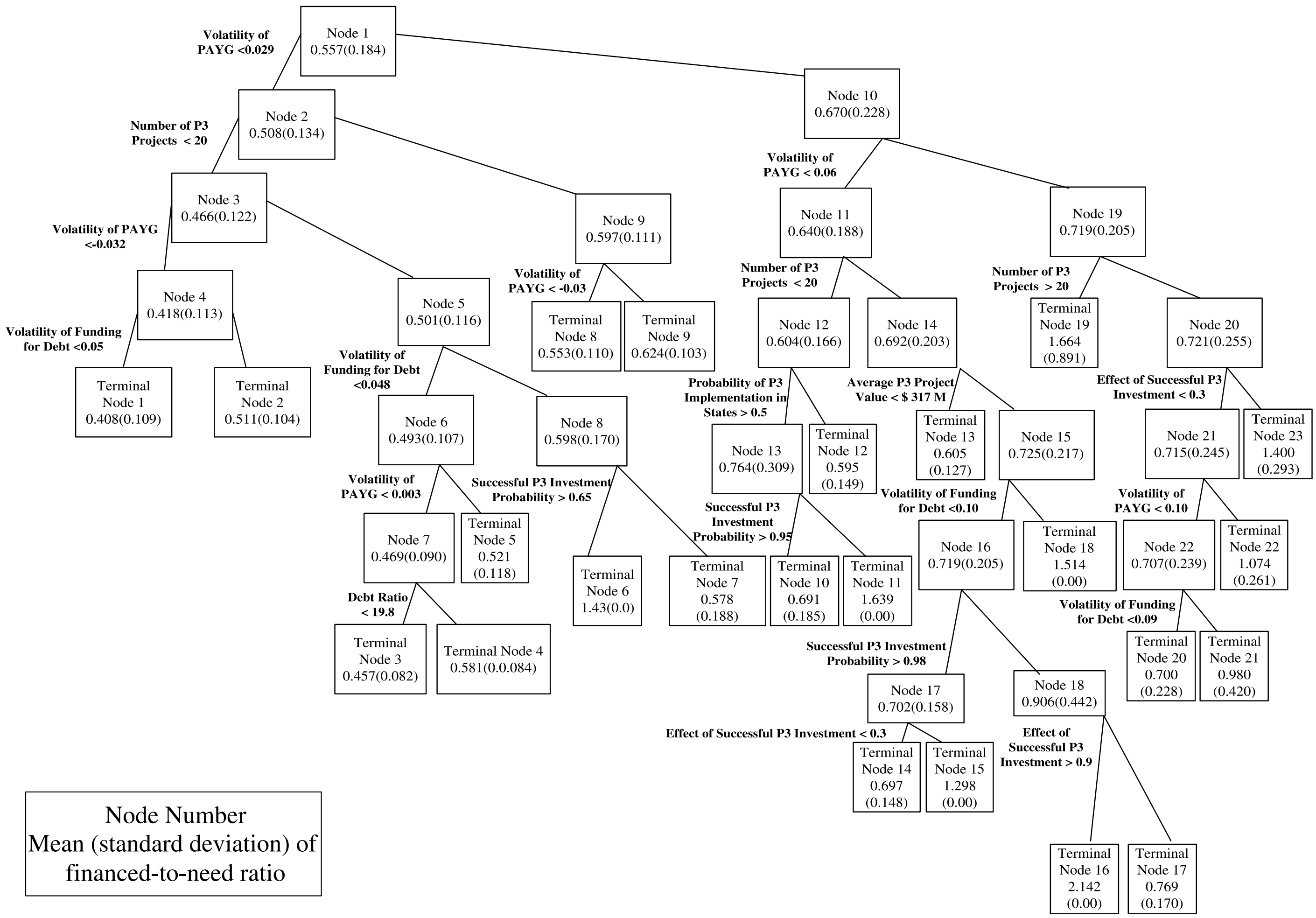

Fig. 8. Simulated policy landscape of U.S. highway transportation infrastructure

Significant Factors Affecting Financing Policies

The volatility of the pay-as-you-go capacity is the most significant factor affecting the total level of investment. The size of the P3 market, volatility of the pay-as-you-go capacity, and probability of successful implementation of P3 projects comprise the next set of significant factors affecting the total level of investment. In addition, the volatility of state and federal grants is 2.5 times more significant than the size of the P3 market for closing the existing financing gap. This result suggests that P3 financing alone is not a panacea for the challenges facing U.S. infrastructure investment. This finding is a reinforcement of observations in previous studies, such as those of Kwak et al. (2009) and NCSL (2011). Unless the pay-as-you-go capacity is increased, achieving a high level of investment will not be very likely.

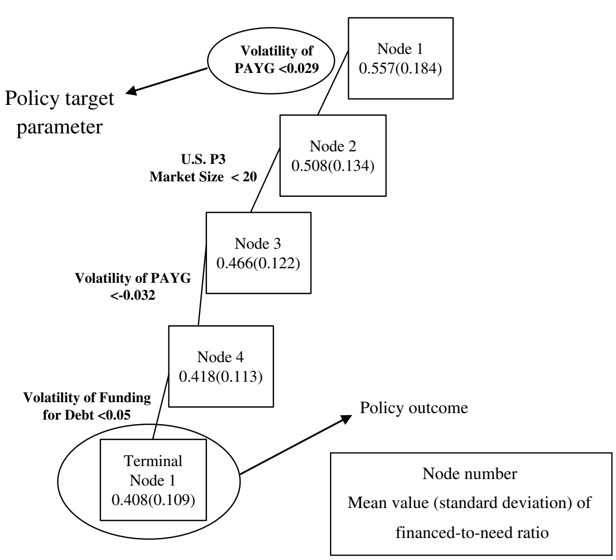

Fig. 9. Example of components of policy scenario

Desired Scenarios for Closure of the Financing Gap

The policy landscape could also be used for a scenario analysis. The simulated landscape (Fig. 8) shows that there are eight desired scenarios (Fig. 10) that can achieve a high level of investment in infrastructure (financed-to-need ratio of greater than 0.8) for the case under consideration. However, the identified desired scenarios for closing the financing gap do not have an equal likelihood of occurrence because of existing uncertainties, e.g., possibility of unsuccessful investment, unfavorable financial market conditions, and public opposition. In the formulation of infrastructure financing policies, the desired scenarios with a significant likelihood should be sought. Using an uncertainty propagation analysis, the likelihood of desired outcomes as a result of different policies was evaluated. Fig. 11, which shows the box plots related to each scenario, provides four desired scenarios that have the highest likelihood of closing the financing gap (financed-to-need ratio greater than 1 at the end of 20 years)

Scenarios /Terminal Node)	Values of Policy Target Parameters				
Scenario I (TN[a] 16)	3% <PAYG financing growth<6%	Number of P3 Projects > 20 projects per year	Average P3 project value > $317 million	Successful P3 investment probability > 95%	Funding for debt repayment growth <10%
Scenario II (TN 6)	0% <PAYG financing growth< 3%	Number of P3 Projects < 20 projects per year	Funding for debt repayment growth > 4.8%	Successful P3 investment probability > 65%	
Scenario III (TN 18)	3% <PAYG financing growth<6%	Number of P3 Projects > 20 projects per year	Average P3 project value > $317 million	Funding for debt repayment growth > 10%	
Scenario IV (TN 11)	3% <PAYG financing growth<6%	Number of P3 Projects < 20 projects per year	Successful P3 investment probability > 95%		
Scenario V (TN 21)	6% <PAYG financing growth<10%	Number of P3 Projects < 20 projects per year	Funding for debt repayment growth > 9%		
Scenario VI (TN19)	6% <PAYG financing growth<10%		Number of P3 Projects > 20 projects per year		
Scenario VII (TN 23)	10% >PAYG financing growth		Number of P3 Projects < 20 projects per year		
Scenario VIII (TN 22)	10% <PAYG financing growth		Number of P3 Projects < 20 projects per year		

Fig. 10. Desired scenarios for closing financing gap in highway transportation infrastructure

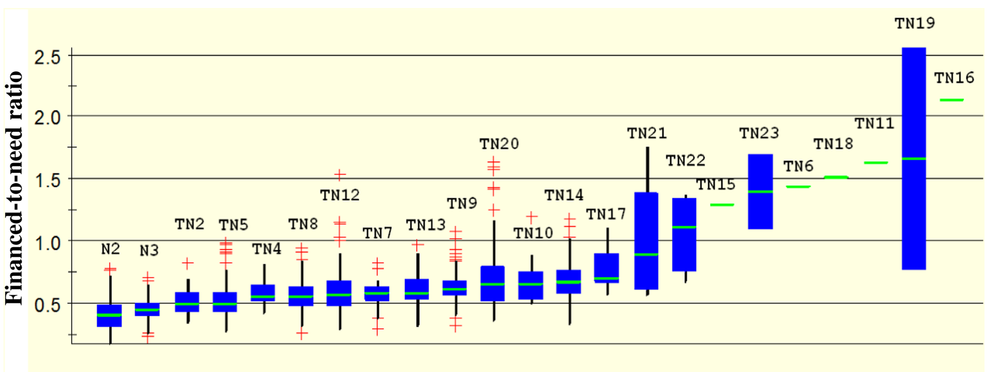

Fig. 11. Uncertainty propagation analysis

- Desired Scenario VI related to Terminal Node 19 in the policy landscape;
- Desired Scenario V related to Terminal Node 21 in the policy landscape;
- Desired Scenario VIII related to Terminal Node 22 in the policy landscape; and
- Desired Scenario VII related to Terminal Node 23 in the policy landscape.

Of the four scenarios, desired Scenario VII (Terminal Node 23) has the highest likelihood for a financed-to-need ratio greater than 1. This scenario includes a more than 10% increase in the pay-as-you-go financing capacity. However, formulating a policy to increase the pay-as-you-go capacity by 10% might not be politically, socially, and economically feasible because it would require an increase in taxes. The alternative scenario to pursue a high level of investment would be desired Scenario VI (Terminal Node 19). This scenario includes a 6–10% increase in the pay-as-you-go capacity and expansion of the size of the U.S. P3 market to more than 20 projects per year. The likelihood that the financed-to-need ratio for this scenario will be less than 1 is not very likely. However, this scenario could lead to high financed-to-need ratio values, e.g., a financed-to-need ratio of 2 or greater. This scenario could lead to a high financed-to-need ratio because of the possibility of successful implementation of P3 projects and consequently expansion of the size of the P3 market in the highway transportation sector in the United States.

In the simulated landscape, desired Scenario V (Terminal Node 21) includes a 6–10% increase in the pay-as-you-go capacity, expansion of the size of the U.S. P3 market to less than 20 projects per year, and a 9% increase of funding for debt repayment. This scenario would be desirable in cases where the expansion of the U.S. P3 market size is not feasible, such as the case of the State of New York where the existing policies do not allow for implementation of P3 projects. However, as shown in Fig. 11, there is a greater than 50% likelihood that the financed-to-need ratio will be less than 1 in this scenario.

The simulated landscape could be used in identifying the highly likely desired financing scenarios leading to the closure of the existing gap in highway transportation infrastructure in the United States. Different financing policies may be used to achieve each desired scenario. The formulation of appropriate financing policies should account for different considerations, such as the unique characteristics and financing practices of different state DOTs, level of risk averseness of the private investors, project-specific requirements, and requirements of different debt and credit instruments to implementation of various PPP schemes.

Summary and Conclusions

Ex-ante simulation models can provide helpful tools for the design, operation, and policy analysis related to civil infrastructure. In particular, the need for models for financing policy analysis is urgent to account for the interactions of different classes of players and various uncertain factors. This paper described a model for ex-ante analysis of financing policies in highway transportation infrastructure in the United States. An agent-based model was created to simulate the dynamics of infrastructure financing for policy analysis purposes. Using the created simulation model along with metamodeling, the landscape of financing policies related to highway transportation infrastructure was created. The model is the first of its kind to explore the landscape of financing policies in highway transportation infrastructure on the basis of the microsimulation of the behaviors and interactions of different players.

Summary of Findings

On the basis of the findings of the policy analysis model, the following recommendations are made for closing the financing gap: (1) expansion of pay-as-you-go capacity, (2) expansion of the P3 market, (3) increase of funding for debt repayment, and (4) change the structure of infrastructure financing.

The findings of the policy analysis model indicate that the key to closure of the financing gap over a long policy horizon, e.g., 20 years, is expansion of the PAYG capacity. The failure to expand the PAYG capacity will significantly increase the uncertainty related to the closure of the infrastructure financing gap. The analysis conducted in this study confirmed that the increase of the PAYG capacity is the only policy analyzed in this study that would lead to the closure of the financing gap in infrastructure in the United States. Expansion of the pay-as-you-go capacity requires policies to (1) increase the revenues to be used as the source of funding by identifying new revenue streams and (2) reduce project costs so that more infrastructure facilities can be built using current revenues.

The expansion of the P3 market is the second most significant factor for closing the financing gap and could complement the pay-as-you-go financing to close the financing gap in a shorter period of time. Expansion of the P3 market size includes increasing the number of projects financed using private equity and the dollar value of P3 projects. The analysis conducted in this study indicates that the policy related to the expansion of the P3 market size has the greatest volatility related to the values of the financed-to-need ratio because it entails significant uncertainties because of economic and financial market conditions.

The increase of funding for debt repayment is equally important for closing the financing gap as the expansion of the P3 market. However, because the current outstanding debt in most of the state Departments of Transportation is very close to their cap limits, increasing the funding for debt repayment would not have an immediate effect in closing the financing gap.

Limitations of the Study

There are a number of limitations in the study presented in this paper. First, there are several parameters and variables affecting the dynamics of investment in infrastructure systems. It is nearly impossible to capture all the parameters and variables in a model. The use of different parameters and variables depends on the objective of the study and significance of the parameters and variables. Within the context of this study, the objective was to understand the impacts of the microbehaviors of state transportation agencies, private investors, and the public on the level of investment in highway transportation projects at the state and national levels. In addition, this study focused on three broad financing methods: pay as you go, debt financing, and private equity. Hence, the project-specific characteristics and detailed differences related to financing schemes were not considered in this study. Second, this study did not intend to consider various financing policies and project-specific schemes. Because of the limitations in the scope of this study, the proposed model only considered three broad financing methods, i.e., pay as you go, debt financing, and private equity. Future studies can expand the model presented in this paper to consider project-specific characteristics and various financing schemes in the ex-ante analysis of financing policies in infrastructure systems.

Another limitation of the model is lack of consideration of emergent properties. Agent-based modeling can be used for the investigation of emergent properties in complex systems. There are different types of emergent properties in complex systems (Bedau 1997). Some emergent properties are referred to as strong emergent properties. These properties are very difficult to predict and model, and hence were outside the scope of this study. Some emergent properties are referred to as weak emergent properties, which are the aggregation of the microbehaviors at the macrolevel. This study considered the aggregation of the outcomes of microbehaviors in determining the levels of investment at state and national levels. Future studies can further investigate the emergent properties in the assessment of financing policies in infrastructure systems.

The other limitation is related to the validation process. First, the data related to the historical values of the parameters used in the model were not available. Therefore, it was not feasible to evaluate the accuracy of the results of the model by making comparisons with the outcomes of past financial innovations. Second, regarding validation of the model, it was difficult to arrange face-to-face meetings with experienced SMEs to implement face validity. Face validity in the first phase included detailed evaluations by five experienced SMEs. Although further evaluations were desirable, difficulties in arranging face-to-face meetings with experienced SMEs inhibited the key researcher from doing so.

Despite its limitations, the study presented in this paper demonstrated the potential benefits of using simulation models in the ex-ante analysis of financing scenarios in infrastructure systems. Future studies could expand the model presented in this study for further analysis of financing policies in infrastructure systems and also adopt ex-ante simulation in the policy analysis related to other aspects of infrastructure systems, e.g., enhancement of sustainability and resilience.

Significance of the Study

Identification of the desired scenarios for the closure of the financing gap is helpful in addressing financing issues in infrastructure renewal. The novel computing aspect of the research presented in this paper is the creation of a computational simulation model using an agent-based approach for capturing the dynamics of transportation infrastructure financing at the state and national levels. To the best knowledge of the authors, there were no computational models in the existing body of knowledge and practice for the analysis of financing policies and identification of the desired scenarios for closure of the financing gap in highway transportation. The model created in this paper is novel with respect to (1) creation of an ex-ante simulation model for analysis of infrastructure financing policies, (2) identification of the desired policy scenarios and their likelihoods for closure of the financing gap in the presence of uncertainties and complex adaptive behaviors, and (3) simulation and visualization of the impacts of financing policies at the state and national levels. The created model enables quantitative analysis of financing scenarios on the basis of consideration of various uncertain factors and dynamic behaviors of the players. It addresses the limitations of the traditional rather than subjective approaches for policy analysis in infrastructure systems and enables a quantitative what-if scenario analysis that enhances the quality of decision making and policy formulation. Policymakers could adopt the model created in this study to analyze the impacts of financing policies on highway transportation infrastructure under the structures and mechanisms that currently exist in the United States for infrastructure investments.

Appendix. Definition of Terms

Private equity investment: An investment made by privately held organization in anticipation of capital gains.

Pay-as-you-go financing: A method financing public infrastructure using the current stream of government revenues obtained primarily through taxation.

Debt financing: A method of financing in which the capital is raised by selling bonds. The buyer of a bond receives a promise that the principal and interest on the debt will be repaid.

Return on invested capital: The capital gain obtained in addition to the initial investment amount.

Interest rate: The rate at which the interest is paid by a borrower to a lender.

Public-private partnership (P3): An organizational structure through which a public facility is built, operated, and maintained through partnerships between public agencies with private organizations.

Public-private partnership market size: The number and value of the infrastructure projects, which are delivered through public-private partnerships.

Highway transportation infrastructure: A subsector of transportation infrastructure, which consists of networks of roads, highways, and bridge systems.

Financing: An activity through which available capital is allocated to acquire different assets.

Funding: An activity through which available capital is provided.

Policy scenario: A possible future outcome as a result of a specific policy.

Agent: A player (actor) that can perceive his/her environment, process the perceived information, and act on the processed information to meet specific objectives.

Object: A data structure in object-oriented programming that can contain functions and data, variables, and other data structures (Merriam-Webster)

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