Proceedings of the 2014 Winter Simulation Conference
A. Tolk, S. Y. Diallo, I. O. Ryzhov, L. Yilmaz, S. Buckley, and J. A. Miller, eds.

A HYBRID SIMULATION FRAMEWORK FOR INTEGRATED MANAGEMENT OF INFRASTRUCTURE NETWORKS

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ABSTRACT

The objective of this paper is to propose and test a framework for integrated assessment of infrastructure systems at the interface between the dynamic behaviors of assets, agencies, and users. For the purpose of this study a hybrid agent-based/mathematical simulation model is created and tested using a numerical example related to a roadway network. The simulation model is then used for investigating multiple performance scenarios pertaining to the road assets at the network level. The results include the simulation and visualization of the impacts of budget constraints on performance of the network over a forty-year policy horizon. Significantly the results highlight the importance of assessing the interactions between infrastructure assets, agencies, and users and demonstrate the capabilities of the proposed modeling framework in capturing the dynamic behaviors and uncertainties pertaining to civil infrastructure management.

1 INTRODUCTION

The National Academy of Engineering recently listed "restoring and improving urban infrastructure" as one of the grand challenges of engineering in the 21st century (NAE 2008). The current condition of infrastructure systems in the United States has been given a grade of "D+" in a recent report by the American Society of Civil Engineers (ASCE 2013). Effective policy formulation and decision making is critical for enhancing the condition of infrastructure. However, policy formulation and decision making in infrastructure systems is complex due to the existence of uncertainties as well as multiple players whose activities and interactions affect the condition of infrastructure systems. Hence, there is a need for robust methodologies that facilitate an integrated assessment of infrastructure systems at the interface between the dynamic behaviors of different players as well as the uncertainties (Moore et al. 2008). Despite appreciable efforts such integrated methodology is still missing in the existing literature.

The objective of this research is to propose and test a hybrid simulation framework for the integrated assessment of infrastructure systems at the interface between the dynamic behaviors of infrastructure assets, agencies, and users. First, the limitations of the existing methodologies are evaluated and the required capabilities of an integrated methodology are identified. Then, the proposed framework is introduced and its components are discussed. The application of the proposed framework is demonstrated in a numerical example respecting to a roadway network. Finally, the results of the case study are presented in order to highlight the significance of the proposed framework.

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2 BACKGROUND

The existing literature pertaining to infrastructure asset management includes various methodologies to support decision-making and policy formulation. In one stream of research, different studies (e.g., Camahan et al. (1987); Keliner (2001); Gharaibeh et al. (2006); and Halfawy (2008)) have developed optimization-based methodologies for evaluating funding allocation and the timing and type of maintenance/rehabilitation strategies. Another stream of research (e.g., Lee et al. (1997); Chootinan et al. (2006); Anayla et al. (2012)) proposed methodologies for predicting the performance of infrastructure assets based on the physical and environmental characteristics of the assets.

Simulation models have also been used in a number of studies pertaining to management of civil infrastructure systems. El-Adaway (2013) integrated macro-level system dynamics modeling and micro-level agent-based simulation to model the overall system change in terms of social, environmental, and economic impacts. Bernhardt and McNeil (2008) showed that better understanding of the dynamics of civil infrastructure systems requires capturing the inherent complexities using simulation approaches such as agent-based modeling. However, an integrated framework for capturing the dynamic behaviors at the interface between agency, user, and asset interactions is still missing in the existing literature.

The interactions between the dynamic behaviors of the infrastructure assets, agencies, and users significantly affect the dynamics of infrastructure management. For example, user demand increases the pressure on assets. Increased pressure leads to expedited deterioration of an asset and hence, affects its performance. Therefore, any changes in the user preference results in subsequent alterations in asset performance. For instance, if road users decide to use more public transportation and less personal vehicles, their behavior causes less traffic load on the road which in turn results in slower deterioration of the pavement. On the other hand, the service that an asset provides also has an impact on user behavior. If the quality of a pavement does not satisfy the expected level of service, users may choose to not utilize the asset; thus the level of demand decreases. The level of service of an asset depends on its condition. The condition of assets as well as the level of available funding affects the prioritization of assets for maintenance/rehabilitation treatments.

To address the limitations of the traditional infrastructure asset management methodologies, Moore et al. (2008) and Osman (2012) proposed agent-based models for incorporation of the dynamic behaviors of agencies and users in infrastructure management models. However, these studies have mainly focused on evaluation of such dynamic behaviors at the asset level. Thus, they do not provide a robust basis for policy formulation and decision making at the network level. To address the limitations of the existing methodologies, this research proposes and tests an integrated simulation framework for policy formulation and decision making pertaining to the management of infrastructure systems.

2 INTEGRATED MODELING FRAMEWORK FOR INFRASTRUCTURE MANAGEMENT

To capture the complex interactions between the dynamic behaviors of infrastructure assets, agencies, and users, an integrated simulation framework is proposed. As shown in Figure 1, the proposed framework captures the dynamic behaviors and interactions between infrastructure assets using a hybrid agent-based/ mathematical simulation approach.

The dynamic behaviors pertaining to the decision-making processes of infrastructure agencies are captured using agent-based modeling. The ultimate goal of the decision-making process at infrastructure agencies is to maintain or improve the performance of the existing network of assets. This decision is mainly affected by the availability of funding sources as well as the existing policies about prioritization of projects for funding allocation. The outcomes of the decision-making processes of agencies include prioritization of assets and the type of maintenance/rehabilitation treatments employed for each asset in the network.

The dynamic behaviors of users affecting demand/pressure on infrastructure assets is also modeled using agent-based modeling. The user behaviors pertaining to utilizing an infrastructure asset is dependent upon the condition of the asset as well as the user threshold for the expected service. The disparity between the asset's level of service and the user's expected level of service leads to a change in the user's behavior which in turn affects the demand/pressure on the asset.

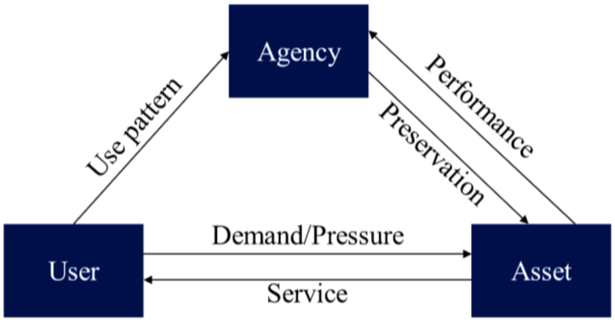


Figure 1: Integrated Simulation Framework for Infrastructure Management.

Finally, the performance behaviors of infrastructure assets are modeled using mathematical simulation. The performance of an infrastructure asset is affected by different factors such as the level of demand, physical characteristics of the asset, environmental conditions, and the quality of maintenance. The level of demand and the quality of maintenance are affected by the user behavior and agency behavior, respectively. Using mathematical simulation, the interactions between different variable and parameters affecting the performance of infrastructure assets could be captured. Table 1 summarizes the characteristics of different components in the proposed integrated framework.

Table 1: The components of integrated simulation framework for infrastructure management.

Component	**Modeling Approach**	**Example of Behavior**	**Examples of Attributes**
Modeling the decision-making process of the agency	Agent-based modeling	Prioritization of available funding sources for allocation to different projects	Availability of funding and policies related to maintenance rehabilitation requirements
Modeling the behaviors of users	Agent-based modeling	Route choice based on road condition	Performance threshold for the expected service
Modeling the performance behavior of assets	Mathematical simulation	Deterioration due to increased traffic level	Demand level, weather condition, and physical characteristics

3 DESCRIPTION OF THE CASE

A sub-portion of the network provided in "The ICMPA7 Investment Analysis and Communication Challenge for Road Assets" (Haas 2008) is used here to elaborate the application of proposed methodology in a road network. Minor assumptions are made wherever the data did not suffice to meet the requirements of this study. The network is comprised of 12 road sections with varying lengths and types as shown in Table 2. All sections are located in the same climatic region (intermediate, freeze zone among 9 types of climate regions defined in (Lee et al. 1993)). The preservation strategy is as follows: prioritize the road with minimum Present Serviceability Rating (PSR) for allocating budget and use a threshold value of 4 for the acceptable pavement condition. This threshold value is chosen due to the definition of excellent performance (FHWA 2014).

Table 2: Characteristics of the case network.

Road Name	**Road Type**	**Pavement Type**	**Length (miles)**	**Width (Yards)**	**Construction year**	**Last Activity**	**STR**	**ESAL/Day** (in base year)
A	R	Flex	1.55	12.03	1987	1987	3.53	224
B	I	Com	0.50	12.47	1962	2006	14.57	1185
C	I	Flex	0.68	13.67	1985	1985	4.35	1645
D	I	Flex	0.19	12.47	1960	2006	7.22	1756
E	R	Flex	0.43	14.22	1997	2007	4.79	864
F	R	JPCP	2.73	13.78	1991	1991	11.02	688
G	I	JPCP	0.62	15.53	1975	2005	17.72	1142
H	R	JRCP	1.06	17.94	2000	2002	13.39	1785
I	R	JRCP	2.80	13.01	1973	2001	13.39	1785
J	I	Com	1.37	13.56	1973	1999	14.57	1185
K	I	Flex	1.68	12.90	1990	2008	5.60	1479
L	I	Flex	0.62	18.15	1960	2004	7.71	1756

R: Rural **I:** Inter-urban **Flex:** Flexible **Comp:** Composite

JPCP: Jointed Plain Concrete pavement **JRCP:** Jointed Reinforced Concrete pavement

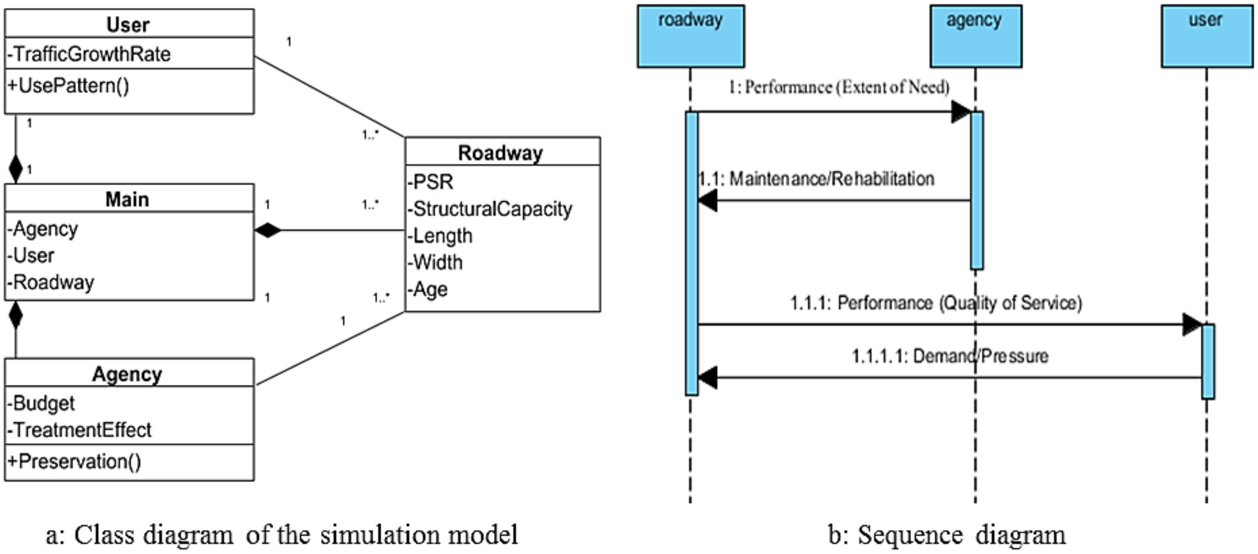
ESAL/Day: Equivalent Single Axle Loads per day (per direction)

STR: Existing Pavement Structure: Structural number for flexible pavement, total Ac overlay (in.) in composite pavement and slab thickness (in.) for concrete pavements

4 SIMULATION MODEL

For purposes of this research, a hybrid Agent Based-Mathematical Simulation model was created for assessing infrastructure networks. This simulation model was then applied to the road network shown in Table 2 by considering the interdependencies between agency, asset, and user behaviors. The three components of the proposed framework are computationally modeled in a java-based object-oriented programming platform (i.e., AnyLogic 7.0).

The computational simulation model is comprised of four classes of objects: *Main*, *Agency*, *User*, and *Roadway*. The Main class is where the simulation environment and the other three classes of objects are defined. The Agency and the User class of objects are modeled as agents. The behaviors of the agents are modeled using action charts capturing the rules underlying the micro-behaviors of the agents. Finally, the Roadway object consists of a mathematical simulation model capturing the performance of the roadway links in the network. Figure 2 demonstrates the class diagram and the sequence diagram pertaining to the computational model using a Unified Modeling Language (UML) protocol suggested by Bersini (2012). The class diagram (Figure 2.a) represents the organization and static relationships between the objects in the model. Figure 2.b shows the communication between different objects in the models. Roadway performance is used as an input by the Agency and User agents. The Agency class uses the performance condition of each road to evaluate the need of the road for maintenance/rehabilitation and plan for appropriate treatment based on predefined preservation strategies. The User class of agents makes decision about its use pattern based on the quality of the service (i.e. the performance of the road). Finally, the use pattern is utilized in the Roadway class in determining the traffic load. Figure 3 demonstrates the relationships among different components of the model. The main three objects of the model are discussed in the following three sections.



a: Class diagram of the simulation model

b: Sequence diagram

Figure 2: UML diagrams pertaining to the simulation model.

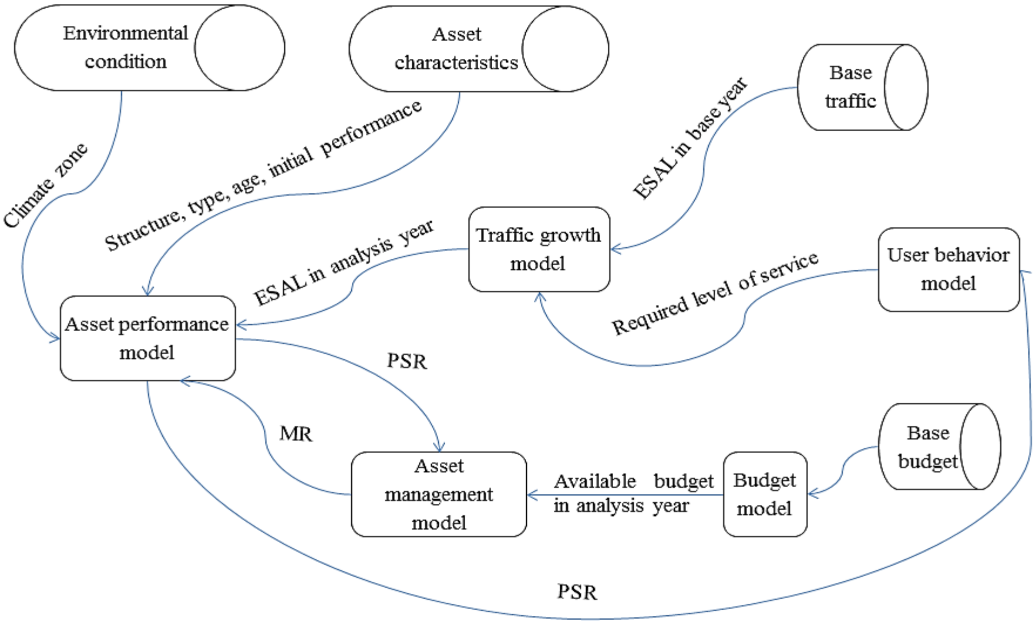


Figure 3: The relationships between different components of the computational model.

4.1 Roadway object

The dynamic performances of the roads are captured in the Roadway object. Each road section is an instance object of the type Roadway (a total of 12 instances in this case). The performance conditions of the roads are assessed based on their Present Serviceability Rating (PSR). There are different formulations in the literature for estimating PSR values. In this study, a simplified prediction model proposed by Lee et al. (1993) is utilized to project the pavements' conditions over a 40 year time horizon. The model predicts the future performance of a pavement given the initial conditions, traffic load, structure of the pavement and weather condition (1):

$$PSR = PSR_i - A.F * a * STR^b * Age^c * CESAL^d \tag{1}$$

In (1) PSR_i denotes the initial value of PSR for a given link right after construction or after a major rehabilitation. This value is assumed to be 4.5 according to Chootinan et al. (2006) and Lee et al. (1993). In (1), a,b,c and d are coefficients whose values depend on the type of pavement (Lee et al. 1993).Cumulative Equivalent Single Axle Loads per day (CESAL) and STR (existing structure of pavement) capture the impact of traffic load and structural design of the pavement, respectively. An adjustment factor is shown as A.F. and is used to customize the prediction based on the effect of climate conditions. Finally, the age of the pavement since initial construction or the last major activity (i.e. rehabilitation or overlay) is shown as Age in (1). For further information about the prediction model and the coefficients, refer to (Lee et al. 1993).

A mathematical simulation model was created in the Roadway object to model the parameter and variables in (1). Two variables (i.e., traffic growth rate and type of maintenances/rehabilitation treatments) are obtained from the User and Agency objects, respectively. At each time interval (i.e. each year) the Traffic Growth Rate (TGR) is obtained based on the user behavior. This value is then used in determining the traffic load (i.e. Equivalent Single Axle Loads per day or ESAL). To incorporate the effects of maintenance rehabilitation treatments, (1) is modified into (2):

$$PSR = max\ (min(PSR_i\text{-}AF*a*pow(STRN,b)*pow(Age,c)*pow(CESAL,d)+MR,4.5),0) \tag{2}$$

In (2), MR denotes the actual improvement to the PSR due to the maintenance/rehabilitation applied to the roadway (Chootinan et al., 2006). A maximum of 4.5 and minimum of 0 is ensured in (2) due to the standard definition for PSR.

4.2 User object

The User object captures the micro-behaviors of the roadway users using an action chart (Figure 4). Certain assumptions have been made in the creation of the action chart. Since all roads are in the same region, it is assumed that the same population is using all roads and hence their behavior is homogeneous with respect to all road sections. The behavior of the users is a function of performance in each link of the road network. The rules listed in Table 3 are assumed in developing the action chart related to the behavior of the User agent.

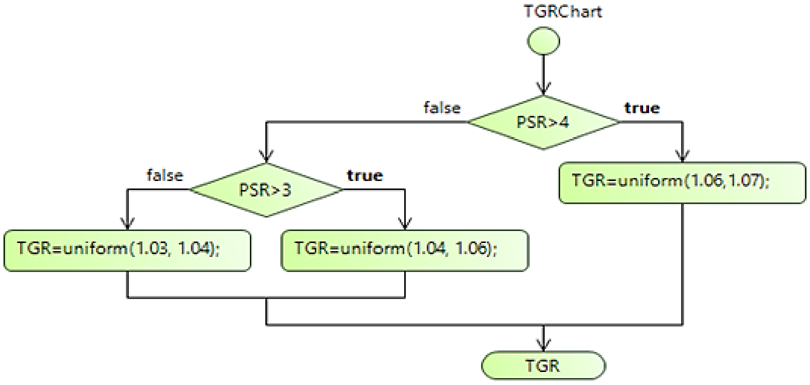


Figure 4: The action chart related to *User* agent.

If the road is in an excellent condition (i.e. PSR greater than 4) the user is satisfied with the level of service and hence the traffic load of the road will increase 6-7 percent. When the PSR value for a link is between 3 and 4, the road is in acceptable condition (but less than excellent), thus traffic growth would be moderate with a rate of 4-6 percent. If the road is in poor condition (PSR<3), the user is least willing to use the road and hence the traffic growth reduces to 3-4 percent. The traffic growth rate is modeled using uniform distributions to capture the inherent uncertainties related to traffic growth.

Table 3: Rules for determining the traffic growth based on the roadways' levels of service

PSR Value	Level of Service	User Satisfaction	Traffic Growth Rate
PSR > 4.0	High	High	High (6%-7%)
3.0 < PSR < 4.0	Medium	Medium	Medium (4%-6%)
PSR < 3/0	Low	Low	Low (3%-4%)

4.3 Agency object

The dynamic behaviors pertaining to the decision-making processes of an infrastructure agency is captured in the Agency object using an action chart. In this study, only the decision-making processes pertaining to the assessment of maintenance/rehabilitation treatments has been considered. Five possible preservation strategies are considered (Lee et al. 1993): Routine maintenance, Surface treatment, Overlay, Major rehabilitation or do nothing. Each of these strategies is associated with a unit cost as presented in Table 4 (Chootinan et al. 2006). Based on the age of the road, these strategies lead to actual improvements in the PSR of the road. For instance, if a road is four years old, routine maintenance results in a 0.45 increase in its PSR, but if the age of the road is 10, the same routine maintenance causes only a 0.225 improvement in the PSR (see Chootinan et al. (2006) for more details). The age of the road is calculated based on the time passed from its initial construction or the latest major preservation activity (i.e. rehabilitation or overlay).

Table 4: Unit cost of preservation activities (Chootinan et al. 2006).

Preservation Activity	Routine Maintenance	Surface Treatment	Overlay	Major Rehabilitation
$/mile^2	0.321868	1.190912	7.515618	12.45629

In this research, the agency adopts a reactive condition-based maintenance/rehabilitation strategy in which the agency prioritizes the roads based on the available level of budget as well as the condition of the roads. In other words, the road with the lowest PSR is considered for preservation first. When a road is selected to receive Maintenance/Rehabilitation (MR) treatment, the appropriate preservation treatment is determined based on the effectiveness of a treatment consistent with the PSR of the road. Starting from the least expensive treatment (i.e. routine maintenance), the model checks whether the MR treatment can improve the road condition to excellent condition (i.e., PSR > 4.0) or not. If the treatment is capable of increasing the PSR of the pavement to more than 4, it is considered to be a viable solution for that pavement; otherwise, the next possible treatment solution is evaluated. After the appropriate treatment solution is determined, the model evaluates whether enough budget is available for the selected treatment. If sufficient budget is available, the selected treatment is implemented. The available budget is then adjusted by subtracting cost of the selected treatment. In case that sufficient budget is not available for implementing the selected treatment, no activity is performed on the road and the MR treatment is postponed. This process continues for all 12 road sections in each time interval of the simulation. Figure 5 depicts the algorithm used for allocating budget and performing the preservation on the road sections.

5 RESULTS

The simulation model, which was created for modeling the user/asset/agency interactions, was used for assessing management strategies for a road network in the numerical example. The model provides the following benefits for decision analysis: (i) simulation and visualization of the performance of different links within the network over the analysis horizon; (ii) evaluating the impacts of budget constraints on the performance of the roads at the network level; and (iii) assessing the sensitivity of network performance to user behaviors.

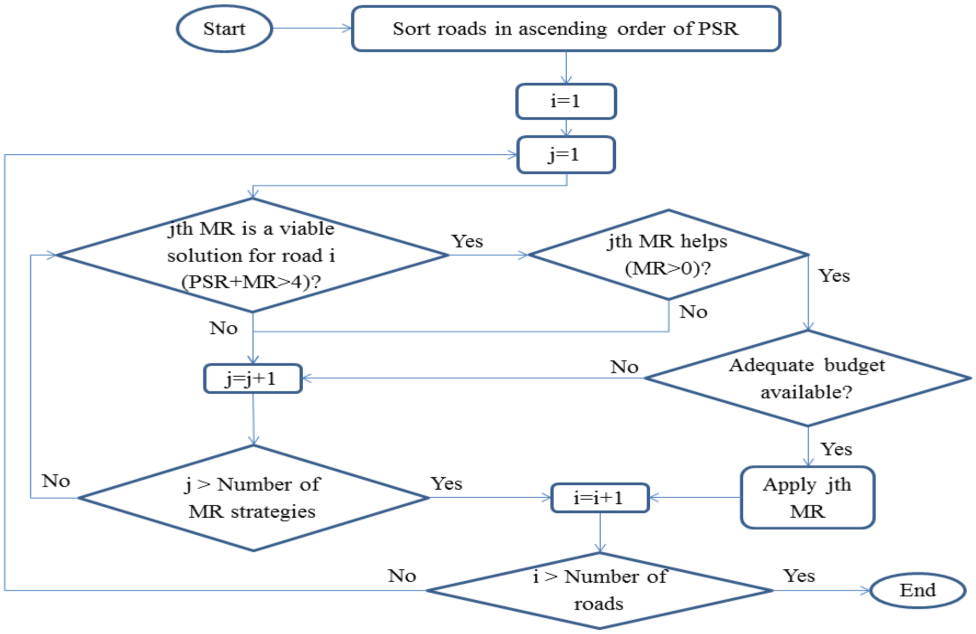


Figure 5: Decision making process at agency.

5.1 Simulation and visualization of road performance at asset level

The simulation model could be used for predicting the performance of different links in the network over the analysis horizon and under uncertain conditions. Figure 6 depicts the simulated performance curves for different links related to one run of the simulation model in which the base level of budget is $200,000.The results of the simulation can be used for decision-making in multiple ways. First, a decision-maker can use the results to identify the links needing major maintenance/rehabilitation in both short and long term. In addition, the results can be used to identify the project load and identify scenarios leading to delayed maintenance, and thus, an increase of the overall cost of maintenance/rehabilitation treatments. For example, the decision maker will know that under the current preservation strategy and budget limitations, the minimum performance occurs in road D and in year 22. This is helpful both for comparing the impact of different preservation strategies and anticipating specific needs at a given time.

One important objective of the integrated framework presented in this study is to support decision makers based on an ex-ante analysis of different preservation strategies. To this end, visualizing the results of the simulation model would help better communication with asset owner/ decision maker. Therefore, this study uses a color-coded representation pertaining to the performance of different links in the network. A color range of green to red is selected for representing excellent (i.e. PSR=4.5) to poor (PSR<3.0) performance of roadways, respectively. Figure 7 depicts the visualization results within 5 year intervals under a base level of $200,000 annual budget. Visualizing performance in the road network, is beneficial in different ways. First, it could assist communication of the results with a diverse group of stakeholders (Mostafavi et al. 2013). Second, it is helpful in identifying and comparing the deterioration and treatment delay patterns across different links in the network.

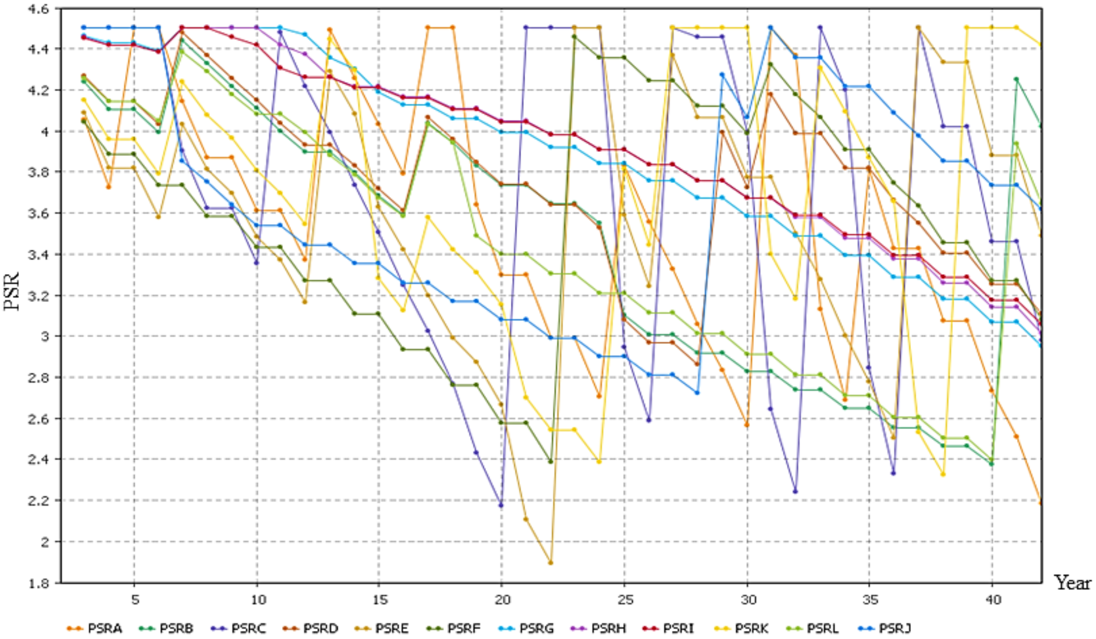


Figure 6: Sample performance of network under baseline budget of $200,000.

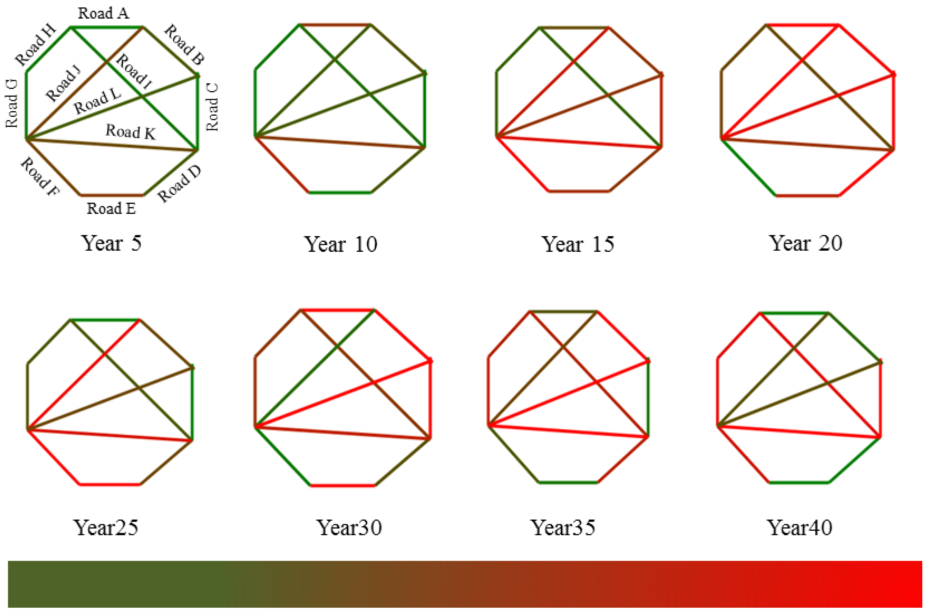


Figure 7: Visualization of the results.

5.2 Evaluation of the impact of budget constraints

The other benefit of the simulation model is to evaluate the overall performance of the network under different budget levels. The preservation activities for pavement networks are sensitive to budget fluctuations. Therefore it is necessary for transportation agencies to quantify the risks of budget changes so that they can take sensible precautions to maintain the quality of their asset network (Liu and Zhang 2011).

Different scenarios for various base budget levels were considered, starting from a zero budget to a maximum of $150,000. In all cases a 20% uncertainty was considered for the budget. A weighted average PSR of all the road sections was used as the metric to evaluate the average condition of the network.

Figure 8 depicts overall performance conditions of the network at different levels of budget. As shown in Figure 8, at lower budget levels, the overall performance of the network decreases over the analysis horizon. For lower budget levels, marginal increase in the availability of funding marginally improves average performance of network. However, an increase in the availability of funding at certain budget levels (i.e., budget levels close to $60,000 and $100,000) causes a significant improvement in the network-level performance. Each of these budget levels can be called a "tipping point budget". The "tipping point budget" is an emergent property as a result of the dynamic interactions between the dynamic behaviors of assets, agency, and users. Another observation obtained from the analysis of varying budget levels is the existence of a "budget saturation level". This budget level (close to $110,000) is the level at which an increase in the amount of budget does not lead to any improvements in the overall performance of the network. Identification and estimation of the "tipping point budget" and "budget saturation level" could be critical to maintain the performance of the network with minimum cost and has important implications for policy formulation pertaining to infrastructure funding.

5.3 Evaluation of sensitivity of performance to user behaviors

The simulation model can also be used in investigation of the sensitivity of the overall performance of the network to the behaviors of the users. Two scenarios are compared to explore the impact of user behavior on network condition. In the first scenario a 5% constant traffic growth occurs each year regardless of the condition of pavement and preferences of the users. The second scenario considers varying traffic growth rates based on different behaviors of the user as explained in section 5.2. Weighted average PSR of all roads is calculated over the analysis period. The mean PSR value of all years is then determined for different levels of budget. Figure 9 demonstrates the results of the simulation model for the two scenarios at different levels of budget. As shown in Figure 9, the overall performance of the network is not sensitive to the user behaviors in cases of very low and very high levels of budget. In scenarios in which the level of budget is at a medium level ($60K -100K in this example), the user behaviors exacerbate the overall performance of the network. The results in Figure 9 also show that the "tipping point budget" for the network is not sensitive to the user behaviors as it occurs for both scenarios at the same level of budget (i.e., close to $60,000and $100,000).

6 CONCLUSION

The objective of this study is to develop a novel integrated framework for management of civil infrastructure systems and demonstrate its capability in capturing complex and dynamic interdependencies between user behaviors, asset performance and agency decision making procedures. The application of the proposed framework is demonstrated in a numerical example pertaining to a road network. Using agent-based and mathematical simulation models, the impacts of the level of budget and user behavior on the overall performance of the network were investigated. The ability of the framework to analyze emergent properties pertaining to networks of infrastructure was highlighted and two potential emergent properties (namely "tipping point budget" and "budget saturation level") of the roadway network were discussed. The results showed the significance of the proposed framework for integrated infrastructure management. This distinctive approach is the first of its kind to simulate and visualize the policy landscape pertaining to the performance of infrastructure systems by simulating the dynamic behaviors at the interface between agencies, users, and assets. The framework and simulation model have the following benefits for policy analysis: (i) understanding of emergent properties in infrastructure systems; (ii) simulation and visualization of the outcomes of policies on the performance of infrastructure at the network level and at various policy horizons, and (iii) comparison of the outcomes of different policies based on varying infrastructure characteristics, agency priorities, and user behaviors.

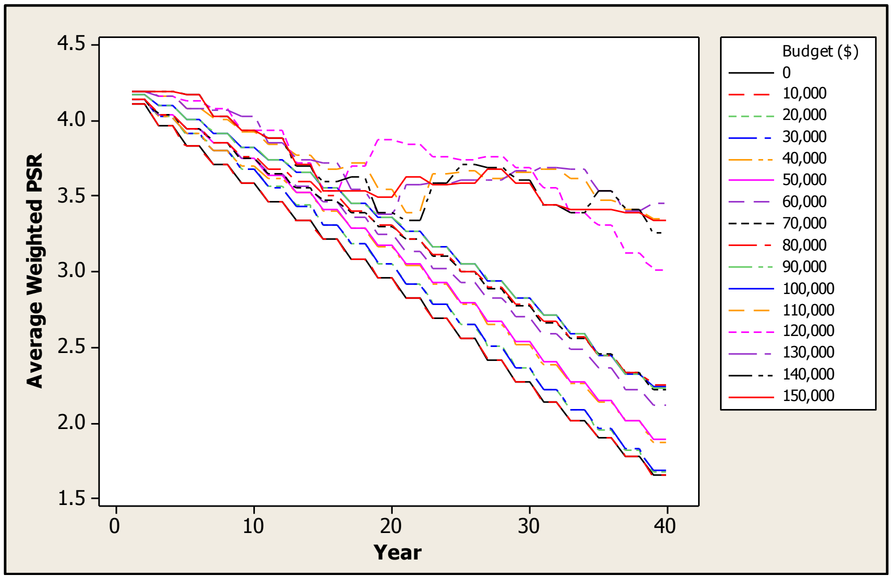


Figure 8: The impact of different budget levels on performance of the network.

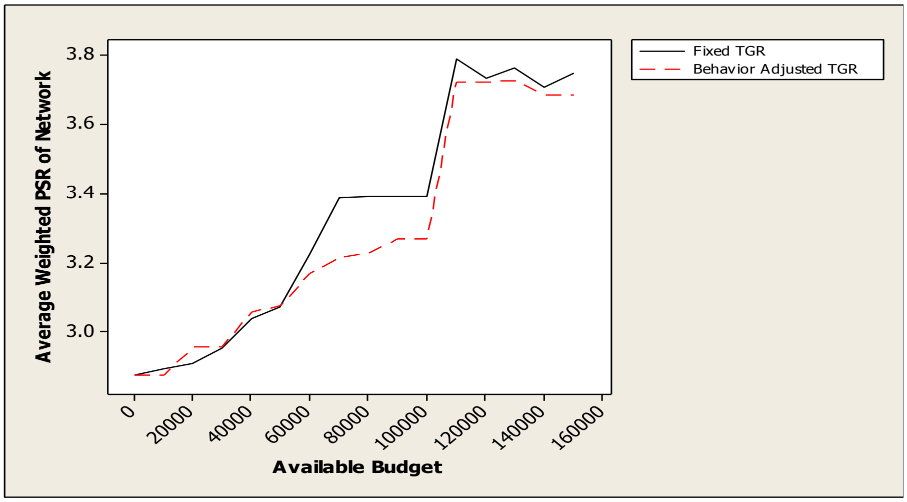


Figure 9: The impact of user behavior on performance of network.

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