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FORECASTING CONSTRUCTION STAFFING NEEDS FOR STATE TRANSPORTATION AGENCIES

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Abstract: State Transportation Agencies across the country continue to face many challenges to repair and enhance highway infrastructure to meet rapidly increasing transportation needs. One of these challenges is maintaining an adequate and efficient agency staff. In order to effectively plan for future staffing levels, State Transportation Agencies need a method for forecasting long term workforce requirements. However, current methods in use cannot function without well-defined projects therefore making long term forecasts is difficult. This work seeks to develop a dynamic model which captures the feedback mechanisms within the system that determines highway workforce requirements. The system dynamics modeling methodology was used to build the forecasting model. The formal model was based on dynamic hypotheses derived from literature review and interviews with transportation experts. Both qualitative and quantitative data from literature and federal and state databases were used to support the values and equations in the model. The model integrates State Transportation Agencies' strategic plans, funding situations and workforce management strategies while determining future workforce requirements, and will hopefully fill the absence of long-term staffing level forecasting tools at State Transportation Agencies. The model was tested using standard system dynamics validation procedures, after which the model was calibrated using input data specific to the Kentucky Transportation Cabinet to simulate an expected retirement wave and search for solutions to address temporary staffing shortages.

1 BACKGROUND

State Transportation Agencies (STAs) across the country continue to face many challenges to repair and enhance roadway infrastructure to meet rapidly increasing transportation needs. One of these challenges is maintaining adequate agency staff. Data collected for a NCHRP (National Cooperative Highway Research Program) synthesis report shows that, between 2000 and 2010, the total lane miles in the systems managed by STAs increased by an average of 4.1% while the in-house personnel available to manage these systems decreased by an average of 9.78% over the same time period (Taylor and Maloney 2013). By any measure, STAs are doing more work with fewer agency employees than they were 10 years ago. Decrease in workforce size is projected to continue in the near future. Based on the age structure of the current transportation workforce, researchers have forecasted that 40-50% of the transportation workforce will retire by the year 2021 (Lucero 2010). In addition to the high retirement rate, fewer people are going into key transportation fields. In a 1999 transportation workforce survey, responses from STAs indicated that they had problems recruiting staff due to limited availability of personnel with adequate skills, low entry-level salaries, and competition with the private sector and other public agencies (Lucero et al. 1999). Adequate staffing is critical to the performance of STAs therefore the US Department of Transportation and STAs have been making efforts in workforce development including education and training programs, internships, scholarships, co-op programs, and "pipeline" activities (Harder 2006). Such investments in future employees requires strategic planning in human resource management, which includes being able to forecast long term workforce requirements.

2 PROBLEM DESCRIPTION AND RESEARCH OBJECTIVES

Data collected through a 1999 survey showed that 39 out of 50 states expressed a strong interest in working with other states on forecasting long term personnel needs (Lucero et al. 1999). The same survey also reviewed that the most commonly used methods for forecasting staffing needs were "historical precedents" and "trend analysis (using factors to explain staff increase or decrease)" (Lucero et al. 1999). A more recent survey identified several formal tools for forecasting construction staffing needs for highway projects (Taylor and Maloney 2013). One characteristic in common among the methods and tools currently applied by STAs is that they all depend on a well-defined project portfolio to be able to predict either a number or a range of employees needed for completing the planned projects. While they can be very accurate when forecasting short term staffing needs, they cannot predict staffing requirements further into the future when projects are not clearly defined. Forecasting long term staffing needs is challenging due to many factors, mostly related to the dynamic nature of transportation infrastructure construction and maintenance. STAs' total work volumes can vary from year-to-year which adds uncertainty to personnel requirements at the central and field office levels. Variation or changes in project type, complexity, personnel experience, staff productivity, available funding, staffing strategies, technology, and above all, the dynamic feedbacks among these factors, further complicate forecasting long term staffing needs.

The current work seeks to develop a dynamic model that is able to forecast a STA's long term highway workforce requirements by using long term pavement and bridge condition goals as input while taking highway funding level, project selection, and recruiting strategies into consideration. To be more specific, the model will identify feedback structures that link long term pavement and bridge condition goals, funding levels, staffing strategies, and future workforce requirements; then identify drivers and constraints that impact future workforce needs under different scenarios; and eventually provide insights on how STAs can effectively address potential staffing shortages and overflows.

3 RESEARCH METHODOLOGY

3.1 Overview of the System Dynamics Modeling Method

System dynamics is a methodology for studying and managing complex systems (Sterman 2000). The system dynamics methodology applies a control theory perspective to the management of complex systems focusing on how the internal structure of a system impacts managerial behavior and performance over time. The approach is unique in its integrated use of causal feedback, stocks and flows, time delays, and adaptive decision making to model processes and management policies. Forrester developed the methodology's philosophy (Forrester 1961) and Sterman specified the modeling process with examples and described numerous applications (Sterman 2000). The methodology's ability to model many diverse system components, processes, and managerial decisions and actions makes it useful for the current work. Building a system dynamics model generally takes 5 steps (Figure 1) (Sterman 2000).

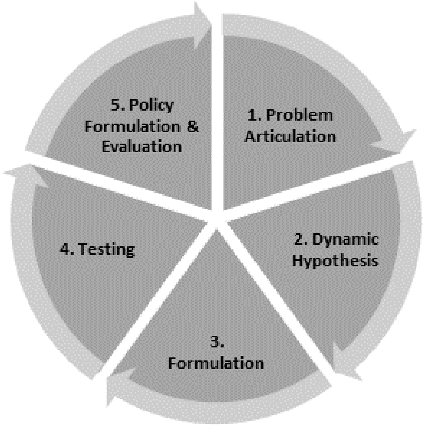

Figure 1: Five steps of the system dynamics modeling process

The first step is problem articulation. Once the research problem is defined, the second step is to establish a dynamic hypothesis to map out the structure of the system. After that values and equations will be assigned to variables and relationships in the formal model. Then the model will be tested and analyzed, and finally policies and strategies can be developed from observing model behaviors. The system dynamics modeling process is an iterative process. Model boundaries and hypotheses may change if testing and analysis indicate they need to be modified.

3.2 Problem Articulation and Dynamic Hypothesis

Besides defining the research question, another necessary step during problem articulation is to identify model boundaries and determine general model settings. In the current work, both qualitative and quantitative data collected through literature review and federal and state databases, and previous related research work were used to identify variables being included in the model. Not all factors that may have an impact on workforce requirements are included as input for the model. This kind of boundary setting is important to keep the model at a manageable size. The model's running time is set to be twenty-five (25) years (300 months), which is consistent with most STAs' strategic planning period. Also taken into consideration is the fact that in many STAs' employees are eligible for retirement after 20 to 25 years of service. The model's 25-year running time should cover a retirement cycle if such a cycle exists. Two types of workforce, engineers and technicians, are simulated in the model.

Once the model boundaries and general settings are defined, information gathered through literature review and previous research was used to establish the dynamic hypotheses for the model. A set of dynamic hypotheses is the conceptual version of the model which maps out causal relationships among model variables. Figure 2 presents the dynamic hypotheses of current work (Figure 2).

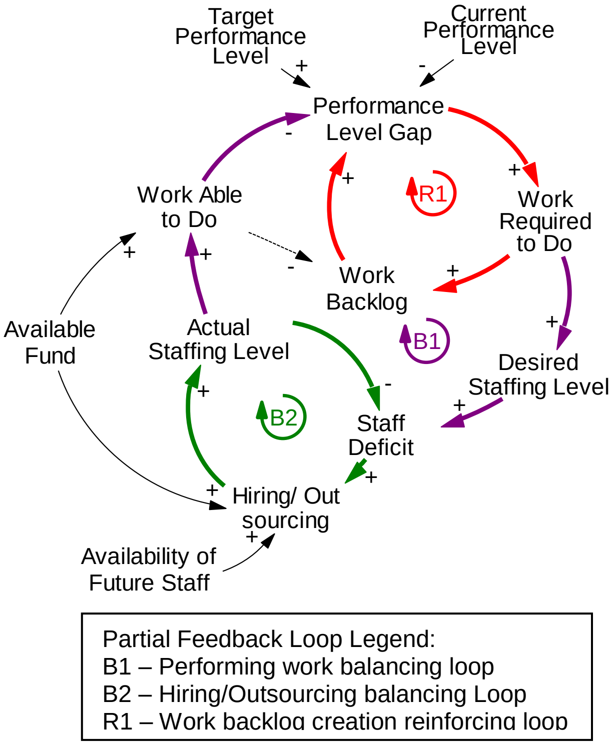

Figure 2: Causal loop diagram of the proposed model

Each arrow in the causal loop diagram indicates a causal relationship exists between the variable at the tail and the variable at the arrowhead. The polarity of a causal arrow describes the impact of variable X (at the tail) on variable Y (at the arrowhead). A "+" indicates a direct relationship (if X increases, then Y increases, all other things being equal, and vice versa). A "-" indicates an inverse relationship (if X increases, then Y decreases, all other things being equal and vice versa). Some arrows form closed feedback loops. Loops are labeled as either "B", which stands for balancing loops or "R", which stands for reinforcing loops. Regardless of how many arrows with positive polarity appear in a feedback loop, a balancing loop should have an even number of arrows with negative polarity, while a reinforcing loop should have an odd number of arrows with negative polarity. Balancing loops produce target seeking behavior where the values of variables in the balancing loop approach their respective equilibrium values as time goes by, and a system driven by a balancing loop maintains a steady condition after it reaches its equilibrium status. Reinforcing loops produce behavior patterns that resemble exponential growth.

Loop B1 describes how STAs work to reach their performance target. When making strategic plans, STAs analyzes system demand and sets a "Target Performance Level" for the highway system within their state. For example, Michigan Department of Transportation's 2040 long-range transportation plan states that MDOT's pavement condition goals are to "improve or sustain 90 percent of highway pavements in fair or better condition (Michigan Department of Transportation 2012). By comparing the "Target Performance Level" with the "Current Performance Level", the agency will be able to determine if a "Performance Level Gap" exists between the target and actual conditions. Given an actual "Current Performance Level" at a certain time, if the "Target Performance Level" increases, the "Performance Level Gap" increases in response, therefore positive polarity is assigned to the arrow linking "Target Performance Level" and "Performance Level Gap". On the other hand, given a "Target Performance Level" at a certain time, the greater (better) the "Current Performance Level" is, the smaller the "Performance Level Gap" will be, hence the negative polarity. The size of the "Performance Level Gap" will determine the amount of "Work Required to Do" during this planning period. The amount of "Work Required to Do" determines the "Desired Staffing Level". If the agency's "Actual Staffing Level" is not as high as the "Desired Staffing Level," the agency experiences a "Staff Deficit" and needs to increase the staffing level by "Hiring/Outsourcing" to fill the deficit. Variables "Actual Staffing Level," "Staff Deficit," and "Hiring/Outsourcing" form a balancing loop (B2) that seeks to bring the "Actual Staffing Level" closer to the "Desired Staffing Level." "Actual Staffing Level" determines the amount of "Work Able to Do" by the agency staff during this planning period and by performing work, the "Performance Level Gap" can be closed.

When Loops B1 and B2 are both strong enough to reach their equilibrium conditions, the STA will have enough personnel to carry out the amount of work needed to reach their performance target. However, the strength of Loops B1 and B2 are constrained by several factors other than the variables within the loops. Two of these factors are the availability of funds and availability of prospective staff. If either becomes insufficient, the STA will not be able to perform enough work to reach their performance target. In that scenario, a "Work Backlog" will be created, which means the agency will not be able to complete all the work planned for this month. If next month's target stays unchanged, the agency will need to perform any planned work for next month plus this month's "Work Backlog" in order to close the "Performance Level Gap" at the end of next month cycle. If the agency still doesn't have sufficient funding or staff, the "Work Backlog" grows larger. Variables "Performance Level Gap," "Work Required to Do," and "Work Backlog" form a reinforcing loop (R1) and if conditions don't change, the "Work Backlog" will not stop growing.

The strength of the feedback loop depends on the values assigned to the variables in the formal model and may change throughout the simulation period. When the balancing loops dominate, the STA will be able to reach the performance goal. However, if the reinforcing loop (R1) dominates, highway work falls behind schedule and the agency is not likely to accomplish their goal.

3.3 Formal Model

In the formal model, variables and relationships represented in the causal loop diagram were quantified. The formal model was built using the Vensim simulation software. The model consists of separate sectors for road and bridge condition, target and actual performance, funding level, fund allocation, staff productivity, in-house engineers and technicians, workforce budget and consultants.

The “Road Work Flow” sector and the “Bridge Work Flow” sector tracks quantities and change rates of highway pavement and bridge deck area in different condition categories. Figure 3 shows the partial structure of the “Road Work Flow” sector (Figure 3).

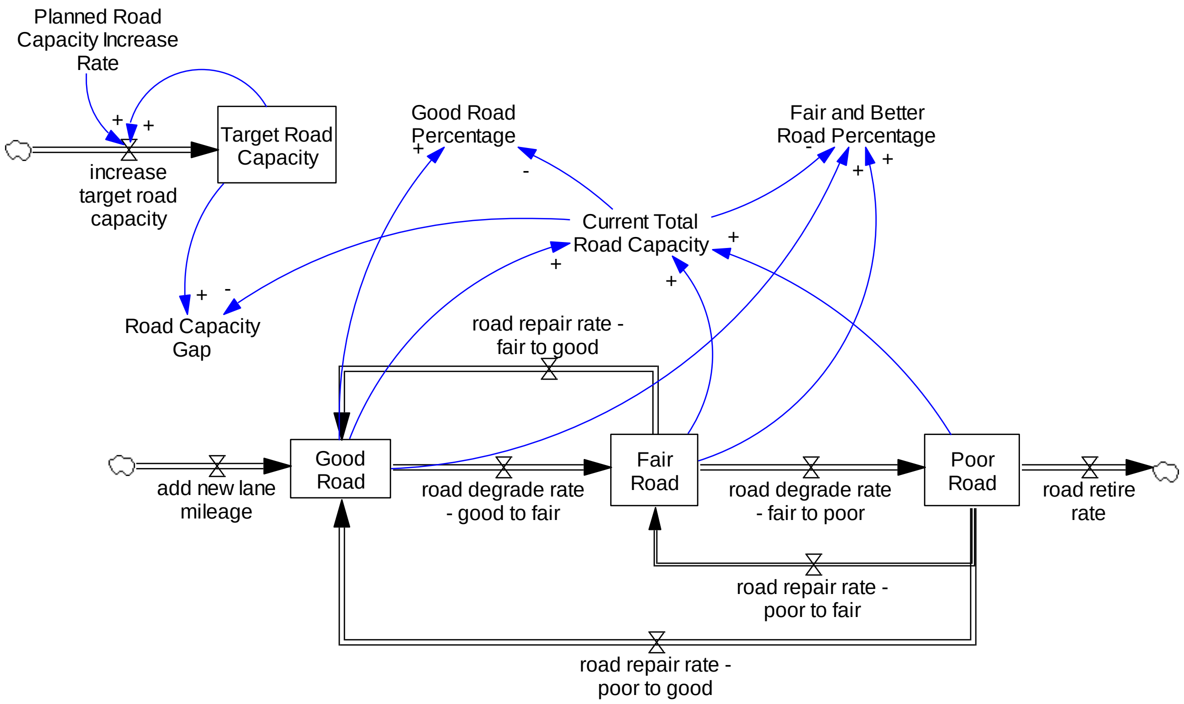

Figure 3: Partial model structure of the road workflow sector

As displayed in Figure 3, highway road surface is categorized into three roughness categories; good road, fair road, and poor road. Immediately after initial construction of a highway section, the road surface is in good condition. When the road is open to traffic, pavement deterioration occurs. Over time, a “Good Road” can become a “Fair Road,” and without proper repair, a “Fair Road” can further deteriorate into “Poor Road.” These changes can happen without any resources being considered in the model (i.e. money and manpower). Values of these change rates depend on how long it takes for highway pavement to degrade into a higher roughness category.

The “Current Total Road Capacity” within the highway system can be found by adding the values of “Good Road,” “Fair Road,” and “Poor Road” together. This is the total lane miles of highway the STA oversees. Due to increasing traffic, the STA may need to increase the total highway capacity by building new routes, widening existing roads, and rebuilding intersections and interchanges. To construct new mileage or to reverse pavement deterioration and move lane miles of road from a higher roughness category to a lower roughness category, the STA must assign resources to new construction and repair work. The amount of work performed through the four flow variables (i.e. “add new lane mileage”, “road repair rate – fair to good”, “road repair rate – poor to fair” and “road repair rate – poor to good”) are restrained by budget and available manpower allocated to each type of road work.

The real-time percentages of good pavement and acceptable pavement can be calculated using the values of “Good Road,” “Fair Road,” and “Current Total Road Capacity.” These performance indicators can then be compared to the agency’s target value to determine the amount of road work required for each planning period.

Another model sector is dedicated to bridge workflow using a similar structure. Bridge work is modeled separately from road work for a few reasons including: bridge structures usually have longer design life than road pavement; bridge structure repairs are usually performed as individual projects rather than included in repair of a road section; bridge projects are different in nature from road repair projects and require different amounts of money and manpower; and STAs usually have dedicated bridge funds within their budget. Similar to road surfaces, bridges (measured in m2 of bridge deck area) are stored in three quality categories: sound, structurally deficient, and functionally obsolete. In order to keep variable names simple and short, this model uses “good,” “fair,” and “poor” to represent these three categories.

Eight types of road and bridge work are represented in the model. During each simulation period, the model calculates the required work to be performed within each of the eight categories in order to reach the STA’s desired performance level (percentage of road/bridge in good condition, percentage of road/bridge in acceptable condition, etc.). Using agency specific project based staffing tools and historic project cost and duration data, the model can then calculate the required budget and workforce.

Available numbers of in-house engineers and technicians are tracked separately in the model. The following figure (Figure 4) shows the model structure used to simulate in-house engineers. This structure is partially based on a previously validated and published model for software project staffing (Abdel-Hamid 1989), and modified to fit the current work.

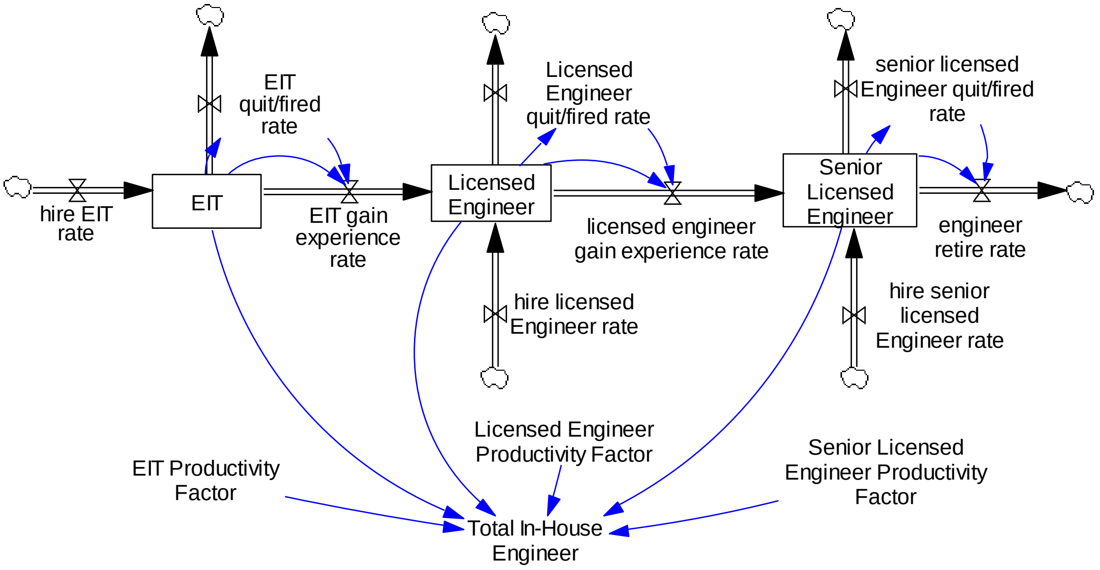

Figure 4: Partial model structure of the in-house Engineers

Newly graduated engineers serve the STAs as EITs (Engineers in Training). EITs have very little experience and require a good amount of supervision; therefore, their productivity is below the level of an average experienced employee. By taking the Professional Engineer (PE) exam, EITs can become licensed Professional Engineers with a minimum of four years of experience. Once they are licensed, they are allowed to performed work independently. Licensed engineers continue to gain experience and their productivity continues to improve until reaching the maximum proficiency level. Engineers who have reached that level are modeled as “Senior Licensed Engineers” in this sector. Eventually senior licensed engineers will retire and leave the agency. Engineers at any of the three levels may also leave the agency by quitting or when the agency decides to downsize.

The numbers of engineers in each of the three stocks multiplied by their productivity factors determines the “Total In-House Engineer,” which is the equivalent number of average engineers currently serving the agency. In-house technicians are also modeled in three productivity levels using a similar structure.

Consultants also contribute to the total manpower available to the STA. In this model, productivity of consultants is considered comparable to the most productive in-house staff, and so are their pay grades.

The model compares the in-house workforce level to the desired level to fully utilize all project funds to determine the need for hiring or outsourcing. Once the need for recruiting is quantified, the STA can decide to fill the gap by an in-house new hire, or using consultants, or a combination of the two options. Within in-house new hire, the agency can also decide the numbers of new hires at each experience level.

3.4 Model Validation

The model was tested using standard system dynamics procedures (5) to insure consistency and robustness of the model. Historical data from the Kentucky Transportation Cabinet was used to test the accuracy of model output. Kentucky Road fund data and pavement condition data from 1998 to 2011 are available on the maintenance portal of KYTC's official website. The road fund, percentage of good pavements, and percentage of acceptable (fair and better) pavements are shown in the following figure (Figure 5).

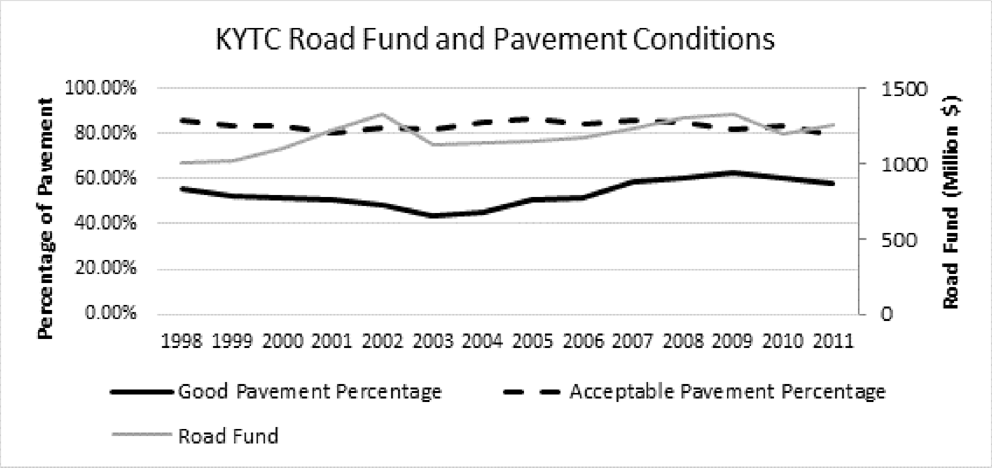

Figure 5: KYTC road fund and pavement conditions from 1998 to 2011

The road fund for each year and beginning pavement conditions in 1998 were used in the model as input. Before 2003, KYTC did not have a rigid performance target regarding good pavement percentage. The focus of road work was to decrease the amount of pavement in poor condition. Starting in 2003, the model included a performance target to increase the percentage of good pavement. Simulated output and actual pavement condition data are shown in the following figure (Figure 6).

Goodness of fit was evaluated using two statistics, Coefficient of Determination (R2) and the Theil's Coefficient of Inequality (U). The R2 value is the squared value of the correlation coefficient between the simulated data and actual data. It indicates the portion of the variance in actual data explained by the model. 72.11% of the variance in good road percentage from 1998 to 2011 was explained by the model, which indicates the model was able to capture the majority of the variance. Only 23.18% of the variance in acceptable road percentage was explained by the model. From 1998 to 2011, the actual acceptable road percentage exhibited only minor fluctuations, which is possibly the reason for the poor R2 value. A continuous model like the one developed in this work was not able to reflect random minor fluctuations in data. The Theil's Inequality Coefficient (U) (Stephan 1992) was used to evaluate the confidence in prediction using the proposed model. U can range between 0 and 1 with 0 indicating perfect prediction and 1 indicating the prediction is no better than a naive guess. Models with U under 0.4 are generally considered good fit (Stephan 1992). The proposed model has a U value of 0.0305 for good road percentage and 0.0232 for acceptable road percentage, which indicates that the majority of the difference between the simulated and actual data is due to natural data variation and that the model is able to predict the trend (or lack of trend in the case of acceptable road percentage) of the highway performance indicators.

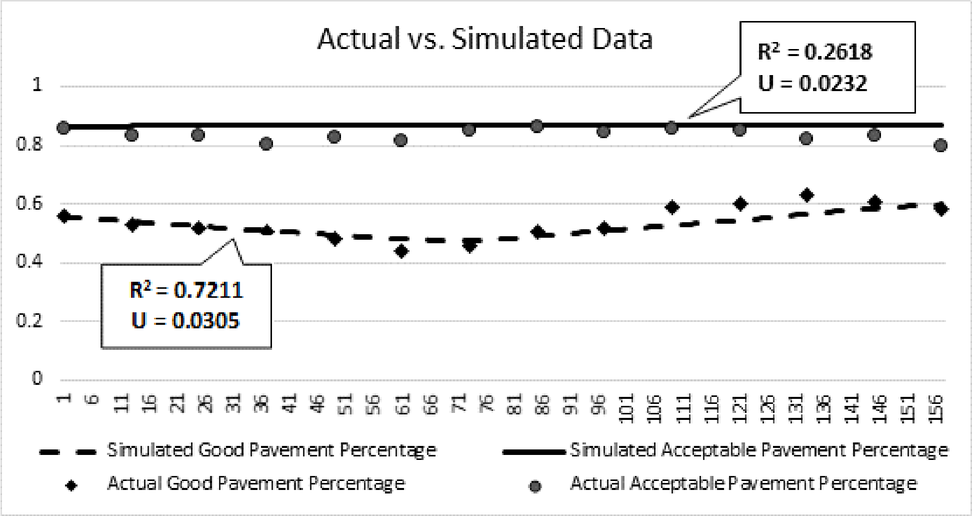

Figure 6: Actual Kentucky pavement conditions vs. simulated Kentucky pavement conditions

3.5 Model Use Example - KYTC's Workforce Challenge

The Kentucky Transportation Cabinet maintains about 63,100 lane-miles of roadway and over 5,261,000 m2 of bridge deck area. As with most STAs, KYTC funding is tied to a fuel tax and struggles to maintain road and bridge funding at a level for optimal performance of the state administered roads and bridges. Funding for road and bridges in the foreseeable future is not expected to increase significantly barring some drastic change in the state policy. A good portion of KYTC's most experienced personnel are getting close to being eligible for retirement. Recruiting has been challenging due to competition with private industry. Most (about 90%) of KYTC's new employees come from a scholarship program, in which KYTC pays a portion of a student's tuition toward an Engineering degree or an Engineering Technology associates degree. In return, the students are required to work for KYTC full-time after graduation for as many years as the student was on the scholarship. This program ensures KYTC has a steady amount of qualified incoming entry level employees. But with the most experienced employees retiring at a high rate, the newly recruited ones may not be able to pick up the work load. KYTC has been using consultants, especially consultant technicians as inspectors in times of need, the fees for consultants have proved to be more expensive than using in-house personnel. The model was re-calibrated to reflect the above stated situation at the KYTC. A series of simulations were run with the number of consultants retained varying from 0% to 100% of the number needed to complete all funded work. Model outputs for good road percentage (Figure 7), acceptable road percentage (Figure 8), and monthly total workforce cost (Figure 9), are displayed in the following figures.

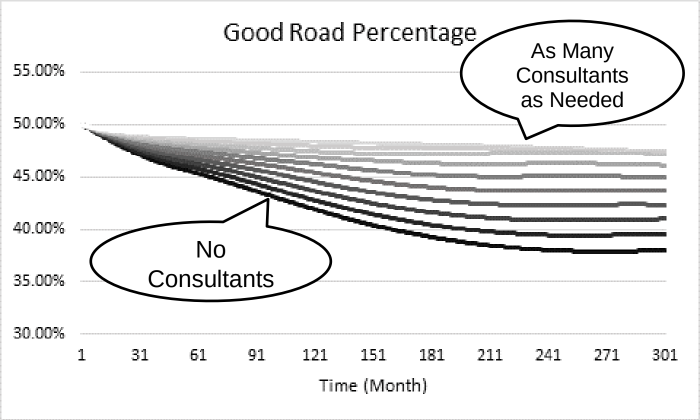

Figure 7: Good road percentages when varying amount of consultants

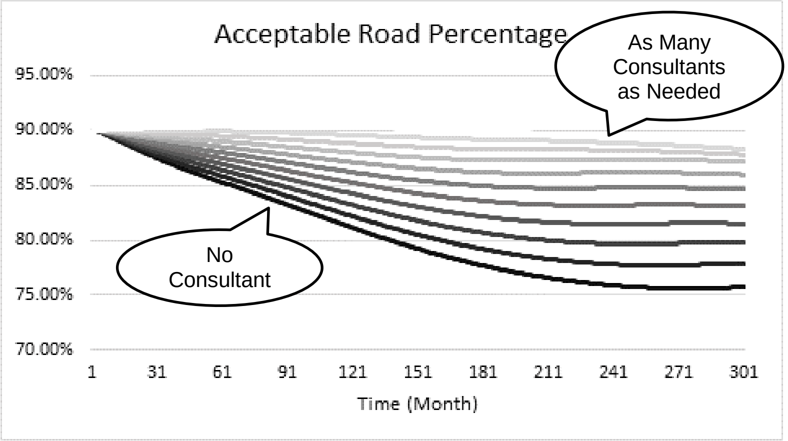

Figure 8: Acceptable road percentages when varying amount of consultants

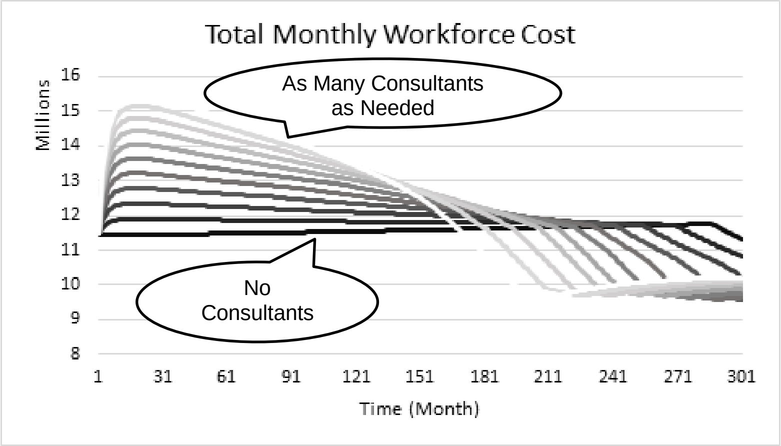

Figure 9: Total monthly workforce cost when varying amount of consultants

Eleven (11) simulations were run. Output from each simulation is represented by a curved line in Figures 7-9. The darkest colored line represents the simulation with no consultants and the lightest colored line represents the simulation with 100% consultants. The outputs show using in-house personnel alone will result in significant degradation in highway pavement performance. The more consultants KYTC retain, the better the overall road conditions are. However, even with unlimited consultants, the agency will not be able maintain their current pavement conditions, as good pavement percentage decreases below 50% and acceptable road percentage decreases below 90% due to sustained funding shortages. The total monthly workforce costs include salary paid to in-house engineers and technicians as well as fees paid to consultants. In early stages of the simulations, hiring a large number of consultants results in increased total workforce cost. However, since hiring consultants helps fill the workforce gap created by high initial retirement rate quickly, not allowing the reinforcing loop (R1) to gain power, therefore this strategy can be cost effective in the long term by allowing hired employees to fill the consultants' role over time. With the help of these figures, decision makers at KYTC can determine how many consultants they can afford to hire to achieve an acceptable pavement condition level.

4 CONCLUSIONS

This work presented a system dynamics model that integrated a STA's long term workforce needs with road and bridge performance levels, the agency's funding level and recruiting strategies. These dynamics hypotheses were derived from literature review and interviews with transportation experts. The formal model was developed in accordance with the dynamics hypotheses with more specific formulas among variables. Part of the model structure and formulas came from previous published research findings. Agencies can benefit from using these types of models to perform simulation runs to evaluate different options based on their priorities (performance, budget, in-house workforce stability, etc.). There are no commons answers as to how an agency should address staffing shortages and overflow at all times. The model must be calibrated to reflect an agency's current status of practice and options must be evaluated on a case to case basis.

This research makes several contributions to the existing body of knowledge regarding staffing issues at STAs. Project based, short term staffing level forecasting tools have been widely used in STAs. While short term staffing tools can be very accurate and reflect an agency's actual practice, they cannot be used to make long term forecasts without a defined project profile. The model developed in the current work also directly links staffing decisions to overall system performance. Many states use these tools such as the state version of the Highway Economic Requirements System (HERS) to predict required funding levels for achieving specific performance targets. The HERS tool does not consider available workforce as a constraint. However, under the current workforce market conditions, available workforce level is becoming a major constraint to STAs' ability to keep the transportation infrastructures in good shape.

The current work has important limitations which must be mentioned. The system dynamics modeling methodology adopted in this work is limited in its inability to make pin-point accurate predictions. The methodology is designed to capture the trends and turning points in a system's behavior and visualize consequences of applying different policies. It generalizes the "stuff" in the system. In this work, highway pavement is categorized into three categories solely based on pavement roughness. Other properties of that section of the highway such as location, traffic, and perceived importance among local societies, are not captured in the model. When performing empirical validation, the model was not able to generate data with good fit level to reflect changes in historical acceptable pavement percentages in the road system monitored by the Kentucky Transportation Cabinet.

The main focus of this work is using the developed model to examine the effect of other factors on required workforce level. Since the model was built using feedback structures rather than single directional causal links, it can also be used for other purposes such as realistic target setting and funding level requirement predictions under a variety of scenarios.

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