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Forecasting Long Term Highway Staffing Requirements for State Transportation Agencies

Ying Li
University of Kentucky, ying.li@uky.edu

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Ying Li, Student

Dr. Timothy R. B. Taylor, Major Professor

Dr. Yi-Tin Wang, Director of Graduate Studies

FORECASTING LONG TERM HIGHWAY STAFFING REQUIREMENTS FOR STATE TRANSPORTATION AGENCIES

DISSERTATION

A dissertation submitted in partial fulfillment of the
requirements for the degree of Doctor of Philosophy in the
College of Engineering
at the University of Kentucky

By

Ying Li

Lexington, Kentucky

Co-Directors: Dr. Timothy R. B. Taylor, Professor of Civil Engineering
and Dr. William F. Maloney, Professor of Civil Engineering

Lexington, Kentucky

ABSTRACT OF DISSERTATION

FORECASTING LONG TERM HIGHWAY STAFFING REQUIREMENTS FOR STATE TRANSPORTATION AGENCIES

The transportation system is vital to the nation's economic growth and stability, as it provides mobility for commuters while supporting the United States' ability to compete in an increasingly competitive global economy. State Transportation Agencies across the country continue to face many challenges to repair and enhance highway infrastructure to meet the rapid 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 staffing requirements. However, current methods in use cannot function without well-defined projects and therefore making long term forecasts is difficult.

This dissertation seeks to develop a dynamic model which captures the feedback mechanisms within the system that determines highway staffing 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, federal and state database 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.

By performing sensitivity simulations and statistical screening on possible drivers of the system behavior, the dynamic impacts of desired highway pavement performance level, availability of road fund and bridge fund on the required numbers of Engineers and Technicians throughout a 25-year simulation period were closely examined. Staffing strategies such as recruiting options (in-house vs. consultants) and hiring levels (entry level vs. senior level) were tested.

Finally the model was calibrated using input data specific to Kentucky to simulate an expected retirement wave and search for solutions to address temporary staffing shortage.

KEYWORDS: State Transportation Agency, Highway Maintenance, Highway Staffing, System Dynamics, Feedback Loops

Ying Li

06/21/2016

Date

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By

Ying Li

Timothy R. B. Taylor
Co-Director of Dissertation

William F. Maloney
Co-Director of Dissertation

Yi-Tin Wang
Director of Graduate Studies

06/21/2016
Date

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I would like to dedicate this dissertation to my husband, Hao Wang for being a loving and supportive partner in life. Throughout the struggles of this work, he has been a constant source of joy.

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CHAPTER I INTRODUCTION AND PROBLEM STATEMENT

I.1 Background

The transportation network is vital to a nation's economic growth and stability. Previous research indicates that a long term equilibrium exists between freight traffic and a nation's Gross Domestic Product (GDP) (Liu and He 2002) and that investing in transportation infrastructure can spur on the development of the national and regional economy (Weisbrod and Treyz 1998; Ever et. al. 1987). The transportation network in the United States not only supports the US's ability to compete in an increasingly competitive global economy, but also provides mobility for commuters, access to recreational facilities, and a quality of life that US citizens have come to expect (Lucero 2011).

Transportation related goods and services account for about 10% of United States' Gross Domestic Product (GDP). Among the available transportation modes, the highway system supports a substantial portion of both passenger and cargo transportation. The Bureau of Transportation Statistics estimates that the highway system accounts for over 80% of the total passenger-miles travelled and that intercity truck freight, which relies on the highway system, accounts for almost 30% of the total ton-miles of cargo transportation (Bureau of Transportation Statistics 2005).

The origins of the US highway system can be traced back to the 1910s when the Federal Aid Road Act of 1916 was initiated. President Franklin Roosevelt's 1939 master plan for a system of interregional highways laid the groundwork for the future interstate highway system. The pressure to construct interstate highways to accommodate new powerful automobiles continued to build until the Federal-Aid Highway Act of 1956 marked the launch of the Interstate Highway Program. After years of heavy duty service, the highway system began to show wear and tear by the early 1980s. Since the physical system envisioned by the 1956 Act was essentially complete, the focus of financial and administrative commitment shifted from building new segments to preserving the existing network. In order to rescue deteriorating road surfaces and aging bridges, the Federal-Aid Highway Act of 1976 included funding for 3R (resurfacing, restoring, and rehabilitating), and a fourth R, reconstruction, was later added in the 1981 Act. The Surface Transportation Assistance Act of 1982 sighed by President Ronald Reagan made pavement reconstruction and resurfacing a priority, which resulted in major improvement in overall pavement conditions, reversing a pattern established in the late 1970s and early 1980s, when highway surface was wearing out faster than it was being replaced. The final initial construction fund to complete the interstate highway system was authorized in the 1990s. Since then, the Interstate Maintenance (IM) program has been in place to keep the nation's highway system in shape. Besides resurfacing, restoring, rehabilitating and reconstruction, IM fund can also be used for preventive maintenance if a State could demonstrate that the work would extend Interstate pavement life in a cost-effective manner (Weingroff 1996, 2015). Although the focus of highway related work has shifted from initial construction to maintenance and to preventive measures, the nation's commitment to protect taxpayers' investment in the highway system remains strong, as President Reagan's statement pointed out when he signed the 1982 Surface Transportation Assistance Act,

"The state of our transportation system affects our commerce, our economy, and our future."

United States' highway system is owned and managed by mainly government agencies. At the federal level, the Federal Highway Administration supports state and local agencies in design, construction, and maintenance by providing financial and technical assistance, while most of the planning, building and operating work are carried out at the state level. State Transportation Agencies (STAs) across the country continue to face many challenges to repair and enhance roadway infrastructure to meet the rapid increasing transportation needs. One of these challenges is maintaining adequate agency staff. Data collected for this dissertation show that, between 2000 and 2010, the total lane miles in the systems managed by State Transportation Agencies 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. By any measure, State Transportation Agencies are doing more work with less agency employees than they were 10 years ago, and the decrease in workforce size is not likely to stop in the near future. Based on the age structure of the current transportation workforce, Lucero (2011) forecasted that 40-50% of the transportation workforce will retire by the year of 2021. In addition to the high retirement rate, fewer people are going into key transportation fields. In a 1999 transportation workforce survey, responses from State Transportation Agencies 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 (Alarid et. al. 1999). Adequate staffing is critical to the performance of State Transportation Agencies, therefore US Department of Transportation and State Transportation Agencies have been making efforts in workforce development, including education and training programs, internships, scholarships, cooperative education programs, and "pipeline" activities (Harder, 2006). Such investments in future employees require strategic planning in human resource management, which includes being able to forecast long term staffing level requirements.

I.2 Problem Description

Data collected through the 1999 survey showed that 39 out of 50 states expressed a strong interest in working with other states on forecasting long term personnel needs (Alarid 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)” (Alarid et. al. 1999). A more recent survey identified several formal tools for forecasting construction staffing needs for highway projects (Taylor and Maloney 2013). The construction staff forecasting tool used at the North Carolina Department of Transportation (NCDOT) focuses on estimating the number of construction inspectors and survey parties needed for a given type of project. Within the bridge, interstate, rural, and urban generic project types, staff requirements are further differentiated based on contract amount and estimated project duration. The user can then identify the recommended number of personnel for each project and then aggregate the personnel across the project portfolio. North Dakota Department of Transportation (NDDOT) estimates construction staffing needs according to the Construction Manpower Planning Staff Standards, which provide guidelines for determining the number of engineers and technicians required to adequately staff construction projects. The system uses a set of 15 construction staffing standards that provide recommended staffing levels for different types of projects. Utah Department of Transportation (UTDOT) developed a staffing tool which aggregates the billable hours for both technicians and engineers by pay period based upon information imported into the system from UTDOT's Electronic Program Management System (ePM). ePM is the system UTDOT uses to track the planning, funding, scheduling, and staffing of their design projects. Information from this system contains the estimates of staffing needs for each project which is imported into an Excel template which includes the names of specific engineers and technicians, their billable rate, and their project assignments. Texas DOT is developing a staffing level forecasting tool using a step-wise regression analysis of historic project staffing needs. The primary input variables for the model are project cost and project type. The model has a number of underlying assumptions, such as "One inspector can handle $250,000/month", "One manager is required for 14 employees", among others, with suitable allowance for seasonal variability by geographic location of work and therefore staffing needs. The system is still under development and is currently being tested in a limited basis by TXDOT personnel.

One characteristic in common among the above described methods and tools currently applied by State Transportation Agencies 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. State Transportation Agencies' total work volumes can vary from year-to-year which adds uncertainty to personnel requirements at the central and field office level. Variations in project type and complexity, variations in personnel experience level and staff productivity, fluctuations in available fund, staffing strategies, changes in technology, and above all, the dynamic feedbacks among these factors may further complicate forecasting long term staffing needs.

I.3 Research Questions

This dissertation seeks to answer the question: How do transportation system demand, desired and actual transportation system performance, funding level, and staffing strategies impact staffing level requirements at State Transportation Agencies? More specifically:

(1) What feedback structures link future transportation system demand, current system performance, funding level, staffing strategy and future staffing requirements?

(2) What are the main drivers and constraints that determine future staffing requirements? How do these drivers and constraints impact State Transportation Agencies' staffing strategies?

(3) How can State Transportation Agencies effectively address potential staffing shortages and overflows?

I.4 Research Methodology

In order to study the dynamics of the system that determines transportation staffing needs at State Transportation Agencies, a structured method that is able to specify, formalize and explain the feedback relationships between factors that impacts staffing needs and changes in staffing level is needed, so that effective policies to address staffing shortage and avoid overstaffing in State transportation Agencies can be developed and tested.

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 describes numerous applications (Sterman 2000).

System dynamics models have been successfully applied to project management issues including the effect of rework on project performance (Cooper 1993,1994; Love et. al. 1999, 2000a, 2000b, 2002; Love and Li 2000; Lee et. al. 2005), construction firm performance (Tang and Ogunlana 2003; Ogunlana et. al. 2003), failures in fast track implementation (Ford and Sterman 1998), poor schedule performance (Abdel-Hamid 1984), schedule risk management (Ford and Bhargav 2006), project contingencies management (Ford 2002), the planning of fast-track construction projects (Pena-Mora and Li 2001; Pena-Mora and Park 2001), construction innovation (Park et. al. 2004), technology development risk (Ford and Sobek 2005), change management (Lee et. al. 2005, 2006; Park and Pena-Mora 2003), concealing rework requirements (Ford and Sterman 2003), tipping point dynamics (Taylor and Ford 2006, 2008), determination of cost predictors for rework in civil infrastructure projects (Love et. al. 2010), and the impact of public policy and societal risk perception on nuclear power plant construction (Taylor et.

al. 2012) among others. The methodology's ability to model many diverse system components, processes, and managerial decision making and actions makes it useful for the current work.

Building a system dynamics model generally takes 5 steps (Figure I.1). The first step is problem articulation. Once the research problem is defined, the second step is to establish 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 boundary and hypothesis may change if testing and analysis indicate they need to be modified.

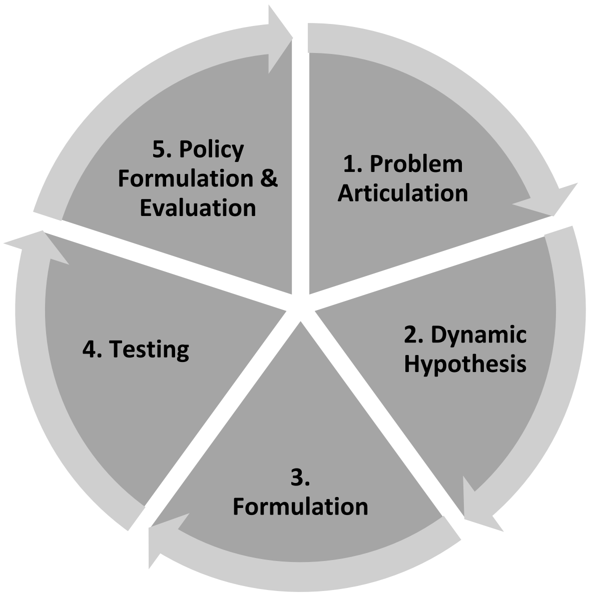


Figure I.1: Five Steps of the System Dynamics Modeling Process

During the problem articulation step, model boundaries and some general model settings must be identified. In this dissertation, both qualitative and quantitative data collected through literature review, federal and state database, and previous related research work were used to identify variables being included in the model. Not all factors that may have an impact on staffing requirements are included as input or control variables. For example, average road surface deterioration time is included as an exogenous variable in the model and can change throughout the forecasting period. It should have a strong impact on staffing level requirements. If road surface deteriorate faster, the State Transportation Agencies need to perform maintenance and repair work more often, and therefore more staff will be required if everything else stays unchanged. However, factors that may affect staffing requirements through impacting road surface deterioration time are not specifically modeled. Average Daily Traffic (ADT), material properties, construction quality, weather, and geographic conditions could all have some impact on road surface deteriorating time, but the model developed in this dissertation will not go to the details to specify the relationships between these variables and desired staffing level. Instead, the model's sensitivity to average road surface deteriorating time is tested in order to provide understanding towards how a change in average road surface deteriorating time results in change of required staffing level. This kind of boundary setting is necessary to keep the model within a manageable size. The model's running time is set to be twenty-five (25) years (300 months). This is consistent with most State Transportation Agencies' strategic planning period. Also taken into consideration is the fact that in many State Transportation Agencies, employees are eligible for retirement after 20 years of service. Twenty-five years of running time should cover a retirement cycle if such cycle exists. The model's unit for time is month considering State Transportation Agencies generally make monthly letting schedules for highway projects.

Once the model boundaries and general settings are defined, information gathered through literature review and previous research were used to establish the dynamic hypothesis for the model. Dynamic hypothesis is the conceptual version of the model which maps out causal relationships among model variables. For example, the NCHRP 450 survey results show that increased staff experience will likely decrease staffing requirements. A causal link between “Staff Experience” and “Staffing Requirements” can be established according to this finding, as shown in Figure I.2. The arrow going from “Staff Experience” to “Staffing Requirements” means a change in experience level will result in a change in required number of staff members. The negative polarity on the arrow means the two variables change in opposite directions. For detailed description of the model’s dynamic hypothesis, please refer to Chapter II.

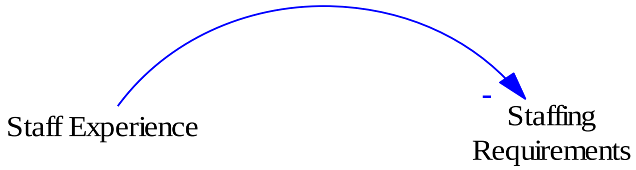


Figure I.2: Example Causal Link between Staff Experience and Staffing Requirements

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 model was tested using standard system dynamics procedures (Sterman 2000). Simulations were run to forecast staffing level requirements under various scenarios (abundant funding vs. limited funding, short hiring delays vs. long hiring delays, improving performance target vs. steady performance target, in-house hire vs. consultants, etc.) to gain basic understanding of the system behavior, after which sensitivity analysis and statistical screening were performed to identify the most influencing exogenous factors.

Understanding gained from analyzing model behavior were then used to develop staffing strategies. The model was re-calibrated to reflect Kentucky Transportation Cabinet's strategic goal and their current staffing and funding levels. Staffing policies were formed based on previous model behavior analysis and tested using model simulation to find effective ways to deal with a potential retirement wave that the Kentucky Transportation Cabinet may face in the near future.

I.5 Dissertation Organization

This dissertation is organized into six chapters. Chapter I discusses the nature of the research and describes the problem. Chapter II develops and describes the dynamic hypotheses for forecasting long term highway staffing requirements for State Transportation Agencies. Chapter III describes the structure of the formal forecasting model. Chapter IV discusses notable model behaviors and analyses of behaviors. Chapter V applies the model to Kentucky Transportation Cabinet's case and searches for solutions to effectively address potential staff shortage in the near future. Chapter VI draws conclusions and discusses future research directions.

CHAPTER II DYNAMIC HYPOTHESIS

II.1 General Hypothesis

A dynamic hypothesis is a feedback structure that is capable of explaining dynamic system behavior (Sterman 2000). This research hypothesizes that one or more clearly discernable dynamic structures and resulting behavior patterns characterize the interaction among long term highway staffing requirements and the factors that impact those requirements. Figure II.1 presents a dynamic hypothesis of a causal structure that can be used to study the dynamic interaction of highway system performance, funding level, and staffing. This structure is the basis of the model being developed in the current work.

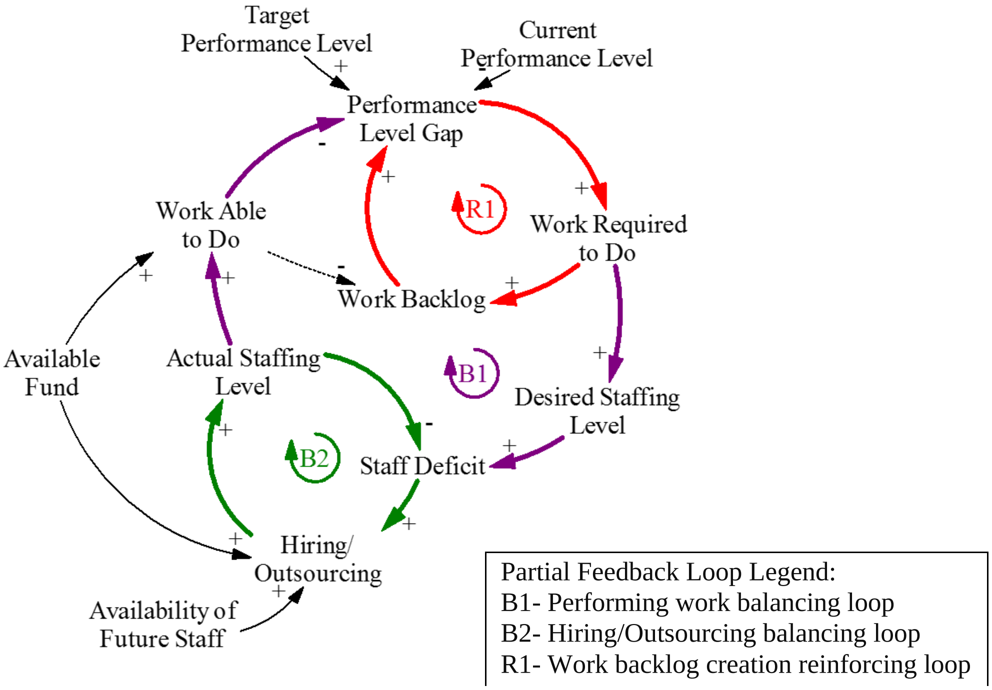


Figure II.1: Causal Loop Diagram of Highway System Performance, Funding Level and Staffing

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 the system driven by the balancing loop maintains a steady condition after it reaches its equilibrium status. Reinforcing loops produce behavior patterns that resemble exponential growth. For a more detailed description of causal loop diagrams see Sterman (2000).

Loop B1 describes how State Transportation Agencies work to reach their performance target. When making strategic plans, State Transportation Agencies 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, hence a 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), which seeks to bring the "Actual Staffing Level" to 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 State Transportation Agency will always have enough personnel to carry out the amount of work need 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 availability of fund and availability of prospective staff. If either one becomes insufficient, the State Transportation Agency 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 work planned for this month. If next month's target stays unchanged, the agency will need to perform any planned work for next months plus this month's "Work Backlog" in order to close the

"Performance Level Gap" at the end of next month. If the agency still don't have sufficient fund or staff next month, the "Work Backlog" grows larger. Variables "Performance Level Gap", "Work Required to Do" and "Work Backlog" forms a reinforcing loop (R1) and if outside conditions doesn't change, the "Work Backlog" will not stop growing.

The strength of the feedback loops 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 State Transportation Agency 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 the goal.

The causal loop diagram shown in Figure II.1 is the essential idea that the model is based on. The causal relationships displayed in the diagram are very general and difficult to quantify. In order to develop formulas for the actual model, more specific dynamic hypothesis are needed to describe exactly how each of the factors (performance target, funding level, staffing strategies, etc.) interacts with long term staffing requirements.

II.2 Performance Target and Staffing Requirements

A commonly used method to determine requirement workforce size is to first find out the desired accomplish rate, i.e. the "Work Required to Do" variable in the causal loop diagram shown in Figure II.1. Given the productivity of an average staff member, the following equation could then be applied to find the desired workforce size:

Desired Workforce Size = Desired Accomplish Rate / Productivity

In the above equation, “Desired Workforce Size” is measured in number of people, “Desired Accomplish Rate” is measured in amount of work done per month, and “Productivity” is measured in amount of work done per person per month.

Staff productivity can be estimated using historical data from previous project experience (more details on how staff productivity is estimated for this research will be discussed in the formal model chapter). However, as stated in the problem description section, a long term forecasting model has to function without well-defined project portfolio, therefore the desired accomplish rate cannot be determined by integrating the amount of work required for all planned projects over time. Instead of relying on project based estimates, the model developed in this dissertation links work accomplish rate to overall highway pavement condition.

Pavement roughness (or pavement smoothness) is the primary measure of pavement performance and is used by most State Transportation Agencies to establish the need for pavement repairs (Smith and Tighe 2006). One commonly used indicator of pavement roughness is the International Roughness Index (IRI) based on the simulated response of a generic motor vehicle to the roughness in a single wheel path of the road surface. The value of IRI is determined by obtaining a suitably accurate measurement of the profile of the road, processing it through an algorithm that simulates the way a reference vehicle would respond to the roughness inputs, and accumulating the suspension travel. IRI is normally reported in inches/mile or meters/kilometer (Minnesota Department of Transportation 2007). The Federal Highway Administration (FHWA) has required states to report IRI on the National Highway System since 1993, and has set the following roughness categories (See Table II.1) for highways (Federal Highway Administration 2015):

Table II.1: Federal Highway Administration (FHWA) Roughness Categories

Roughness Category	IRI Value	
	inches/mile	m/km
Good	< 95	< 1.5
Acceptable	< 170	< 2.7
Poor	≥ 170	≥ 2.7

The Federal Highway Administration has also established pavement performance goals based on International Roughness Index (IRI). The mobility goals of the 1998 FHWA National Strategic Plan included increasing the percentage of miles on the National Highway System (NHS) that meet the standard for acceptable ride quality to 93% by 2008. In 2002, a secondary performance goal was established which focused on increasing miles with good ride quality to 58.5%. And in 2006, the goals were further modified to make good ride quality as the primary target and acceptable ride quality as the secondary target (Federal Highway Administration 2015). State Transportation Agencies have set similar performance goals for their highway systems in their strategic plans as well, although target levels may vary slightly among states.

Besides target pavement condition levels, total highway mileage is another important factor to consider while estimating amount of work required. More mileage means more heavy maintenance work. And although State Transportation Agencies nowadays don't often build new highway mileage with new corridors, projects including widening and exit reconstruction to accommodate increasing vehicle traffic may still change the total highway mileage.

Highway pavement conditions are ever-changing due to traffic and aging. When deciding how much work is required, State Transportation Agencies need to take anticipated pavement deterioration during the planning period into consideration.

Figure II.2 illustrates the causal relationships when determining the amount of work required for a State Transportation Agency in order to reach the target pavement condition performance level.

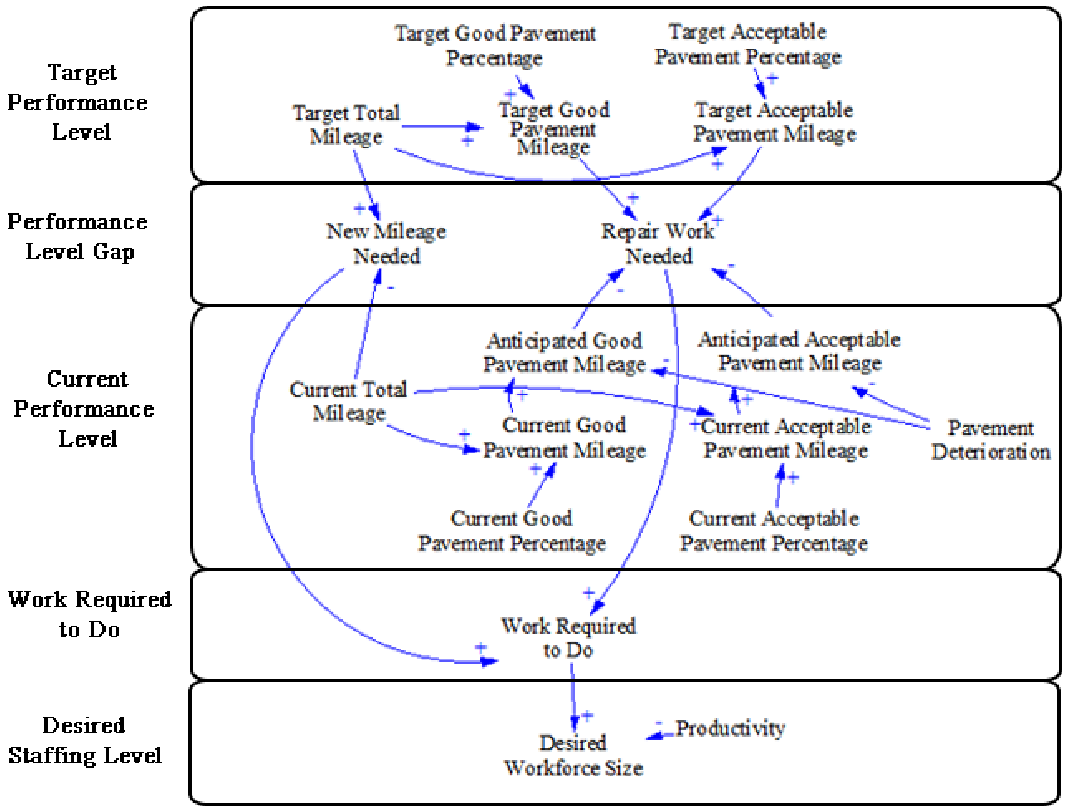


Figure II.2: Determining Desired Workforce Size from Target Highway Pavement Performance Levels

The variables on the left side of Figure II.2 correspondent to variables in Figure II.1. Knowing the “Target Total Mileage”, the “Target Good Pavement Percentage”, and the “Target Acceptable Pavement Percentage”, State Transportation Agencies can find out the “Target Good Pavement Mileage” and the “Target acceptable Pavement Mileage” at the end of the planning period. The “Anticipated Good Pavement Mileage” and the “Anticipated Acceptable Pavement Mileage” can be determined using the current mileages (“Current Good Pavement Mileage” and “Current Acceptable Pavement Mileage”) minus anticipated “Pavement Deterioration”. If the “Target Total Mileage” is greater than the “Current Total Mileage”, the State Transportation Agency needs to build new mileage into their highway system. If the “Anticipated Good Pavement Mileage” is less than the “Target Good Pavement Mileage” or the “Anticipated Acceptable Pavement Mileage” is less than the “Target Acceptable Pavement Mileage”, the State Transportation Agency needs to perform repair work to improve pavement condition. Total amount of “Work Required to Do” can then be determined by combining new mileage construction and repair work. And finally the “Desired Workforce Size” can be calculated.

II.3 Funding Level and Staffing Requirements

In an ideal situation, State Transportation Agencies always have adequate fund to keep their highway system in good shape. In the context of this model, having adequate fund keeps the balancing loop (B1) strong so that work is completed as scheduled. However, with increasing traffic, fluctuating construction cost and not to mention unpredictable economic environment, State Transportation Agencies very rarely get all the money they need to improve or keep the performance level of their highway systems. Even during times when investing in highway is favorable, State Transportation Agencies’ road fund may not be adjusted to the desired level instantly. Meanwhile, not being able to complete all required work will create or increase “Work Backlog” (Figure II.1) and result in temporary unsatisfactory performance. The dynamic process of adjusting road fund level can be described using Figure II.3

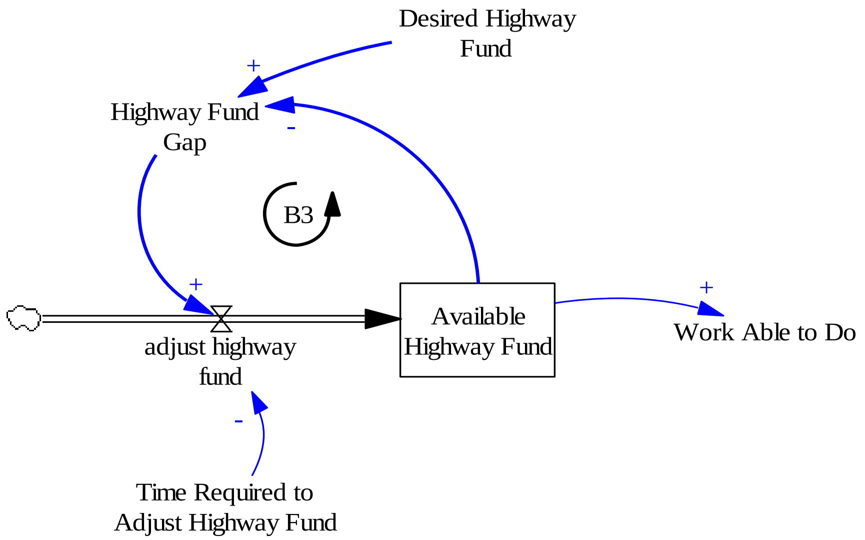


Figure II.3: The Dynamics Process to Adjust Highway Fund to the Desired Level

Figure II.3 shows a typical "Stock and Flow" structure that's commonly used in system dynamics modeling for a "Close Gap" scenario (Hines 1996). The boxed variable "Available Highway Fund" tracks really-time highway funding level over time. At any time when a gap exists between the "Available Highway Fund" and the "Desired Highway Fund", State Transportation Agencies will try to acquire more money to fill the gap, and by doing so creating a balancing loop (B3). "Available Highway Fund" has a direct relationship with "Work Able to Do", thus can impact staffing level requirement through the balancing loop B1 in Figure II.1. When the highway system is under-funded, "Work Able to Do" is less than "Work Required to Do", creating or increasing the "Work

Backlog". When that happens, the reinforcing loop (R1) in Figure II.1 goes into effect and increases required future staffing level.

II.4 Project Selection and Staffing Requirements

Not all highway repair work types are equal in cost and manpower requirements. To achieve the same pavement performance target, State Transportation Agencies may have different alternatives to select when trying to improve the pavement condition of a highway section to meet the standards of a better category (i.e. poor to acceptable, acceptable to good, or poor to good). For example, when the surface of a highway section becomes rough and requires repair, the State Transportation Agency can choose to resurface the pavement or reconstruct the section. Resurfacing is faster, costs less and requires less manpower than reconstruction. However since resurfacing does not fix any potential problem below the road surface, aging road base may cause the road renewed road surface to wear out fast, and repair work will be needed again before long. Reconstruction has a higher initial cost and requires more engineering work, but the section after repair could last longer. The same comparison applies to bridge replacement versus bridge rehabilitation. Finding the balance between reaching the performance goal and utilizing limited fund and workforce is worth investigating. Figure II.4 illustrate conceptually how this model simulates the impact of project selection on desired funding level and staffing level.

By selecting simple alternatives over complex alternatives, Loop R2 ("Work Required to Do" to "Simple Alternative" to "Repair Frequency Needed") gains power and "Work Required to Do" increases, while selecting complex alternatives shifts the power to

Loop B4 (“Work Required to Do” to “Complex Alternative” to “Repair Frequency Needed”). “Desired Funding Level” and “Desired Staffing Level” in Figure II.4 will further impact system behavior by interacting with the other feedback loops in the system.

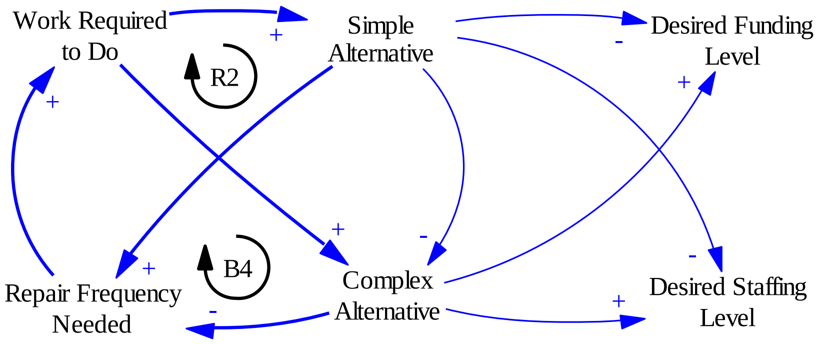


Figure II.4: Dynamic Impact of Project Selection on Desired Funding Level and Staffing Level

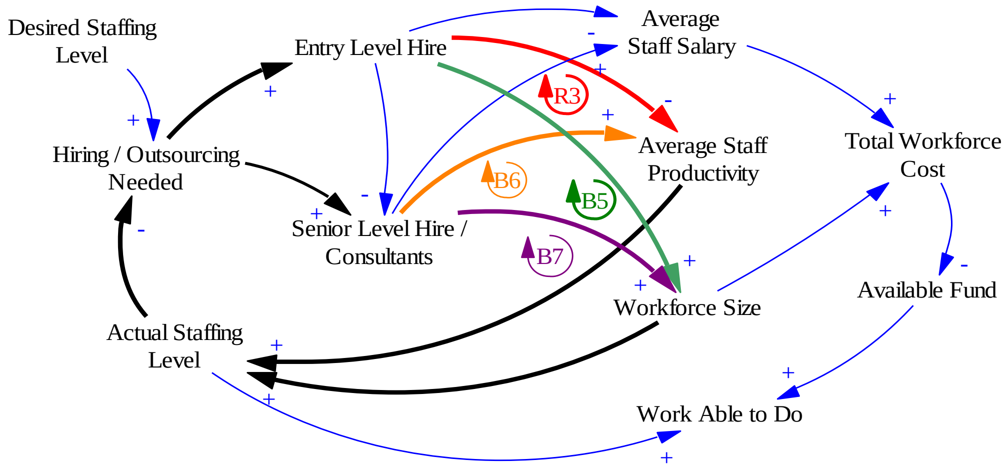
II.5 Recruiting Strategy and Staffing Requirements

A well-balanced staff in a State Transportation Agency should consist of personnel with all necessary expertise and should maintain a healthy age and experience structure so that the agency will be able to function at a sustainable productivity level. Recruiting qualified employees is critical for State Transportation Agencies in the near future due to the prominent aging problem of the US transportation workforce. Figure II.5 shows the six strategic components of effective recruiting for a typical organization (Mathis et al 2016).

The six components apply to strategic recruiting in State Transportation Agencies as well. State Transportation Agencies are government agencies that operate on tax dollars, which means their workforce budget is not likely to be as flexible as that of a private organization, therefore financial limits plays an important part when it comes to recruiting decisions. They are expected by the public to performance at a certain standard. Retaining qualified workforce within any time limits to complete required work is necessary. Labor market dynamics dictates the level of difficulty in retaining qualified Engineers and Technicians to carry out design and inspection of road work. Business strategies can be reflected by target setting tactics and project selection. And finally, quantity and quality of talent directly affect how much work can be performed by the agency staff.

Figure II.5: Strategic Components of Effective Recruiting

With most of the construction work outsourced to private Contractors, State Transportation Agencies mainly need to retain a number of Engineers and Technicians for the planning, design and inspection of highway work. The experience levels of Engineers and Technicians determine the overall productivity and salary rate of the agency staff. While entry level engineers and Technicians may be less expensive and easier to hire, lack of experience and need for supervision make them less productive than well-paid, more experienced personnel. Figure II.6 illustrates the interactions of recruiting strategies and future staffing requirements through feedbacks involving financial limits and time limits.



Partial Feedback Loop Legend:

R3 - Entry Level Hire - Productivity Reinforcing Loop
B5 - Entry Level Hire - Workforce Size Balancing Loop
B6 - Senior Level Hire - Productivity Balancing Loop
B7 - Senior Level Hire - Workforce Size Balancing Loop

Figure II.6: Interactions of Recruiting Strategies and Staffing Level

At least four additional feedback loops are formed by varying hiring levels (Loops R3, B5, B6, and B7). When a State Transportation Agency mainly hires at the entry level, Loops R3 and B5 gains strength, and when an agency hires at more experienced level, Loops B6 and B7 gains strength. While competition among these loops may appear to be a competition of numbers versus experience in short terms, hiring level decisions have long term ramifications on workforce age and experience structure and should be made carefully to suit long term staffing needs. Loops R3, B5, B6 and B7 are not isolated from the other feedback loops in the system. Dominance of B6 and B7 may seem to be able to fill the workforce gap nicely to complete required work, it also results in higher workforce cost which decreases fund available, and therefore decreases “Work Able to Do”.

In recent years State Transportation Agencies are outsourcing a portion of the design and inspection work mainly due to shortage of in-house personnel and unavailability of qualified prospective permanent employees. The experience level of consulting Engineers and Technicians are usually comparable to the more experienced in-house personnel and as is their pay grade. Hiring consultants produces a temporary increase in total staff available for completing required work when a short term increase in required manpower is needed.

II.6 Other Factors Affecting Staffing Requirements

In order to keep the model within a manageable size, not all factors that may have an impact on long term highway staffing requirements are specifically modeled, however, the effect of those factors can be reflected by varying some of the control variables in the model. For example, investing in technology could impact several control variables in the model. New communication technology can increase average staff productivity by enabling more effective information communication, and improved average staff productivity can decrease required workforce size and potentially save money on workforce budget, or even strengthen the power of feedback loop B1 in Figure II.1 through being able to perform work faster. If a certain development in communication technology can result in a 1% increase in average staff productivity, the impact on funding requirements and staffing requirements can be simulated and tested using the model to perform benefit-cost analysis. More tests of other scenarios will be discussed later in the formal model chapter.

II.7 Summary

The dynamic hypotheses presented with causal loop diagrams in this chapter qualitatively describe the feedback mechanisms within the system that determines long term highway staffing requirements for State Transportation Agencies. These hypotheses are next tested using a computer simulation model that formally describes and quantifies the feedback relationships within the system.

CHAPTER III FORMAL MODEL

III.1 Model Overview

The formal model developed for this dissertation was built using the Vensim simulation software. The model is comprised of 14 sectors.

(1) Road Workflow - The “Road Work Flow” sector tracks the quantities (in lane miles) of highway pavement in good (IRI<95), fair (IRI between 95 and 170), and poor (IRI>170) conditions as well as the change rates in these quantities during each time step.

(2) Bridge Workflow - The “Bridge Work Flow” sector tracks the quantities (in square meters) of bridge deck area in good (structurally sound), fair (structurally deficient), and poor (functionally obsolete) conditions and the change rates.

(3) Road Work Volume Forecast - The “Road Work Volume Forecast” sector calculates the amount of pavement repair work required during each time step in order to accomplish performance goals.

(4) Bridge Work Volume Forecast - The “Bridge Work Volume Forecast” sector calculates the amount of bridge work required during each time step in order to accomplish performance goals.

(5) Road Fund - The “Road Fund” sector tracks available road fund and changes in available road fund in response to desired road fund. This sector also allocates available road fund to different road work types based on work volume or priority of the agency.

(6) Bridge Fund - The “Bridge Fund” sector tracks available bridge fund and changes in available bridge fund in response to desired bridge fund. This sector also

allocates available bridge fund to different bridge work types based on work volume or priority of the agency.

(7) Road Workforce Requirement - This sector calculates required number of Engineers and Technicians for road work based on work volume and productivity.

(8) Bridge Workforce Requirement - This sector calculates required number of Engineers and Technicians for bridge work based on work volume and productivity.

(9) Engineers - This sector tracks the numbers of in-house Engineers in different experience levels as well as the change rates.

(10) Technicians - This sector tracks the numbers of in-house Technicians in different experience levels as well as the change rates.

(11) Consultants - This sector tracks the number of consultants the agency is paying to.

(12) Workforce Assignment - This sector assigns all available workforce, including in-house staff and consultants, to different work types in accordance to fund allocation.

(13) Work Accomplish Rate - This sector calculates work accomplish rates in each work type considering both fund and workforce limits.

(14) In-House Workforce Budget - This sector tracks the total salary paid to all in-house personnel and restrains hiring through a budget cap.

The model was tested using standard methods for system dynamics models (Sterman 2000). The model's behavior for typical conditions is consistent with previous project models and practice. Use of previously validated model structure improves the model's structural similarity to processes in the real system. The model's structural validity is further improved through the extensive use of standard, previously validated, system dynamics formulations (e.g., first-order negative feedback, goal seeking structures) (Sterman 2000). Dimensional consistency tests strengthen model validity by ensuring variable units are internally consistent, consistent with units used in the real system, and that model equations do not violate logical unit convention by using fictitious conversion variables not used in the real system (Sterman 2000). Extreme conditions tests validate the ability of the model to simulate reasonable behavior across a wide range of conditions (Forrester 1961; Sterman 2000). These tests were performed on the current model by setting model inputs to zero or other extreme values, simulating system behavior, and then assessing the reasonableness of the simulated behavior. These and other model tests support the usefulness of the model for the purpose of the current work.

More detailed model sector descriptions are provided in Sections III.2 -III.5. Some notable model behavior and analysis are discussed in Section III.6.A text file of the Vensim model code is included in Appendix A.

III.2 Work Flow Model Sectors

III.2.1 Work Flow Model Structure

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 III.1 shows the model structure of the "Road Work Flow" sector.

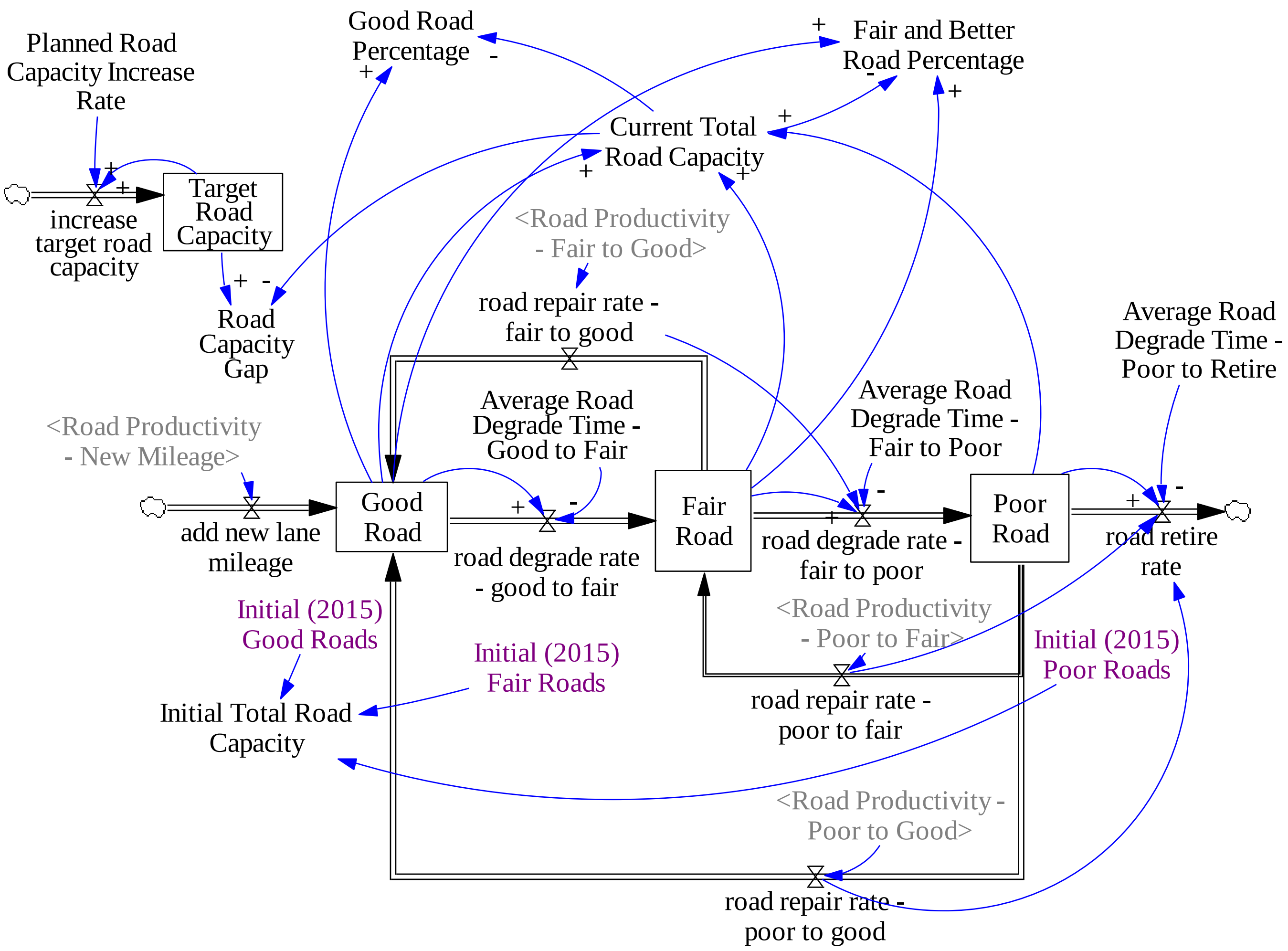


Figure III.1: Model Structure of the Road Workflow Sector

Highway pavement is classified into three categories (good, fair, and poor) in accordance with the pavement roughness categories set by the Federal Highway Administration (FHWA). Quantity (in Lane Miles) of highway pavement in each category is stored in a boxed variable. These boxed variables are called “stocks” in system dynamics terms. Values of “stocks” can only be changed through “flows”. In system dynamics models, “flows” are represented by double lined arrows. Stocks, flows, and auxiliary variables are the three main types of variables in system dynamics models. Values of all three types of variables can change throughout the simulation period. System dynamics modelers often use stocks to model the “important stuff” in the system when not only their values but also the change rates in their values is of great interest to the modeler. Since values of stocks can only be changed through flows, modelers can conveniently track change rates in stocks by tracking real-time values of flows. Auxiliary variables independent from other model variables except “time” are considered “exogenous variables” for the model. In the sketch view of a model sector (like Figure III.1), exogenous variables are the ones that don’t have any arrows pointing to them but may have arrows pointing from them to other variables (e.g. “Planned Road Capacity Increase Rate”). Values of exogenous variables are either constant or follow a function of time. All other variables are endogenous variables and their values and change rates depend on other model variables. In the sketch view of a model sector, endogenous variables have arrows pointing to them. Variables in chevrons (“< >”) are called “Shadow Variables” and are variables appearing in other sectors of the model. With a complex model, it is best to divide the model into smaller sectors so that each sector is easier to read and understand. As the name suggests, “shadow variables” are duplicates of variables originally introduced in other sectors of the model. When cutting a model into smaller sectors, shadow variables are used to model the impact of original variables in other sectors to one or more variables in this sector without displaying causal relationships between the original variables and other variables not appearing in this sector. Shadow variables can be endogenous or exogenous depending on how they are originally modeled in other sectors. Table III.1 summarize the classifications of variables used in system dynamics models.

Table III.1: Classification of Variables in System Dynamics Models

By Modeling Method	Variable Type	Appearance in Sketch	How Value Changes over Time
	Stock	Boxed	Only through flows
	Flow	Double lined arrows with valves	Function of time or other model variables
	Auxiliary	Plain text	
By Relation to Other Variables	**Variable Type**	**Appearance in Sketch**	**How Value Changes over Time**
	Exogenous	No arrows pointing to them	Constant or function of time
	Endogenous	Have arrows pointing to them	Functions of other model variables besides time

As displayed in Figure III.1, highway road surface are categorized into three roughness categories, good road, fair road and poor road. Since State Transportation Agencies periodically evaluate highway pavement conditions and report to the Federal Highway Administration, the initial values of the three stocks should be known and can be used as input for the model. 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 “Good Road” can become “Fair Road” without proper repair and “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. Previous research has discovered a non-linear relationship between the IRI (International Roughness Index) of highway pavement and pavement age. As the pavement ages, the IRI increases at an increasing rate (Smith and Tighe 2006). This is consistent with common asset management knowledge that the condition of an asset degrades in an increasing rate without proper maintenance. Figure III.2 illustrates how pavement condition degrade over time figuratively.

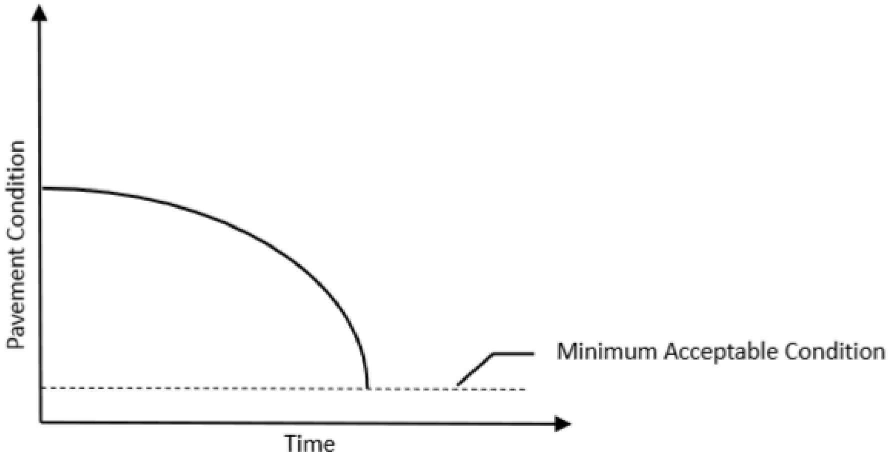


Figure III.2: Highway Pavement Conditions over Time without Repair

For highway pavement with a 30-year design life, according to regression analysis conducted by Smith and Tighe, the estimated average time for a section of new pavement to degrade into the fair condition is around 12 years (144 months), the average time for fair pavement to deteriorate into poor pavement is about 10 years (120 months), and the average time for poor pavement to further deteriorate to the minimum acceptable level is about 8 years (96 months). These estimates provide the basis for the values of the "average road degrade time" variables in Figure III.1. The exact values of these variables should vary state by state due to preference of pavement material and traffic volume.

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 State Transportation Agency oversees. Due to increasing traffic, the State Transportation Agency may need to increase the total highway capacity by widening existing roads and rebuilding intersections and exits. In recent years and the foreseeable future, it is unlikely that a State Transportation Agency would build a large amount of entirely new routes with undeveloped corridors, so increase in total road capacity should be incremental. In Kentucky, the total highway lane-mileage saw an average monthly increase rate of 0.0228% from Year 2000 to Year 2015. Other states may have growing highway systems, but most State Transportation Agencies are trying to maintain their current highway capacities while keeping the system in good shape.

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, State Transportation Agency must assign resources to new construction and repair work. And the amounts 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 the real-time percentage of 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, with the assumption that the total bridge deck area in the highway system increases at the same rate at which the total road lane mileage increases. 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 required different amount of money and manpower; and State Transportation Agencies usually have dedicated bridge fund within their budget. Figure III.3 shows the sketch of the bridge workflow sector.

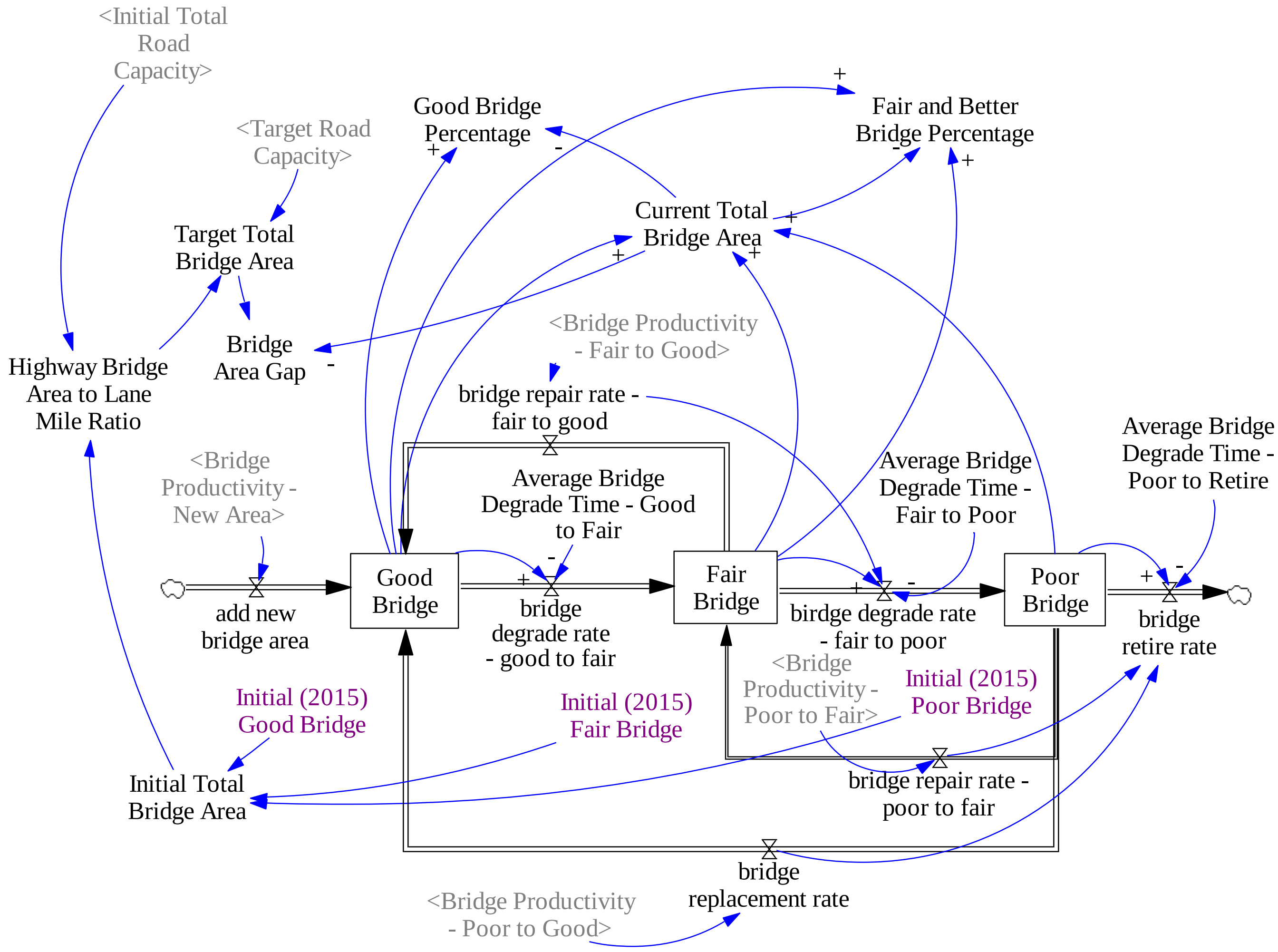


Figure III.3: Model Structure of the Bridge Workflow Sector

State Transportation Agencies are required to report to the Federal Highway Administration periodically the amounts (in m^2 or ft^2) of bridge deck area 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.

III.2.2 Exogenous Variables in Work Flow Sectors

Among exogenous variables displayed in Figure III.1 and Figure III.3, some can be impacted by the State Transportation Agency’s decisions throughout the simulation period, such as “Planned Road Capacity Increase Rate”. To some level, the agency can decide how much new lane mileage to build, although the decision rely heavily on transportation demand. Values of other exogenous variables, such as “Initial (2015) Good Road”, are facts that has little to do with the agency’s decision making in the next 25 years. Variables whose values depend on the agency’s decision making are considered “control variables” in system dynamics models, and model behaviors are often analyzed while changing the values of control variables within their reasonable ranges to search for solutions for problems. Table III.2 is a list of all exogenous variable used in the workflow sectors. None of the exogenous variables in these two sectors are considered control variables.

Table III.2: Exogenous Variable in the Workflow Sectors

Sector	Variable Name	Value/Range	Unit
Road Workflow	"Average Road Degrade Time - Fair to Poor"	120	Month
	"Average Road Degrade Time - Good to Fair"	144	Month
	"Average Road Degrade Time - Poor to Retire"	96	Month
	Initial Good Road Percentage	50%	Dimensionless
	Initial Fair and Better Road Percentage	90%	Dimensionless
	Initial Total Road Capacity"	60000	Lane Mile
	Planned Road Capacity Increase Rate	0.0002	Dimensionless
Bridge Workflow	"Average Bridge Degrade Time - Fair to Poor"	240	Month
	"Average Bridge Degrade Time - Good to Fair"	360	Month
	"Average Bridge Degrade Time - Poor to Retire"	120	Month
	Initial Fair and Better Bridge Percentage	77.9%	Dimensionless
	Initial Good Bridge Percentage	73.5%	Dimensionless
	"Initial (2015) Total Bridge Area"	5440000	Square Meter

III.3 Work Volume Forecast Sectors

III.3.1 Performance Target Variables

The “Road Work Volume Forecast” sector uses the agency’s highway performance targets and currently conditions from the road workflow sector as input and is designed to find out the amount of work required in each type of road work. Three performance targets are specified in the model:

(1) Planned Road Capacity Increase Rate

This is the average anticipated monthly road capacity increase rate.

(2) Desired Good Road Percentage Increment

This is the planned monthly improvement of good road percentage. If the agency plans to keep the current good road percentage for the 25-year forecasting period, this target variable stays at zero. If the agency plans to gradually increase the good road percentage by 5% at the end of the 25-year forecasting period, the monthly increase would be 0.0167%.

(3) Desired Fair and Better Road Percentage Increment

This is the planned monthly improvement of fair and better road percentage.

III.3.2 Amount of Work Required

Amount of work needed for four types of road work represented by four flow variables in the workflow sector are calculated in this road work volume forecast sector: new mileage, road repair from fair condition to good condition, road repair from poor condition to fair condition, and road repair from poor condition to good condition. The priority goal should be keeping the existing capacity in good shape, which means the agency need to perform repair work on highway sections with pavement condition approaching the minimum acceptable level. The agency can choose to restore the pavement to either good condition or fair condition. Due to increasing traffic, necessary new mileage needs to be built in order to manage delay time and accident rate in the highway system. If the brand new road surface from new mileage combined with the amount of poor pavement being restored to good condition is not enough to fill the gap between design good road quantity and the actual good road quantity, the agency may need to perform pavement repair on current fair road or poor road that do not need immediate attention, as increasing good road percentage has priority over increasing acceptable road percentage. In practice, the Federal Highway Administration encourages State Transportation Agencies to perform preventative repairs on highway pavements if such repairs prove to be cost efficient for the entire life cycle of highway pavement. Scheduling the first pavement rehab around the time that pavement section drop from the good category to the fair category is cost efficient because of the non-linear relationship between IRI and pavement age. Figure III.4 shows the process for determining the amount of work required for each road work type.

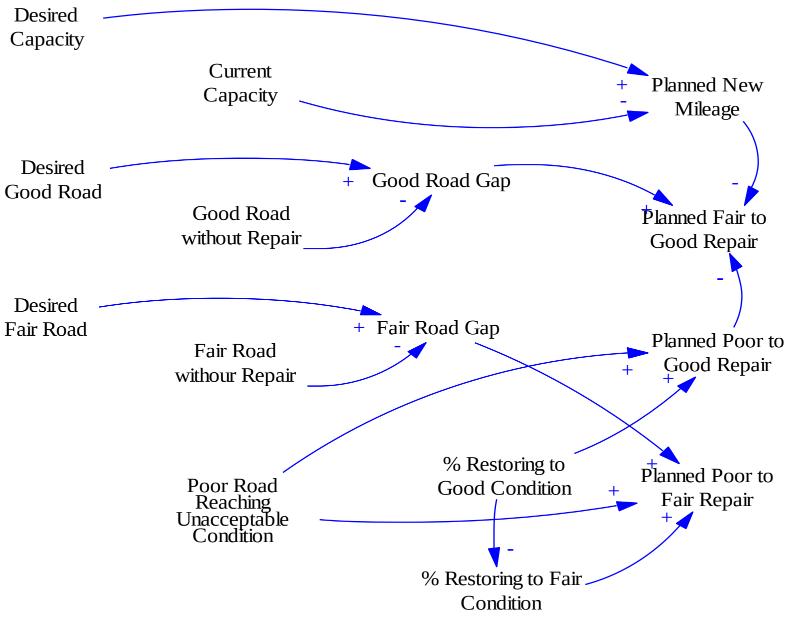


Figure III.4: Process for Determining Work Volume for Road Work

The logic to determine the amount of bridge work required is similar to the above process for determining road work volume. When a bridge reaches its designed life span, the State Transportation Agency should decide whether to replace it or to rehabilitate it. According to historical cost data, the average cost for bridge rehabilitation is about 68% of the cost for bridge replacement (Federal Highway Administration 2014). However, rehabilitation does not restore the condition of a bridge to brand new level.

III.3.3 Exogenous Variables in Work Volume Forecast Sectors

Table III.3 lists all exogenous variables in the work volume forecast sectors with control variables highlighted. All exogenous variables in these sectors can be considered control variables, because the agency can influence the values of these variables relatively freely through decision making.

Table III.3: Exogenous Variable in the Work Volume Forecast Sectors

Sector	Variable Name	Value/ Range	Unit
Road Work Volume	"% Retiring Road to Be Reconstructed into Good Road"	0-100	Dimensionless
	"% Retiring Road to Be Repaired into Fair Road"	0-100	Dimensionless
	desired fair and better road percentage increment	Vary	Dimensionless/Month
	desired good road percentage increment	Vary	Dimensionless/Month
Bridge Work Volume	"% Retiring Bridge to Be Rehabilitated"	0-100	Dimensionless
	"% Retiring Bridge to Be Replaced"	0-100	Dimensionless
	desired fair and better bridge percentage increment	Vary	Dimensionless/Month
	desired good bridge percentage increment	Vary	Dimensionless/Month

III.4 Fund Sectors

III.4.1 Required Fund

The “Road Fund” sector uses the planned work volumes for each of the four road work types as input. Unit prices for the four work types can be estimated using the agency’s historical project data. And the total monthly desired road fund can be calculated by multiplying the work volume of each work type with its unit price and adding all four work types together. Figure III.5 shows the causal link diagram that describes the process of determining the desired monthly total road fund. The desired monthly bridge fund is determined in the same manner.

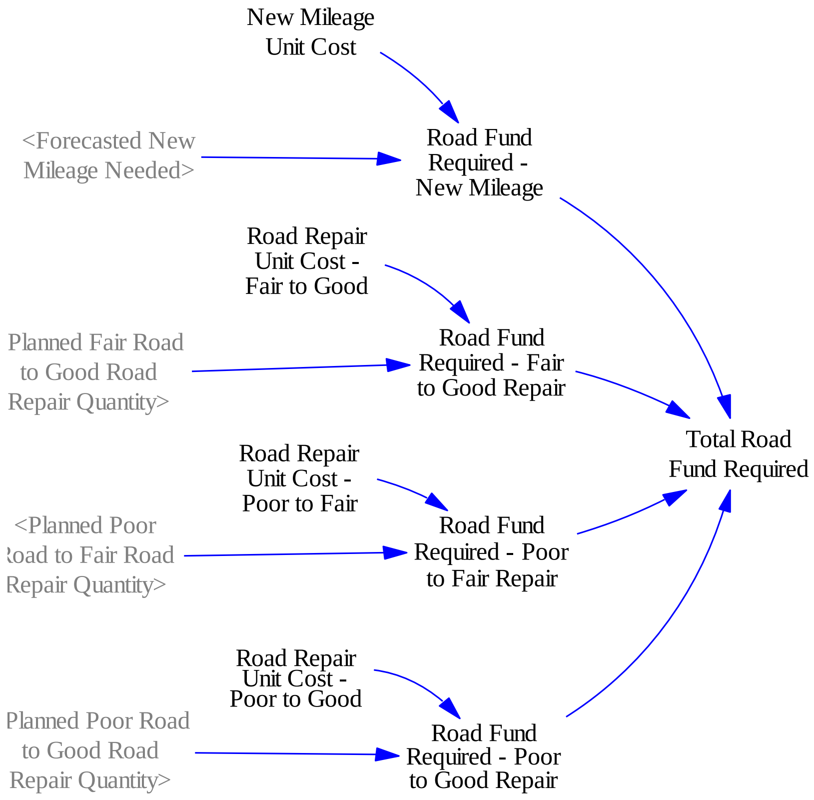


Figure III.5: Determining the Desired Monthly Total Road Fund

III.4.2 Available Fund

In the beginning of the forecasting period, the State Transportation Agency should have a budget for all road work for the first month (and maybe longer). The budget may or may not be exactly the same amount as the desired total monthly road fund to complete all required to road work to reach their performance target. As the simulation goes on, the available funding level for road work changes due to possible change in the economic environment and the agency's lobbying activities. Figure III.6 shows the model structure that simulates how available road fund changes.

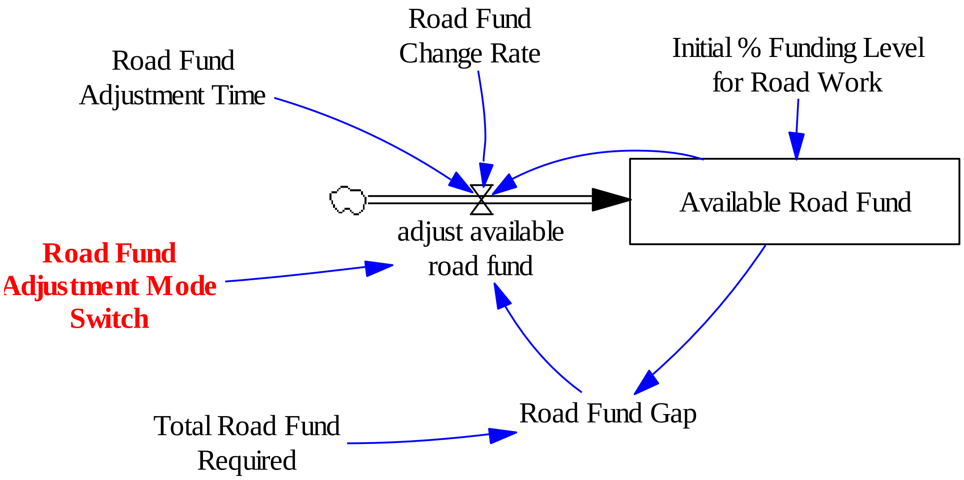


Figure III.6: Adjusting Available Road Fund

This structure allows the available road fund to be adjusted in two different ways. One is to continuously adjust the available road fund to the desired level with a possible time delay ("Road Fund Adjustment Time"). The other is manually change the adjustment rate through the "Road Fund Change Rate" variable so that the model can simulate any sudden increase /decrease in funding level. The model can switch between the two modes by setting the "Road Fund Adjustment Mode Switch" variable to either 0 or 1. Table III.4 summarizes the two ways simulated in this model of how available road fund changes. The same structure is used for determining available bridge fund during each simulation step.

Table III.4: Summary of the Two Simulated Road Fund Adjustment Modes

	Adjustment Mode 1	**Adjustment Mode 2**
Description	Automatically continuously adjust available fund towards the desired level with a possible time delay	Manually adjust monthly available road fund
Value of the "Road Fund Adjustment Mode Switch"	1	0
Control Variable	Road Fund Adjustment Time	Road Fund Change Rate

III.4.3 Fund Allocation

Once the available road fund is determined for the next simulation step, money will be allocated to the four types of road work. The State Transportation Agency can allocated available fund proportionally according to the required fund for the four work types, which the model calculates, or manually determine each work type's monthly budget based on priority. Actual money allocated to each type of road work and their respective unit prices will determine how much work in each category can be performed based on budget restraint alone. Using the same method, the model will be able to find out the amount of bridge work in each of the four bridge work categories the agency is able to carry out based on bridge budget.

III.4.4 Exogenous Variables in the Fund Sectors

Table III.5 lists all exogenous variables used in the work volume forecast sectors with control variables highlighted.

Table III.5: Exogenous Variables in the Fund Sectors

Sector	Variable Name	Value/Range	Unit
Road Fund	Road Fund Adjustment Time	≥ 1	Month
	"Initial % Funding Level for Road"	0-100	Dimensionless
	Manual Fraction of Road Fund Allocated to Fair to Good Repair"	0-1	Dimensionless
	Manual Fraction of Road Fund Allocated to New Mileage"	0-1	Dimensionless
	Manual Fraction of Road Fund Allocated to Poor to Fair Repair	0-1	Dimensionless
	Manual Fraction of Road Fund Allocated to Poor to Good Repair	0-1	Dimensionless
	Road Fund Adjustment Mode Switch	0 or 1	Dimensionless
	Road Fund Change Rate	Vary	Dollar/Month
	Road Fund Limit Switch	0 or 1	Dimensionless
	"Road Fund Proportional/Manual Allocation Switch"	0 or 1	Dimensionless
	New Mileage Unit Cost	1500000	Dollar/Lane Mile
	"Road Repair Unit Cost - Fair to Good"	450000	Dollar/Lane Mile
	"Road Repair Unit Cost - Poor to Fair"	600000	Dollar/Lane Mile
	"Road Repair Unit Cost - Poor to Good"	1000000	Dollar/Lane Mile
	Bridge Fund Adjustment Mode Switch	1	Dimensionless

Table III.5 (Continued): Exogenous Variables in the Fund Sectors

Sector	Variable Name	Value/Range	Unit
Bridge Fund	Bridge Fund Change Rate	Vary	Dollar/Month
	Bridge Fund Limit Switch	0 or 1	Dimensionless
	"Bridge Fund Proportional/Manual Allocation Switch"	0 or 1	Dimensionless
	New Bridge Unit Cost	1500	Dollar/Square Meter
	"Bridge Repair Unit Cost - Fair to Good"	500	Dollar/Square Meter
	"Bridge Repair Unit Cost - Poor to Fair"	900	Dollar/Square Meter
	"Bridge Repair Unit Cost - Poor to Good"	1300	Dollar/Square Meter
	Bridge Fund Adjustment Time	≥ 1	Month
	Initial % Funding Level for Bridge	0-100	Dimensionless
	Manual Fraction of Bridge Fund Allocated to Fair to Good Repair	0-1	Dimensionless
	Manual Fraction of Bridge Fund Allocated to New Mileage	0-1	Dimensionless
	Manual Fraction of Bridge Fund Allocated to Poor to Fair Repair	0-1	Dimensionless
	Manual Fraction of Bridge Fund Allocated to Poor to Good Repair	0-1	Dimensionless

III.5 Workforce Sectors

III.5.1 Workforce Required

Since construction work is mostly outsourced to Contractors, State Transportation Agencies generally require two types of technical personnel to perform design and inspection work of highway projects: Engineers and Technicians. Staffing requirements for different project types vary based on complexity of work, therefore the amount of work that an average engineer or an average technician can handle each month vary by project type. An average engineer or an average technician's productivity for each project type can be estimated using historical project data and project-based staffing tools in use at the agency. In order to find reasonable estimates of productivity values for the generic model (not calibrated to reflect a specific state), the following worksheet (Table III.6) was used. This worksheet was designed to fit some of the project-based staffing tools identified in an NCHRP (National Cooperative of Highway Research Program) synthesis project (Taylor and Maloney 2013). Average project size and duration values were calculated using historical data in Kentucky Transportation Cabinet's project archive. The "% Engagement" values indicate how much of an engineer or a technician's attention a single project generally requires, since more often than not an engineer or a technician will be working on multiple projects at the same time.

The staff productivity values from the worksheet can then be used to convert work volumes (measured in dollar) into required workforce levels. Figure III.7 demonstrates how to convert planned new mileage amount into required number of engineers using the following equations:

$$\text{“Engineers Required – Target – New Mileage”} = \frac{\text{“Road Fund Required – New Mileage”}}{\text{“Engineer Productivity”}}$$

$$\text{“Engineers Required – Budget – New Mileage”} = \frac{\text{“Road Fund Allocated to New Mileage”}}{\text{“Engineer Productivity”}}$$

Table III.6: Determining Staff Productivity by Work Type

Road Projects				
Work Type	**New Mileage**	**Road Repair - Fair to Good**	**Road Repair - Poor to Fair**	**Road Repair - Poor to Good**
Average Project Size (Dollar)	$1,265,589.40	$459,343.48	$842,063.59	$863,064.27
Average Project Duration (Month)	9	3	4	6
No. of Engineers Required	5	3	3	4
% Engineer Engagement	50%	20%	30%	50%
No. of Technicians Required	4	2	2	4
% Technician Engagement	100%	100%	100%	100%
Engineer Productivity (Dollar/Month/Person)	56,248	255,191	233,907	71,922
Technician Productivity (Dollar/Month/Person)	35,155	76,557	105,258	35,961

Table III.6 (Continued): Determining Staff Productivity by Work Type

Bridge Projects				
Work Type	**New Bridge**	**Bridge Repair - Fair to Good**	**Bridge Repair - Poor to Fair**	**Bridge Repair - Poor to Good**
Average Project Size (Dollar)	$252,437.24	$352,636.24	$553,394.47	$356,664.91
Average Project Duration (Month)	9	4	4	6
No. of Engineers Required	5	3	3	4
% Engineer Engagement	50%	20%	30%	50%
No. of Technicians Required	4	2	2	4
% Technician Engagement	100%	100%	100%	100%
Engineer Productivity (Dollar/Month/Person)	11,219	146,932	153,721	29,722
Technician Productivity (Dollar/Month/Person)	7,012	44,080	69,174	14,861

The “Engineers Required – Target – New Mileage” variable (in Figure III.7) indicates the number of engineers required for the amount of new mileage construction work in order to successfully reach the agency’s performance target, while the “Engineers Required – Budget – New Mileage” indicates the number of engineers required to fully utilize any money allocated to construction of new mileage. The number of technicians required for new mileage construction and workforce required for other project types can be calculated using the same method. The total number of engineers and technicians required can be determined by summing up the staffing level requirements for all work types.

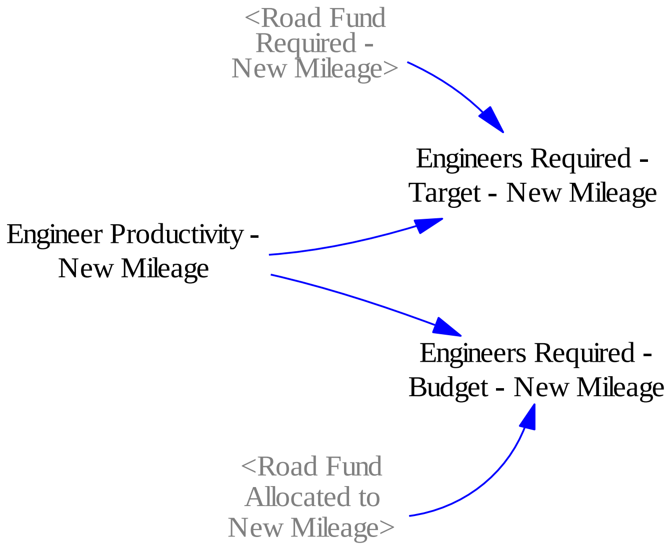


Figure III.7: Converting Work Volume to Staffing Level

III.5.2 Workforce Available

Available workforce can be either in-house personnel or consultants hired to address temporary staff shortage. In-house personnel who stay in the agency until retirement generally go through a training period during which they are less productive than an average staff member. As they accumulate experience, their productivity increases and so will their pay grades. State employees are usually required to serve for 20-25 years (varies among states) before they are eligible for retirement. Assuming an engineer or a technician starts working at the a State Transportation Agency immediately after acquiring a qualifying degree (usually engineer positions require 4-year college degrees in civil engineering and technician positions require 2-year associate degrees), by the time he or she is eligible for retirement, he/she could be under 50 years old. A good portion of retired transportation experts from State Transportation Agencies choose to continue working for private companies, provided that state law permits it. Through contracting between the

State Transportation Agency and the private industry, these experienced engineers and technicians may be retained as consultants for the agency. This could be one of the factors that contribute to the fact that consultants, although more expensive, are more productive than average in-house personnel. Figure III.8 shows the model structure used to simulate the dynamic flow of in-house engineers at a State Transportation Agency. 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.

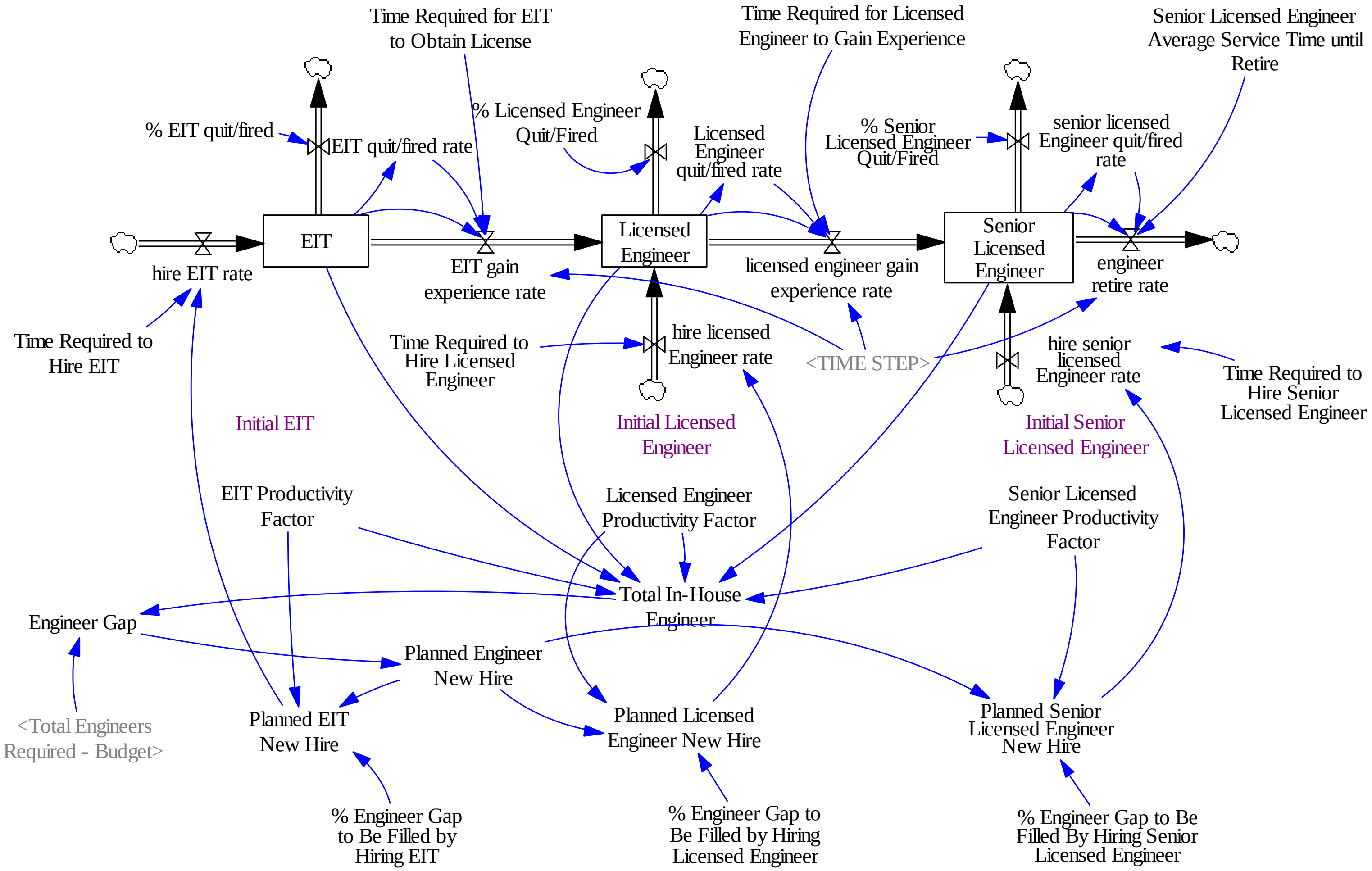


Figure III.8: Model Structure for In-House Engineers

Newly graduated engineers serve the State Transportation Agency as EITs (Engineers in Training). EITs have very little experience and require a good amount of supervising, 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 4 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, although neither situation happen often.

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 an identical structure.

III.5.3 Consultants

Consultants also contribute to the total manpower available to the State Transportation Agency. Productivity of consultants is considered comparable to the most productive in-house staff in this model, and so is their pay grade.

III.5.4 Workforce Allocation

The workforce allocation sector of the model assigns all available workforce including in-house staff and consultants proportionally to the eight types of work according to their respective required workforce to utilize the budget.

III.5.5 Workforce Budget

The size and total salary of the in-house staff are often restricted by an internal workforce budget at State Transportation Agencies. This model simulates the restriction by setting a budget cap. When employees exit the agency, a portion of the current budget becomes available for hiring new employees, and the agency can only use the freed budget for in-house new hire. When the available budget for new hire is not enough, the agency may try to adjust the in-house workforce budget the same way they adjust road and bridge fund. However, adjustments may not be instant since change in budget requires approval from the state.

Unlike in-house staff, payment to consultants can be charged to project fund from the specific project the consultants are retained to work on. Therefore the model tracks payment paid to consultants separately from the in-house workforce budget.

III.5.6 Recruiting Decisions

The model compares the in-house workforce level to the desired level to fully utilize all project fund to determine the need for hiring or outsourcing instead of comparing the in-house level to the desired level for reaching the performance target, since hiring new employees or consultants for unfunded work is completely unproductive. Once the need for recruiting is quantified, the State Transportation Agency can decide between in-house new hire and consultants. Within in-house new hire, the agency also need to decide at which experience level they should be hiring. Table III.7 summarizes the advantages and disadvantages of different recruiting strategies that the model is able to reflect.

Table III.7: Advantages and Disadvantages of Different Recruiting Strategy

		Advantages	**Disadvantages**
In-House vs. Consultants	**In-House**	Less Expensive; Provide sustainable increase in available manpower	Require more time to fill position, especially when hiring at high experience level
	Consultants	More productive; Less time required to fill position	Expensive; Unsustainable
In-House Low Experience vs. In-House High Experience	**Low Experience Level**	Less expensive; Easier/faster to hire; Has potential to gain experience	Less productive
	High Experience Level	More expensive; More productive	Harder to find and hire

The difference in recruiting strategies can be simulated by varying the values of several control variables. Simulation runs can be used to find the most cost effective or the best performing strategy.

III.5.7 Exogenous Variable in the Workforce Sectors

Table III.8 lists all exogenous variables used in the workforce sectors with control variables highlighted.

Table III.8: List of Exogenous Variables in the Workforce Sectors

Sector	Variable Name	Value/Range	Unit
Road Workforce Requirement	"Engineer Productivity - New Mileage"	56,248	Dollar/Eqv Person
	"Engineer Productivity - Road Fair to Good Repair"	255,191	Dollar/Eqv Person
	"Engineer Productivity - Road Poor to Fair Repair"	233,907	Dollar/Eqv Person
	"Engineer Productivity - Road Poor to Good Repair"	71,922	Dollar/Eqv Person
	"Technician Productivity - New Mileage"	35,155	Dollar/Eqv Person
	"Technician Productivity - Road Fair to Good Repair"	76,557	Dollar/Eqv Person
	"Technician Productivity - Road Poor to Fair Repair"	105,258	Dollar/Eqv Person
	"Technician Productivity - Road Poor to Good Repair"	35,961	Dollar/Eqv Person
Bridge Workforce Requirement	"Engineer Productivity - Bridge Fair to Good Repair"	146,932	Dollar/Eqv Person
	"Engineer Productivity - Bridge Poor to Fair Repair"	153,721	Dollar/Eqv Person
	"Engineer Productivity - Bridge Poor to Good Repair"	29,722	Dollar/Eqv Person
	"Engineer Productivity - New Bridge Area"	11,219	Dollar/Eqv Person
	"Technician Productivity - Bridge Fair to Good Repair"	44,080	Dollar/Eqv Person
	"Technician Productivity - Bridge Poor to Fair Repair"	69,174	Dollar/Eqv Person
	"Technician Productivity - Bridge Poor to Good Repair"	14,861	Dollar/Eqv Person
	"Technician Productivity - New Bridge Area"	7,012	Dollar/Eqv Person

Table III.8 (Continued): List of Exogenous Variables in the Workforce Sectors

Sector	Variable Name	Value/Range	Unit
Engineer	Initial EIT	192	Person
	"% EIT quit/fired"	0.02999	Dimensionless/Month
	"% Engineer Gap to Be Filled by Hiring EIT"	0-100	Dimensionless
	"% Engineer Gap to Be Filled by Hiring Licensed Engineer"	0-100	Dimensionless
	"% Engineer Gap to Be Filled by Hiring Senior Licensed Engineer"	0-100	Dimensionless
	"% Licensed Engineer Quit/Fired"	0.20000	Dimensionless/Month
	"% Senior Licensed Engineer Quit/Fired"	0.10000	Dimensionless/Month
	EIT Productivity Factor	0.5	Dimensionless
	Initial Licensed Engineer	288	Person
	Initial Senior Licensed Engineer	479	Person
	Licensed Engineer Productivity Factor	1	Dimensionless
	Senior Licensed Engineer Average Service Time until Retire	120	Month
	Senior Licensed Engineer Productivity Factor	2	Dimensionless
	Time Required for EIT to Obtain License	48	Month
	Time Required for Licensed Engineer to Gain Experience	72	Month
	Time Required to Hire EIT	1	Month
	Time Required to Hire Licensed Engineer	2	Month
	Time Required to Hire Senior Licensed Engineer	3	Month

III.6 Work Accomplish Rate Sector

The actual amount of work in each type that the agency is able to accomplish is restrained by planned amount, budget, available engineers and available technicians. Figure III.9 shows the factors taken into consideration when determining work accomplish rate for new highway mileage construction. Actual productivity shall be the minimum of the four factors considered. Accomplish rates for other types of work shall be determined in the same manner.

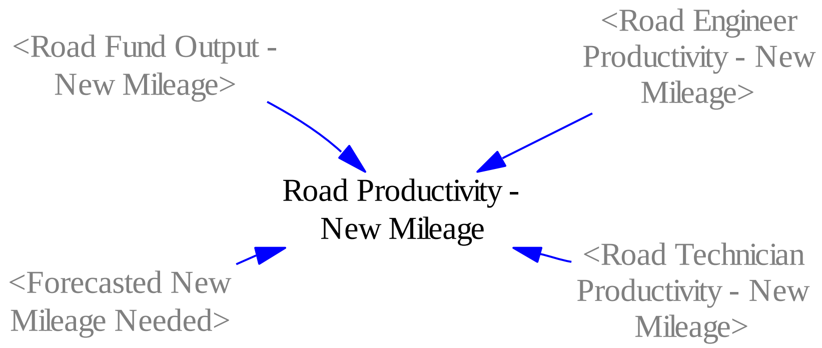


Figure III.9: Determining Actual Work Accomplish Rate

The work accomplish rates determined from this sector are fed back into the workflow sectors as work actually performed.

III.7 Summary

The formal model was built upon reasonable dynamic hypotheses derived from literature review and meeting with transportation experts. Data from literature, federal database and state database were used to provide basis for values and equations in the formal model. Possible drivers (control variables) of system behavior were identified. In the next chapter, output from simulation runs will be used to analyze the model’s behavior in response to changes in control variable.

CHAPTER IV NOTABLE MODEL BEHAVIORS AND ANALYSES

IV.1 Overview

The formal model was used to conduct simulation runs to mimic a variety of scenarios by differing model input representing target performance levels, funding levels, and recruiting strategies. Output of the simulation runs were observed to test whether the model was able to generate reasonable behavior modes as well as to gain insight on drivers of system behavior. Sensitivity runs and statistical screening will be conducted on key drivers to identify each driver's influencing power. By performing these analyses of model output, decision makers in State Transportation Agencies can be able to target certain drivers when designing policies to solve staffing problems.

IV.2 Base Case Behaviors

The base case run simulates a set of ideal conditions at a State Transportation Agency. Inputs of the base case simulation assumes that the state's highway system is already in relatively good shape (with 50% of the road pavement in good condition, 90% of the road pavement in acceptable condition, 74% of the bridge area in good condition and 78% of the bridge area in acceptable conditions), and would like to maintain the current performance level while increasing total highway capacity by 0.02% each month. The agency will repair all the highway pavement and bridges that are becoming unsuitable for driving (about to retire from the "Poor Road" or the "Poor Bridge" stocks). The simulation also assumes the agency has unlimited fund for road and bridge work and can hire as many Engineers and Technicians as needed. In this scenario, the agency is always able to complete all required work to maintain the performance level. In context of the causal loop diagram showed in Figure II.1, Loop B1 should be the dominating loop, and Loop R1 is never in effect. When a balancing loop dominates, dynamic systems should produce a "goal seeking" behavior mode, in which the performance variables move towards their equilibrium values. Figure IV.1 shows the percentage of good pavement and the percentage of good bridge area over the 25-year (300 months) simulation period. Figure IV.2 shows the percentage of acceptable (fair and better) pavement and the percentage of acceptable bridge area.

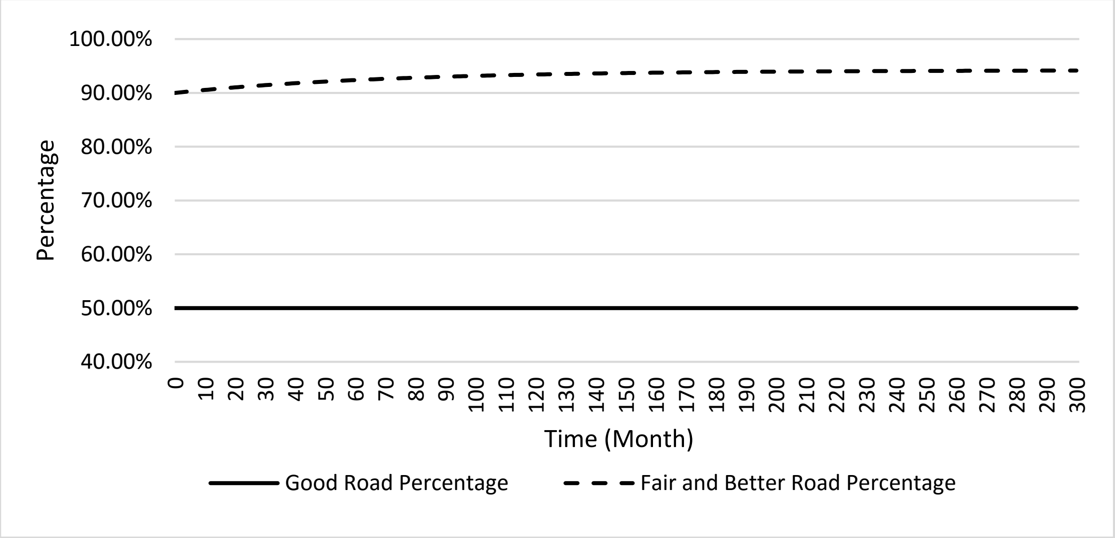


Figure IV.1: Base Case Pavement Conditions

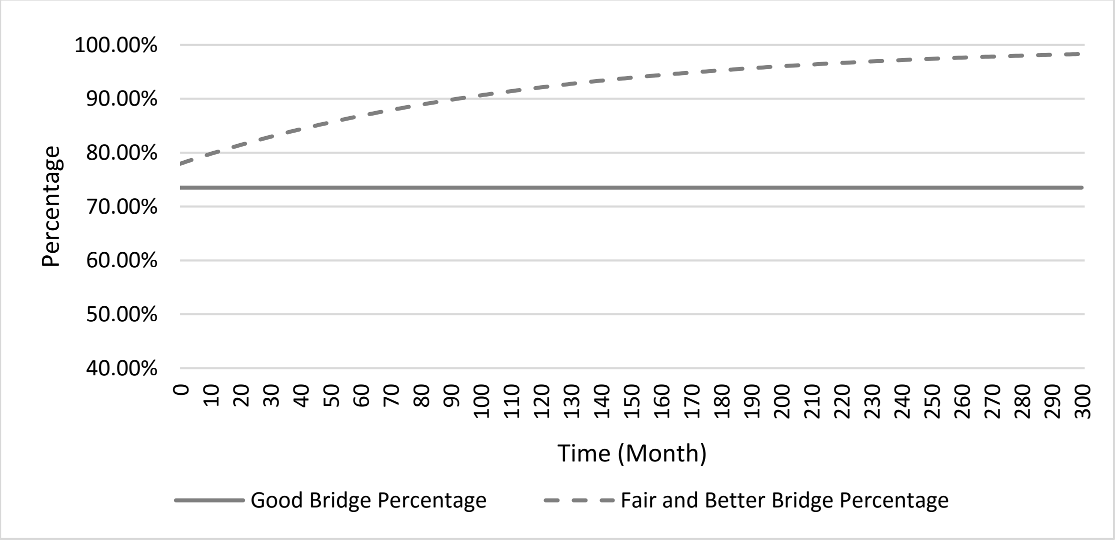


Figure IV.2: Base Case Bridge Conditions

As expected, the percentage of good pavement and the percentage of good bridge area stayed at 50% and 74% respectively, however the percentage of acceptable road and the percentage of acceptable bridge increases beyond their target values before the system reaches equilibrium status. This happens because the State Transportation Agency's goal includes maintaining their highway capacity, which means the agency can't allow any section of the road or any bridge currently categorized as "Poor Road" and "Poor Bridge" to further degrade and exit the system. So on top of performing work required to reach the percentage goals, the agency also restores the road and bridges that are about to exit the system to fair conditions at least.

Figure IV.1 and Figure IV.2 supports the Federal Highway Administration's decision back in 2006 on replacing the percentage of acceptable road with the percentage of good road as the priority performance goal of the highway system. Simulation output suggests that due to the dynamic flow within the "stock-and-flow" system, as long as the State Transportation Agency maintains a decent percentage of good pavement while maintaining the total highway capacity, the percentage of acceptable pavement will stay at a desirable level.

Figure IV.3 shows the required road fund for the base case scenario and Figure IV.4 shows the required bridge fund. Both curves display typical "goal seeking" behavior which is consistent with the behavior mode of a system dominated by a balancing loop. At the beginning of the simulation, the system is the furthest from its equilibrium status therefore flows within the system are at their maximum values, which means most work is required. As the system moves towards the equilibrium status, flows slow down and approaches a constant value. Since flows indicate the amount of work performed in different categories, flow rates have a direct relationship with required funding level.

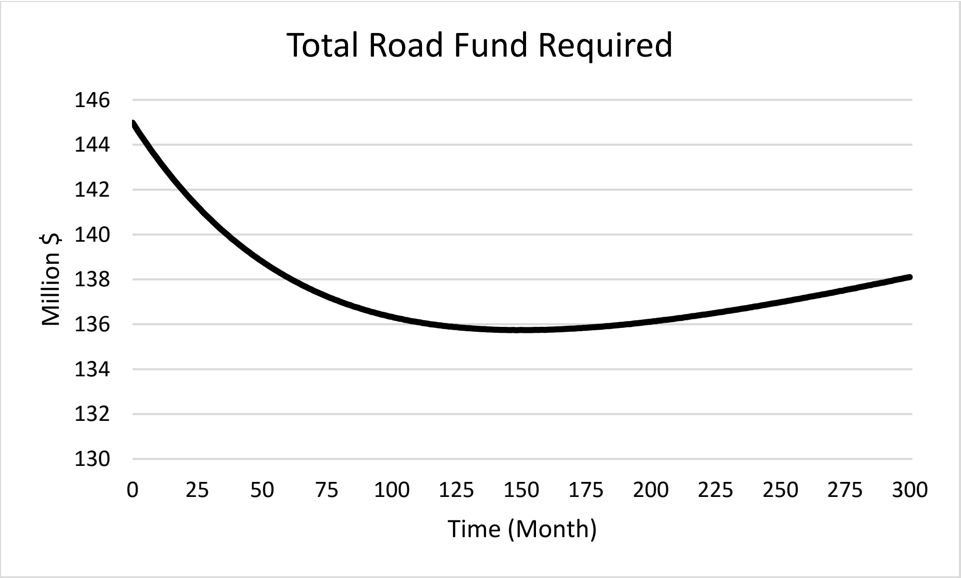


Figure IV.3: Base Case Required Road Fund

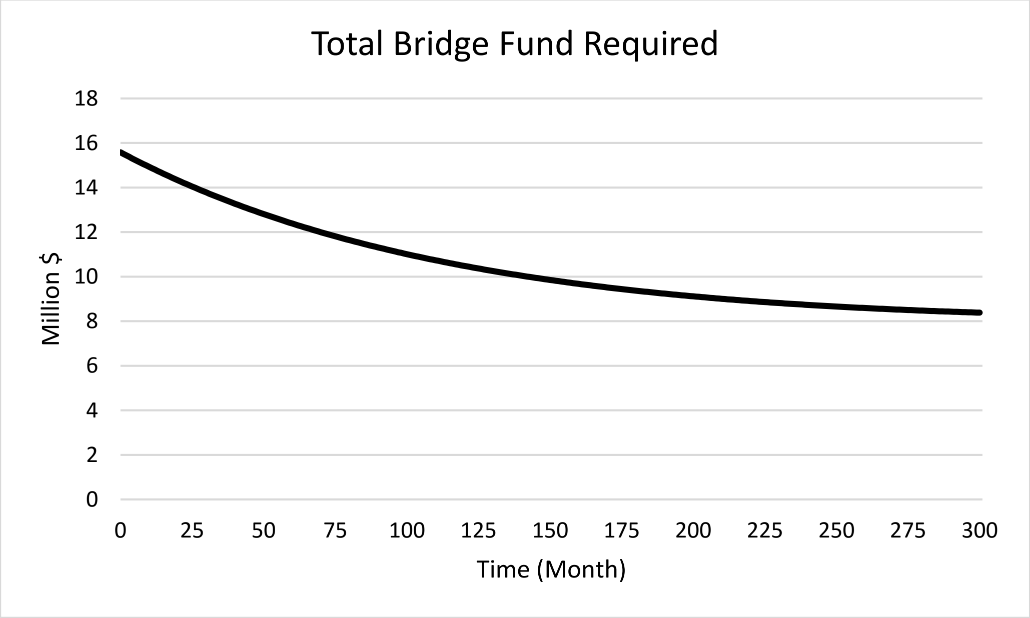


Figure IV.4: Base Case Required Bridge Fund

In Figure IV.3, the required road fund decreases as the system gets closer to the equilibrium status, stays flat around Month 150, and begins increasing since the total road capacity is increasing. In Figure IV.4, the required bridge fund is yet to reach its equilibrium status at the end of the simulation.

Figure IV.5 shows the required equivalent number of Engineers and Technicians throughout the simulation period.

Goal seeking behavior mode is again observed in both curves. As the system approaches the equilibrium status, the flow rates within the system representing work accomplish rates decrease until reaching constant levels that allows the system to maintain a steady-flow condition. As required work accomplish rates decrease, required number of Engineers and Technicians also decrease. Another factor that contributes to the decreasing of required fund and workforce is that as the system moves towards the equilibrium status, the amounts of “Poor Road” and “Poor Bridge” decrease. When there is a large amount of “Poor Road” and “Poor Bridge” in the system, the State Transportation Agency is forced to carry out more expensive repair works as suggested by the unit prices for the eight work types (See unit pries in Table III.5.).

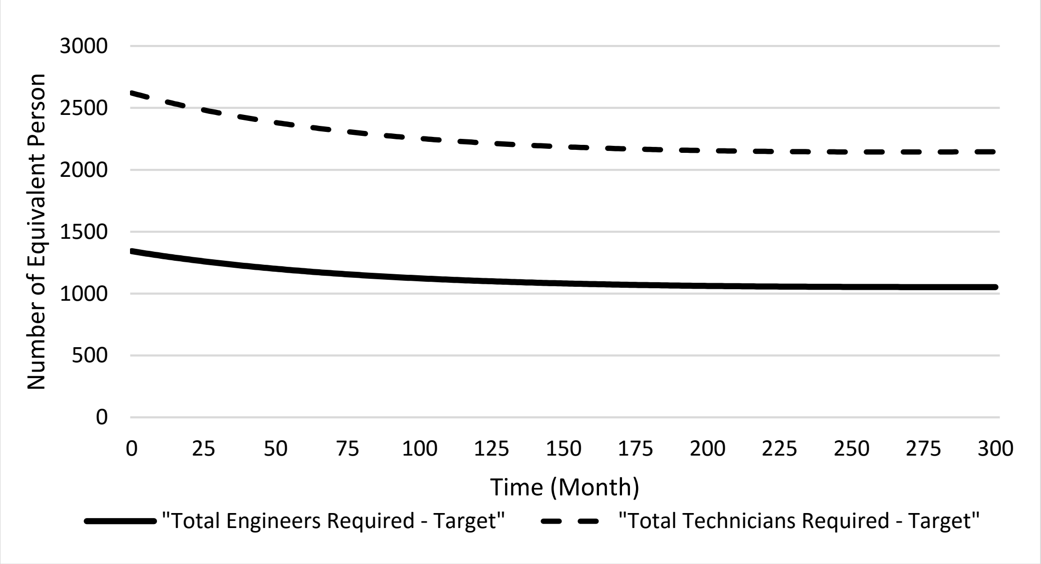


Figure IV.5: Base Case Required Workforce

IV.3 Impact of Performance Target on Model Behavior

IV.3.1 Notable Behaviors Due to Varying Performance Targets

Varying the initial performance levels and the target performance levels results in variation in required funding level and workforce. Figure IV.6 – Figure IV.8 shows the model output for 3 simulation runs (Table IV.1 shows the settings for each simulation), each assuming the State Transportation Agency has access to unlimited fund and workforce:

Table IV.1: Settings for Simulations Varying Initial and Target Performance Levels

	Base Case	Simulation 1	Simulation 2
Initial Good Road Percentage	50%	50%	55%
Initial Acceptable Road Percentage	90%	90%	95%
Target Good Road Percentage	50%	55%	55%
Target Acceptable Road Percentage	90%	95%	95%

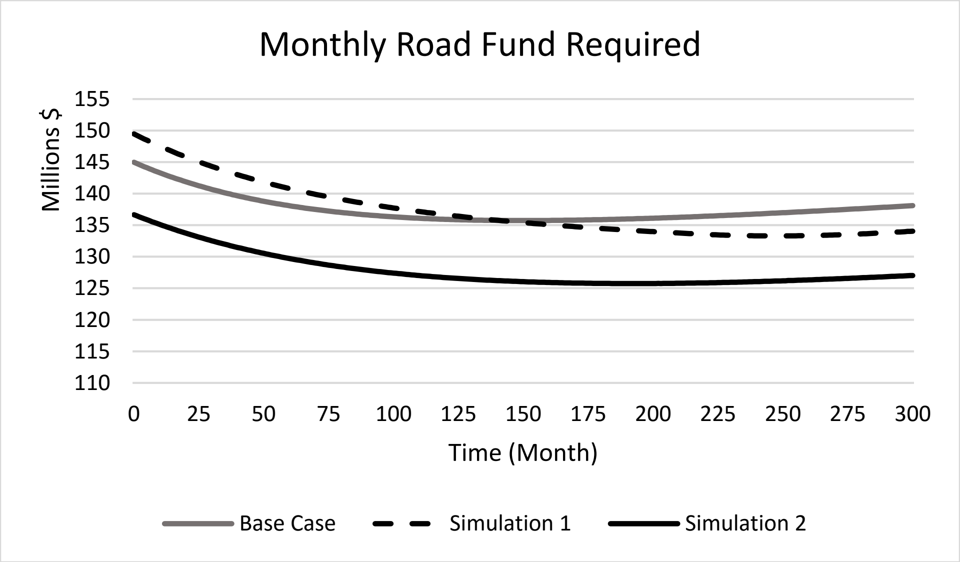


Figure IV.6: Monthly Road Fund Required for Different Performance Levels

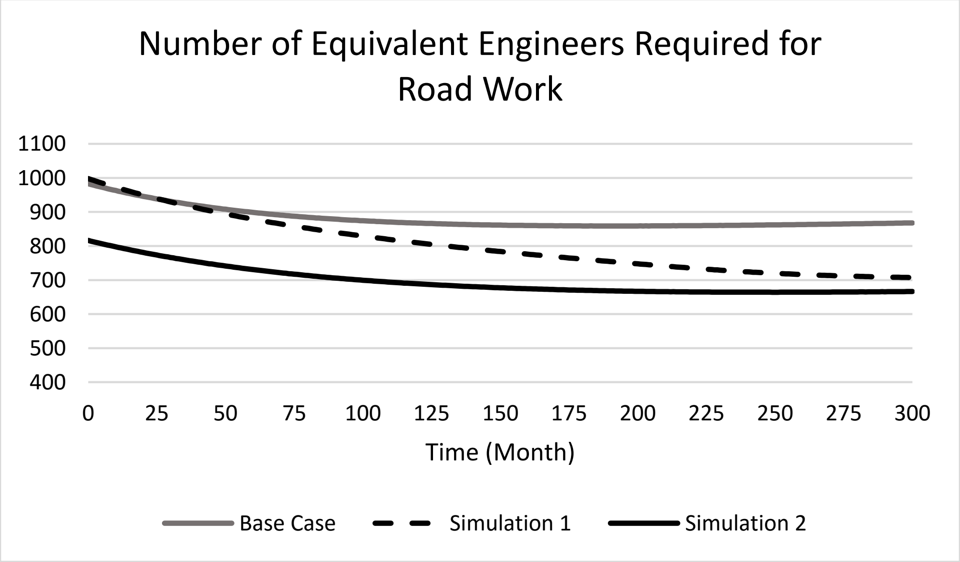


Figure IV.7: Engineers Required for Different Performance Levels

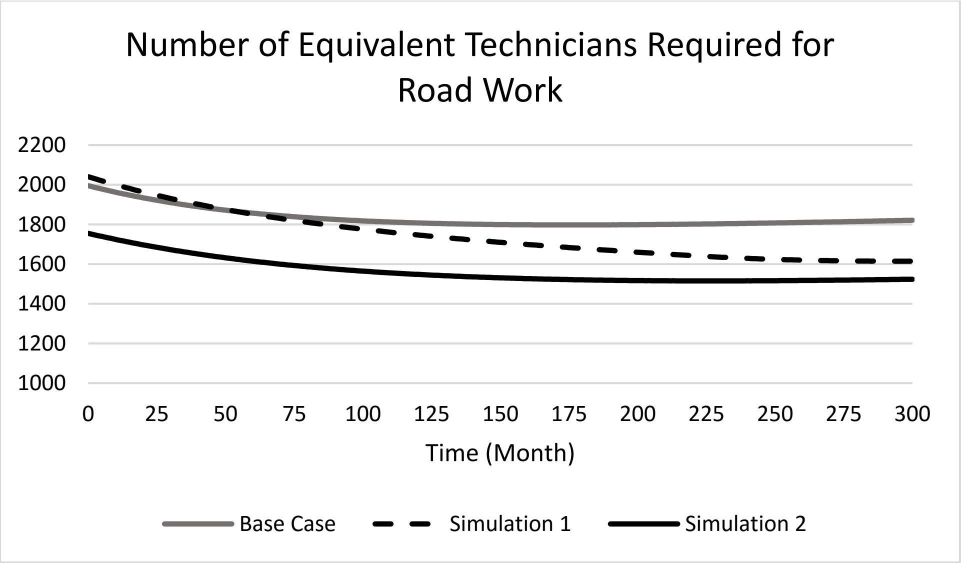


Figure IV.8: Technicians Required for Different Performance Levels

The base case mimics a scenario in which the State Transportation Agency plans to maintain the road performance level. Simulation 1 mimics a scenario in which the State Transportation Agency plans to improve the road performance level. And Simulation 2 mimics scenario in which the State Transportation Agency plans to maintain their performance at an already higher (than the base case) level.

Simulation 1 requires more fund, more Engineers and more Technicians than the base case during the early stages of the simulation, since chasing a higher performance target usually means having to do more work. However, as the simulation goes on, Simulation 1 becomes less demanding than the base case in each of the three figures. Potential reason for this observation could be that, as the system performance improves, less road remains in the poor category and the agency don't have to do as much expensive repairs as they do in the base case. This reason also supports the comparison of Simulation 2 to the base case. In both scenarios the State Transportation Agency is planning to maintain the performance level, but maintaining a higher performance level could be less demanding than maintaining a lower performance level, because lower level requires more expensive work. In this comparison, a system's performance is somewhat similar to a person's health. Just like a healthy person requires less care and received less medical bill, a highway system in a healthier condition requires less heavy maintenance.

IV.3.2 Sensitivity Runs on Performance Target

Previous simulations already demonstrated that maintaining good road percentage at 55% and fair acceptable road percentage at 95% is less demanding than maintaining the percentages at 50% and 90% respectively. To test whether maintaining a higher performance level is always less demanding than maintaining a lower performance, sensitivity runs were performed by varying the initial performance level. In these runs, the good road percentage ranges from 50% to 60%, and the acceptable road percentage ranges from 90% to 95% at the beginning of the simulation (according to Federal Highway Administration's database, most states fall within these ranges). A total of 11 simulations were run using the software. Initial performance levels of the 11 runs are listed in Table IV.2.

Table IV.2: Initial Performance Level for Sensitivity Simulations 3-13

Simulation #	3	4	5	6	7	8	9	10	11	12	13
Good Road Percentage	50	51	52	53	54	55	56	57	58	59	60
Acceptable Road Percentage	90	90.5	91	91.5	92	92.5	93	93.5	94	94.5	95

Figure IV.9 is a contour plot for required road fund generated using the sensitivity output.

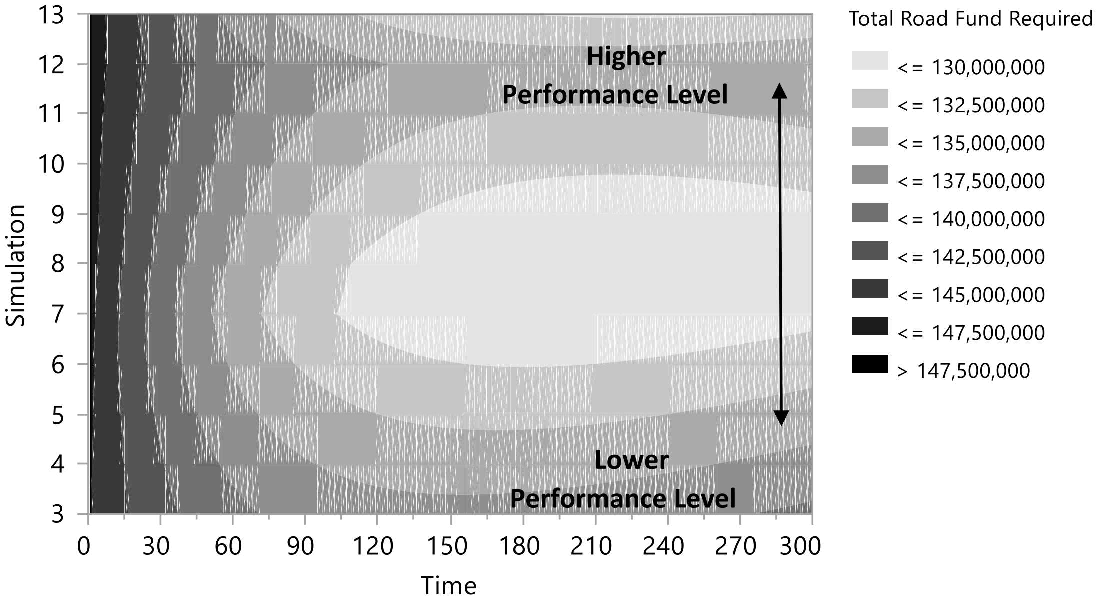


Figure IV.9: Contour Plot of Required Road Fund for Maintaining Different Performance Levels

In Figures IV.9 to IV.11, the “Simulation #” matches the “Simulation #” in Table IV.2, in which a higher simulation number also represents a higher performance level. The contour plot suggests that, for performance levels represented by Simulations 3-7, at any time during the simulation period, maintaining a higher performance level requires less fund. When the performance level falls between the levels marked by Simulation 8 and Simulation 12, at any time during the simulation period, maintaining a higher level requires more fund.

Figure IV.10 and IV.11 show the required road fund at the initial time and the final time respectively.

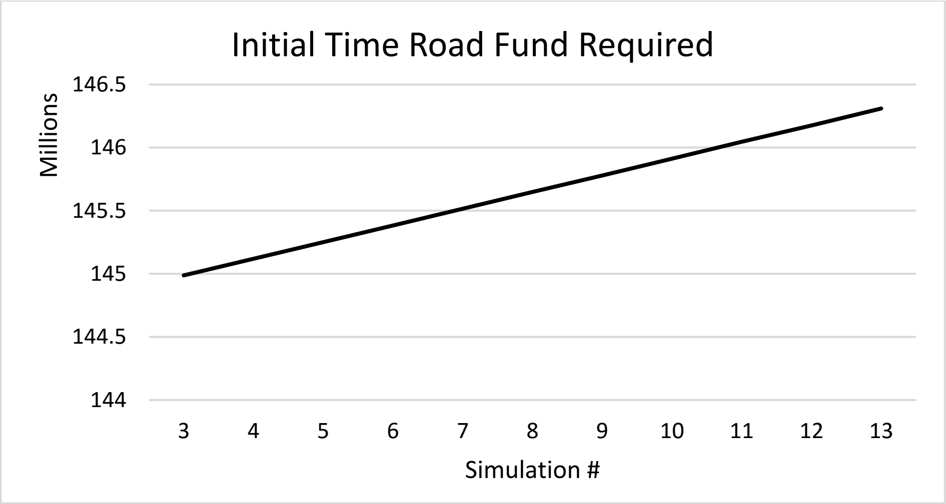


Figure IV.10: Sensitivity Output of Initial Time Required Road Fund by Maintaining Different Performance Levels

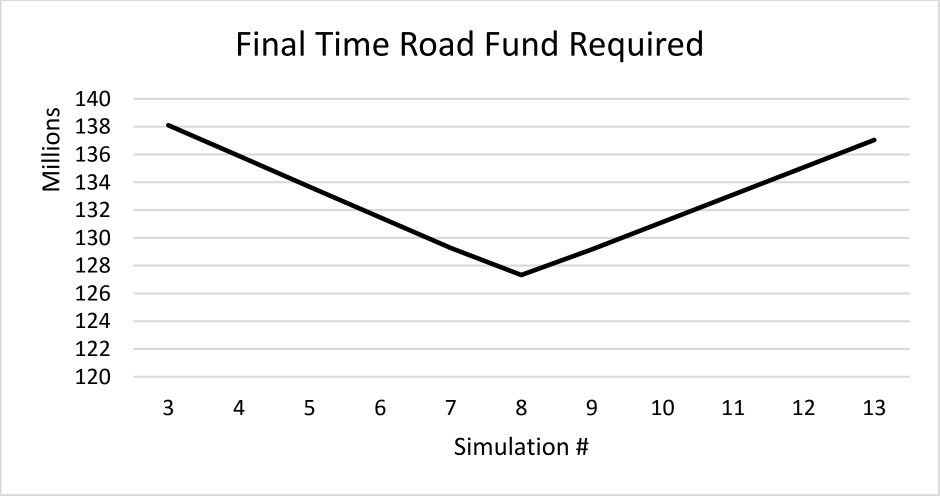


Figure IV.11: Sensitivity Output of Final Time Required Road Fund by Maintaining Different Performance Levels

The output suggests during the early stages of the simulation, maintaining a higher performance is more demanding than maintaining a lower performance level, and the required road fund at the initial time of the simulation appears to have a positive linear relationship with the performance level (See Figure IV.10).

Sensitivity output near the final time of the simulation suggests that, as the performance level moves higher, the required road fund decreases linearly at first (Simulation 3-Simulation 8 in Figure IV.11). After Simulation 8, the required road fund begins increasing. Referring back to the analogy between the performance of a highway system and the health conditions of a person, maintaining an extremely high road performance level is similar to maintaining an extremely healthy body. The State Highway Administration may need to perform preventive care of the infrastructure and a lot of additional minor maintenance activities, and the reduced amount of expensive repair work is not enough to balance it out.

At the final time of the simulation, the system has already reached its equilibrium status, which means the amount of road fund required is used to maintain a steady flow within the system that could go on indefinitely. Therefore, the performance level in Simulation 8, which required the agency to keep 55% of the pavement in good condition and 92.5% of the pavement in acceptable condition, may be close to the most cost efficient performance target for the long run.

Figure IV.12 and Figure IV.13 shows the contour plots created using the sensitivity output for required Engineers and required Technicians for all road work.

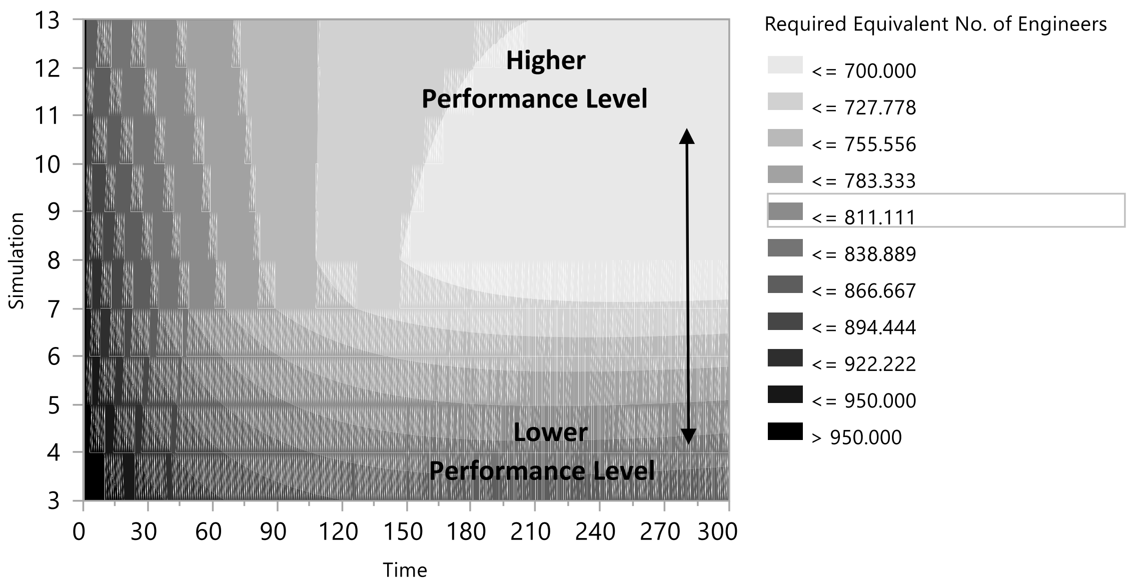


Figure IV.12: Contour Plot of Required Engineers for Maintaining Different Performance Levels

The output suggests at the early stages of the simulation, higher performance level demands more Engineers. Between the performance levels marked by Simulation 8 and Simulation 13, before Month 150, required Engineers decrease very slowly as the performance level raises, but after Month 150, required Engineers increases slightly. Model output for required Engineers is much less sensitive to changes in performance at higher performance levels (good road percentage greater than 55% and acceptable road percentage greater than 92.5%) than at lower performance levels. As the performance level raises from Simulation 3 to Simulation 8, required Engineers decreases mainly due to reduced amount of expensive, complex repair work associated with poor pavement. However, from Simulation 8 to Simulation 13, the required Engineers increases mainly due to additional amount of minor repair work and preventive care of highway pavement, which require much less design and inspection work than the complex repair work, therefore required number of Engineers are not as sensitive to changes in performance levels.

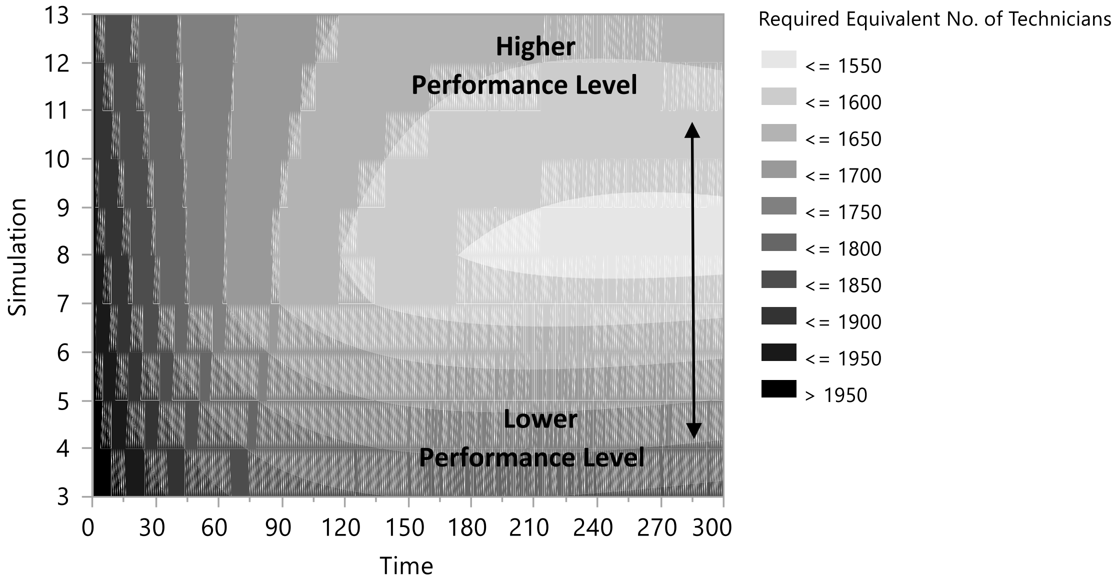


Figure IV.13: Contour Plot of Required Technicians for Maintaining Different Performance Levels

The sensitivity output for required Technicians shows similar behavior mode to that of required Engineers, although near the final time of the simulation, the required number of Technicians appear to be more sensitivity to increased amount of minor road repair work.

The previous sensitivity runs provide output to analyze system behavior while maintaining a constant performance level. The next set of sensitivity runs focus on improving performance. Assume a state's highway system currently has 50% of road pavement in good condition and 90% of road pavement in acceptable condition and the agency plans to increase the percentages linearly towards the target values throughout the .25-year simulation period. Table IV.3 lists the target performance levels at the end of the simulation period for a set of 10 sensitivity runs.

Table IV.3: Target Performance Level for Sensitivity Simulations 14-23

Simulation #	14	15	16	17	18	19	20	21	22	23
Target Good Road Percentage	51	52	53	54	55	56	57	58	59	60
Target Acceptable Road Percentage	91	92	93	94	95	96	97	98	99	100

Figure IV.14 to Figure IV.16 exhibit the sensitivity output as contour plots for required road fund, required equivalent of Engineers and required equivalent of Technicians for the 10 runs.

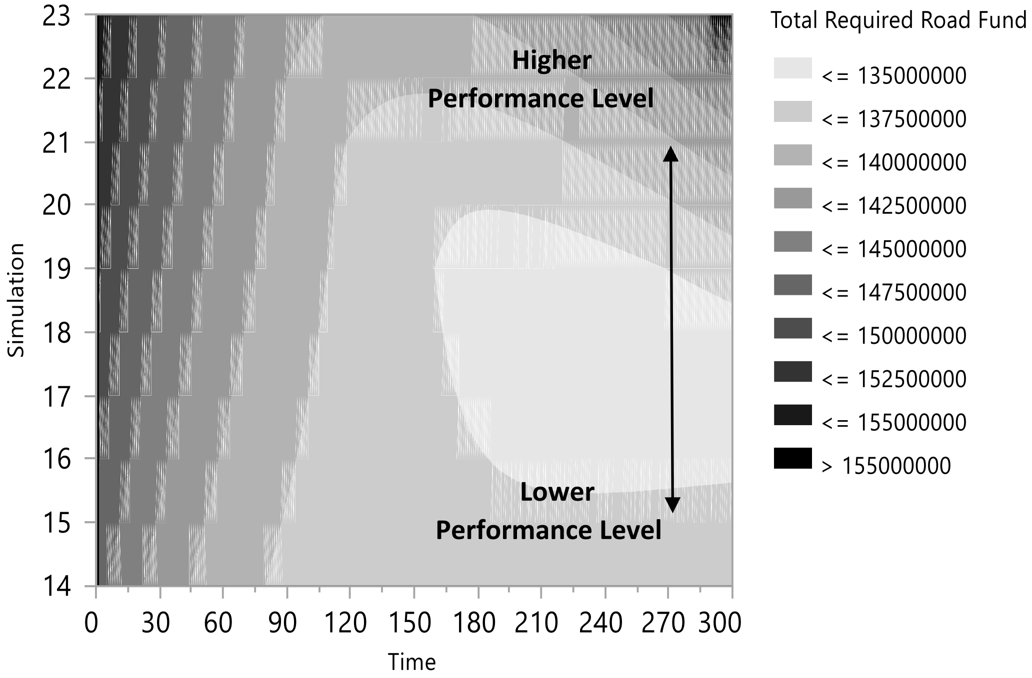


Figure IV.14: Contour Plot of Required Equivalent No. of Engineers for Chasing Different Performance Levels

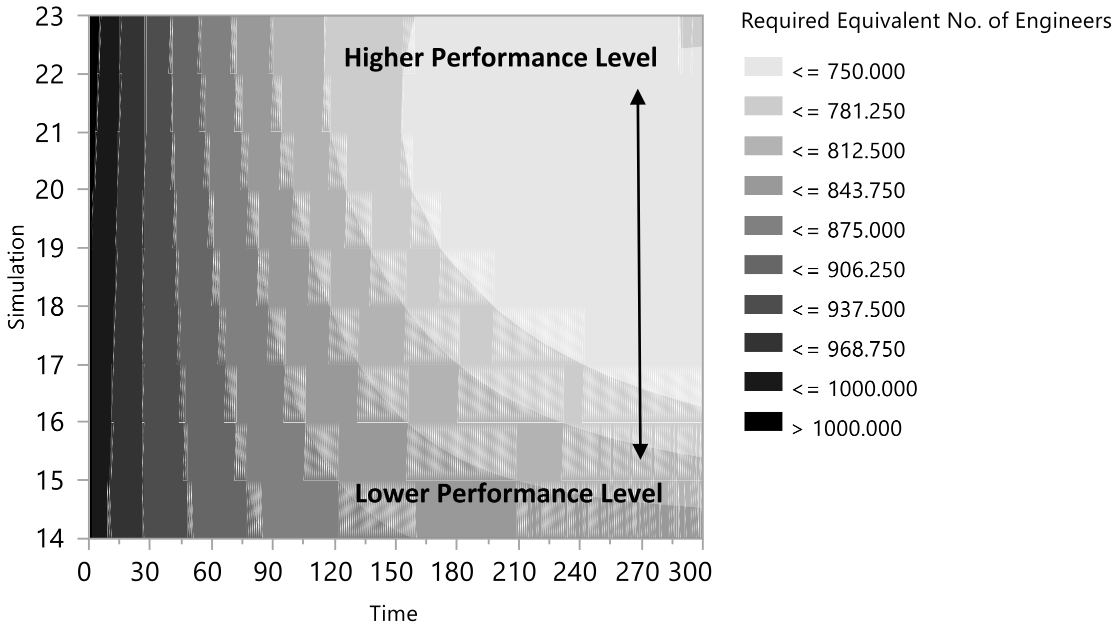


Figure IV.15: Contour Plot of Required Equivalent No. of Technicians for Chasing Different Performance Levels

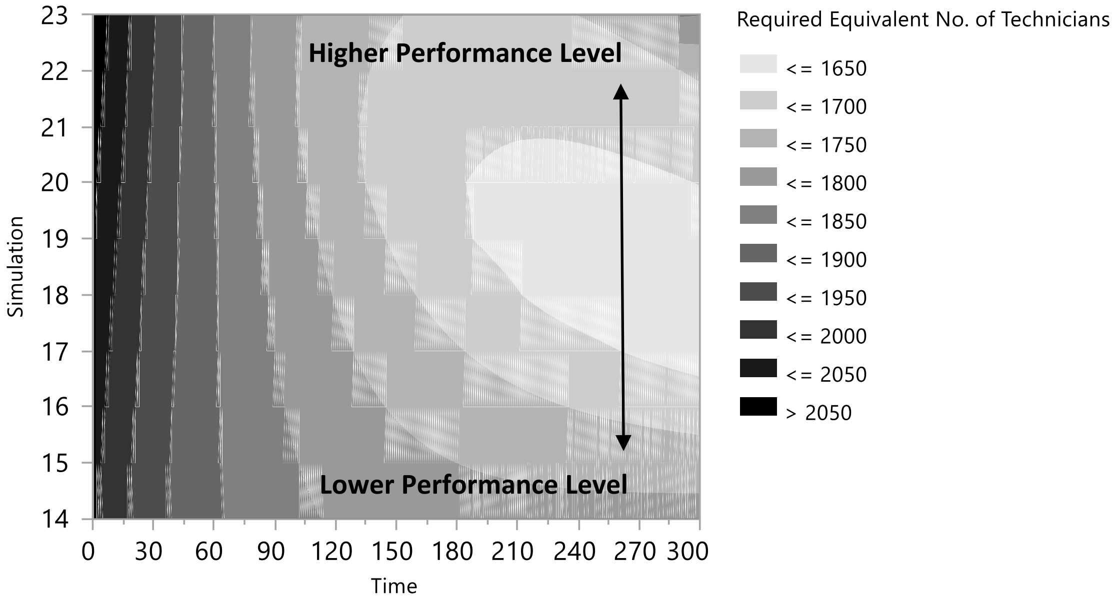


Figure IV.16: Contour Plot of Required Road Fund for Chasing Different Performance Levels

The three types of resource (fund, Engineers and Technicians) have some similarity in their behavior. In the early stages of the simulations, chasing higher performance targets demands more fund, more Engineers and more Technicians. As the simulation goes on, the system approaches the equilibrium status, keeping the system in a better shape gets rewarded, and the required fund, Engineers and Technicians decrease as the target performance level raises.

Of the three type of resources, road fund is the most sensitive to changes in target performance levels during the early stages of the simulation, followed by Technicians, and Engineers are the least sensitive to changing target levels.

IV.4 Impact of Alternative Selection on Model Behavior

IV.4.1 Notable Behaviors Due to Varying Alternative Selection

In order to maintain the existing highway capacity, the State Transportation Agency must repair sections of the road and the bridges that are close to exit the system due to poor condition. When the need for such repairs becomes imminent, decisions have to be made as to whether the agency should perform major repair such as reconstruction to restore the pavement back in good condition or perform simpler repair such as resurfacing to restore the pavement in fair condition. For degrading functionally obsolete bridges, the agency needs to decide whether to replace or rehabilitate. Choice between these alternatives will result in different levels of requirements for fund and workforce.

Three simulation runs were performed to model three alternative selection strategies: Simulation 24 reconstructs all retiring poor road into good and replaces all retiring poor bridges with good bridges; Simulation 25 reconstructs 50% of retiring poor road into good road and repairs the rest 50% into fair road, while replacing 50% of the retiring poor bridges with good bridges and rehabilitating the rest 50% into fair bridges: and Simulation 26 repairs all retiring good road into fair road and rehabilitates all retiring bridges into fair bridges. Figure IV.17 to Figure IV.19 display the required fund, Engineers and Technicians for road work and Figure IV.20 to Figure IV.23 display the required resources for bridge work.

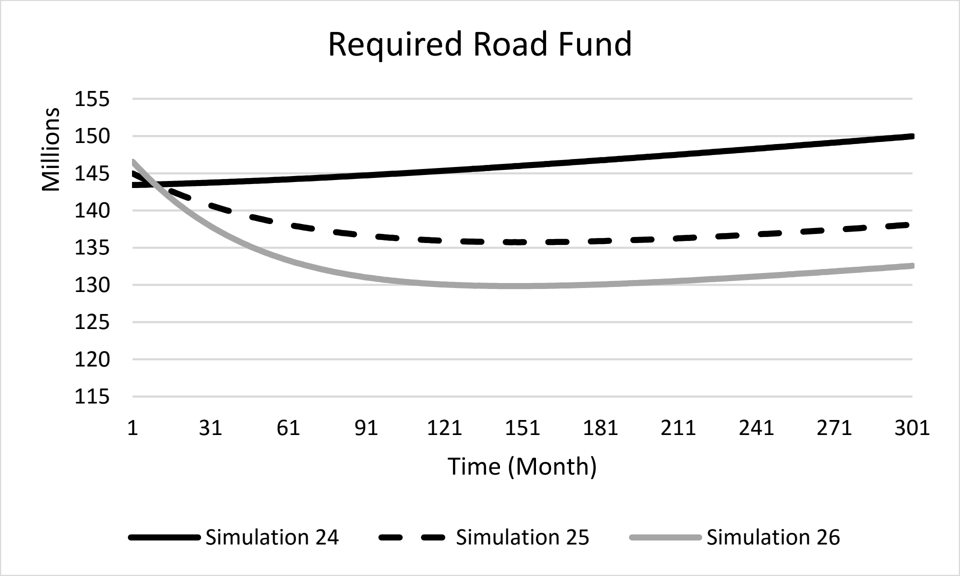


Figure IV.17: Required Road Fund Due to Varying Alternative Selection

The required road fund for the three simulations starts close to each other during the initial several months, then begins to separate. Simulation 24 which requires performing more expensive works demands more money for the long term. And Simulation 26 which always chooses the less expensive alternative requires the least amount of money.

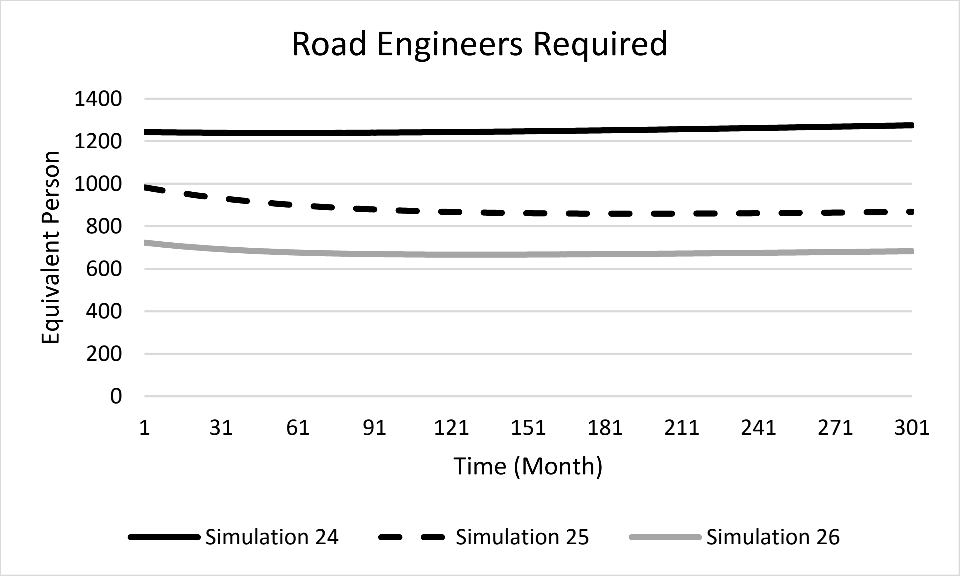


Figure IV.18: Required Road Engineers Due to Varying Alternative Selection

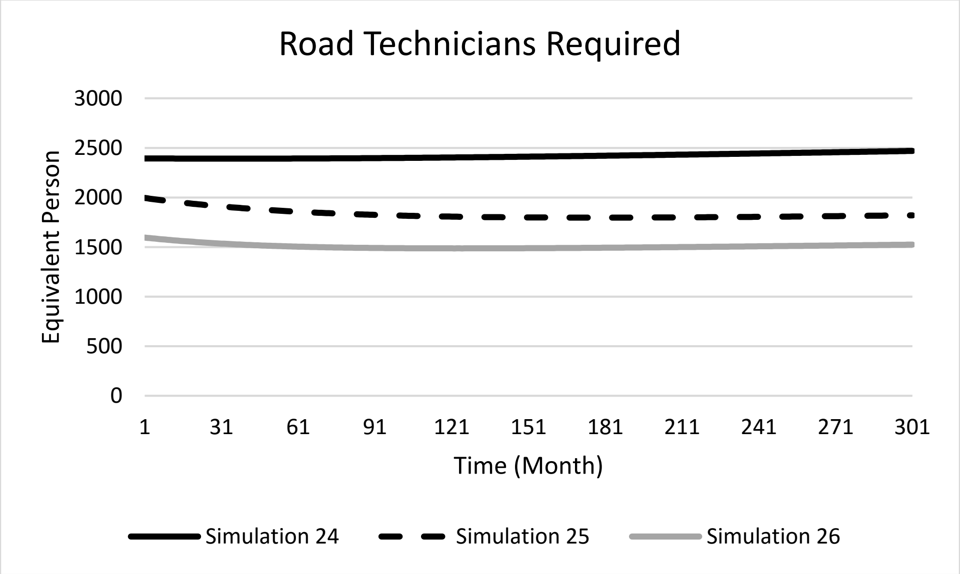


Figure IV.19: Required Road Technicians Due to Varying Alternative Selection

The more expensive, complex alternative also require more workforce including both Engineers and Technicians.

The model output for road work completely favors performing less expensive, simple repairs as opposed to performing costly and complex repairs. In Section II.4, Figure

II.4, the dynamic hypotheses suggested there could be a trade-off in required funding level when choosing more expensive alternative over simple alternative, because more expensive alternative results in longer lasting pavement quality and can reduce the frequency of future repair work. However, based on the current settings of performance targets and the values of the road stocks at equilibrium status, that trade-off will not happen.

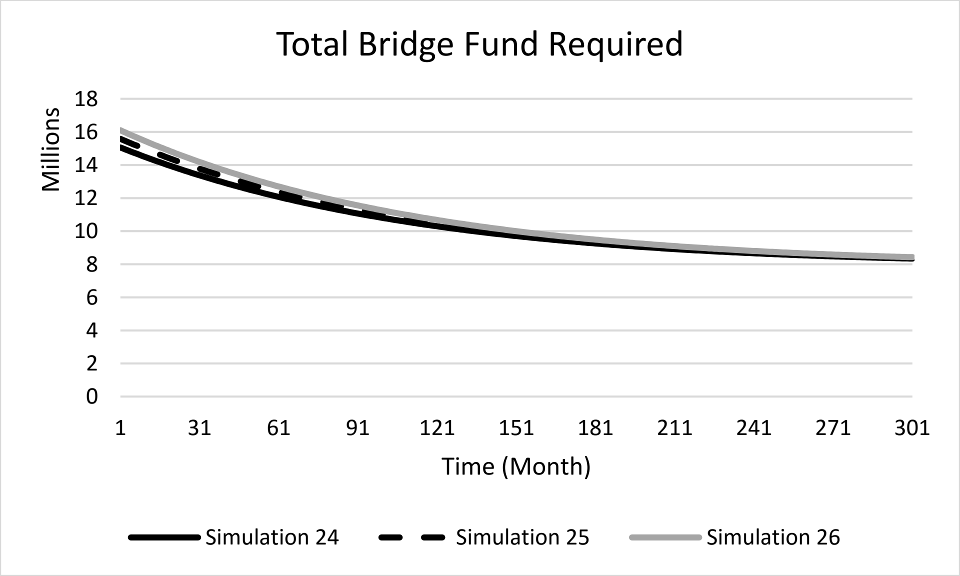


Figure IV.20: Required Bridge Fund Due to Varying Alternative Selection

Required bridge fund is not particularly sensitive to alternative selection based on the current target settings. Unexpectedly, Simulation 24 which replaces all retiring bridges with good bridges requires the least amount of bridge fund. However, the output can be explained by the graph for “Fair Bridge to Good Bridge Repair Rate” in Figure IV.21.

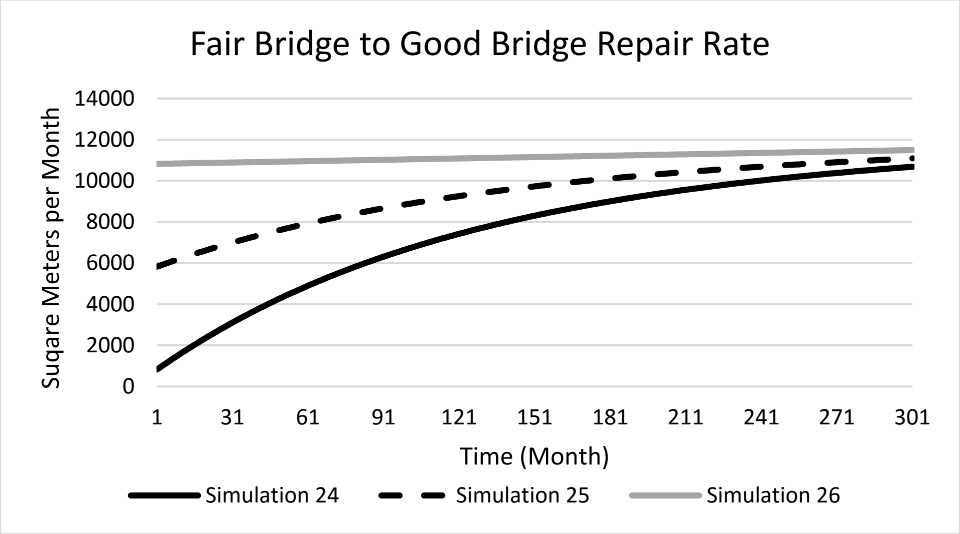


Figure IV.21: Fair Bridge to Good Bridge Repair Rate When Varying Alternative Selection

By replacing all retiring poor bridges rather than rehabilitating, the agency is required to perform a lot less bridge repair work to restore fair bridges to good bridges in order to maintain the good bridge percentage, which results in more saving than the extra cost associated with bridge replacement.

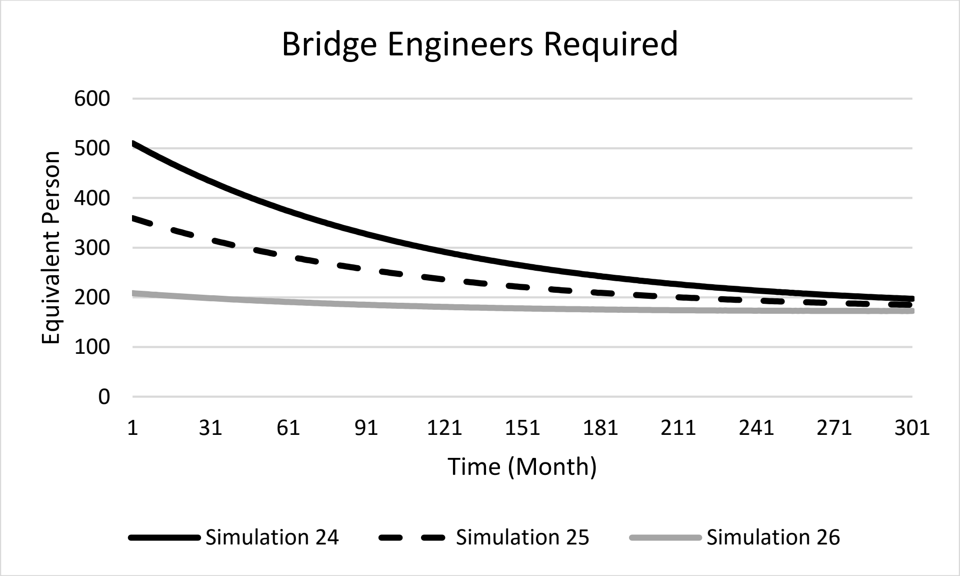


Figure IV.22: Required Bridge Engineers Due to Varying Alternative Selection

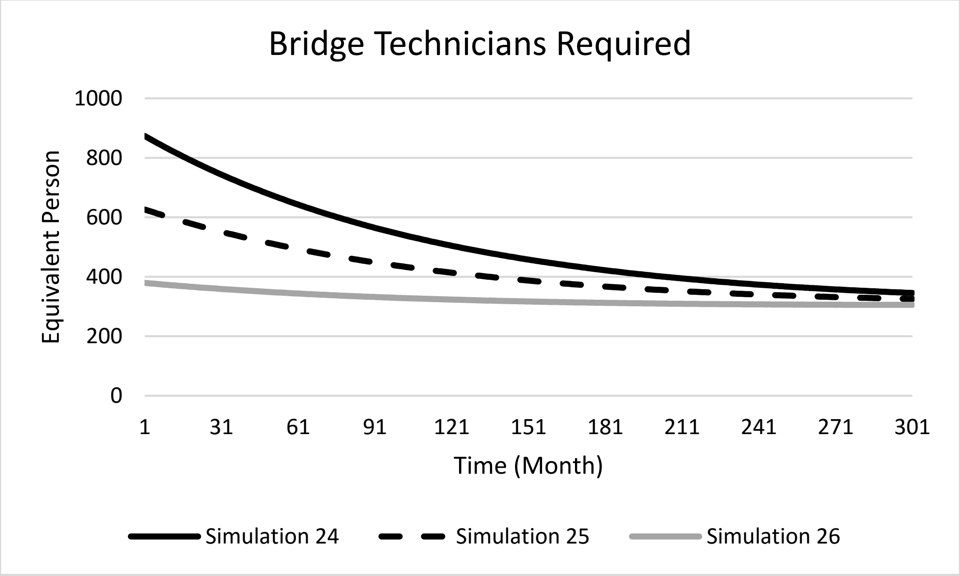


Figure IV.23: Required Bridge Technicians Due to Varying Alternative Selection

Although Simulation 24 requires the least amount of funding, performing more complex bridge replacement over bridge rehabilitation requires more Engineers and Technicians as displayed in Figure IV.22 and Figure IV.23.

IV.4.2 Sensitivity Runs on Alternative Selection

To examine system behavior in response to incremental changes in alternative selection, a set of 11 runs were performed in a sensitivity simulation. Table IV.4 is a summary of control values for the sensitivity simulation. Output are displayed in Figure IV.24 to Figure IV.29.

Table IV.4: Control Variable Settings for Sensitivity Simulation Varying Alternative Selection

Simulation #	% Retiring Road to Be Reconstructed into Good Road	% Retiring Road to Be Repaired into Fair Road	% Retiring Bridges to be Replaced	% Retiring Bridges to be Rehabilitated	Line Color in Figures
27	100	0	100	0	Dark
28	90	10	90	10	↑
29	80	20	80	20	
30	70	30	70	30	
31	60	40	60	40	
32	50	50	50	50	
33	40	60	40	60	
34	30	70	30	70	
35	20	80	20	80	
36	10	90	10	90	↓
37	0	100	0	100	Light

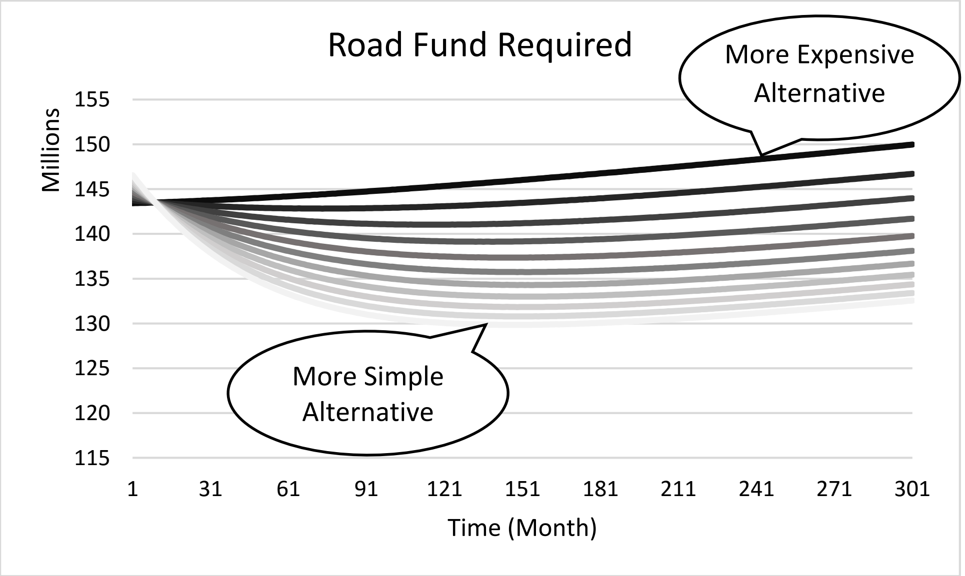


Figure IV.24: Sensitivity Output of Required Road Fund Due to Varying Alternative Selection

Required road fund is not sensitive to varying choices of alternatives during the initial several months in the simulation. As the simulation goes on, the sensitivity level of required road fund to alternative selection increases (lines spread apart). At any given time during the simulation, sensitivity level of required road fund to alternative selection is relatively low when the agency prefers simple and less expensive alternatives, and is higher when the agency prefers more expensive and complex alternatives.

Choosing to perform more of the complex projects over simple road repairs always results in increased demand of workforce as displayed in Figure IV.25 and IV.26. In general, the number of Engineers required for road work is more sensitive to alternative selection than the number of Technicians required. And both workforce types are more sensitive to alternative selection when the agency prefers complex alternatives over simple alternatives.

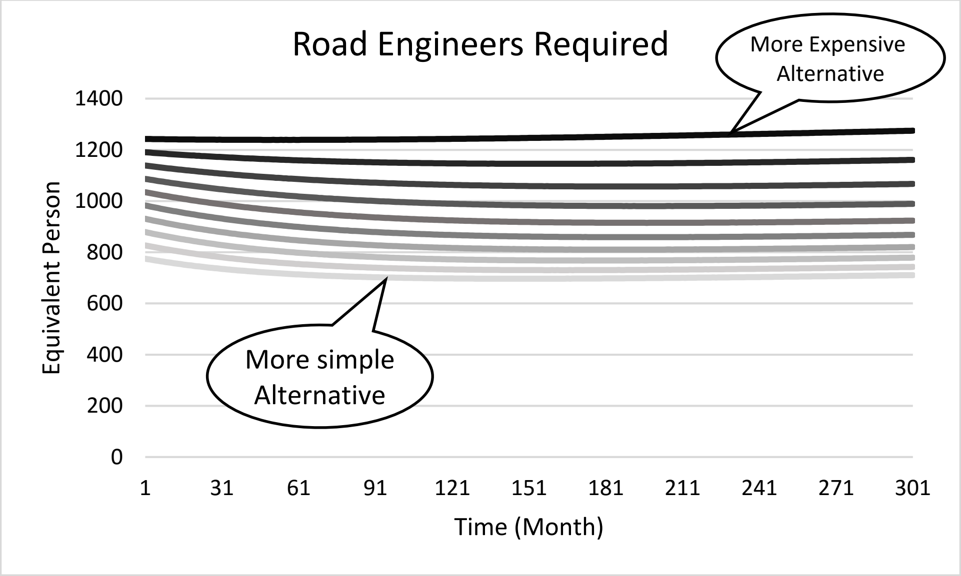


Figure IV.25: Sensitivity Output of Required Road Engineers Due to Varying Alternative Selection

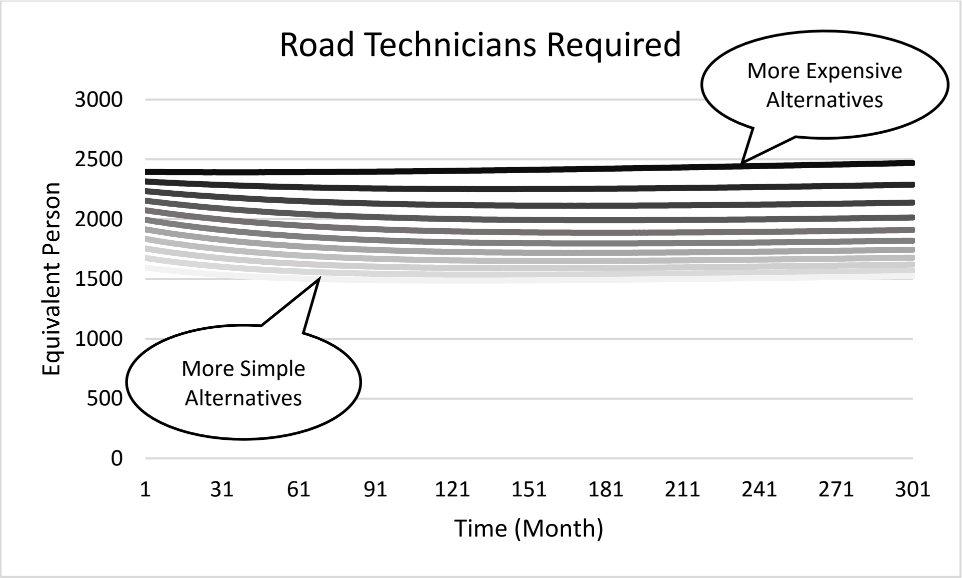


Figure IV.26: Sensitivity Output of Required Road Technicians Due to Varying Alternative Selection

The behavior of the bridge subsystem is different from that of the road subsystem. Based on the settings for the current bridge performance, the sensitivity level of required bridge fund to varying alternative selection stays low throughout the simulation although in the early stages, performing more bridge replacement is slightly more cost effective than bridge rehabilitation (Figure IV.27). Possible reason of such behavior could be that the agency is trying to maintain a higher percentage of good bridge (73%) with a very low percentage of fair bridge (only 1%). Performing a lot of bridge rehabilitation alone will not help the agency accomplish their performance target.

Required number of bridge Engineers and Technicians are very sensitive to alternative selection during the early stages of the simulation, and their sensitivity levels both decreases as time goes by and the system reaches equilibrium status. Again, required Engineers is more sensitive than required Technicians to alternative selection.

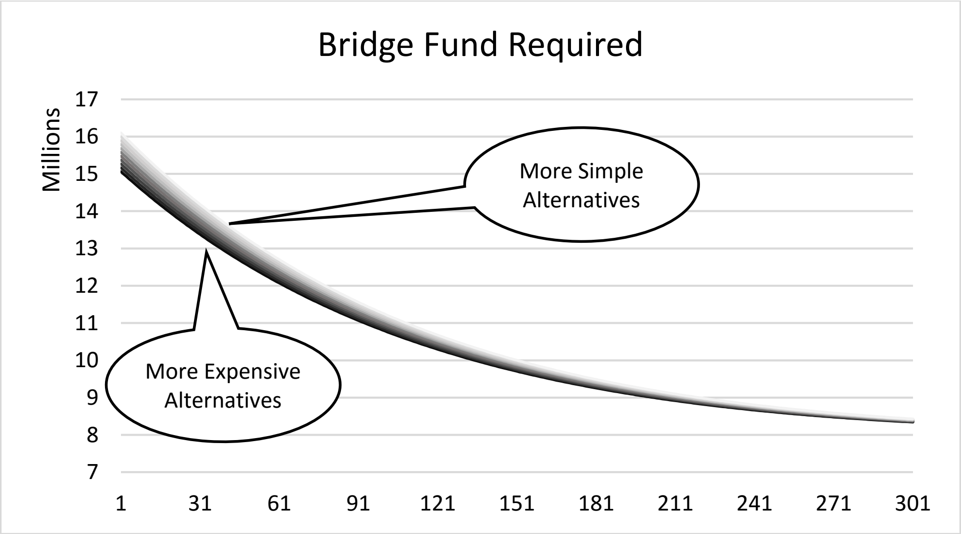


Figure IV.27: Sensitivity Output of Required Bridge Fund Due to Varying Alternative Selection

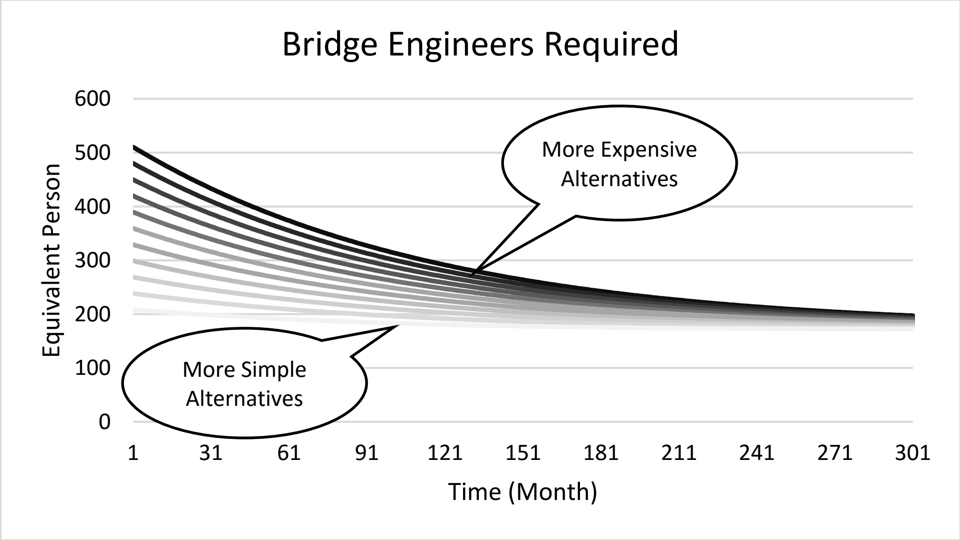


Figure IV.28: Sensitivity Output of Required Bridge Engineers Due to Varying Alternative Selection

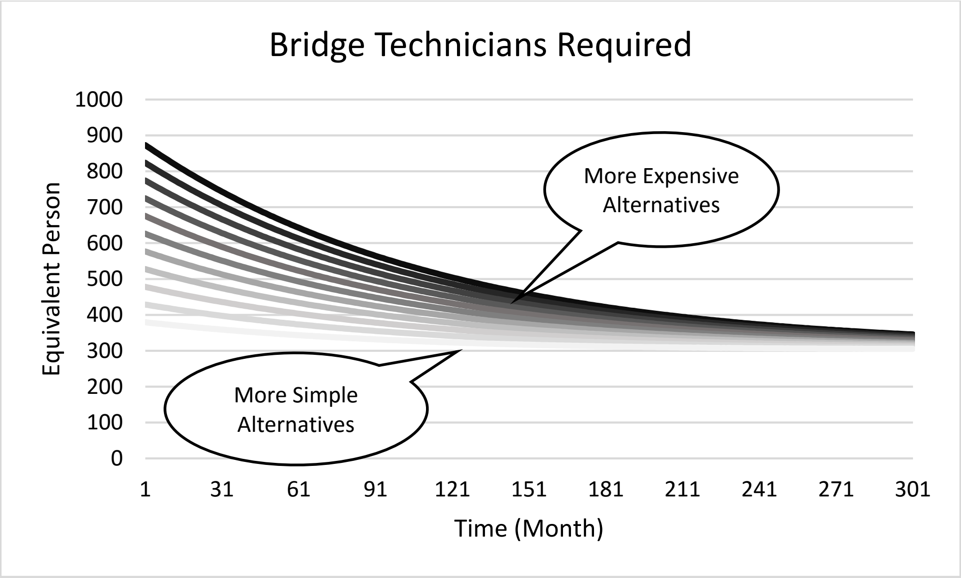


Figure IV.29: Sensitivity Output of Required Bridge Technicians Due to Varying Alternative Selection

IV.5 Impact of Funding Level on Model Behavior

IV.5.1 Model Behavior in Response to Fund Shortage

The previous simulations were run under the assumption that the State Transportation Agency always has unlimited fund and workforce to complete any necessary work to reach the performance goal. Simulations in this section will test the model's behavior in response to shortage in fund, a situation that many State Transportation Agencies cannot avoid coping with from time to time. As the dynamic hypotheses in Section II.3 suggests, shortage in fund may result in the agency's not being able to complete all required work and consequently increase required fund and workforce for the future.

Simulation 38 assumes a State Transportation Agency plans to maintain their highway performance at the current level for the next 25 years (target and initial condition setting are the same as the base case), and repair 50% of the retiring poor road and poor bridges back to good condition and the rest 50% to fair condition. In the beginning of the simulation period, the agency has just enough fund to complete required work. However, the state's highway fund will be cut by 10% at the end of Year 2 (Month 24), and it takes the agency 2 years to adjust the available fund to any changes in desired level. When underfunded, the model allocate available fund proportionally to the eight types of work in accordance to the desired amounts. Simulation 38 does not consider any effect on model behavior caused by workforce shortage. Figure IV.30 show the behaviors of required fund and available fund in response to the temporary fund shortage.

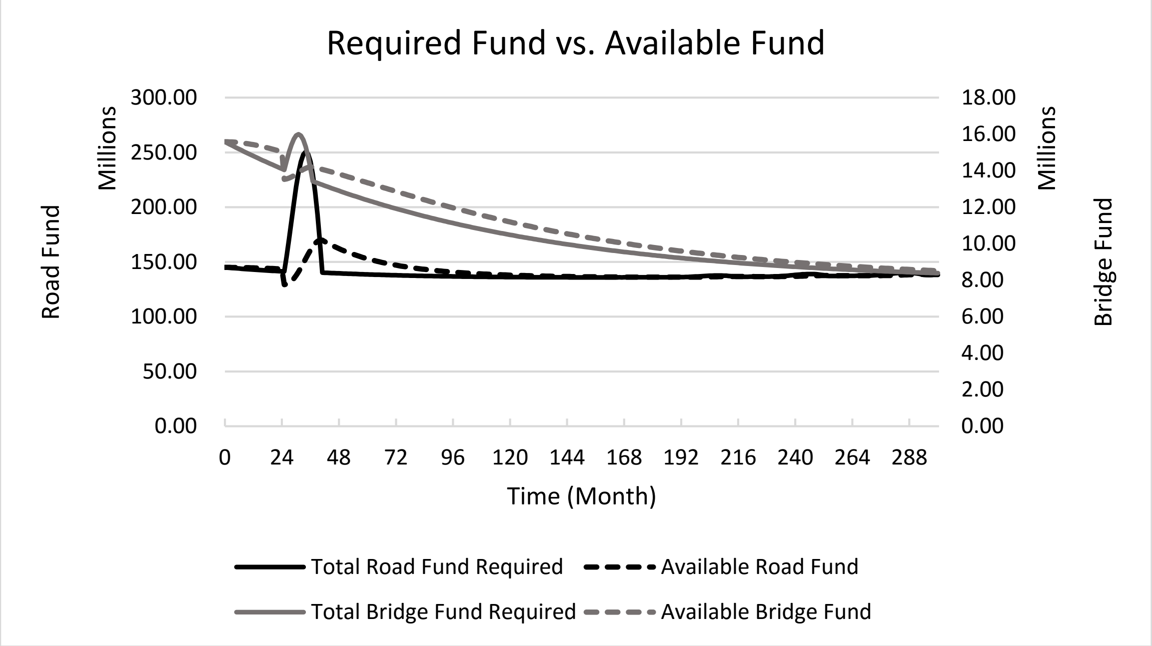


Figure IV.30: Required Fund vs. Available Fund in Response of Temporary Fund Shortage

Both the available road fund and bridge fund curves display a sudden drop at Month 24 due to the cut in highway fund. As a result, the agency will not complete all required work. If the performance targets stay unchanged, the agency will need to complete additional work in the near future to catch up. While still underfunded, the system is dominated by the reinforcing loop R1 in Figure II.1, and required fund keeps increasing until available fund is adjust to the level to clear any work backlog. After that, the required fund decreases back to the normal (base case) value.

When work backlog exists, the agency also require more workforce to help them get back on track. The behavior of total required equivalent number of Engineers and Technicians are displayed in Figure IV.31.

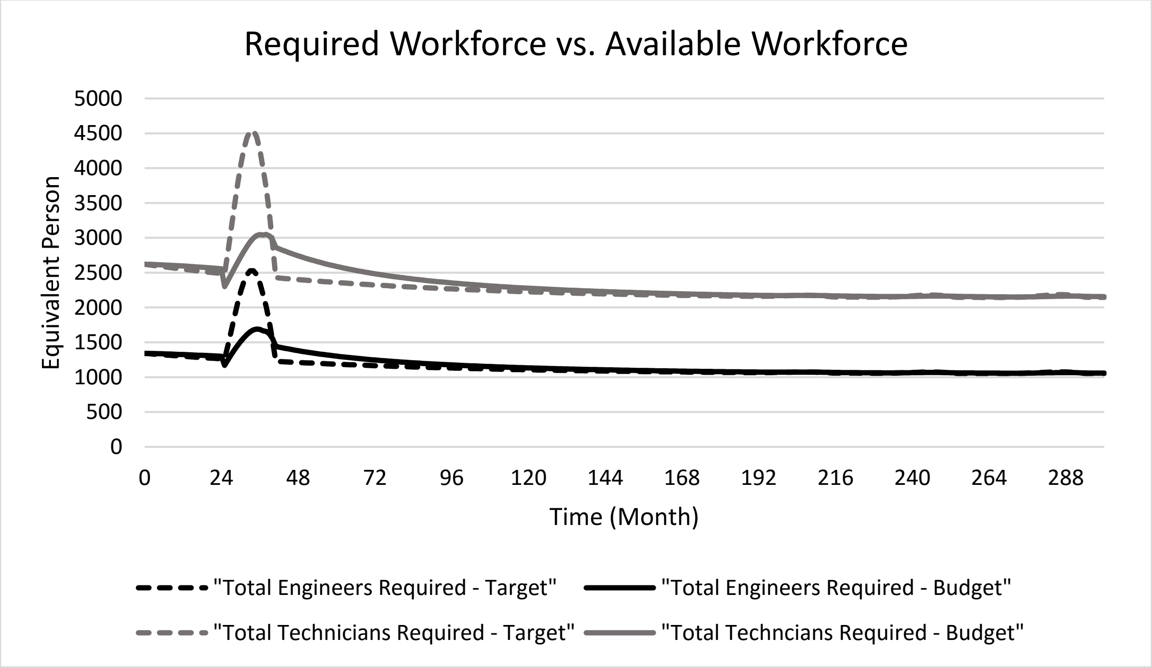


Figure IV.31: Required Workforce in Response of Temporary Fund Shortage

The behaviors of required workforce levels to reach performance targets resemble the behavior of the required fund, and behaviors of required workforce levels to fully utilize available fund resemble the behavior of the available fund.

IV.5.2 Sensitivity of Required Workforce to Funding Level Recovery Time

When an undesirable reinforcing loop dominates a system's behavior, any deviation from the baseline behavior tends to amplify itself as time moves on. The longer the reinforcing loop is allowed to be in effect, the more disastrous the result will be. When the reinforcing loop R1 (see Figure II.1) gains power from increased work backlog, the longer it takes for the agency to recover from a underfunded situation, the harder it will be for them to get back to chasing their target. Unfortunately, shortage in highway fund is often resulted from declining economy or policies against investing in highway infrastructure, which could have impact on the amount of available highway fund for years, therefore it is important to understand how sensitive the system's behavior is to the time it takes to reverse the underfunded situation.

Sensitivity simulations (Simulations 39-48) test the model's behavior with the time needed to fully adjust funding level ranging from 1 year to 10 years. Table IV.5 shows the variables values for the simulations and their corresponding line color in Figure IV.32 and IV.33.

Table IV.5: Variable Values for Sensitivity Simulations on Fund Level Recovery Time

Simulation #	39	40	41	42	43	44	45	46	47	48
Road Fund Adjustment Time (Month)	12	24	36	48	60	72	84	96	108	120
Bridge Fund Adjustment Time (Month)	12	24	36	48	60	72	84	96	108	120
Line Color	Dark		←→						Light	

Figure IV.32 and Figure IV.33 show the behavior of total required Engineers (including both road and bridge work) and total required Technicians when varying fund level recovery time. As expected, the longer the recovery time, the more workforce is required to get the performance back on track. However, in the figure, darker lines are further away from each other than the lighter colored lines, which means the amount increased in required Engineers and required Technicians between two consecutive simulations decreases from Simulation 39 to Simulation 48. Therefore, model behavior is more sensitive to shorter recovery time than longer recovery time. Such behavior suggests State Transportation Agency should try to prevent fund shortage from happening at all if possible.

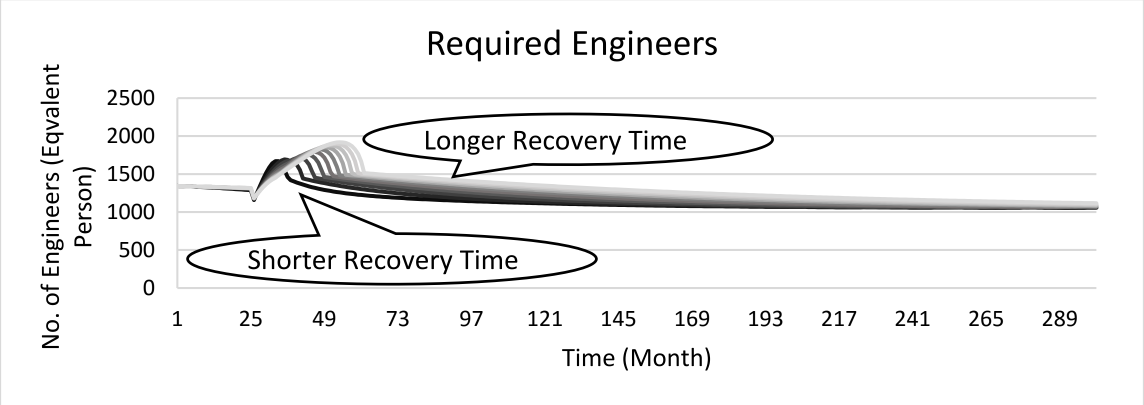


Figure IV.32: Sensitivity Output for Total Required Engineers by Varying Fund Recovery Time

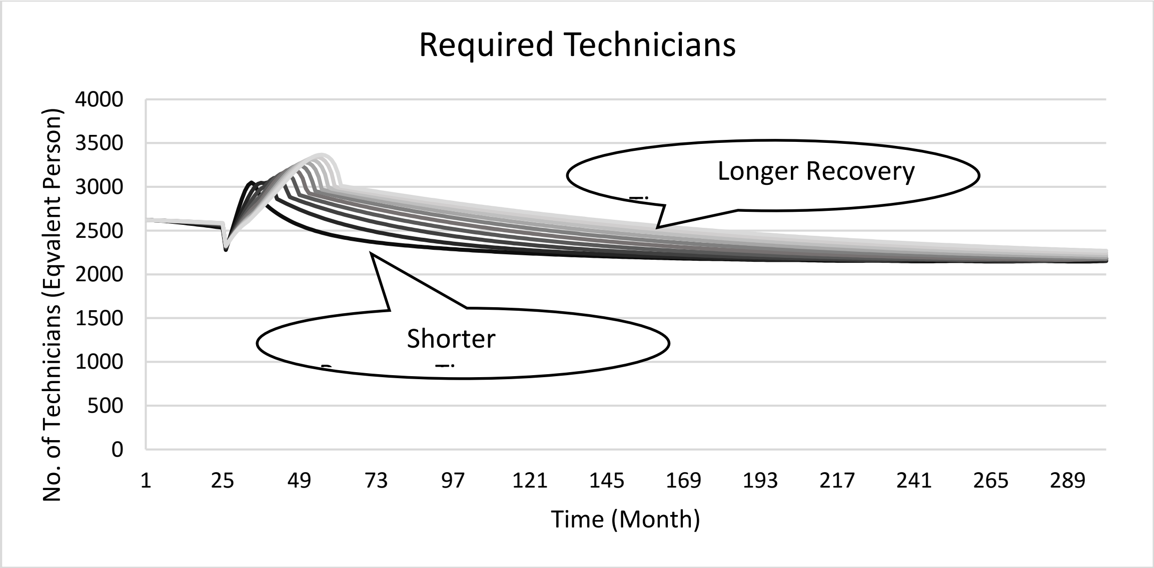


Figure IV.33: Sensitivity Output for Total Required Technicians by Varying Fund Recovery Time

IV.6 Impact of Recruiting Strategy on Model Behavior

IV.6.1 Model Behavior in Response to Limited Workforce

With a large portion of the transportation workforce turning eligible for retirement, recruiting is crucial in maintaining a sustainability workforce at State Transportation Agencies. Table III.7 listed the advantages and disadvantages of the recruiting options available for State Transportation Agencies. In order to make a sensible choice, knowing what to expect is important.

Previous simulations all assumed the agency has access to unlimited number of Engineers and Technician to perform work in order to reach the performance targets or to fully utilize highway fund. In reality, most State Transportation Agencies are currently operating with aging workforce and are experiencing difficulties recruiting younger qualified people, which means when the agency's most experienced employees retire, there workload cannot be fully picked up by incoming employees, not immediately at least. In-House hiring are not only limited to availability of qualified potential employees, but also limited to a relatively rigid workforce budget, with State Transportation Agencies being public agencies.

Model settings for Simulation 49 seeks to recreate a challenging situation for a State Transportation Agency, in which the agency will be facing high retire rate for the first two years of the simulation. In-house hiring is limited to workforce budget. The workforce budget can be adjust towards the required level, but an average two year delay is in effect due to the state's budget approval process. Also in-house hiring can only fill required workforce gap with a hiring delay. The delay varies by hiring level. Since more experienced potential employees are harder to find, the hiring delay will be longer than the entry level. Other settings are the same as the base case run.

In regard to recruiting plans, this simulation assumes the agency do not plan to use consultants, and when a gap exists between the available workforce level and the desired workforce level, the agency fills 60% of the gap by entry level hire (for both Engineers and Technicians), 30% by mid-level hire and 10% by senior level hire. These recruiting plan settings are not chosen to reflect any specific state's practice, but only to generate a set of model behavior for analysis. Model output for required Engineers and Technicians to fully utilize budget versus the available levels are displayed in Figure IV.34.

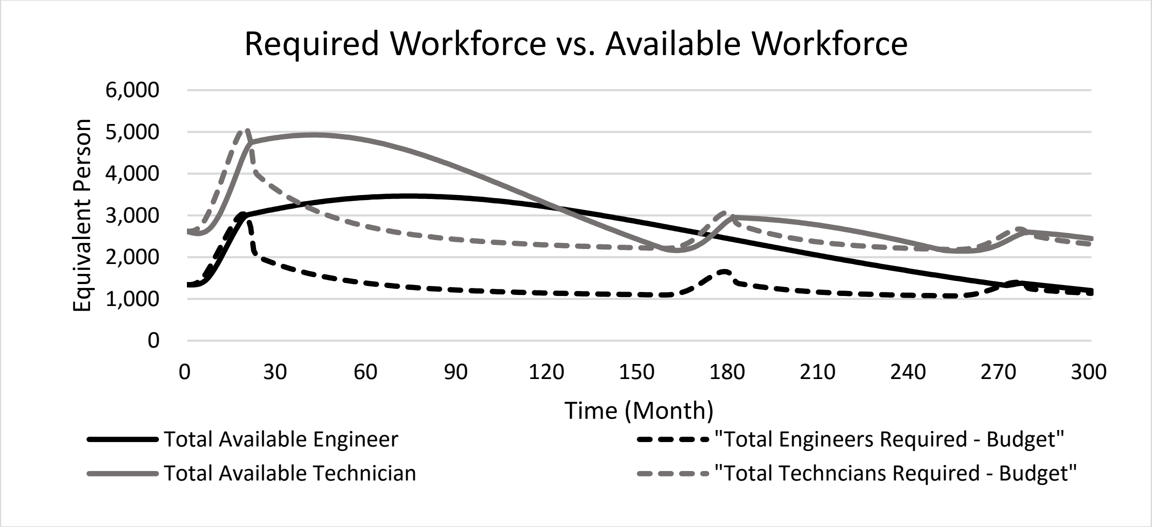


Figure IV.34: Required Workforce vs. Available Workforce Due to Limited In-House Only Hiring

Due to temporary high retire rate and not being able to fill staffing level gap with new employees in time, the agency experiences shortage in workforce. Work backlog is created and strengthens the reinforcing loops that drives the system behavior into an even more demanding mode. Eventually the available workforce levels adjust and catch up with the required levels, but at that time the required levels have already increased to significantly higher values. As the agency clears the work backlog, the required workforce levels drops back to normal. However, because the agency has hired a great amount of in-house personnel, without downsizing, the agency will be left with an unnecessarily large workforce. The required number of Engineers and Technicians both shows noticeable increase around Month 180 and again around Month 270, right around the times when the newly hired mid-level employees and entry level employees become eligible for retirement.

While the behavior in Simulation 49 seems extreme, it could happen, although probably to less extent, when an agency do not have a clear understanding of the dynamic flows of the system. As a shortage in workforce occurs, without knowing how long it will last, decision makers in the agency begin worrying about their highway performance level, which appears to be falling more and more behind. As they evaluate their performance and perceive more work needs to be done, over-hire is likely to happen.

If the agency realizes the shortage in workforce is only temporary due to short-term high retire rate, decision makers can choose to hire consultants from outside the agency to quickly fill the workforce gap, although this option may seem more expensive. Simulation 50 assumes the agency always fills 50% of any workforce gap by in-house hiring and the rest 50% by retaining consultants. Output for required workforce levels and available workforce levels are displayed in Figure IV.35.

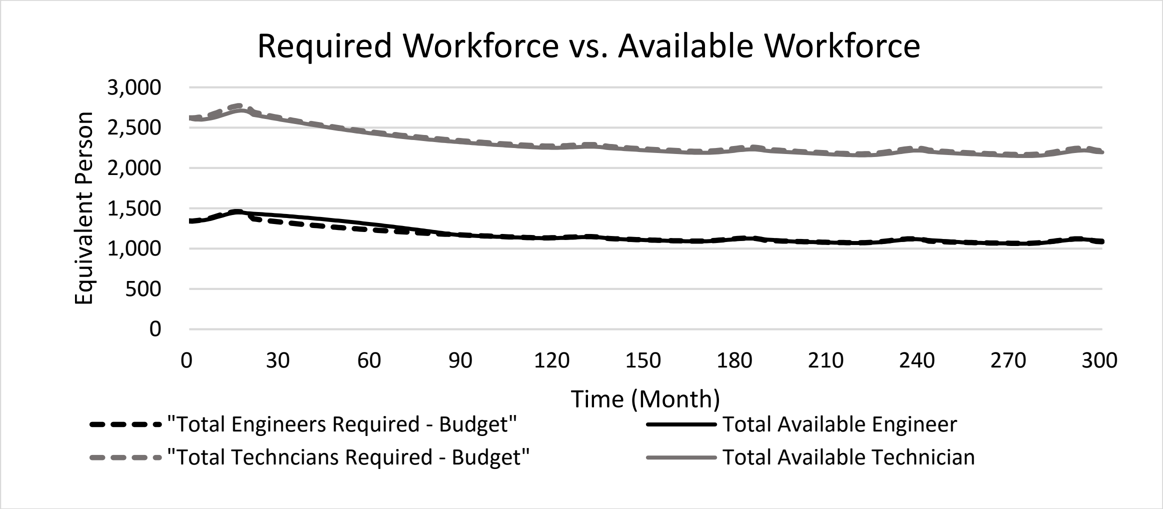


Figure IV.35: Required Workforce vs. Available Workforce with 50% In-House Hiring and 50% Consultants

IV.6.2 Sensitivity of Model Behavior to Varying In-House Hiring Levels

Previous discussions have already included the advantages and disadvantages of hiring at different levels. Although State Transportation Agencies mostly hire at the entry level in recent years. It may still be beneficial to test the system’s sensitivity to different hiring level combinations in case the workforce market dynamics change in the next 25 years.

Simulation runs were produced using the modeling software while varying the percentages of new hires in each level. Since hiring a large portion of new employees at the senior level is very unlikely, these simulations assume only 10% of the workforce gap will be filled by hiring new senior Engineers and senior Technicians. The combinations of entry levels hiring percentage and mid-level hiring percentage are summarized in Table IV.6.

Table IV.6: Variable Values for Sensitivity Simulations on Hiring Experience Level

Simulation #	51	52	53	54	55	56	57	58	59	60
% of Workforce Gap to be Filled by Hiring at Entry Level	0	10	20	30	40	50	60	70	80	90
% of Workforce Gap to be Filled by Hiring at Mid-Level	90	80	70	60	50	40	30	20	10	0
Line Color	Dark ⟷ Light									

Sensitivity Output for required Engineers and available Engineers are shown in Figure IV.36 and Figure IV.37. Simulations with lower entry level percentages are more demanding and results in the most over-hire. In general, hiring at higher levels, if possible, is favorable to address short term staffing shortages.

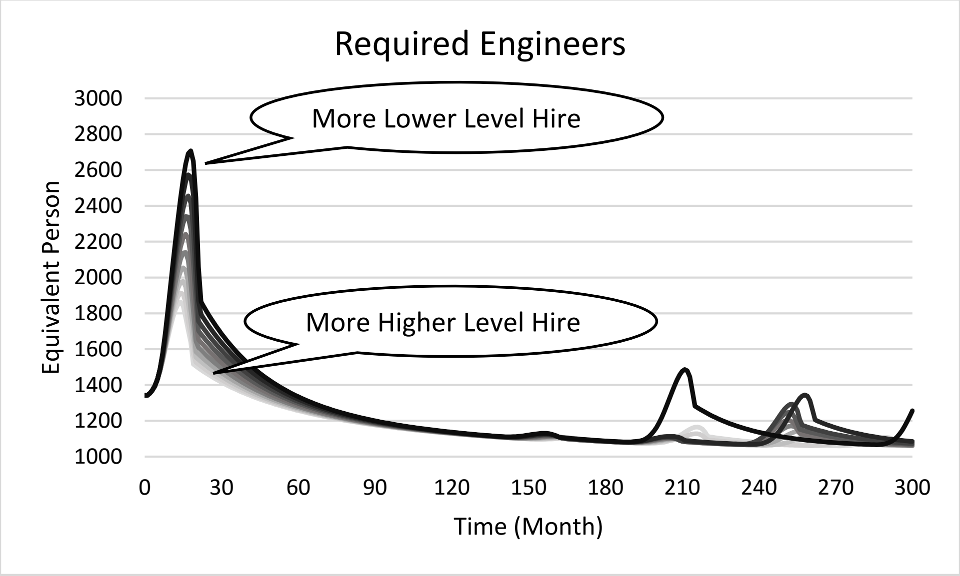


Figure IV.36: Sensitivity Output of Required Engineers by Varying Hiring Level

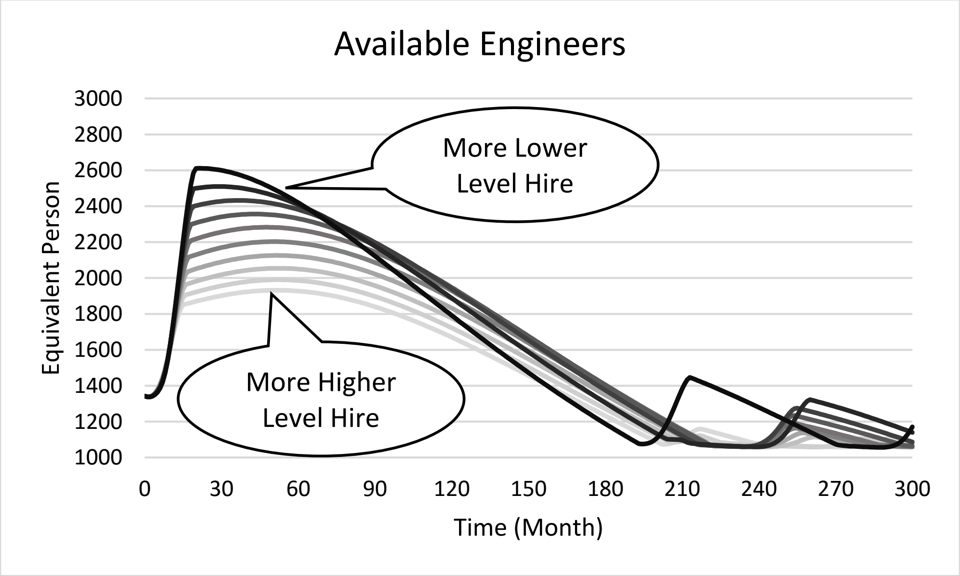


Figure IV.37: Sensitivity Output of Available Engineers by Varying Hiring Level

Required Technicians and available Technicians display very similar behavior to those of required Engineers and available Engineers.

IV.6.3 Sensitivity of Model Behavior to Varying In-House to Consultants Ratio

When expecting a short term workforce shortage due to either temporary retire rate or temporary increase of work amount, hiring consultants is usually a good choice as opposed to hiring new permanent in-house personnel. Consultants are generally more productive than average in-house personnel, but are also more expensive. When dealing with increasing demand of workforce, finding the balancing between the amount of in-house hire and consultants can be difficult without fully understanding the dynamic consequences of the recruiting choices. Using this model, decision makers can compare different alternatives by performing sensitivity simulations. Simulations 61-70 assume the State Transportation Agency is open to hiring consultants to perform a portion of the required work. The agency will first attempt to fill a certain percentage of the workforce gap with in-house hire (when in-house workforce budget allows), and that percentage vary gradually from 10% to 100% from Simulation 61 to Simulation 70 (0% in-house hire will leave the agency will no in-house staff at the end of the 25-year simulation period). If the in-house workforce budget does not allow them to hire as many new in-house personnel as needed to fill the attempted percentage of the workforce gap, the agency hires consultants to fill the rest of the workforce gap. From interviewing State Transportation Agency employees and observed data from the Federal Highway Administration’s database, it is clear that workforce cost is only a small portion of a State Transportation Agency’s expenditures, not significant when compared to highway construction and maintenance cost. Therefore, when a highway project is funded, it is reasonable to assume that the agency will be able to hire an unlimited number of consultants when needed.

Table IV.7 summarizes the control variable values for Simulations 61-70.

Table IV.7: Variable Values for Sensitivity Simulations on In-House Hire to Consultant Ratio

Simulation #	61	62	63	64	65	66	67	68	69	70
% of Workforce Gap to be Filled by In-House New Hire	10	20	30	40	50	60	70	80	90	100
Line Color	Dark ◄									► Light

Figure IV.38 shows the required Engineers for each simulation run, and Figure IV.39 shows the total monthly cost on all workforce including in-house personnel and consultants for the State Transportation agency.

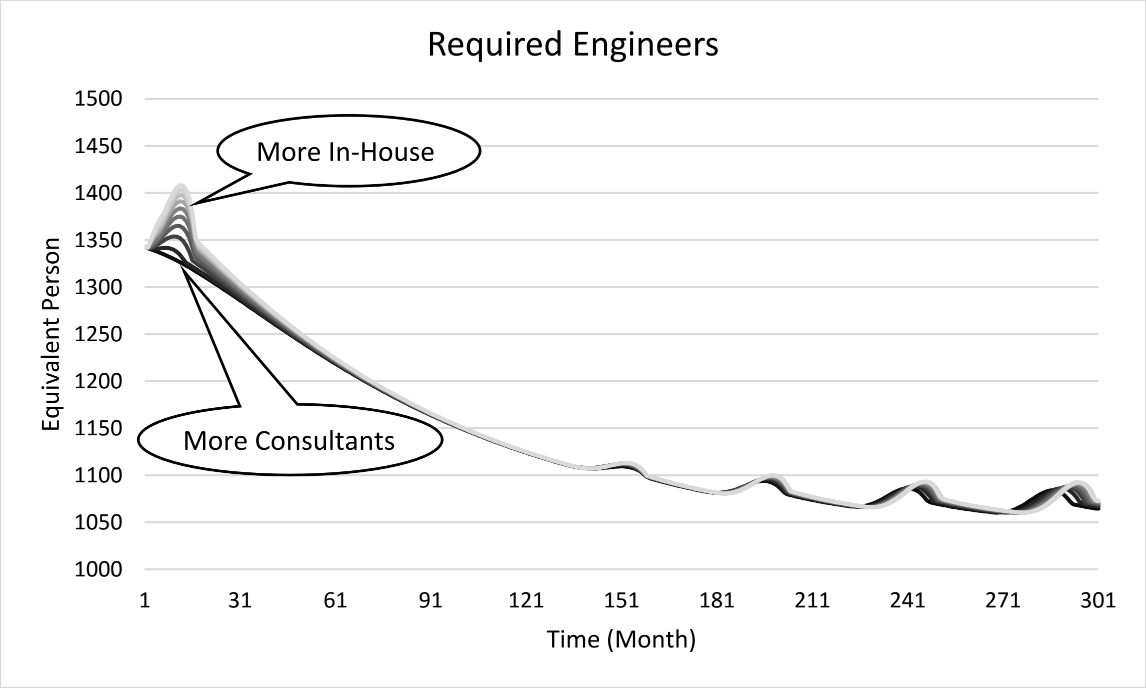


Figure IV.38: Sensitivity Output of Required Engineers by In-House Hire to Consultant Ratio

The output suggests using consultants is very effective when addressing temporary workforce shortage, as it quickly fills any workforce gap and prevents work backlog from being created. No work backlog means the reinforcing loop R1 (see Figure II.1) never gains power, so that required Engineers will not keep increasing until the agency hires addition workforce to catch up. Figure IV.39 also indicates during the early stages in the simulation, hiring consultants is more cost effective than in-house personnel. However, when the period of high retirement rate has passed and the system behavior returns to resemble the base case behavior (after Month 60 in Figure IV.39), keep filling workforce gap with consultants becomes more costly than in-house personnel. Therefore maintaining a large number of consultants is not desirable when work load is relatively stable.

After Month 150, the required Engineers starts to fluctuate slightly possibly due to retirement of newly hired in-house employees before Month 30. At peak times of these fluctuations, hiring consultants appear to be just as cost effective as in-house personnel. To summarize the model behavior shown in Figure IV.38 and Figure IV.39, when the agency’s workforce and workload are both perceived to be relatively stable, small gaps between available workforce level and desired workforce level should be filled by hiring new permanent in-house personnel. Temporary workforce shortage of large magnitude can best be address by hiring consultants. Within proper calibration using accurate cost data, the model can help find the most cost effective and combination of in-house hire and consultants in different scenarios.

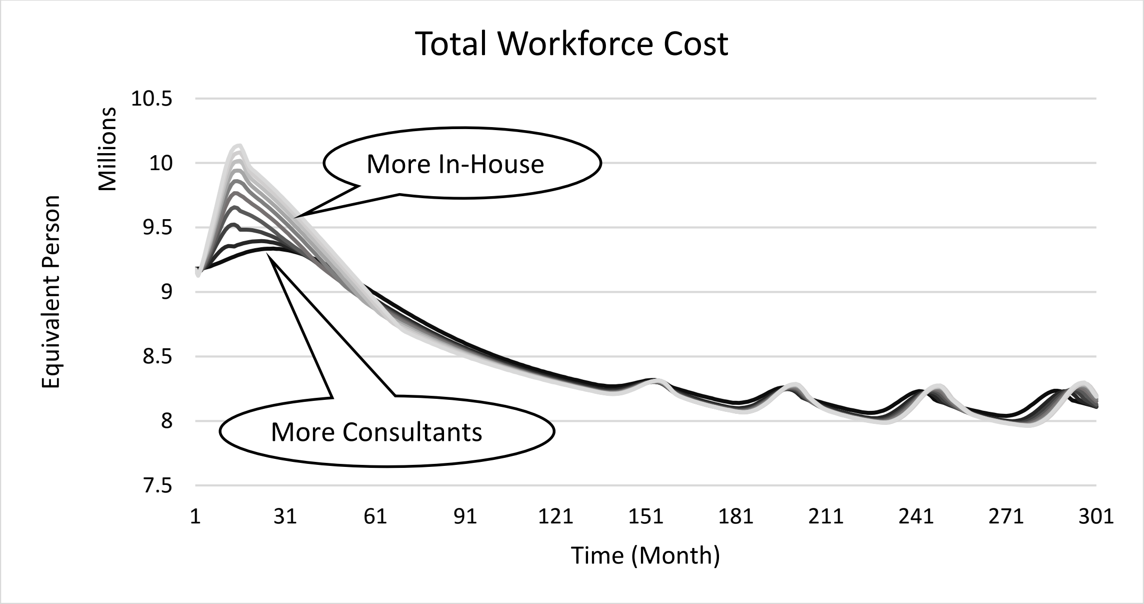


Figure IV.39: Sensitivity Output of Total Workforce Cost by In-House Hire to Consultant Ratio

IV.7 Other Factors that May Impact Staffing Requirements

IV.7.1 Statistical Screening on Potential Influential Model Parameters

Statistical screening analyses were performed on several exogenous variables to identify potential influential behavior drivers. The model currently do not simulate decision making with these parameters, but if a variable proves to be strongly related to required workforce, State Transportation Agency should take measures to influence the value of that variable.

Statistical screening measures the influence of model parameters on system behavior over time by selecting random values for the input parameter within a reasonable range, performing simulations with selected values, recording the step-by-step value of the output variable of interest, and calculating the correlation coefficient between the input parameter and the output variable (Taylor Ford and Ford 2007, 2010; Ford and Flynn 2005).

Correlation coefficients for each time step between the input parameter and the output variable are then plotted over the time axis, making it possible to understand how strongly the two variables are related at each time step. Correlation coefficients range from -1 and 1. Generally speaking, if the correlation coefficient between two variables is between -0.2 and 0.2, the two variables are considered unrelated. A positive value indicates the two variables increase or decrease in the same direction, while a negative value indicates the two variables change in opposite directions. The absolute value of the correlation coefficient indicate how strongly the two variables are related, with a larger absolute value indicating stronger relation.

Statistical screening analyses were performed on required number of Engineer and required number of Technicians, both as output variable, to each of the following exogenous variables (See Table IV.8, output is displayed Figure IV.40 to Figure IV.45):

Table IV.8: Ranges of Input Parameters for Statistical Screening Analyses

Variable Name	Unit	Model Value	Range in Statistical Screening Analyses (+/- 50% of Model Value)
Time Required to Hire EIT	Month	1	0.5 – 1.5
Time Required to Hire Licensed Engineer	Month	2	1 -3
Time Required to Hire Senior Licensed Engineer	Month	3	1.5 – 4.5
Time Required to Hire Entry Level Technician	Month	1	0.5 – 1.5
Time Required to Hire Mid-Level Technician	Month	1	0.5 – 1.5
Time Required to Hire Senior Technician	Month	2	1 -3
% EIT Quilt/Fired	Dimensionless/Month	0.03	0.015 – 0.045
% Licensed Engineer Quit/Fired	Dimensionless/Month	0.2	0.1 – 0.3
% Senior Engineer Quit/Fired	Dimensionless/Month	0.1	0.05 – 0.15
% Entry Level Technician Quit/Fired	Dimensionless/Month	0.1	0.05 – 0.15
% Mid-Level Technician Quit/Fired	Dimensionless/Month	0.5	0.25 – 0.75
% Senior Technician Quit/Fired	Dimensionless/Month	1	0.5 – 1.5
Senior Licensed Engineer Average Service Time	Month	120	60 - 180

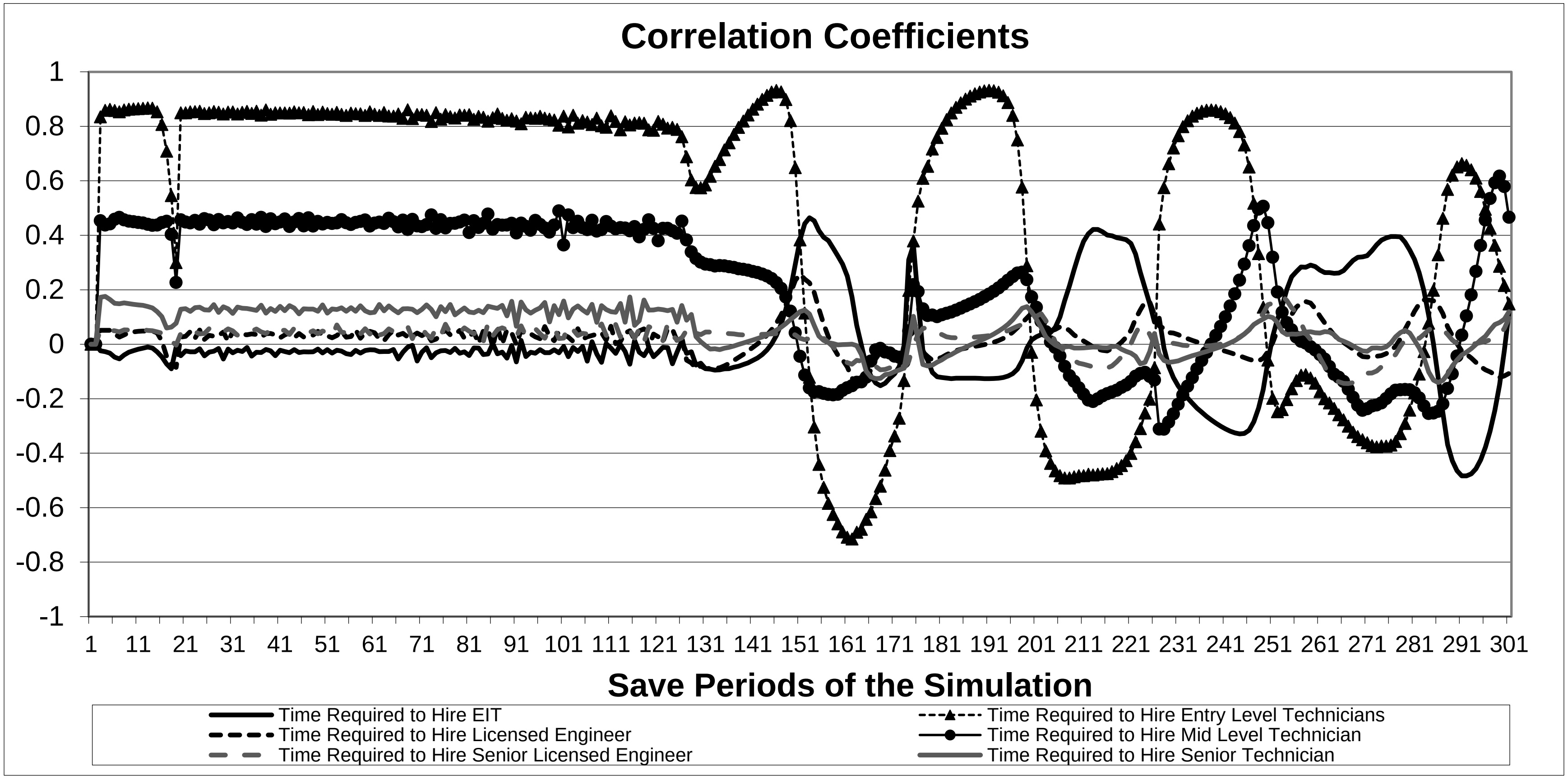


Figure IV.40: Correlation Coefficients between Required Engineers and Hiring Delays

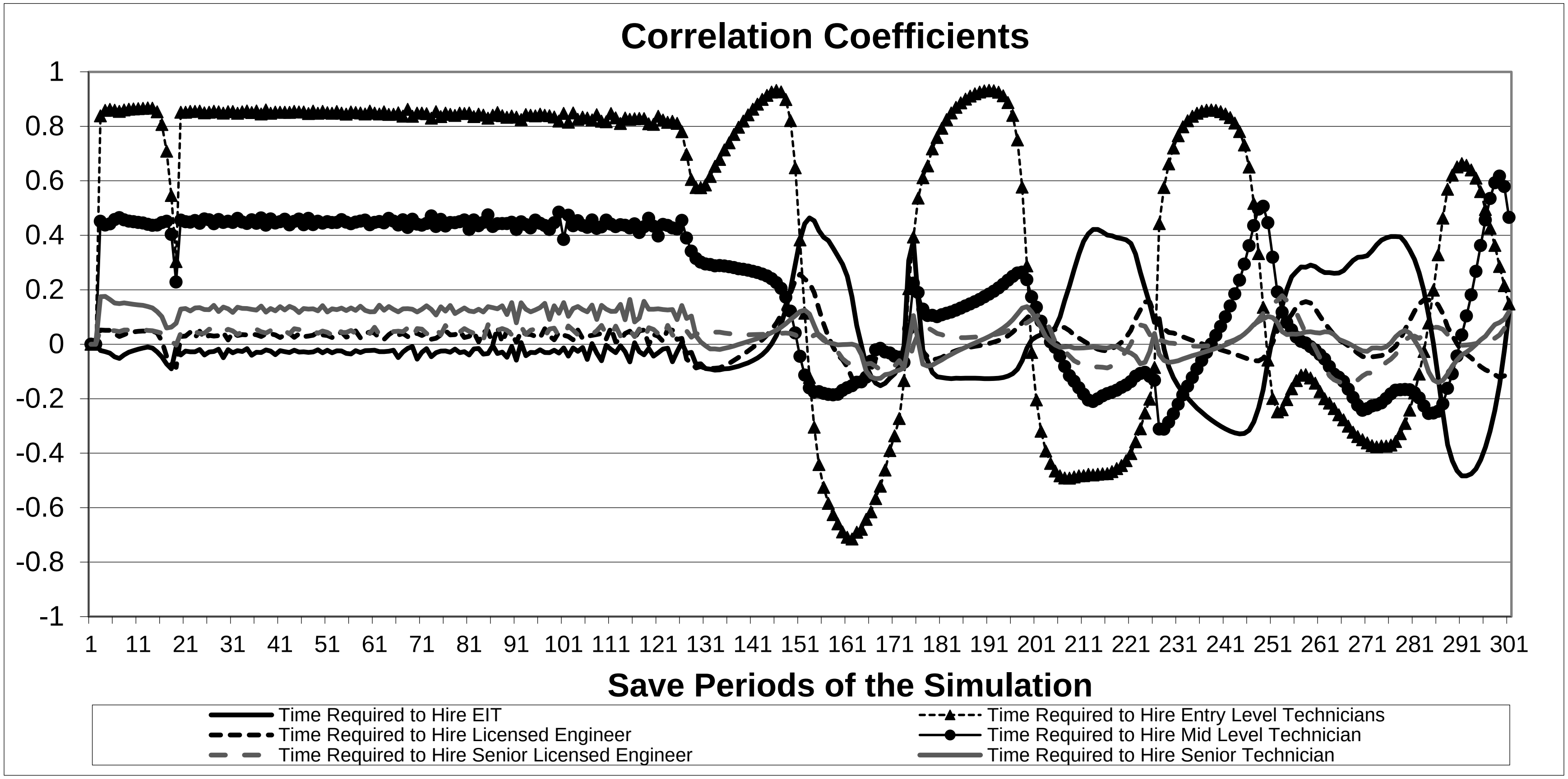


Figure IV.41: Correlation Coefficients between Required Technicians and Hiring Delays

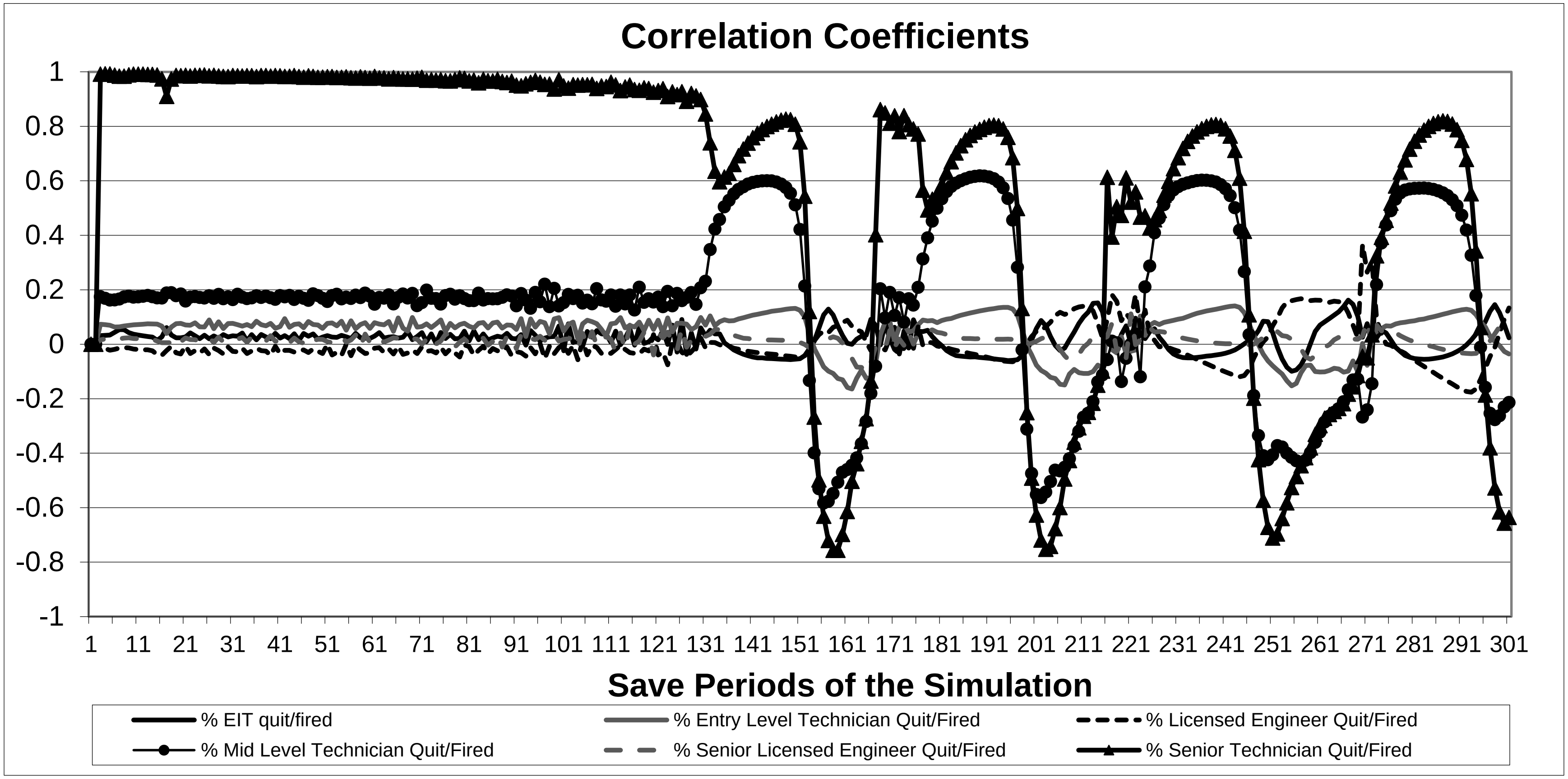


Figure IV.42: Correlation Coefficients between Required Engineers and Turn-Over Rates

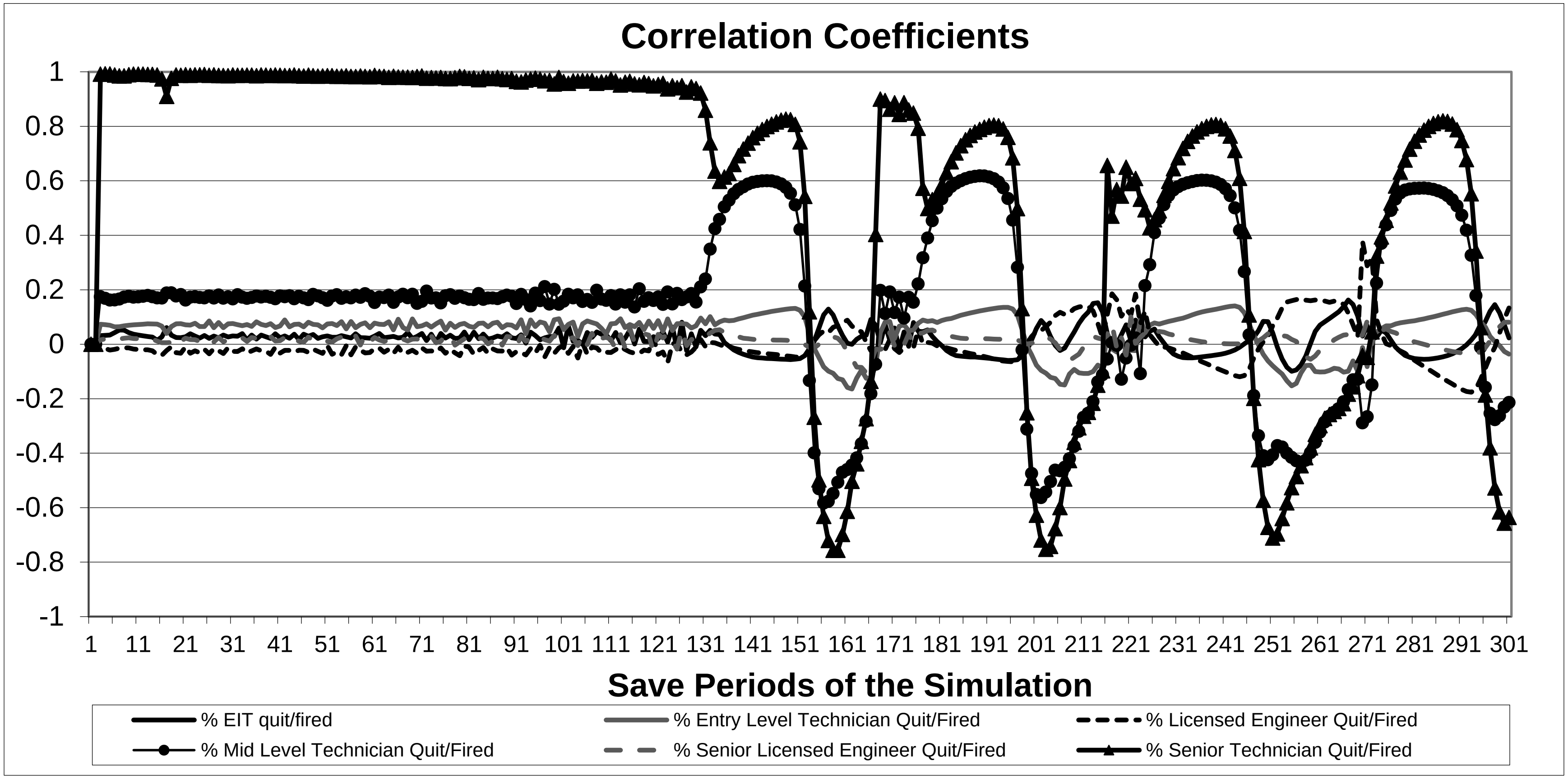


Figure IV.43: Correlation Coefficients between Required Technicians and Turn-Over Rates

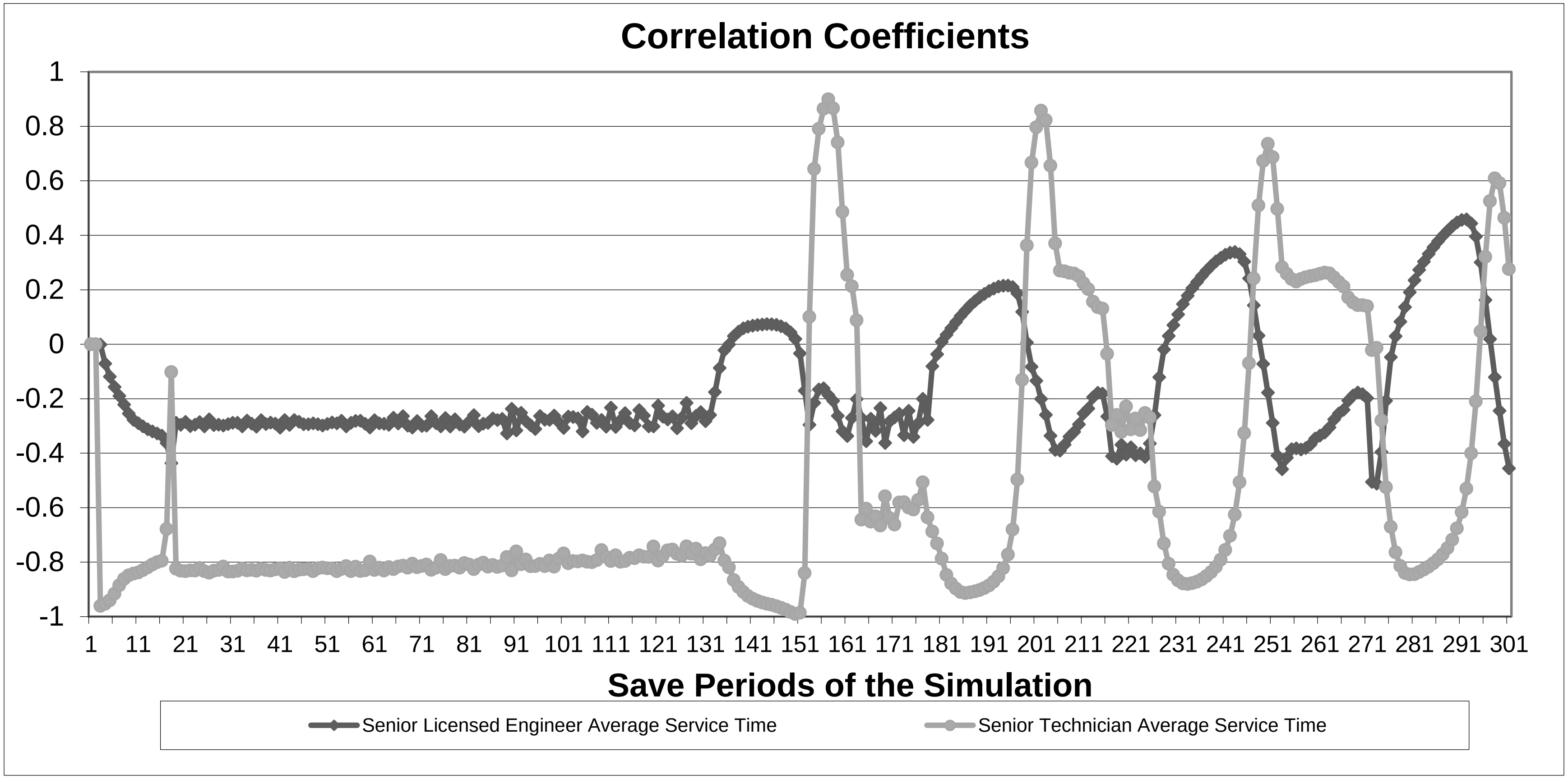


Figure IV.44: Correlation Coefficients between Required Engineers and Senior Workforce Average Service Time

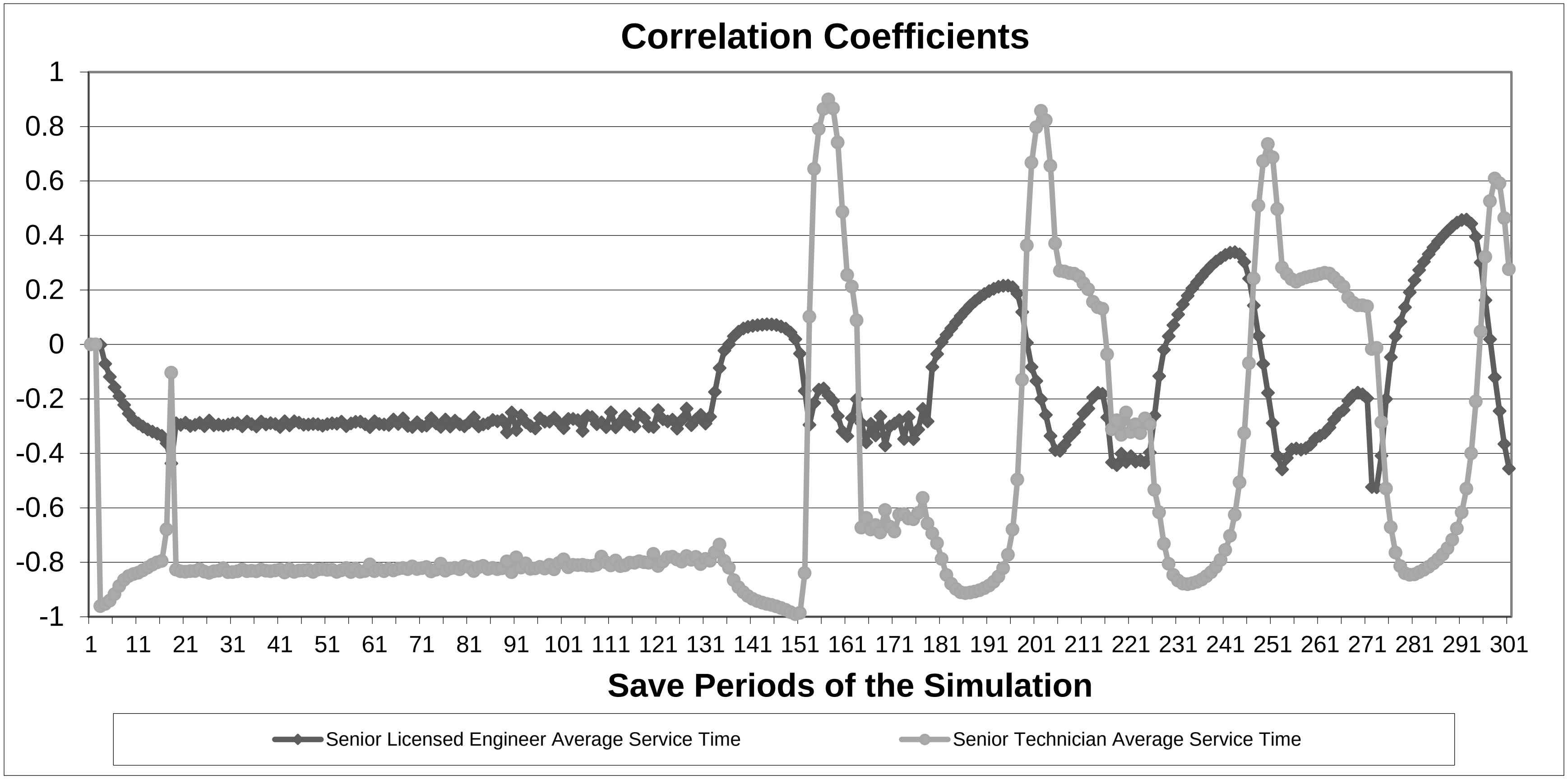


Figure IV.45: Correlation Coefficients between Required Technicians and Senior Workforce Average Service Time

IV.7.2 Parameters to Target

The simulations for statistical careening analyses were set to simulate a shortage in workforce early in the simulation. The agency is able to adjust and eventually required workforce stabilizes and exhibits only minor fluctuations (similar to simulations in Section IV.6.2). Required Engineers and required Technicians displayed almost identical behaviors in the statistical screening analyses.

Figure IV.40 and Figure IV.41 show that during workforce shortage, required workforce is most strongly related to hiring delays associated with hiring entry level and mid-level Technicians, but not likely to be related to hiring delays associated with the other hiring categories. The longer it requires to hire entry level and mid-level Technicians, especially entry level Technicians, the more workforce will be required due to feedbacks within the system. In order to shorten the time required to hire entry level Technicians, the agency could consider investing in future workforce development programs and providing incentives to attract more entry level Technicians.

Figure IV.42 and Figure IV.43 indicate a strong relationship between required workforce and turn-over involving senior Technicians. In these simulations, senior Technicians contribute a great portion towards the total productivity of Technicians within the agency, therefore understandably make a great difference in model behavior if a lot of them leave the agency. The conclusion can be drawn from the output in Figure IV.44 and Figure IV.45. The agency should consider taking measures to keep the senior Technicians for longer. Considering some State Transportation Agencies are allowing their employees to retire from the in-house workforce after only 20 years of service, prolong the average service time of senior Technicians is not impossible with proper designed benefits, including pension plans.

The output of statistical screening analyses suggests model behaviors have stronger relationships with variables involving Technicians then with variables involving Engineers, which indicate the availability of Technicians is a more severe issue than the availability of Engineers under the scenario being simulated.

IV.8 Summary

This chapter examined model behaviors in response to changes in several key variables that State Transportation Agencies could design policies with. Performing simulations of a variety of scenarios tested the robustness of the model. Studying model behavior patterns and running sensitivity simulations helped improve understandings of the system's behavior and identify how the model could be used to search for solutions when workforce related challenges present themselves. This chapter also identified parameters in the model that State Transportation Agencies would target in addition to those already being considered as control variables.

CHAPTER V MODEL APPLICATION: KENTUCKY TRANSPORTATION CABINET’S WORKFORCE CHALLENGE

V.1 Overview

In this chapter, the model will be re-calibrated using specific variable values that fit Kentucky Transportation Cabinet’s practice. First, historical road fund data and pavement condition data published by the Kentucky Transportation Cabinet (KYTC) will be used to further validate part of the model structure. Then the model will be calibrated using variable values reflecting KYTC’s conditions in 2015 and attempt to find solutions to address perceived workforce issues.

V.2 Empirical Testing between Funding Level and Pavement Condition

Kentucky Road fund data and pavement condition data from Year 1998 to Year 2011 are available on the maintenance portal of KYTC’s official website. Road fund, percentage of good pavement and percentage of acceptable (fair and better) pavement are shown in Figure V.1.

Road fund for each year and beginning pavement conditions in 1998 were used in the model as input. The simulation assumed road fund was the only resource restraining work accomplish rate between 1998 and 2011. A former KYTC employee interviewed for this work stated that as long as a project was funded, KYTC was able to assign workforce to complete it. In 2002, the Federal Highway Administration added a National Highway System performance goal that aimed at increasing good pavement percentage to above 60%. In the model, 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 Figure V.2.

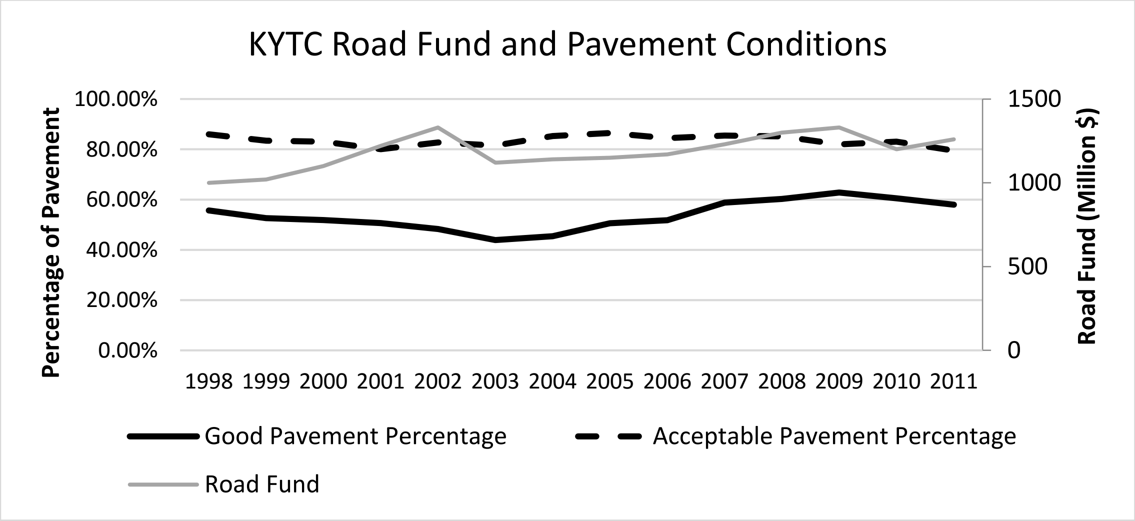


Figure V.1: KYTC Road Fund and Pavement Conditions from Year 1998 to Year 2011

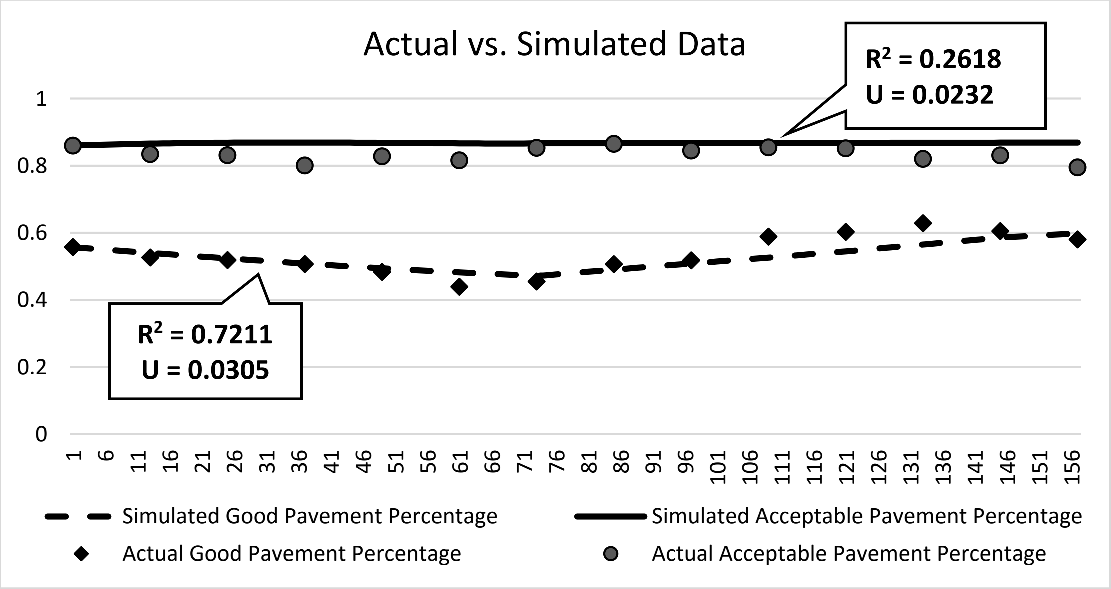


Figure V.2: Actual Kentucky Pavement Conditions vs. Simulated Kentucky Pavement Conditions

Goodness of fit was evaluated using two statistics, Coefficient of Determination (R^2) and the Theil's Coefficient of Inequality (U). The R^2 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 Year 1998 to Year 2011 was explained by the model, which indicate the model was able to capture the majority of the variance, but only 23.18% of the variance in acceptable road percentage was explained by the model. From Year 1998 to Year 2011, the actual acceptable road percentage exhibited only minor fluctuations, which is possibly the reason for the poor R^2 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. The statistics are defined as:

$$U = \frac{\sqrt{\frac{1}{n}\sum_{t=1}^{n}(S_t - A_t)^2}}{\sqrt{\frac{1}{n}\sum_{t=1}^{n}S_t^2} + \sqrt{\frac{1}{n}\sum_{t=1}^{n}A_t^2}}$$

Where n- number of observations;

t- time, t=1,2,…,n;

S_t – simulated value at time t;

A_t - actual value at time t.

U can range between 0 and 1 with 0 indicating perfect prediction and 1 indicating the prediction is no better than a naïve 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 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.

The trend of the actual pavement conditions can also be explained by model structure. Before 2002, the agency did not have a specific goal for good pavement percentage, only one for acceptable pavement percentage, so resources were focused on reducing poor road. From a single project point of view, repairing into fair road is less expensive and can increase acceptable pavement percentage as desired. However, reducing good road percentage drives the system behavior into a more demanding mode (refer to Section IV.3). As a result, although road fund increased between 1998 and 2002, overall pavement conditions degraded. After 2002, resources were assigned to increase good road percentage. With steady funding level between 2003 and 2007, good road percentage increased. Acceptable road percentage did not increase instantly possibly due to resources being assigned to focus on good road. As road fund decreased again from 2009 to 2010, both percentages suffered.

V.3 KYTC's Workforce Challenge

The Kentucky Transportation Cabinet maintains about 63100 lane-miles of road and over 5261000 m^2 of bridge deck area. The agency has been struggling to secure sufficient road and bridge fund to keep the performance of state administered roads and bridges at desired levels. Fund for road and bridges in the foreseeable future is not expected to increase significantly unless some drastic change in the State's policy were to happen.

Like a lot of other transportation agencies in the country, a good portion of KYTC's most experienced personnel is getting close to being eligible for retirement. KYTC currently adopts a defined pension program, under which a retired employee's pension will be determined by the average salary of the last five years in service. About 4 years ago, the agency raised the salary levels of its employees, therefore it is expected that some of the Engineers and Technicians who will be eligible for retirement will choose to leave the agency within a year.

Recruiting has been challenging as well 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 towards an Engineering degree or an Engineering Technology associate degree. In return, students receiving this scholarship is required to work for the KYTC full time immediately after graduate for as many years as the student was on the scholarship. This program ensures the 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 consulting Technicians as inspectors in times of need, the fees for consultants have proved to be more expensive than using in-house personnel.

Since the KYTC only require employees to serve for 20 years to become eligible for retirement, a lot of employees are still in their 40s when they become eligible, and will be more than happy to continue working for private companies while claiming their pension (they are not allowed to receive income from government agencies while collecting pension due to the “double dipping” law). In recent years, due to foreseeable shortage in workforce, the KYTC has been allowing former retired employees to come back to the agency with reduced salary levels. Around 15% of the formerly retired employees choose to return. These returning employees may increase temporary productivity of agency staff immediately, but compared to new employees who do not have a pension to collect, they have more freedom to leave the agency.

The model was re-calibrated to reflect the above stated situation at the Kentucky Transportation Agency. For a complete list of exogenous variable values, see Appendix II. Simulations 71-31 seeks to recreate the following situations:

Simulation 71 – the agency only uses in-house personnel to attempt to complete all funded work without;

Simulation 72 – the agency only used in-house personnel, also hires 15% of formerly retired employees back;

Simulation 73 – the agency retains as many consultants as needed in addition to hiring 15% of formerly retired employees back to complete all funded work.

Model output for several variables are displayed in Figure V.3 to Figure V.7.

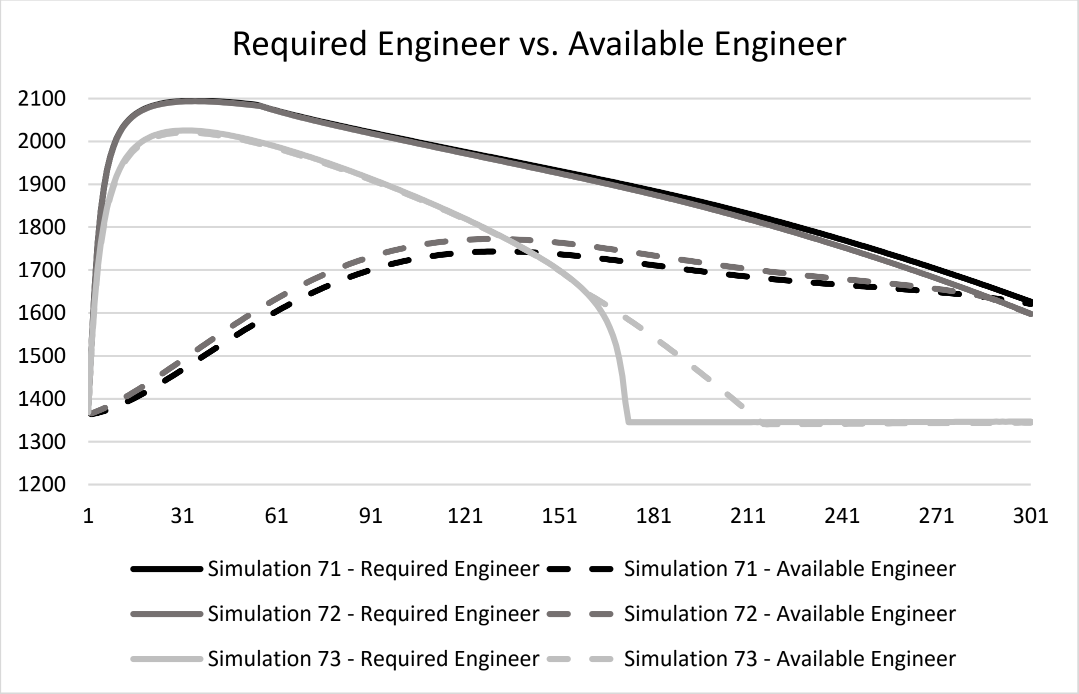


Figure V.3: Required Engineer vs. Available Engineer by Only Using In-House Employees

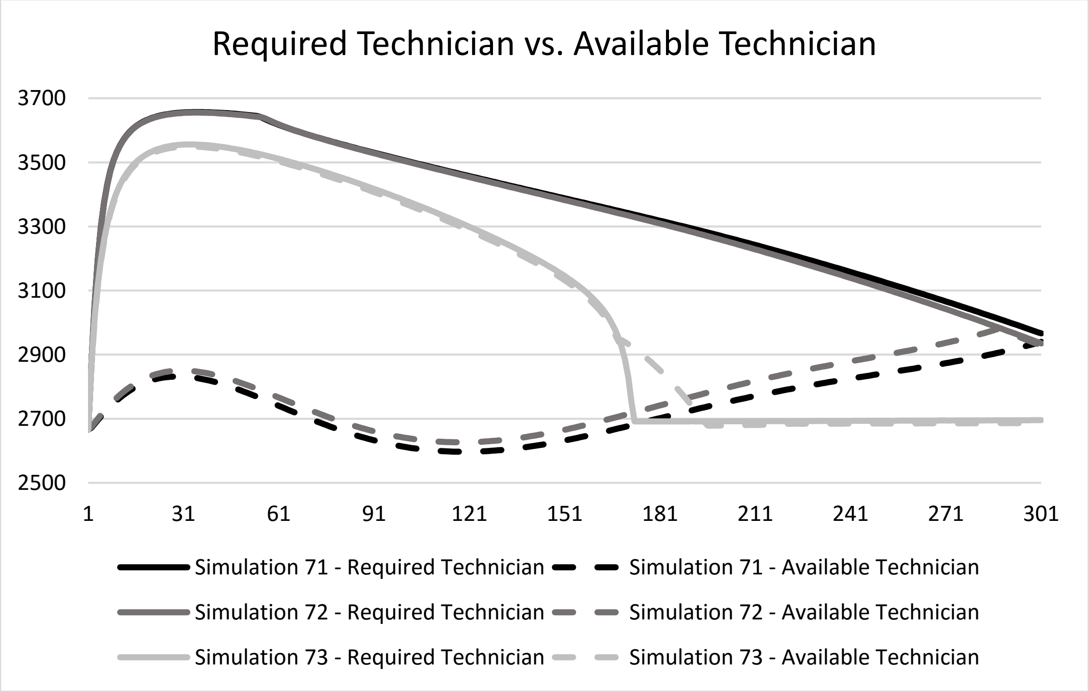


Figure V.4: Required Technician vs. Available Technician by Only Using In-House Employees

Figure V.3 and Figure V.4 show the required workforce levels and the corresponding available workforce levels for the three simulations. Due to fund shortage and initial high retire rate, a workforce shortage appears immediately at the beginning of the simulations. Since the KYTC’s in-house hiring is very limited by workforce budget and availability of qualified applications, using in-house personnel along will not be able to complete all funded work, and reinforcing loop within the system drives the required workforce levels even further away from the available levels (Simulation 71 and 72). Hiring 15% of formerly retired senior employees (Simulation 72) does bring the required level and available level a little closer together, but does not change the model’s behavior pattern. Only by using consultants can the agency be able to quickly fill any workforce gap (in Simulation 73, the required lines and the available lines stay close).

The numbers shown on the vertical axis of Figure V.3 and Figure V.4 are theoretical values of required and available Engineers to help the agency fully reach the performance targets regardless of how far behind the current levels are. It is difficult to understand to magnitude of the challenge by only looking at these outrageous numbers. To help better understand the impact of fund shortage and high initial retire rate on highway system performance, the simulated real-time good pavement percentage and acceptable road percentage are shown in Figure V.5 and Figure V.6.

The output shows using in-house personnel alone will result in significant degrades in highway pavement performance. Even with unlimited consultants, the agency will not be able to fully achieve their goals as the good pavement percentage decreases below 50% due to sustained fund shortage.

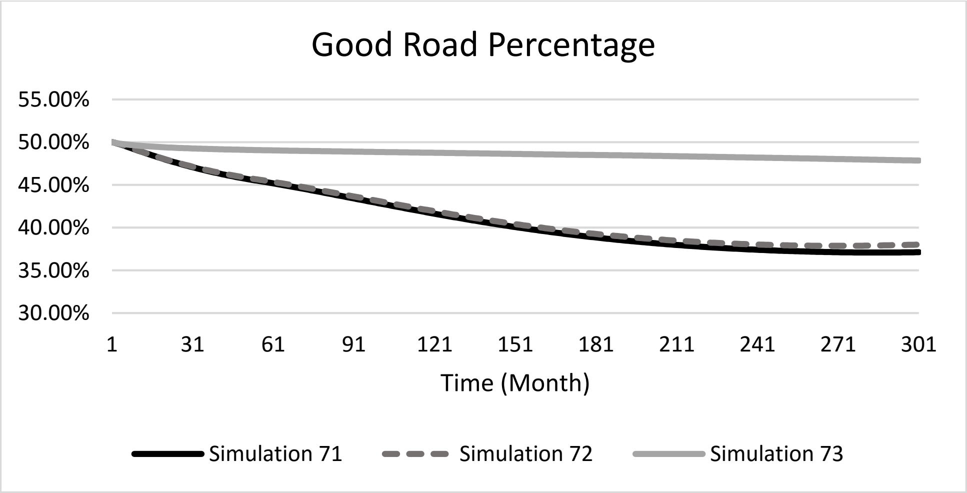


Figure V.5: KY Good Road Percentage for Simulations 71-73

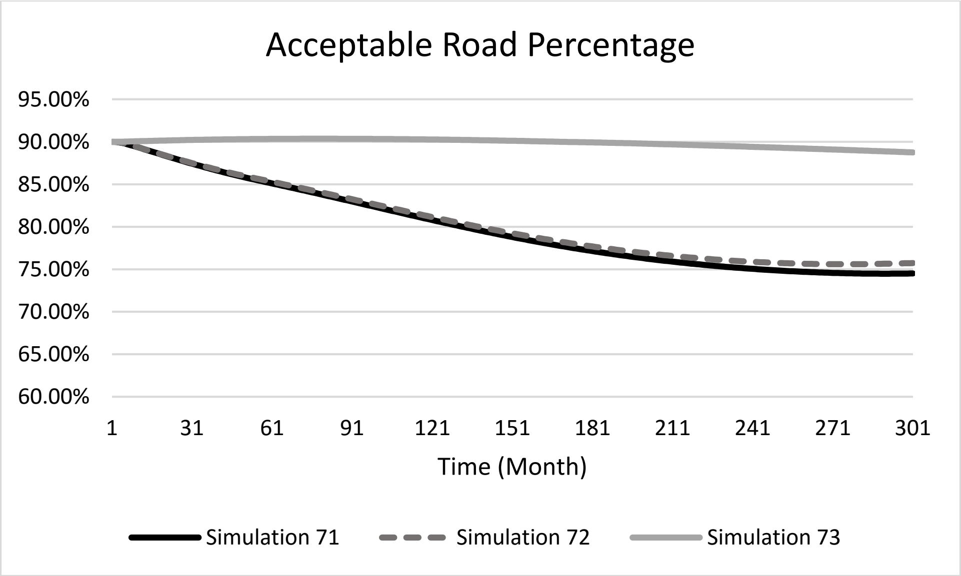


Figure V.6: KYTC Acceptable Road Percentage for Simulations 71-73

Figure V.7 displays the total monthly cost spent on workforce (including in-house and consultants) for the three simulations. Since in-house workforce budget is relatively stable, extensive use of consultants results in huge increase in total workforce cost during the period of workforce shortage. However, due to feedbacks within the system, using consultants fills workforce gaps quickly, thus reduces the amount of in-house hires. This appeared to result in savings starting around Month 170. But it may not be entirely desirable since it could also result in severe aging problems of the in-house workforce and create more disastrous behaviors beyond the model's simulation period.

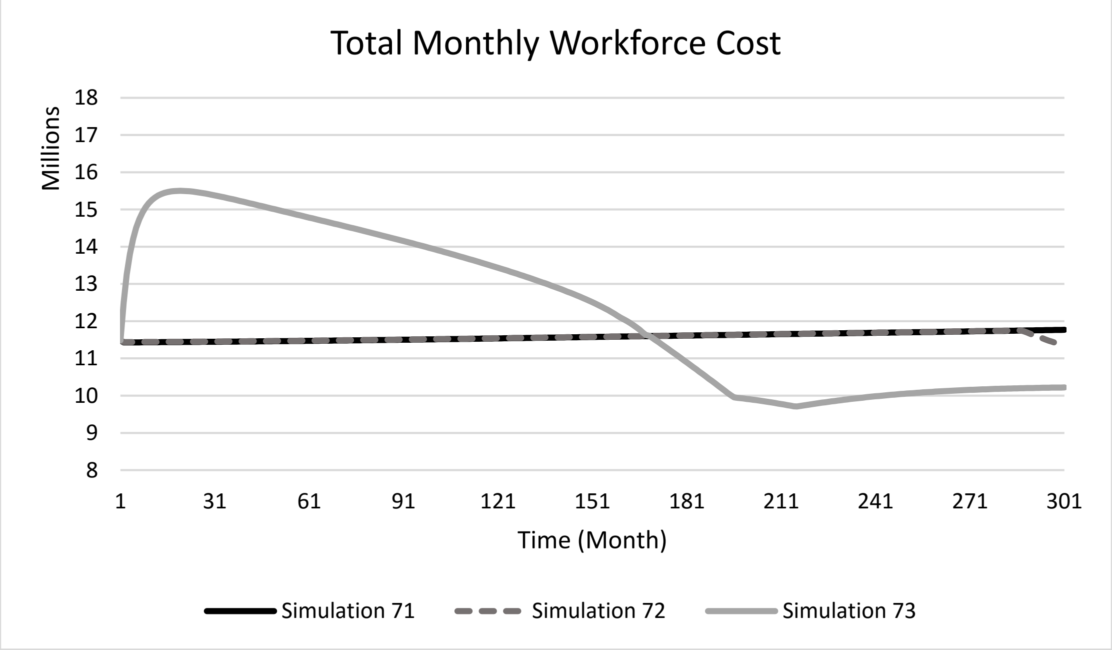


Figure V.7: KYTC Total Monthly Workforce Cost for Simulations 71-73

Since using consultants have its advantages and disadvantages, sensitivity runs were performed on the amount of consults retained as a percentage of amount needed. Sensitivity output for pavement performance indicators and total workforce cost are shown in Figure V.8 and Figure V.10. With the help of these figures, decision makers at the KYTC can determine how many consultants they can afford to hire to achieve an acceptable performance level.

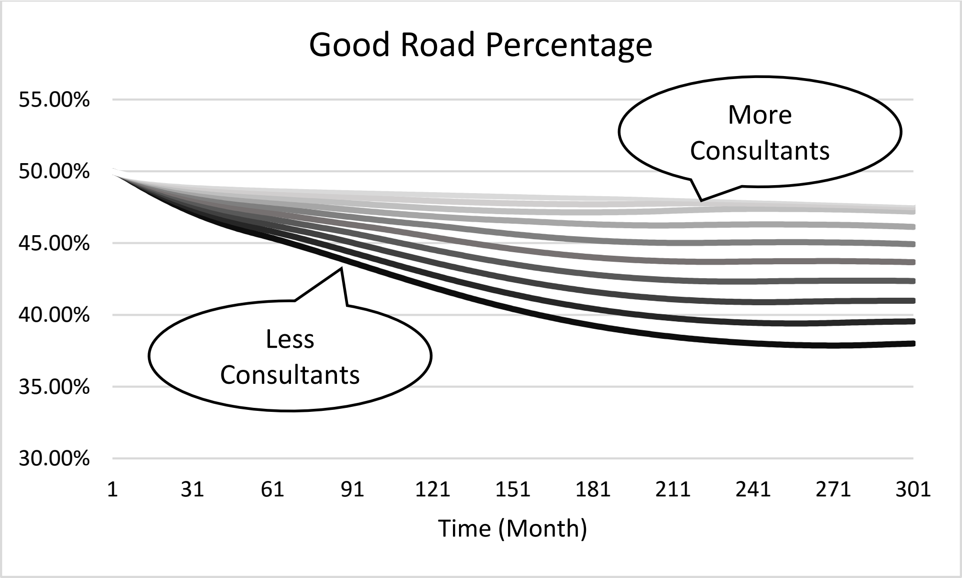


Figure V.8: Sensitivity of Good Road Percentage to Varying Amount of Consultants

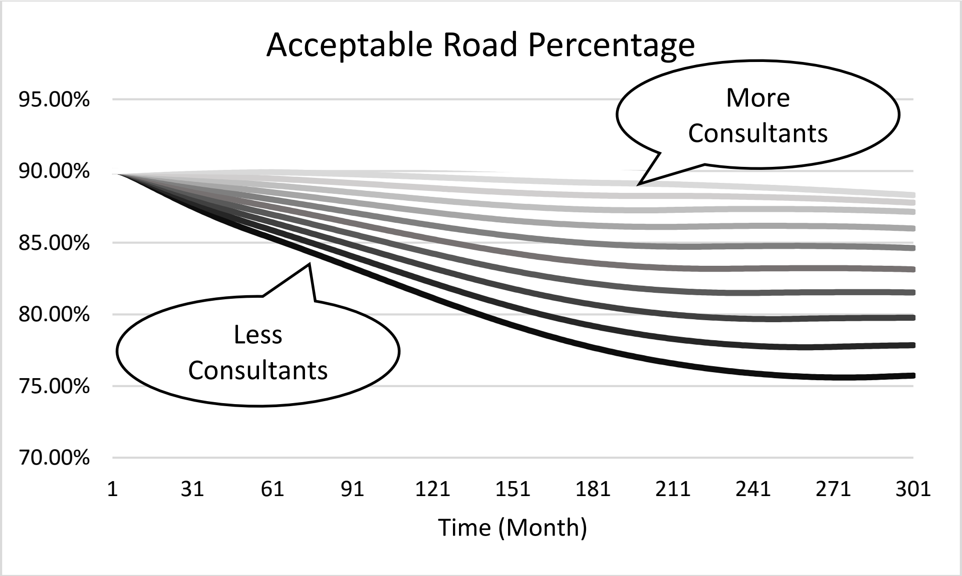


Figure V.9: Sensitivity of Acceptable Road Percentage to Varying Amount of Consultants

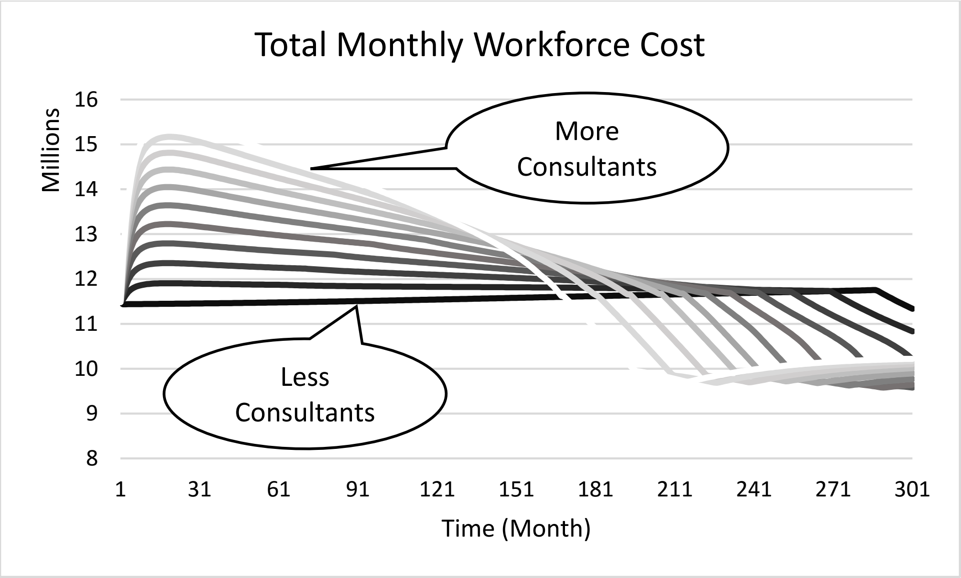


Figure V.10: Sensitivity of Total Monthly Workforce Cost to Varying Amount of Consultants

CHAPTER VI CONCLUSIONS

VI.1 Answers to Research Questions Investigated

What feedback structures link future transportation system demand, current system performance, funding level, staffing strategy and future staffing requirements?

This work presented a system dynamics model that integrated a State Transportation Agency's long term staffing need with road and bridge performance level, the agency's funding level and staffing strategies. This dissertation adapted a standard system dynamics modeling procedure and derived a series of dynamic hypotheses about the feedback structures among factors impacting staffing needs. These dynamics hypotheses were derived from literature review and interviews with transportation experts. The dynamic hypotheses included balancing loops that, when in power, would drive the system into a goal seeking mode where the State Transportation Agency was able to achieve their performance goal. When resources were insufficient, the balancing loops could lose control of the system behavior and shift their power to reinforcing loops within the system that would deviate highway performance from the STA's goal. 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. After applying collected data as input into the formal model, simulations were performed to reflect a variety of situations and model behavior was examined. The model produced reasonable behaviors that are both consistent with observations from actual practice and the model's dynamic hypotheses. Therefore, the feedback structures within the system that impact long term staffing requirements for State

Transportation Agencies should be able to provide insight into forecasting future staffing needs.

What are the main drivers and constraints that determine future staffing requirements? How do these drivers and constraints impact State Transportation Agencies' staffing strategies?

Performance Target setting, available fund for road and bridges and the dynamic flows within the current and future workforce can both impact the behavior of the system. Model output reveal that the amount of work required to be perform in order to achieve varying levels of performance target can differ significantly, which in turn results in differing workforce requirements. High targets require more initial effort, but could drive the system into a healthier state and have long term benefits. Insufficient funding level creates work backlogs that can drive the system into a more demanding mode. Dynamic flows within the workforce dictates the amount of work the agency can handle over time. Not being able to fill workforce gaps in time can strengthen the power of the reinforcing loops and can also drive the system into a more demanding mode. Differences in productivity, difference in pay grades, difference in availability and average service time among employees with varying experience levels make each group of them unique in the way they impact system's behavior. Recruiting options should be evaluated carefully. In workforce shortage under the current workforce market conditions, consultants may also play an important role in addressing temporary shortage in available workforce. These findings indicate that staffing strategies should not be made without considering the agency's long term goal and the interactions among different types of resources in order to maintain a sustainable workforce at State Transportation Agencies.

How can State Transportation Agencies effectively address potential staffing shortages and overflows?

In addition to understanding the feedback structures within the system that drives system behavior, State Transportation Agency can benefit from using this model to perform simulation runs to evaluate different options based on the agency's priorities (performance, budget, in-house workforce stability, etc.). There are no commons answers as to how an agency should address staffing shortage 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.

VI.2 Research Contributions

This research makes several contributions to the existing body of knowledge regarding staffing issues at State Transportation Agencies. Project based, short term staffing level forecasting tool have been widely used in State Transportation Agencies. While short term staffing tools can be very accurate and reflect an agency's actual practice very well, they cannot be used to make long term forecasts without a defined project profile. The model developed in the current work also directly link staffing decisions to overall system performance. Long term consequences of project selection and recruiting strategies can be captured using simulations. Many states use the 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 State Transportation Agencies' ability to keep the transportation infrastructures in good shape.

VI.3 Limitations

Although the current work makes a number of contributions to the existing body of knowledge within the fields of dynamic modeling, highway infrastructure maintenance, and highway staffing, the current work also 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 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 a good R^2 value to reflect minor changes in historical acceptable pavement percentage in the road system monitored by the Kentucky Transportation Cabinet, therefore, despite of the model's ability to forecast trends and behavior modes of the variables of interest, it would not be able to predict values with pin-point accuracy.

VI.4 Future Work

The main focus of this dissertation was 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, although additional behavioral and empirical validation will be required.

The model was developed using the Vensim software, which is not widely used among State Transportation Agencies. To actually make the model useful to transportation experts in decision making, it will be necessary to develop a decision tool with a more user-friendly interface.

In addition to serving State Transportation Agencies in forecasting long term staffing requirements, the model structure can potentially be adapted for other fleet management systems as well.

APPENDIX A TEXT VERSION OF THE FORMAL MODEL

This appendix contains the raw Vensim model code for the current work. The model was created in Vensim DSS32 version 5.0. Contained within each variable are the variable name, equation, unit, and a description of the variable.

```
{UTF-8}
"% of Required Consulting Engineers Retained"=
        100
        ~       Dmnl
        ~       This varibale represent the amount of consulting Engineers the agency \
                actually hires as a percentage of the needed amount.
        |

"% of Required Consulting Technicians Retained"=
        100
        ~       Dmnl
        ~       This variable represent the amount of consulting Technicians the agency \
                actually hires as a percentage of the needed amount.
        |

Number of Consulting Engineers=
        (Engineer Gap-Planned Engineer New Hire)/Consulting Engineer Productivity
Factor*Consulting Engineer Switch\
                *"% of Required Consulting Engineers Retained"/100
        ~       Person
        ~       Number of consulting engineers currently hired by the STA.
        |

Number of Consulting Technicians=
        (Technician Gap-Planned Technician New Hire)/Consulting Technician Productivity
Factor\
                *Consulting Technician Switch*"% of Required Consulting Technicians
Retained"/100
        ~       Person
        ~       Number of consulting technicians currently hired by the STA.
        |

Total Workforce Cost=
        Total Salary+Total Payment to Consultants
        ~       Dollar/Month
        ~       The monthly cost for both in-house salary and consultants' fees.
        |

"Total In-House Workforce Budget"= INTEG (
        adjust total workforce budget,
                Total Salary)
        ~       Dollar/Month
        ~               |
```

```
Total Payment to Consultants=
        Payment to Consulting Engineers+Payment to Consulting Technicians
        ~       Dollar/Month
        ~       This is the combined monthly payment to consulting Engineers and \
                consulting Technicians.
        |

Time Required to Adjust Total Workforce Budget=
        IF THEN ELSE(Workforce Budget Restraint Switch=0, 1 , 1e+010)
        ~       Month
        ~       Time required to adjust total workforce budget to desired level.
        |

Road Fund Adjustment Mode Switch=
        1
        ~       Dmnl
        ~       1 means the STA adjust available funding level according to the required \
                funding level, filling a portion or all of the gap each month. 0 means the \
                STA change the available funding level at a constant change rate.
        |

Road Fund Limit Switch=
        1
        ~       Dmnl
        ~       When this switch is on (value equals 1), road fund is limited. When the \
                switch is off (value equals 0), the STA always gets plenty of money.
        |

Bridge Fund Limit Switch=
        1
        ~       Dmnl
        ~       When this switch is on (value equals 1), bridge fund is limited. When the \
                switch is off (value equals 0), the STA always gets plenty of money.
        |

"Initial (2015) Fair Roads"=
        Initial Total Road Capacity*(Initial Fair and Better Road Percentage-Initial Good Road
Percentage\
                )/100
        ~       Lane Mile
        ~       24000 is the test value in the generic model. In 2015, KYTC administers a \
                total of 63100 lane miles of highways. About 40% were rated as fair.
        |

"Initial (2015) Good Bridge"=
        Initial Total Bridge Area*Initial Good Bridge Percentage/100
        ~       Square Meter
        ~       The amount of bridge deck area classified as "good" at the beginning of \
                the simulation. 4000000 is the test value for the generic model. KY has \
                3900253 in 2015.
```

```
	|

"Initial (2015) Good Roads"=
	Initial Total Road Capacity*Initial Good Road Percentage/100
	~	Lane Mile
	~	30000 is the test value in the generic model. In 2015, KYTC administers a \
		total of 63100 lane miles of highways. About 50% were rated as good.
	|

"Initial (2015) Poor Bridge"=
	Initial Total Bridge Area-"Initial (2015) Good Bridge"-"Initial (2015) Fair Bridge"
	~	Square Meter
	~	1200000 is the test value in the generic model. In 2015, KYTC administers \
		a total of 5261333 square meters of highway bridges. About 21.47% (1129553 \
		square meters) were rated as functionally obsolete.
	|

"Initial (2015) Poor Roads"=
	Initial Total Road Capacity-"Initial (2015) Good Roads"-"Initial (2015) Fair Roads"
	~	Lane Mile
	~	6000 is the test value in the generic model. In 2015, KYTC administers a \
		total of 63100 lane miles of highways. About 10% were rated as poor.
	|

Time Required to Hire Entry Level Technicians=
	1
	~	Month
	~	The average time needed to hire an entry level technician.
	|

Workforce Budget Restraint Switch=
	1
	~	Dmnl
	~	When this switch is on (=1), in-house workforce budget is limited and \
		adjust with 24-month delay. When this switch is off (=0), in-house \
		workforce budget adjusts to the required level within 1 time step.
	|

Initial Fair and Better Bridge Percentage=
	78
	~	Dmnl
	~	This is the fair and better bridge percentage at the beginning of the \
		simulation.
	|

Initial Fair and Better Road Percentage=
	90
	~	Dmnl
	~	This is the fair and better road percentage at the beginning of the \
		simulation.
	|
```

```
Initial Good Bridge Percentage=
	74
	~	Dmnl
	~	This is the good bridge percentage at the beginning of the simulation.
	|

Initial Good Road Percentage=
	50
	~	Dmnl
	~	This is the good road percentage at the beginning of the simulation.
	|

Total Available Technician=
	IF THEN ELSE(Workforce Restraint Switch=0, "Total Technicians Required - Budget" ,
"Total In-House Technician"\
		+Number of Consulting Technicians*Consulting Technician Productivity Factor )
	~	Eqv Person
	~	The total available equivalent number of technicians including in-house \
		staff and consultants.
	|

"Initial (2015) Fair Bridge"=
	Initial Total Bridge Area*(Initial Fair and Better Bridge Percentage-Initial Good Bridge
Percentage\
		)/100
	~	Square Meter
	~	240000 is the test value in the generic model. In 2015, KYTC administers a \
		total of 5261333 square meters of highway bridges. About 4.4% (231527 \
		square meters) were rated as structurally deficient.
	|

Workforce Restraint Switch=
	1
	~	Dmnl
	~	When this switch is on (=1), the number of technicians available is \
		limited.When this switch is off (=0), the STA always have enough \
		technicians to carry out required work.
	|

Time Required to Hire Senior Technician=
	2
	~	Month
	~	The average time needed to hire a senior technician.
	|

Initial Total Road Capacity=
	63100
	~	Lane Mile
	~	The total road capacity on 01-01-2015. 60000 is the test value in the \
		generic model, KY value is 63100.
```

```
	|

Time Required to Hire Mid Level Technician=
	1
	~	Month
	~	The average time needed to hire a mid level technician.
	|

Total Available Engineer=
	IF THEN ELSE(Workforce Restraint Switch=0, "Total Engineers Required - Budget" ,
"Total In-House Engineer"\
		+Number of Consulting Engineers*Consulting Engineer Productivity Factor )
	~	Eqv Person
	~	The total available equivalent number of engineers including in-house \
		staff and consultants.
	|

Monthly Budget Available due to Turn Over=
	("EIT quit/fired rate"*EIT Average Salary+"Licensed Engineer quit/fired rate"*Licensed
Engineer Average Salary\
		+("senior licensed Engineer quit/fired rate"
	+engineer retire rate-hire formerly retired engineer rate)*Senior Licensed Engineer
Average Salary\
		+"Entry Level Technician quit/fired rate"*Entry Level Technician Average Salary
	+"mid level Technician quit/fired rate"*Mid Level Technician Average Salary+("senior
Technician quit/fired rate"\
		+Technician retire rate-hire formerly retired technician rate
	)*Senior Technician Average Salary-EIT gain experience rate*(Licensed Engineer Average
Salary\
		-EIT Average Salary)-licensed engineer gain experience rate
	*(Senior Licensed Engineer Average Salary-Licensed Engineer Average Salary)-entry
level technician gain experience rate
	*
	(Mid Level Technician Average Salary-Entry Level Technician Average Salary)-mid level
Technician gain experience rate\
		*(
	Senior Technician Average Salary
	-Mid Level Technician Average Salary))*TIME STEP
	~	Dollar/Month
	~	The monthly workforce budget becoming available for new hire due to \
		retirement, quitting, firing, and salary raise for increased experience of \
		existing workforce.
	|

hire formerly retired engineer rate=
	engineer retire rate*Fraction of Formerly Retired Engineers Returning to the Agency*\
		Formerly Retired Engineer Back Hire Switch
	~	Person/Month
	~	The number of formerly retired Engineers coming back to the agency this \
		month.
	|
```

```
Formerly Retired Engineer Back Hire Switch=
        1
        ~       Dmnl
        ~       When this switch is on (1), the agency hires a portion of retired \
                Engineers back to work. When this switch is off (0), retired Engineers do \
                not return to work for the agency as in-house staff.
        |

Formerly Retired Technician Back Hire Switch=
        1
        ~       Dmnl
        ~       When this switch is on (1), the agency hires a portion of retired \
                Technicians back to work. When this switch is off (0), retired Technicians \
                do not return to work for the agency as in-house staff.
        |

Fraction of Formerly Retired Engineers Returning to the Agency=
        0.15
        ~       Dmnl
        ~       This is the fraction of retiring Engineers who are coming back to the \
                agency as in-house staff.
        |

Senior Technician= INTEG (
        hire formerly retired technician rate+hire senior Technician rate+mid level Technician gain
experience rate\
                -"senior Technician quit/fired rate"-Technician retire rate,
                Initial Senior Technician)
        ~       Person
        ~       Current number of seasoned technicians serving the STA.
        |

Senior Licensed Engineer= INTEG (
        hire formerly retired engineer rate+hire senior licensed Engineer rate+licensed engineer
gain experience rate\
                -engineer retire rate-"senior licensed Engineer quit/fired rate",
                Initial Senior Licensed Engineer)
        ~       Person
        ~       Current number of seasoned engineers serving the STA.
        |

hire formerly retired technician rate=
        Technician retire rate*Fraction of Formerly Retired Technicians Returning to the Agency\
                *Formerly Retired Technician Back Hire Switch
        ~       Person/Month
        ~       The number of formerly retired Technicians coming back to the agency this \
                month.
        |

Fraction of Formerly Retired Technicians Returning to the Agency=
```

```
	0.15
	~	Dmnl
	~	This is the fraction of retiring technicians who are coming back to the \
		agency as in-house staff.
	|

Budget Required for Engineer New Hire=
	Engineer Gap*Desired Fraction of Engineer Gap to Be Filled by New Hire*Engineer New
Hire Average Salary\
		/Engineer New Hire Productivity Factor
	~	Dollar/Month
	~	Monthly budget required for new hire to fill engineer gap.
	|

Consulting Technician Switch=
	1
	~	Dmnl
	~	When "Consulting Technician Switch" is on (1), the agency hires consulting \
		technicians to fill the portion of the Technician Gap that can not be \
		filled by in-house hire. When the switch is off (0), no consulting \
		Technicians will be hired.
	|

Desired Fraction of Technician Gap to Be Filled by New Hire=
	1
	~	Dmnl
	~	Desired fraction of the technician gap to be filled by hiring in-house \
		Technicians. This may or may not be achievable depending on available \
		internal workforce budget.
	|

Actual Fraction of Engineers Gap to Be Filled by New Hire=
	XIDZ(Planned Engineer New Hire, Engineer Gap , 1)
	~	Dmnl
	~	The actual fraction of Engineer Gap to be filled by in-house hire based on \
		available internal workforce budget.
	|

Actual Fraction of Technician Gap to Be Filled by New Hire=
	XIDZ(Planned Technician New Hire, Technician Gap , 1 )
	~	Dmnl
	~	The actual fraction of Technician Gap to be filled by in-house hire based \
		on available internal workforce budget.
	|

Ratio of Available Technician to Budget Required Technician=
	Total Available Technician/"Total Technicians Required - Budget"
	~	Dmnl
	~	This is the ratio of available workforce to budget required workforce.
	|
```

```
Desired Fraction of Engineer Gap to Be Filled by New Hire=
        1
        ~       Dmnl
        ~       Desired fraction of the Engineer gap to be filled by hiring in-house \
                Engineers. This may or may not be achievable depending on available \
                internal workforce budget.
        |

Budget Required for Technician New Hire=
        Technician Gap*Desired Fraction of Technician Gap to Be Filled by New Hire*Technician
New Hire Average Salary\
                /Technician New Hire Productivity Factor
        ~       Dollar/Month
        ~       Monthly budget required for new hire to fill technician gap.
        |

Consulting Engineer Switch=
        1
        ~       Dmnl
        ~       When "Consulting Engineer Switch" is on (1), the agency hires consulting \
                engineers to fill the portion of the Engineer Gap that can not be filled \
                by in-house hire. When the switch is off (0), no consulting Engineers will \
                be hired.
        |

Consulting Technician Wage=
        5166
        ~       Dollar/(Month*Person)
        ~       Assume consulting technicians get paid the same rate as senior licensed \
                technicians
        |

Payment to Consulting Engineers=
        Number of Consulting Engineers*Consulting Engineer Wage
        ~       Dollar/Month
        ~       Monthly payment to consulting Engineers.
        |

Payment to Consulting Technicians=
        Number of Consulting Technicians*Consulting Technician Wage
        ~       Dollar/Month
        ~       Monthly payment to consulting Technicians.
        |

Consulting Engineer Wage=
        8000
        ~       Dollar/(Month*Person)
        ~       Assume consulting engineers get paid the same rate as senior licensed \
                engineers.
        |
```

```
"Total In-House Engineer"=
        EIT*EIT Productivity Factor+Licensed Engineer*Licensed Engineer Productivity
Factor+\
                Senior Licensed Engineer*Senior Licensed Engineer Productivity Factor
        ~       Eqv Person
        ~       The equivalent number of average engineers serving the STA.
        |

Consulting Engineer Productivity Factor=
        2
        ~       Eqv Person/Person
        ~       Assume consulting engineers have the same productivity factor as senior \
                licensed engineers.
        |

Ratio of Available Engineer to Budget Required Engineer=
        Total Available Engineer/"Total Engineers Required - Budget"
        ~       Dmnl
        ~       This is the ratio of available workforce to budget required workforce.
        |

Consulting Technician Productivity Factor=
        2
        ~       Eqv Person/Person
        ~       Assume consulting technicians have the same productivity factor as senior \
                technicians.
        |

Planned Technician New Hire=
        Budget for Technician New Hire/Technician New Hire Average Salary*Technician New
Hire Productivity Factor
        ~       Eqv Person
        ~       The equivalent number of Technicians the STA plan to hire this month.
        |

Technician Gap=
        MAX("Total Technicians Required - Budget"-"Total In-House Technician", 0)
        ~       Eqv Person
        ~       The difference between desired equivalent number of engineers and actual \
                available equivalent number of engineers.
        |

Technician New Hire Average Salary=
        Entry Level Technician Average Salary*"% Technician Gap to Be Filled by Hiring Entry
Level Technicians"\
                /100+Mid Level Technician Average Salary*"% Technician Gap to Be Filled by
Hiring Mid Level Technician"\
                /100+Senior Technician Average Salary*"% Technician Gap to Be Filled By
Hiring Senior Technician"\
                /100
        ~       Dollar/(Month*Person)
```

```
	~	The average salary of all incoming Technicians.
	|

Planned Senior Licensed Engineer New Hire=
	Planned Engineer New Hire*"% Engineer Gap to Be Filled By Hiring Senior Licensed
Engineer"\
		/100/Senior Licensed Engineer Productivity Factor
	~	Person
	~	Planned number of seasoned engineers to be hired this month.
	|

Planned Senior Technician New Hire=
	Planned Technician New Hire*"% Technician Gap to Be Filled By Hiring Senior
Technician"\
		/100/Senior Technician Productivity Factor
	~	Person
	~	Planned number of senior technicians to be hired this month.
	|

Technician New Hire Productivity Factor=
	Entry Level Technician Productivity Factor*"% Technician Gap to Be Filled by Hiring
Entry Level Technicians"\
		/100+Mid Level Technician Productivity Factor*"% Technician Gap to Be Filled
by Hiring Mid Level Technician"\
		/100+Senior Technician Productivity Factor*"% Technician Gap to Be Filled By
Hiring Senior Technician"\
		/100
	~	Eqv Person/Person
	~	The average productivity factor of all incoming Technicians.
	|

Engineer New Hire Average Salary=
	EIT Average Salary*"% Engineer Gap to Be Filled by Hiring EIT"/100+Licensed Engineer
Average Salary\
		*"% Engineer Gap to Be Filled by Hiring Licensed Engineer"/100+Senior
Licensed Engineer Average Salary\
		*"% Engineer Gap to Be Filled By Hiring Senior Licensed Engineer"/100
	~	Dollar/(Month*Person)
	~	Average Salary of all incoming Engineers.
	|

Engineer New Hire Productivity Factor=
	EIT Productivity Factor*"% Engineer Gap to Be Filled by Hiring EIT"/100+Licensed
Engineer Productivity Factor\
		*"% Engineer Gap to Be Filled by Hiring Licensed Engineer"/100+Senior
Licensed Engineer Productivity Factor\
		*"% Engineer Gap to Be Filled By Hiring Senior Licensed Engineer"/100
	~	Eqv Person/Person
	~	The average productivity factor of all incoming Engineers.
	|
```

```
Budget for Technician New Hire=
        MIN(Budget Required for Technician New Hire,Budget Available for Technician New
Hire\
                )
        ~       Dollar/Month
        ~       Monthly budget for incoming Technicians.
        |

Engineer Gap=
        MAX( "Total Engineers Required - Budget"-"Total In-House Engineer", 0)
        ~       Eqv Person
        ~       The difference between desired equivalent number of engineers and actual \
                available equivalent number of engineers.
        |

Planned EIT New Hire=
        Planned Engineer New Hire*"% Engineer Gap to Be Filled by Hiring EIT"/100/EIT
Productivity Factor
        ~       Person
        ~       Planned number of EITs to be hired this month.
        |

Planned Engineer New Hire=
        Budget for Engineer New Hire/Engineer New Hire Average Salary*Engineer New Hire
Productivity Factor
        ~       Eqv Person
        ~       The equivalent number of Engineers the STA plan to hire this month.
        |

Planned Entry Level Technician New Hire=
        Planned Technician New Hire*"% Technician Gap to Be Filled by Hiring Entry Level
Technicians"\
                /100/Entry Level Technician Productivity Factor
        ~       Person
        ~       Planned number of Entry Level Technicians to be hired this month.
        |

Budget for Engineer New Hire=
        MIN(Budget Required for Engineer New Hire,Budget Available for Engineer New Hire)
        ~       Dollar/Month
        ~       Monthly budget for incoming Engineers.
        |

Budget Available for Engineer New Hire=
        Budget Available for New Hire*ZIDZ(Budget Required for Engineer New Hire,Budget
Required for New Hire\
                )
        ~       Dollar/Month
        ~       Monthly budget available for incoming Engineers.
        |
```

Budget Available for Technician New Hire=
Budget Available for New Hire*ZIDZ(Budget Required for Technician New Hire,Budget Required for New Hire\
)
~ Dollar/Month
~ Monthly budget available for incoming Technicians.
|

Planned Licensed Engineer New Hire=
Planned Engineer New Hire*"% Engineer Gap to Be Filled by Hiring Licensed Engineer"/\
100/Licensed Engineer Productivity Factor
~ Person
~ Planned number of average engineers to be hired this month.
|

Planned Mid Level Technician New Hire=
Planned Technician New Hire*"% Technician Gap to Be Filled by Hiring Mid Level Technician"\
/100/Mid Level Technician Productivity Factor
~ Person
~ Planned number of mid level technicians to be hired this month.
|

EIT Average Salary=
3000
~ Dollar/(Month*Person)
~ The average monthly salary of EITs.
|

Senior Licensed Engineer Average Salary=
5833
~ Dollar/(Month*Person)
~ The average monthly salary of senior licensed engineers.
|

Licensed Engineer Average Salary=
4000
~ Dollar/(Month*Person)
~ The average monthly salary of licensed engineers.
|

Senior Technician Average Salary=
2917
~ Dollar/(Month*Person)
~ The average monthly salary of senior technicians.
|

Mid Level Technician Average Salary=
2583
~ Dollar/(Month*Person)
~ The average monthly salary of mid level technicians.

```
	|

Budget Required for New Hire=
	Budget Required for Engineer New Hire+Budget Required for Technician New Hire
	~	Dollar/Month
	~	The combined monthly budget required to fill engineer gap and technician \
		gap.
	|

adjust total workforce budget=
	New Hire Budget Gap/Time Required to Adjust Total Workforce Budget
	~	Dollar/(Month*Month)
	~	Adjustment made to total workforce budget this month.
	|

New Hire Budget Gap=
	Budget Required for New Hire-Monthly Budget Available due to Turn Over
	~	Dollar/Month
	~	The difference between required monthly budget to fill workforce gap and \
		available monthly budget for new hire.
	|

Total Salary=
	Total Engineer Salary+Total Technician Salary
	~	Dollar/Month
	~	The total combined monthly salary of engineers and technicians.
	|

Budget Available for New Hire=
	Monthly Budget Available due to Turn Over+adjust total workforce budget*TIME STEP
	~	Dollar/Month
	~	Monthly budget available for new hire.
	|

Total Engineer Salary=
	EIT*EIT Average Salary+Licensed Engineer*Licensed Engineer Average Salary+Senior
Licensed Engineer\
		*Senior Licensed Engineer Average Salary
	~	Dollar/Month
	~	The total monthly salary of all engineers.
	|

Total Technician Salary=
	Entry Level Technician*Entry Level Technician Average Salary+Mid Level
Technician*Mid Level Technician Average Salary\
		+Senior Technician*Senior Technician Average Salary
	~	Dollar/Month
	~	The total monthly salary of all technicians.
	|

Entry Level Technician Average Salary=
```

```
	2083
	~	Dollar/(Month*Person)
	~	The average monthly salary of entry level technicians.
	|

"Bridge Engineer Productivity - Fair to Good"=
	"Bridge Fund Output - Fair to Good"*Ratio of Available Engineer to Budget Required
Engineer
	~	Square Meter
	~	The amount (in square meters) of fair to good bridge repair work the STA \
		is able to carry out with available workforce this month.
	|

"Bridge Engineer Productivity - New Area"=
	"Bridge Fund Output - New Area"*Ratio of Available Engineer to Budget Required
Engineer
	~	Square Meter
	~	The amount (in square meters) of new bridge area the STA is able to build \
		with available workforce this month.
	|

"Bridge Engineer Productivity - Poor to Fair"=
	"Bridge Fund Output - Poor to Fair"*Ratio of Available Engineer to Budget Required
Engineer
	~	Square Meter
	~	The amount (in square meters) of poor to fair bridge repair work the STA \
		is able to carry out with available workforce this month.
	|

"Road Productivity - Fair to Good"=
	MIN("Road Fund Output - Fair to Good",MIN(Planned Fair Road to Good Road Repair
Quantity\
		,MIN("Road Engineer Productivity - Fair to Good","Road Technician Productivity
- Fair to Good"\
		)))/TIME STEP
	~	Lane Mile/Month
	~	How much work the STA can perform based on available resource (money, \
		Engineers, Technicians).	MIN("Road Fund Output - Fair to Good",Planned \
		Fair Road to Good Road Repair Quantity)/TIME STEP
	|

"Road Productivity - New Mileage"=
	MIN("Road Fund Output - New Mileage",MIN(Forecasted New Mileage
Needed,MIN("Road Engineer Productivity - New Mileage"\
		,"Road Technician Productivity - New Mileage")))/TIME STEP
	~	Lane Mile/Month
	~	How much work the STA can perform based on available resource (money, \
		Engineers, Technicians).	MIN("Road Fund Output - New \
		Mileage",Forecasted New Mileage Needed)/TIME STEP
	|
```

```
"Road Productivity - Poor to Good"=
	MIN("Road Fund Output - Poor to Good",MIN(Planned Poor Road to Good Road Repair
Quantity\
		,MIN("Road Engineer Productivity - Poor to Good","Road Technician
Productivity - Poor to Good"\
		)))/TIME STEP
	~	Lane Mile/Month
	~	How much work the STA can perform based on available resource (money, \
		Engineers, Technicians).   MIN("Road Fund Output - Poor to Good",Planned \
		Poor Road to Good Road Repair Quantity)/TIME STEP
	|

"Road Productivity - Poor to Fair"=
	MIN("Road Fund Output - Poor to Fair",MIN(Planned Poor Road to Fair Road Repair
Quantity\
		,MIN("Road Engineer Productivity - Poor to Fair","Road Technician Productivity
- Poor to Fair"\
		)))/TIME STEP
	~	Lane Mile/Month
	~	How much work the STA can perform based on available resource (money, \
		Engineers, Technicians).     MIN("Road Fund Output - Poor to Fair",Planned \
		Poor Road to Fair Road Repair Quantity)/TIME STEP
	|

"Road Technician Productivity - Poor to Fair"=
	"Road Fund Output - Poor to Fair"*Ratio of Available Technician to Budget Required
Technician
	~	Lane Mile
	~	The amount (in lane miles) of poor to fair road repair work the STA is \
		able to carry out with available workforce this month.
	|

"Road Technician Productivity - Poor to Good"=
	"Road Fund Output - Poor to Good"*Ratio of Available Technician to Budget Required
Technician
	~	Lane Mile
	~	The amount (in lane miles) of poor to good road repair work the STA is \
		able to carry out with available workforce this month.
	|

"Bridge Technician Productivity - Fair to Good"=
	"Bridge Fund Output - Fair to Good"*Ratio of Available Technician to Budget Required
Technician
	~	Square Meter
	~	The amount (in square meters) of fair to good bridge repair work the STA \
		is able to carry out with available workforce this month.
	|

"Road Technician Productivity - Fair to Good"=
	"Road Fund Output - Fair to Good"*Ratio of Available Technician to Budget Required
Technician
```

```
        ~       Lane Mile
        ~       The amount (in lane miles) of fair to good road repair work the STA is \
                able to carry out with available workforce this month.
        |

"Road Technician Productivity - New Mileage"=
        "Road Fund Output - New Mileage"*Ratio of Available Technician to Budget Required
Technician
        ~       Lane Mile
        ~       The amount (in lane miles) of new road the STA is able to build with \
                available workforce this month.
        |

"Bridge Productivity - Poor to Good"=
        MIN("Bridge Fund Output - Poor to Good",MIN(Planned Poor Bridge to Good Bridge
Repair Quantity\
                ,MIN("Bridge Engineer Productivity - Poor to Good","Bridge Technician
Productivity - Poor to Good"\
                )))/TIME STEP
        ~       Square Meter/Month
        ~       How much work the STA can perform based on available resource (money, \
                Engineers, Technicians).
        |

"Road Engineer Productivity - Poor to Good"=
        "Road Fund Output - Poor to Good"*Ratio of Available Engineer to Budget Required
Engineer
        ~       Lane Mile
        ~       The amount (in lane miles) of poor to good road repair work the STA is \
                able to carry out with available workforce this month.
        |

"Road Engineer Productivity - Poor to Fair"=
        "Road Fund Output - Poor to Fair"*Ratio of Available Engineer to Budget Required
Engineer
        ~       Lane Mile
        ~       The amount (in lane miles) of poor to fair road repair work the STA is \
                able to carry out with available workforce this month.
        |

"Bridge Productivity - New Area"=
        MIN("Bridge Fund Output - New Area",MIN(Forecasted New Bridge Area
Needed,MIN("Bridge Engineer Productivity - New Area"\
                ,"Bridge Technician Productivity - New Area")))/TIME STEP
        ~       Square Meter/Month
        ~       How much work the STA can perform based on available resource (money, \
                Engineers, Technicians).
        |

"Bridge Productivity - Poor to Fair"=
        MIN("Bridge Fund Output - Poor to Fair",MIN(Planned Poor Bridge to Fair Bridge Repair
```

```
Quantity\
                ,MIN("Bridge Engineer Productivity - Poor to Fair","Bridge Technician
Productivity - Poor to Fair"\
                )))/TIME STEP
        ~       Square Meter/Month
        ~       How much work the STA can perform based on available resource (money, \
                Engineers, Technicians).
        |

"Bridge Technician Productivity - Poor to Fair"=
        "Bridge Fund Output - Poor to Fair"*Ratio of Available Technician to Budget Required
Technician
        ~       Square Meter
        ~       The amount (in square meters) of poor to good bridge repair work the STA \
                is able to carry out with available workforce this month.
        |

"Bridge Technician Productivity - Poor to Good"=
        "Bridge Fund Output - Poor to Good"*Ratio of Available Technician to Budget Required
Technician
        ~       Square Meter
        ~       The amount (in square meters) of poor to good bridge repair work the STA \
                is able to carry out with available workforce this month.
        |

"Bridge Productivity - Fair to Good"=
        MIN("Bridge Fund Output - Fair to Good",MIN(Planned Fair Bridge to Good Bridge
Repair Quantity\
                ,MIN("Bridge Engineer Productivity - Fair to Good","Bridge Technician
Productivity - Fair to Good"\
                )))/TIME STEP
        ~       Square Meter/Month
        ~       How much work the STA can perform based on available resource (money, \
                Engineers, Technicians).
        |

"Road Engineer Productivity - Fair to Good"=
        "Road Fund Output - Fair to Good"*Ratio of Available Engineer to Budget Required
Engineer
        ~       Lane Mile
        ~       The amount (in lane miles) of fair to good road repair work the STA is \
                able to carry out with available workforce this month.
        |

"Bridge Technician Productivity - New Area"=
        "Bridge Fund Output - New Area"*Ratio of Available Technician to Budget Required
Technician
        ~       Square Meter
        ~       The amount (in square meters) of new bridge area the STA is able to build \
                with available workforce this month.
        |
```

```
"Bridge Engineer Productivity - Poor to Good"=
	"Bridge Fund Output - Poor to Good"*Ratio of Available Engineer to Budget Required
Engineer
	~	Square Meter
	~	The amount (in square meters) of poor to good bridge repair work the STA \
		is able to carry out with available workforce this month.
	|

"Road Engineer Productivity - New Mileage"=
	"Road Fund Output - New Mileage"*Ratio of Available Engineer to Budget Required
Engineer
	~	Lane Mile
	~	The amount (in lane miles) of new road the STA is able to build with \
		available workforce this month.
	|

increase senior technician total time in service=
	Senior Technician
	~	Person
	~	Each senior technician in service gain one more week of experience \
		(service time) each month.
	|

Planned Poor Bridge to Fair Bridge Repair Quantity=
	MAX(MIN("Poor Bridge Becoming Undrivable w/o Repair"*"% Retiring Bridge to Be
Rehabilitated"\
		/100, Poor Bridge-Planned Poor Bridge to Good Bridge Repair Quantity
	),0)
	~	Square Meter
	~	The only way to increase the amount of fair bridge through work is to \
		repair poor bridge.
	|

Senior Technician Maximum Service Time=
	144
	~	Month
	~	The maximum number of months a senior technician serves the STA as a \
		senior technician until retire.
	|

Planned Fair Bridge to Good Bridge Repair Quantity=
	MIN( MAX( Good Bridge Gap to Be Filled by Repairing-Planned Poor Bridge to Good
Bridge Repair Quantity\
		, 0 ) , Fair Bridge-Degrading Fair Bridge)
	~	Square Meter
	~	To increase the amount of good bridge by repairing, STAs can either repair \
		fair bridge or reconstruct poor bridge.
	|

Senior Technician Total Time in Service= INTEG (
```

```
        increase senior technician total time in service-decrease senior technician total time in
service\
                ,
                "2015 Senior Technician Average Time Served"*Initial Senior Technician)
        ~       Person*Month
        ~       The total time (in Person*Month) all senior technicians in service have \
                served the STA.
        |

Good Road Gap to Be Filled by Repairing=
        MAX(Forecasted Good Road Gap-Forecasted New Mileage Needed, 0 )
        ~       Lane Mile
        ~       A portion of the good road gap can be filled my building new lane miles. \
                The rest need to be filled by repairing existing capacity.
        |

Senior Technician Average Service Time until Retire=
        Senior Technician Maximum Service Time-Senior Technician Average Time Served
        ~       Month
        ~       The average time an senior technician serves the STA as a senior \
                technician until retirement.
        |

Senior Technician Average Time Served=
        Senior Technician Total Time in Service/Senior Technician
        ~       Month
        ~       Current average time a senior technician has served the STA as a senior \
                technician.
        |

decrease senior technician total time in service=
        Technician retire rate*Senior Technician Maximum Service Time
        ~       Person
        ~       When a senior technician completes 20 years of service (within which 12 \
                years as a senior technician), his/her service time is subtracted from \
                senior technician total service time.
        |

"Road Fund Required - New Mileage"=
        Forecasted New Mileage Needed*New Mileage Unit Cost
        ~       Dollar
        ~       Amount of fund required for planned new mileage.
        |

"Road Fund Required - Fair to Good Repair"=
        Planned Fair Road to Good Road Repair Quantity*"Road Repair Unit Cost - Fair to Good"
        ~       Dollar
        ~       Amount of fund required for planned fair to good road repair.
        |

"2015 Senior Technician Average Time Served"=
```

```
        96
        ~       Month
        ~       The average number of months all senior technician have served the STA on \
                1/1/2015.
        |

decrease senior licensed engineer total time=
        engineer retire rate*Senior Licensed Engineer Maximum Service Time
        ~       Person
        ~       Senior licensed engineer total service time lost due to retirement.
        |

increase senior licensed engineer total time=
        Senior Licensed Engineer
        ~       Person
        ~       Senior licensed engineer total service time increase as time moves on.
        |

Senior Licensed Engineer Maximum Service Time=
        120
        ~       Month
        ~       A senior licensed engineer serves the STA for 10 years before becoming \
                eligible for retirement.
        |

Senior Licensed Engineer Total Time in Service= INTEG (
        increase senior licensed engineer total time-decrease senior licensed engineer total time\
                ,
                "2015 Senior Licensed Engineer Average Time Served"*Initial Senior Licensed
Engineer\
                )
        ~       Person*Month
        ~       Total time (months) that all active senior licensed engineers have served \
                in the STA.
        |

Senior Licensed Engineer Average Service Time until Retire=
        Senior Licensed Engineer Maximum Service Time-Senior Licensed Engineer Average
Time Served
        ~       Month
        ~       The average time an seasoned engineer can still serve the STA before \
                retirement.
        |

Senior Licensed Engineer Average Time Served=
        Senior Licensed Engineer Total Time in Service/Senior Licensed Engineer
        ~       Month
        ~       The average time served by a senior engineer as a senior engineer.
        |

"2015 Senior Licensed Engineer Average Time Served"=
```

```
        72
        ~       Month
        ~       The average time served by a senior engineer as a senior engineer at the \
                beginning of the simulation.
        |

"% Licensed Engineer Quit/Fired"=
        0.2
        ~       Dmnl/Month
        ~       Percentage of average engineers quitting or getting fired each month.
        |

"% Mid Level Technician Quit/Fired"=
        0.5
        ~       Dmnl/Month
        ~       Percentage of mid level technicians quitting or getting fired each month.
        |

hire entry level technician rate=
        Planned Entry Level Technician New Hire/Time Required to Hire Entry Level Technicians
        ~       Person/Month
        ~       Number of entry level technician hired this month.
        |

mid level Technician gain experience rate=
        (Mid Level Technician-"mid level Technician quit/fired rate"*TIME STEP)/Time Required
for Mid Level Technician to Gain Experience
        ~       Person/Month
        ~       The number of mid level technicians becoming seasoned technicians this \
                month.
        |

Mid Level Technician Productivity Factor=
        1
        ~       Eqv Person/Person
        ~       The relative productivity of an mid level technician.
        |

"mid level Technician quit/fired rate"=
        Mid Level Technician*"% Mid Level Technician Quit/Fired"/100
        ~       Person/Month
        ~       The number of mid level technicians quitting or getting fired this month.
        |

"% EIT quit/fired"=
        0.03
        ~       Dmnl/Month
        ~       Percentage of EIT quitting or getting fired each month.
        |

"% Engineer Gap to Be Filled by Hiring Licensed Engineer"=
```

```
        10
        ~       Dmnl
        ~       Percentage of the engineer gap to be filled by hiring average engineers.
        |

"% Engineer Gap to Be Filled by Hiring EIT"=
        90
        ~       Dmnl
        ~       Percentage of the engineer gap to be filled by hiring EITs.
        |

"% Engineer Gap to Be Filled By Hiring Senior Licensed Engineer"=
        0
        ~       Dmnl
        ~       Percentage of the engineer gap to be filled by hiring seasoned engineers.
        |

Entry Level Technician= INTEG (
        hire entry level technician rate-entry level technician gain experience rate-"Entry Level
Technician quit/fired rate"\
                ,
                Initial Entry Level Technician)
        ~       Person
        ~       Current number of  Entry Level Technicians serving the STA.
        |

"% Retiring Bridge to Be Rehabilitated"=
        50
        ~       Dmnl
        ~       At the end of this month, some of the existing poor bridge will become \
                undrivable without repair or reconstruction. The STA determines what \
                percentage of these bridge is to be reconstructed or repaired.
        |

Initial Licensed Engineer=
        590
        ~       Person
        ~       The number of average engineers working for the STA on 01-01-2015.
        |

Initial Mid Level Technician=
        1705
        ~       Person
        ~       The number of mid level technicians working for the STA on 01-01-2015.
        |

Initial EIT=
        261
        ~       Person
        ~       The number of EIT working for the STA on 01-01-2015.
        |
```

```
Initial Senior Licensed Engineer=
	324
	~	Person
	~	The number of seasoned engineers working for the STA on 01-01-2015.
	|

Initial Senior Technician=
	361
	~	Person
	~	The number of senior technicians working for the STA on 01-01-2015.
	|

Initial Entry Level Technician=
	478
	~	Person
	~	The number of Entry Level Technicians working for the STA on 01-01-2015.
	|

"% Senior Licensed Engineer Quit/Fired"=
	0.1
	~	Dmnl/Month
	~	Percentage of seasoned engineers quitting or getting fired each month.
	|

"% Senior Technician Quit/Fired"=
	1
	~	Dmnl/Month
	~	Percentage of senior technicians quitting or getting fired each month.
	|

"% Technician Gap to Be Filled by Hiring Mid Level Technician"=
	10
	~	Dmnl
	~	Percentage of the technician gap to be filled by hiring mid level \
		technicians.
	|

"% Technician Gap to Be Filled By Hiring Senior Technician"=
	0
	~	Dmnl
	~	Percentage of the technician gap to be filled by hiring senior technicians.
	|

"% Technician Gap to Be Filled by Hiring Entry Level Technicians"=
	90
	~	Dmnl
	~	Percentage of the technician gap to be filled by hiring Entry Level \
		Technicians.
	|
```

```
"% Entry Level Technician Quit/Fired"=
        0.1
        ~       Dmnl/Month
        ~       Percentage of Entry Level Technician quitting or getting fired each month.
        |

Time Required to Hire EIT=
        1
        ~       Month
        ~       The average time needed to hire an EIT.
        |

Time Required to Hire Senior Licensed Engineer=
        3
        ~       Month
        ~       The average time needed to hire a seasoned engineer.
        |

engineer retire rate=
        (Senior Licensed Engineer-"senior licensed Engineer quit/fired rate"*TIME STEP)/Senior
Licensed Engineer Average Service Time until Retire
        ~       Person/Month
        ~       The number of seasoned engineers retiring this month.
        |

Forecasted Fair Bridge Gap=
        MAX(Forecasted Target Fair Bridge+Degrading Fair Bridge-Degrading Good Bridge-Fair
Bridge
        , 0 )
        ~       Square Meter
        ~       The difference between end-of-planning-period target amount of fair bridge \
                and start-of-planning-period actual amount of fair bridge. This is how \
                many square meters of fair bridge the STA need to increase during this \
                planning period.
        |

Licensed Engineer= INTEG (
        EIT gain experience rate+hire licensed Engineer rate-licensed engineer gain experience
rate\
                -"Licensed Engineer quit/fired rate",
                Initial Licensed Engineer)
        ~       Person
        ~       Current number of average engineers serving the STA.
        |

licensed engineer gain experience rate=
        (Licensed Engineer-"Licensed Engineer quit/fired rate"*TIME STEP)/Time Required for
Licensed Engineer to Gain Experience
        ~       Person/Month
        ~       The number of average engineers becoming seasoned engineers this month.
        |
```

```
Licensed Engineer Productivity Factor=
	1
	~	Eqv Person/Person
	~	The relative productivity of an average engineer compared to an average \
		engineer.
	|

"Licensed Engineer quit/fired rate"=
	Licensed Engineer*"% Licensed Engineer Quit/Fired"/100
	~	Person/Month
	~	The number of average engineers quitting or getting fired this month.
	|

hire EIT rate=
	Planned EIT New Hire/Time Required to Hire EIT
	~	Person/Month
	~	Number of new EIT hired this month.
	|

Planned Retiring Bridge=
	"Poor Bridge Becoming Undrivable w/o Repair"*(100-"% Retiring Bridge to Be Replaced"\
		-"% Retiring Bridge to Be Rehabilitated")/100
	~	Square Meter
	~	Planned amount of undrivable bridge retiring at the end of this month.
	|

hire senior Technician rate=
	Planned Senior Technician New Hire/Time Required to Hire Senior Technician
	~	Person/Month
	~	Number of new senior technicians hired this month.
	|

Mid Level Technician= INTEG (
	entry level technician gain experience rate+hire mid level Technician rate-mid level Technician gain experience rate\
		-"mid level Technician quit/fired rate",
		Initial Mid Level Technician)
	~	Person
	~	Current number of mid level technicians serving the STA.
	|

Technician retire rate=
	(Senior Technician-"senior Technician quit/fired rate"*TIME STEP)/Senior Technician Average Service Time until Retire
	~	Person/Month
	~	The number of seasoned engineers retiring this month.
	|

Bridge Fund Allocated to Poor to Good Repair=
```

```
	IF THEN ELSE( Bridge Fund Limit Switch=1, Available Bridge Fund*"% Bridge Fund
Allocated to Poor to Good Repair"\
		, Total Bridge Fund Required*"% Bridge Fund Allocated to Poor to Good Repair" )
	~	Dollar
	~	Monthly fund for poor to good bridge repair.
	|

EIT Productivity Factor=
	0.5
	~	Eqv Person/Person
	~	The relative productivity of an EIT compared to an average engineer.
	|

Time Required for Licensed Engineer to Gain Experience=
	72
	~	Month
	~	The average time required for an average engineer to become a seasoned \
		engineer.
	|

entry level technician gain experience rate=
	(Entry Level Technician-"Entry Level Technician quit/fired rate"*TIME STEP)/Time
Required for Entry Level Technicians to Gain Experience
	~	Person/Month
	~	The number of Entry Level Technicians becoming average engineers this \
		month.
	|

Bridge Fund Allocated to Fair to Good Repair=
	IF THEN ELSE( Bridge Fund Limit Switch=1, Available Bridge Fund*"% Bridge Fund
Allocated to Fair to Good Repair"\
		, Total Bridge Fund Required*"% Bridge Fund Allocated to Fair to Good Repair" )
	~	Dollar
	~	Monthly fund for fair to good bridge repair.
	|

Bridge Fund Allocated to New Area=
	IF THEN ELSE( Bridge Fund Limit Switch=1, Available Bridge Fund*"% Bridge Fund
Allocated to New Area"\
		, Total Bridge Fund Required*"% Bridge Fund Allocated to New Area" )
	~	Dollar
	~	Monthly fund for new bridge area.
	|

Bridge Fund Allocated to Poor to Fair Repair=
	IF THEN ELSE( Bridge Fund Limit Switch=1, Available Bridge Fund*"% Bridge Fund
Allocated to Poor to Fair Repair"\
		, Total Bridge Fund Required*"% Bridge Fund Allocated to Poor to Fair Repair" )
	~	Dollar
	~	Monthly fund for poor to fair bridge repair.
	|
```

```
"Total In-House Technician"=
	Entry Level Technician*Entry Level Technician Productivity Factor+Mid Level
Technician\
		*Mid Level Technician Productivity Factor+Senior Technician*Senior Technician
Productivity Factor
	~	Eqv Person
	~	The equivalent number of average engineers serving the STA.
	|

hire mid level Technician rate=
	Planned Mid Level Technician New Hire/Time Required to Hire Mid Level Technician
	~	Person/Month
	~	Number of mid level technicians hired this month.
	|

Time Required for Mid Level Technician to Gain Experience=
	60
	~	Month
	~	The average time required for a mid level technician to become a senior \
		technician.
	|

Time Required for EIT to Obtain License=
	48
	~	Month
	~	The average time required for an EIT to become an average engineer.
	|

Time Required for Entry Level Technicians to Gain Experience=
	36
	~	Month
	~	The average time required for an Entry Level Technician to become an \
		average Technician.
	|

Time Required to Hire Licensed Engineer=
	2
	~	Month
	~	The average time needed to hire an average engineer.
	|

hire licensed Engineer rate=
	Planned Licensed Engineer New Hire/Time Required to Hire Licensed Engineer
	~	Person/Month
	~	Number of new average engineers hired this month.
	|

"senior licensed Engineer quit/fired rate"=
	Senior Licensed Engineer*"% Senior Licensed Engineer Quit/Fired"/100
	~	Person/Month
```

```
	~	The number of seasoned engineers quitting or getting fired this month.
	|

Senior Technician Productivity Factor=
	2
	~	Eqv Person/Person
	~	The relative productivity of a senior technician compared to an average \
		technician.
	|

hire senior licensed Engineer rate=
	Planned Senior Licensed Engineer New Hire/Time Required to Hire Senior Licensed
Engineer
	~	Person/Month
	~	Number of new seasoned engineers hired this month.
	|

Entry Level Technician Productivity Factor=
	0.5
	~	Eqv Person/Person
	~	The relative productivity of an Entry Level Technician compared to an \
		average technician.
	|

"Entry Level Technician quit/fired rate"=
	Entry Level Technician*"% Entry Level Technician Quit/Fired"/100
	~	Person/Month
	~	The number of Entry Level Technician quitting or getting fired this month.
	|

"EIT quit/fired rate"=
	EIT*"% EIT quit/fired"/100
	~	Person/Month
	~	The number of EIT quitting or getting fired this month.
	|

EIT= INTEG (
	hire EIT rate-EIT gain experience rate-"EIT quit/fired rate",
		Initial EIT)
	~	Person
	~	Current number of EITs serving the STA.
	|

EIT gain experience rate=
	(EIT-"EIT quit/fired rate"*TIME STEP)/Time Required for EIT to Obtain License
	~	Person/Month
	~	The number of EITs becoming average engineers this month.
	|

"senior Technician quit/fired rate"=
	Senior Technician*"% Senior Technician Quit/Fired"/100
```

```
	~	Person/Month
	~	The number of senior engineers quitting or getting fired this month.
	|

Planned Poor Bridge to Good Bridge Repair Quantity=
	MAX("Poor Bridge Becoming Undrivable w/o Repair"*"% Retiring Bridge to Be Replaced"/\
		100,0)
	~	Square Meter
	~	To increase the amount of good bridge by repairing, STAs can either repair \
		fair bridge or reconstruct poor bridge.
	|

Forecasted New Bridge Area Needed=
	MAX( Forecasted Target Total Bridge Area
	+Planned Retiring Bridge-Current Total Bridge Area, 0 )
	~	Square Meter
	~	In order to reach the capacity target at the end of this planning period, \
		the STA need to build new bridge area to close the current gap and meet \
		the planned increase.
	|

Senior Licensed Engineer Productivity Factor=
	2
	~	Eqv Person/Person
	~	The relative productivity of a seasoned engineer compared to an average \
		engineer.
	|

"Total Technicians Required - Target"=
	"Road Technicians Required - Target"+"Bridge Technicians Required - Target"
	~	Eqv Person
	~	Total number of average-experienced Technicians required to reach full \
		performance target.
	|

Planned Poor Road to Fair Road Repair Quantity=
	MIN( MAX( "Poor Road Becoming Undrivable w/o Repair"*"% Retiring Road to Be Repaired into Fair Road"\
		/100, Forecasted Fair Road Gap
	), Poor Road-Planned Poor Road to Good Road Repair Quantity)
	~	Lane Mile
	~	The only way to increase the amount of fair road through work is to repair \
		poor road.
	|

"Engineers Required - Target - R - PTG"=
	"Road Fund Required - Poor to Good Repair"/"Engineer Productivity - Road Poor to Good Repair"
	~	Eqv Person
	~	The number of average-experienced Engineers required to reach full \
```

```
		performance target.
	|

Planned Retiring Road=
	"Poor Road Becoming Undrivable w/o Repair"*(100-"% Retiring Road to Be
Reconstructed into Good Road"\
		-"% Retiring Road to Be Repaired into Fair Road")/100
	~	Lane Mile
	~	Planned amount of undrivable road retiring at the end of this month.
	|

"Engineers Required - Target - B - FTG"=
	"Bridge Fund Required - Fair to Good Repair"/"Engineer Productivity - Bridge Fair to
Good Repair"
	~	Eqv Person
	~	The number of average-experienced Engineers required to reach full \
		performance target.
	|

"Engineers Required - Budget - B - PTF"=
	Bridge Fund Allocated to Poor to Fair Repair/"Engineer Productivity - Bridge Poor to Fair
Repair"
	~	Eqv Person
	~	The number of average-experienced Engineers required to complete all \
		funded work.
	|

"Engineers Required - Budget - B - PTG"=
	Bridge Fund Allocated to Poor to Good Repair/"Engineer Productivity - Bridge Poor to
Good Repair"
	~	Eqv Person
	~	The number of average-experienced Engineers required to complete all \
		funded work.
	|

"% Retiring Road to Be Repaired into Fair Road"=
	80
	~	Dmnl
	~	At the end of this month, some of the existing poor road will become \
		undrivable without repair or reconstruction. The STA determines what \
		percentage of these road is to be reconstructed or repaired.
	|

"Technician Productivity - Bridge Poor to Fair Repair"=
	67513
	~	Dollar/Eqv Person
	~	The average amount (in dollar value) of work an average-experienced \
		Technician can handle in a month.
	|

"Technician Productivity - Bridge Poor to Good Repair"=
```

```
	14504
	~	Dollar/Eqv Person
	~	The average amount (in dollar value) of work an average-experienced \
		Technician can handle in a month.
	|

"Engineer Productivity - Bridge Fair to Good Repair"=
	126362
	~	Dollar/Eqv Person
	~	The average amount (in dollar value) of work an average-experienced \
		Engineer can handle in a month.
	|

"Engineer Productivity - Bridge Poor to Fair Repair"=
	132200
	~	Dollar/Eqv Person
	~	The average amount (in dollar value) of work an average-experienced \
		Engineer can handle in a month.
	|

"Engineer Productivity - Bridge Poor to Good Repair"=
	25561
	~	Dollar/Eqv Person
	~	The average amount (in dollar value) of work an average-experienced \
		Engineer can handle in a month.
	|

"Engineer Productivity - New Bridge Area"=
	9648
	~	Dollar/Eqv Person
	~	The average amount (in dollar value) of work an average-experienced \
		Engineer can handle in a month.
	|

"Engineer Productivity - New Mileage"=
	48373
	~	Dollar/Eqv Person
	~	The average amount (in dollar value) of work an average-experienced \
		Engineer can handle in a month.
	|

"Engineer Productivity - Road Fair to Good Repair"=
	219464
	~	Dollar/Eqv Person
	~	The average amount (in dollar value) of work an average-experienced \
		Engineer can handle in a month.
	|

"Engineer Productivity - Road Poor to Fair Repair"=
	201160
	~	Dollar/Eqv Person
```

~ The average amount (in dollar value) of work an average-experienced \
Engineer can handle in a month.
|

"Engineer Productivity - Road Poor to Good Repair"=
61853
~ Dollar/Eqv Person
~ The average amount (in dollar value) of work an average-experienced \
Engineer can handle in a month.
|

"Engineers Required - Budget - B - New"=
Bridge Fund Allocated to New Area/"Engineer Productivity - New Bridge Area"
~ Eqv Person
~ The number of average-experienced Engineers required to complete all \
funded work.
|

"Engineers Required - Budget - B - FTG"=
Bridge Fund Allocated to Fair to Good Repair/"Engineer Productivity - Bridge Fair to Good Repair"
~ Eqv Person
~ The number of average-experienced Engineers required to complete all \
funded work.
|

"Technicians Required - Budget - R - PTF"=
Road Fund Allocated to Poor to Fair Repair/"Technician Productivity - Road Poor to Fair Repair"
~ Eqv Person
~ The number of average-experienced Technicians required to complete all \
funded work.
|

"Engineers Required - Budget - R - FTG"=
Road Fund Allocated to Fair to Good Repair/"Engineer Productivity - Road Fair to Good Repair"
~ Eqv Person
~ The number of average-experienced Engineers required to complete all \
funded work.
|

"Engineers Required - Budget - R - New"=
Road Fund Allocated to New Mileage/"Engineer Productivity - New Mileage"
~ Eqv Person
~ The number of average-experienced Engineers required to complete all \
funded work.
|

"Engineers Required - Budget - R - PTF"=
Road Fund Allocated to Poor to Fair Repair/"Engineer Productivity - Road Poor to Fair

```
Repair"
        ~       Eqv Person
        ~       The number of average-experienced Engineers required to complete all \
                funded work.
        |

"Engineers Required - Budget - R - PTG"=
        Road Fund Allocated to Poor to Good Repair/"Engineer Productivity - Road Poor to Good
Repair"
        ~       Eqv Person
        ~       The number of average-experienced Engineers required to complete all \
                funded work.
        |

"Engineers Required - Target - B - New"=
        "Bridge Fund Required - New Bridge"/"Engineer Productivity - New Bridge Area"
        ~       Eqv Person
        ~       The number of average-experienced Engineers required to reach full \
                performance target.
        |

"Engineers Required - Target - B - PTF"=
        "Bridge Fund Required - Poor to Fair Repair"/"Engineer Productivity - Bridge Poor to Fair
Repair"
        ~       Eqv Person
        ~       The number of average-experienced Engineers required to reach full \
                performance target.
        |

Planned Fair Road to Good Road Repair Quantity=
        MIN( MAX( Good Road Gap to Be Filled by Repairing-Planned Poor Road to Good Road
Repair Quantity\
                , 0 ) , Fair Road )
        ~       Lane Mile
        ~       To increase the amount of good road by repairing, STAs can either repair \
                fair road or reconstruct poor road.
        |

"Bridge Engineers Required - Budget"=
        "Engineers Required - Budget - B - New"+"Engineers Required - Budget - B -
PTF"+"Engineers Required - Budget - B - PTG"\
                +"Engineers Required - Budget - B - FTG"
        ~       Eqv Person
        ~       The number of average-experienced Engineers required to complete all \
                funded road work.
        |

"Bridge Engineers Required - Target"=
        "Engineers Required - Target - B - New"+"Engineers Required - Target - B -
PTF"+"Engineers Required - Target - B - PTG"\
                +"Engineers Required - Target - B - FTG"
```

```
          ~       Eqv Person
          ~       The number of average-experienced Engineers required to reach full \
                  performance target.
          |

"Engineers Required - Target - R - New"=
          "Road Fund Required - New Mileage"/"Engineer Productivity - New Mileage"
          ~       Eqv Person
          ~       The number of average-experienced Engineers required to reach full \
                  performance target.
          |

"Engineers Required - Target - R - PTF"=
          "Road Fund Required - Poor to Fair Repair"/"Engineer Productivity - Road Poor to Fair
Repair"
          ~       Eqv Person
          ~       The number of average-experienced Engineers required to reach full \
                  performance target.
          |

"Technicians Required - Budget - R - FTG"=
          Road Fund Allocated to Fair to Good Repair/"Technician Productivity - Road Fair to Good
Repair"
          ~       Eqv Person
          ~       The number of average-experienced Technicians required to complete all \
                  funded work.
          |

"Technicians Required - Budget - R - New"=
          Road Fund Allocated to New Mileage/"Technician Productivity - New Mileage"
          ~       Eqv Person
          ~       The number of average-experienced Technicians required to complete all \
                  funded work.
          |

"Technician Productivity - Road Fair to Good Repair"=
          74720
          ~       Dollar/Eqv Person
          ~       The average amount (in dollar value) of work an average-experienced \
                  Technician can handle in a month.
          |

"Road Engineers Required - Budget"=
          "Engineers Required - Budget - R - New"+"Engineers Required - Budget - R -
FTG"+"Engineers Required - Budget - R - PTF"\
                  +"Engineers Required - Budget - R - PTG"
          ~       Eqv Person
          ~       The number of average-experienced Engineers required to complete all \
                  funded road work.
          |
```

```
"Technician Productivity - Bridge Fair to Good Repair"=
	43022
	~	Dollar/Eqv Person
	~	The average amount (in dollar value) of work an average-experienced \
		Technician can handle in a month.
	|

"bridge repair rate - poor to fair"=
	"Bridge Productivity - Poor to Fair"
	~	Square Meter/Month
	~	The amount of repair work performed on poor bridges to turn them into fair \
		bridges each month. Restricted by required work volume, available money \
		and man power.
	|

Road Fund Allocated to Poor to Good Repair=
	IF THEN ELSE(Road Fund Limit Switch=1, Available Road Fund*"% Road Fund
Allocated to Poor to Good Repair"\
		 , Total Road Fund Required*"% Road Fund Allocated to Poor to Good Repair" )
	~	Dollar
	~	Monthly fund for poor to good road repair.
	|

Forecasted Fair Road Gap=
	MAX(Forecasted Target Fair Road+Degrading Fair Road-Degrading Good Road-Fair
Road,
	0 )
	~	Lane Mile
	~	The difference between end-of-planning-period target amount of fair road \
		and start-of-planning-period actual amount of fair road. This is how many \
		lane miles of fair road the STA need to increase during this planning \
		period.
	|

"Technician Productivity - New Mileage"=
	34311
	~	Dollar/Eqv Person
	~	The average amount (in dollar value) of work that an average-experienced \
		Technician can handle in a month.
	|

Road Fund Allocated to Poor to Fair Repair=
	IF THEN ELSE(Road Fund Limit Switch=1, Available Road Fund*"% Road Fund
Allocated to Poor to Fair Repair"\
		 , Total Road Fund Required*"% Road Fund Allocated to Poor to Fair Repair" )
	~	Dollar
	~	Monthly fund for poor to fair road repair.
	|

"Technician Productivity - Road Poor to Fair Repair"=
	102732
```

```
	~	Dollar/Eqv Person
	~	The average amount (in dollar value) of work an average-experienced \
		Technician can handle in a month.
	|

Forecasted New Mileage Needed=
	MAX( Forecasted Target Capacity
	+Planned Retiring Road-Current Total Road Capacity, 0 )
	~	Lane Mile
	~	In order to reach the capacity target at the end of this planning period, \
		the STA need to add new mileage to close the current gap and meet the \
		planned increase.
	|

"Technicians Required - Budget - B - PTF"=
	Bridge Fund Allocated to Poor to Fair Repair/"Technician Productivity - Bridge Poor to
Fair Repair"
	~	Eqv Person
	~	The number of average-experienced Technicians required to complete all \
		funded work.
	|

"Technicians Required - Budget - B - PTG"=
	Bridge Fund Allocated to Poor to Good Repair/"Technician Productivity - Bridge Poor to
Good Repair"
	~	Eqv Person
	~	The number of average-experienced Technicians required to complete all \
		funded work.
	|

Road Fund Allocated to New Mileage=
	IF THEN ELSE(Road Fund Limit Switch=1, Available Road Fund*"% Road Fund
Allocated to New Mileage"\
		 , Total Road Fund Required*"% Road Fund Allocated to New Mileage" )
	~	Dollar
	~	Monthly fund for new mileage.
	|

"Technicians Required - Budget - B - New"=
	Bridge Fund Allocated to New Area/"Technician Productivity - New Bridge Area"
	~	Eqv Person
	~	The number of average-experienced Technicians required to complete all \
		funded work.
	|

"Total Engineers Required - Budget"=
	"Road Engineers Required - Budget"+"Bridge Engineers Required - Budget"
	~	Eqv Person
	~	Total number of average-experienced Engineers required to complete all \
		funded road work.
	|
```

```
"Road Engineers Required - Target"=
        "Engineers Required - Target - R - New"+"Engineers Required - Target - R -
FTG"+"Engineers Required - Target - R - PTF"\
                +"Engineers Required - Target - R - PTG"
        ~       Eqv Person
        ~       The number of average-experienced Engineers required to reach full \
                performance target.
        |

"Technicians Required - Budget - R - PTG"=
        Road Fund Allocated to Poor to Good Repair/"Technician Productivity - Road Poor to
Good Repair"
        ~       Eqv Person
        ~       The number of average-experienced Technicians required to complete all \
                funded work.
        |

"Road Technicians Required - Budget"=
        "Technicians Required - Budget - R - New"+"Technicians Required - Budget - R - FTG"+\
                "Technicians Required - Budget - R - PTF"+"Technicians Required - Budget - R -
PTG"
        ~       Eqv Person
        ~       The number of average-experienced Technicians required to complete all \
                funded road work.
        |

Road Fund Allocated to Fair to Good Repair=
        IF THEN ELSE( Road Fund Limit Switch=1 , Available Road Fund*"% Road Fund
Allocated to Fair to Good Repair"\
                 , Total Road Fund Required*"% Road Fund Allocated to Fair to Good Repair" )
        ~       Dollar
        ~       Monthly fund for fair to good road repair.
        |

"Technicians Required - Budget - B - FTG"=
        Bridge Fund Allocated to Fair to Good Repair/"Technician Productivity - Bridge Fair to
Good Repair"
        ~       Eqv Person
        ~       The number of average-experienced Technicians required to complete all \
                funded work.
        |

"Technicians Required - Target - R - FTG"=
        "Road Fund Required - Fair to Good Repair"/"Technician Productivity - Road Fair to Good
Repair"
        ~       Eqv Person
        ~       The number of average-experienced Technicians required to reach full \
                performance target.
        |
```

```
"Technician Productivity - New Bridge Area"=
        6844
        ~       Dollar/Eqv Person
        ~       The average amount (in dollar value) of work that an average-experienced \
                Technician can handle in a month.
        |

"Bridge Technicians Required - Budget"=
        "Technicians Required - Budget - B - FTG"+"Technicians Required - Budget - B - New"+\
                "Technicians Required - Budget - B - PTF"+"Technicians Required - Budget - B -
PTG"
        ~       Eqv Person
        ~       The number of average-experienced Technicians required to complete all \
                funded road work.
        |

"Bridge Technicians Required - Target"=
        "Technicians Required - Target - B - FTG"+"Technicians Required - Target - B - New"+\
                "Technicians Required - Target - B - PTF"+"Technicians Required - Target - B -
PTG"
        ~       Eqv Person
        ~       The number of average-experienced Technicians required to reach full \
                performance target.
        |

"Total Technicians Required - Budget"=
        "Road Technicians Required - Budget"+"Bridge Technicians Required - Budget"
        ~       Eqv Person
        ~       Total number of average-experienced Technicians required to complete all \
                funded road work.
        |

"Technician Productivity - Road Poor to Good Repair"=
        35098
        ~       Dollar/Eqv Person
        ~       The average amount (in dollar value) of work an average-experienced \
                Technician can handle in a month.
        |

"Technicians Required - Target - B - PTG"=
        "Bridge Fund Required - Poor to Good Replacement"/"Technician Productivity - Bridge
Poor to Good Repair"
        ~       Eqv Person
        ~       The number of average-experienced Technicians required to reach full \
                performance target.
        |

"Engineers Required - Target - B - PTG"=
        "Bridge Fund Required - Poor to Good Replacement"/"Engineer Productivity - Bridge Poor
to Good Repair"
        ~       Eqv Person
```

```
		~	The number of average-experienced Engineers required to reach full \
			performance target.
		|

"Technicians Required - Target - B - FTG"=
	"Bridge Fund Required - Fair to Good Repair"/"Technician Productivity - Bridge Fair to
Good Repair"
		~	Eqv Person
		~	The number of average-experienced Technicians required to reach full \
			performance target.
		|

"Technicians Required - Target - B - New"=
	"Bridge Fund Required - New Bridge"/"Technician Productivity - New Bridge Area"
		~	Eqv Person
		~	The number of average-experienced Technicians required to reach full \
			performance target.
		|

"Technicians Required - Target - R - PTF"=
	"Road Fund Required - Poor to Fair Repair"/"Technician Productivity - Road Poor to Fair
Repair"
		~	Eqv Person
		~	The number of average-experienced Technicians required to reach full \
			performance target.
		|

"Engineers Required - Target - R - FTG"=
	"Road Fund Required - Fair to Good Repair"/"Engineer Productivity - Road Fair to Good
Repair"
		~	Eqv Person
		~	The number of average-experienced Engineers required to reach full \
			performance target.
		|

"Road Technicians Required - Target"=
	"Technicians Required - Target - R - New"+"Technicians Required - Target - R - FTG"+\
		"Technicians Required - Target - R - PTF"+"Technicians Required - Target - R -
PTG"
		~	Eqv Person
		~	The number of average-experienced Technicians required to reach full \
			performance target.
		|

"Total Engineers Required - Target"=
	"Road Engineers Required - Target"+"Bridge Engineers Required - Target"
		~	Eqv Person
		~	Total number of average-experienced Engineers required to reach full \
			performance target.
		|
```

```
"Technicians Required - Target - R - PTG"=
	"Road Fund Required - Poor to Good Repair"/"Technician Productivity - Road Poor to
Good Repair"
	~	Eqv Person
	~	The number of average-experienced Technicians required to reach full \
		performance target.
	|

"Technicians Required - Target - R - New"=
	"Road Fund Required - New Mileage"/"Technician Productivity - New Mileage"
	~	Eqv Person
	~	The number of average-experienced Technicians required to reach full \
		performance target.
	|

"Technicians Required - Target - B - PTF"=
	"Bridge Fund Required - Poor to Fair Repair"/"Technician Productivity - Bridge Poor to
Fair Repair"
	~	Eqv Person
	~	The number of average-experienced Technicians required to reach full \
		performance target.
	|

"Fund Gap - Road Capital Outlay"=
	Total Road Fund Required-Available Road Fund
	~	Dollar
	~	Difference between required funding level and available funding level.
	|

Bridge Fund Adjustment Mode Switch=
	1
	~	Dmnl
	~	1 means the STA adjust available funding level according to the required \
		funding level, filling a portion or all of the gap each month. 0 means the \
		STA change the available funding level at a constant change rate.
	|

adjust available fund for bridge=
	IF THEN ELSE(Bridge Fund Adjustment Mode Switch=1, "Fund Gap - Bridge Capital
Outlay"\
		/Bridge Fund Adjustment Time , Available Bridge Fund*Bridge Fund Change
Rate )
	~	Dollar/Month
	~	Monthly adjustment to bridge fund for capital outlay.
	|

"bridge degrade rate - fair to poor"=
	MAX( Fair Bridge/"Average Bridge Degrade Time - Fair to Poor"-"bridge repair rate - fair
to good"\
		 , 0 )
	~	Square Meter/Month
```

```
	~	The amount of fair bridge degrading into poor bridge during each time step.
	|

"bridge repair rate - fair to good"=
	"Bridge Productivity - Fair to Good"
	~	Square Meter/Month
	~	The amount of repair work performed on fair bridges each month. Restricted \
		by required work volume, available money and man power.
	|

add new bridge area=
	"Bridge Productivity - New Area"
	~	Square Meter/Month
	~	The minimum time needed to make any addition to the existing bridge deck \
		area, no matter how much resource is available.
	|

Degrading Fair Bridge=
	Fair Bridge/"Average Bridge Degrade Time - Fair to Poor"*TIME STEP
	~	Square Meter
	~	The amount of fair bridge flowing out of the fair bridge stock during this \
		planning period, either by degrading into poor bridge, or by being \
		repaired into good bridge.
	|

bridge replacement rate=
	"Bridge Productivity - Poor to Good"
	~	Square Meter/Month
	~	The amount of replacement work performed on poor bridges to turn them into \
		good bridges each month. Restricted by required work volume, available \
		money and man power.
	|

"Initial % Funding Level for Road Work"=
	80
	~	Dmnl
	~	100% means at the beginning of the simulation, the STA has just enough \
		fund for the first month's road work.
	|

Forecasted Good Bridge Gap=
	MAX( Forecasted Target Good Bridge+Degrading Good Bridge-Good Bridge , 0 )
	~	Square Meter
	~	The difference between end-of-planning-period target amount of good bridge \
		and start-of-planning-period actual amount of good bridge. This is how \
		many square meters of good bridge the STA need to increase during this \
		planning period.
	|

Bridge Fund Change Rate=
	0
```

```
	~	Dmnl/Month
	~		|

adjust available road fund=
	IF THEN ELSE(Road Fund Adjustment Mode Switch=1, "Fund Gap - Road Capital Outlay"/Road Fund Adjustment Time\
		, Available Road Fund*Road Fund Change Rate )
	~	Dollar/Month
	~	Change made to available fund during this month.
	|

Degrading Good Bridge=
	Good Bridge/"Average Bridge Degrade Time - Good to Fair"*TIME STEP
	~	Square Meter
	~	The amount of good bridge degrading into fair bridge during this planning \
		period.
	|

Road Fund Adjustment Time=
	1e+011
	~	Month
	~	Time needed to adjust funding level.
	|

Forecasted Good Road Gap=
	MAX( Forecasted Target Good Road+Degrading Good Road-Good Road , 0 )
	~	Lane Mile
	~	The difference between end-of-planning-period target amount of good road \
		and start-of-planning-period actual amount of good road. This is how many \
		lane miles of good road the STA need to increase during this planning \
		period.
	|

Degrading Fair Road=
	Fair Road/"Average Road Degrade Time - Fair to Poor"*TIME STEP
	~	Lane Mile
	~	The amount of fair road degrading into poor road or being repaired during \
		this planning period.
	|

add new lane mileage=
	"Road Productivity - New Mileage"
	~	Lane Mile/Month
	~		|

Degrading Good Road=
	Good Road/"Average Road Degrade Time - Good to Fair"*TIME STEP
	~	Lane Mile
	~	The amount of good road turning into fair road during this planning period.
	|
```

```
Road Fund Change Rate=
        0
        ~       Dmnl/Month
        ~               |

Available Road Fund= INTEG (
        adjust available road fund,
                Total Road Fund Required*"Initial % Funding Level for Road Work"/100)
        ~       Dollar
        ~       Real time available fund for road capital outlay.
        |

"road repair rate - fair to good"=
        "Road Productivity - Fair to Good"
        ~       Lane Mile/Month
        ~               |

"road repair rate - poor to fair"=
        "Road Productivity - Poor to Fair"
        ~       Lane Mile/Month
        ~               |

"road repair rate - poor to good"=
        "Road Productivity - Poor to Good"
        ~       Lane Mile/Month
        ~               |

"Road Fund Output - Fair to Good"=
        Road Fund Allocated to Fair to Good Repair/"Road Repair Unit Cost - Fair to Good"
        ~       Lane Mile
        ~       The amount of work the STA is able to perform during this planning period \
                based on available funding.
        |

"Road Fund Output - New Mileage"=
        Road Fund Allocated to New Mileage/New Mileage Unit Cost
        ~       Lane Mile
        ~       The amount of work the STA is able to perform during this planning period \
                based on available funding.
        |

"Road Fund Output - Poor to Good"=
        Road Fund Allocated to Poor to Good Repair/"Road Repair Unit Cost - Poor to Good"
        ~       Lane Mile
        ~       The amount of work the STA is able to perform during this planning period \
                based on available funding.
        |

"Bridge Fund Output - Poor to Good"=
        Bridge Fund Allocated to Poor to Good Repair/"Bridge Repair Unit Cost - Poor to Good"
        ~       Square Meter
```

```
        ~       The amount of work the STA is able to perform during this planning period \
                based on available funding.
        |

"Road Fund Output - Poor to Fair"=
        Road Fund Allocated to Poor to Fair Repair/"Road Repair Unit Cost - Poor to Fair"
        ~       Lane Mile
        ~       The amount of work the STA is able to perform during this planning period \
                based on available funding.
        |

"Bridge Fund Output - Fair to Good"=
        Bridge Fund Allocated to Fair to Good Repair/"Bridge Repair Unit Cost - Fair to Good"
        ~       Square Meter
        ~       The amount of work the STA is able to perform during this planning period \
                based on available funding.
        |

"Bridge Fund Output - Poor to Fair"=
        Bridge Fund Allocated to Poor to Fair Repair/"Bridge Repair Unit Cost - Poor to Fair"
        ~       Square Meter
        ~       The amount of work the STA is able to perform during this planning period \
                based on available funding.
        |

"Bridge Fund Output - New Area"=
        Bridge Fund Allocated to New Area/New Bridge Unit Cost
        ~       Square Meter
        ~       The amount of work the STA is able to perform during this planning period \
                based on available funding.
        |

"% Bridge Fund Allocated to Fair to Good Repair"=
      IF THEN ELSE("Bridge Fund Proportional/Manual Allocation Switch"=1, "Proportional %
Bridge Fund Allocated to Fair to Good Repair"\
                 , "Manual % Bridge Fund Allocated to Fair to Good Repair" )
        ~       Dmnl
        ~       Actual portion of bridge fund allocated to fair to good repair.
        |

"% Bridge Fund Allocated to New Area"=
      IF THEN ELSE("Bridge Fund Proportional/Manual Allocation Switch"=1, "Proportional %
Bridge Fund Allocated to New Mileage"\
                 , "Manual % Bridge Fund Allocated to New Mileage" )
        ~       Dmnl
        ~       Actual portion of bridge fund allocated to new mileage.
        |

"% Bridge Fund Allocated to Poor to Fair Repair"=
      IF THEN ELSE("Bridge Fund Proportional/Manual Allocation Switch"=1, "Proportional %
Bridge Fund Allocated to Poor to Fair Repair"\
```

```
                , "Manual % Bridge Fund Allocated to Poor to Fair Repair" )
        ~       Dmnl
        ~       Actual portion of bridge fund allocated to poor to fair repair.
        |

"% Bridge Fund Allocated to Poor to Good Repair"=
      IF THEN ELSE("Bridge Fund Proportional/Manual Allocation Switch"=1, "Proportional %
Bridge Fund Allocated to Poor to Good Repair"\
                , "Manual % Bridge Fund Allocated to Poor to Good Repair" )
        ~       Dmnl
        ~       Actual portion of bridge fund allocated to poor to good.
        |

"Bridge Repair Unit Cost - Poor to Fair"=
        884
        ~       Dollar/Square Meter
        ~       Cost for repairing 1 square meter of highway bridge from poor condition to \
                fair condition.
        |

"Bridge Repair Unit Cost - Poor to Good"=
        1300
        ~       Dollar/Square Meter
        ~       Cost for replacing 1 square meter of highway bridge from poor condition to \
                good condition.
        |

"Proportional % Road Fund Allocated to Fair to Good Repair"=
        "Road Fund Required - Fair to Good Repair"/Total Road Fund Required
        ~       Dmnl
        ~       Percentage of road fund allocated to fair to good repair. Determined \
                proportionally based on requirement.
        |

"% Road Fund Allocated to Fair to Good Repair"=
        IF THEN ELSE("Road Fund Proportional/Manual Allocation Switch"=1, "Proportional %
Road Fund Allocated to Fair to Good Repair"\
                , "Manual % Road Fund Allocated to Fair to Good Repair" )
        ~       Dmnl
        ~       Actual portion of road fund allocated to fair to good repair.
        |

"% Road Fund Allocated to New Mileage"=
        IF THEN ELSE("Road Fund Proportional/Manual Allocation Switch"=1, "Proportional %
Road Fund Allocated to New Mileage"\
                , "Manual % Road Fund Allocated to New Mileage" )
        ~       Dmnl
        ~       Actual portion of road fund allocated to new mileage.
        |

"% Road Fund Allocated to Poor to Fair Repair"=
```

```
	IF THEN ELSE("Road Fund Proportional/Manual Allocation Switch"=1, "Proportional %
Road Fund Allocated to Poor to Fair Repair"\
		 , "Manual % Road Fund Allocated to Poor to Fair Repair" )
	~	Dmnl
	~	Actual portion of road fund allocated to poor to fair repair.
	|

"% Road Fund Allocated to Poor to Good Repair"=
	IF THEN ELSE("Road Fund Proportional/Manual Allocation Switch"=1, "Proportional %
Road Fund Allocated to Poor to Good Repair"\
		 , "Manual % Road Fund Allocated to Poor to Good Repair" )
	~	Dmnl
	~	Actual portion of road fund allocated to poor to good.
	|

"Initial % Funding Level for Bridge Work"=
	80
	~	Dmnl
	~	100% means at the beginning of the simulation, the STA has just enough \
		fund for the first month's bridge work.
	|

"Manual % Bridge Fund Allocated to New Mileage"=
	0.25
	~	Dmnl
	~	Percentage of bridge fund allocated to new mileage. Determined manually \
		based on priority.
	|

"Manual % Bridge Fund Allocated to Poor to Fair Repair"=
	0.25
	~	Dmnl
	~	Percentage of bridge fund allocated to poor to fair repair. Determined \
		manually based on priority.
	|

Available Bridge Fund= INTEG (
	adjust available fund for bridge,
		Total Bridge Fund Required*"Initial % Funding Level for Bridge Work"/100)
	~	Dollar
	~	Monthly fund for bridge capital outlay.
	|

"Manual % Road Fund Allocated to New Mileage"=
	0.25
	~	Dmnl
	~	Percentage of road fund allocated to new mileage. Determined manually \
		based on priority.
	|

"Manual % Road Fund Allocated to Poor to Fair Repair"=
```

```
	0.25
	~	Dmnl
	~	Percentage of road fund allocated to poor to fair repair. Determined \
		manually based on priority.
	|

"Manual % Road Fund Allocated to Poor to Good Repair"=
	0.25
	~	Dmnl
	~	Percentage of road fund allocated to poor to good repair. Determined \
		manually based on priority.
	|

"Proportional % Bridge Fund Allocated to New Mileage"=
	ZIDZ( "Bridge Fund Required - New Bridge" , Total Bridge Fund Required )
	~	Dmnl
	~	Percentage of bridge fund allocated to new bridge area. Determined \
		proportionally based on requirement.
	|

"Proportional % Bridge Fund Allocated to Poor to Fair Repair"=
	ZIDZ("Bridge Fund Required - Poor to Fair Repair",Total Bridge Fund Required)
	~	Dmnl
	~	Percentage of bridge fund allocated to poor to fair repair. Determined \
		proportionally based on requirement.
	|

"Road Repair Unit Cost - Fair to Good"=
	450000
	~	Dollar/Lane Mile
	~	Cost for repairing 1 lane mile of highway from fair condition to good \
		condition,
	|

"Road Repair Unit Cost - Poor to Fair"=
	600000
	~	Dollar/Lane Mile
	~	Cost for repairing 1 lane mile of highway from poor condition to fair \
		condition,
	|

New Bridge Unit Cost=
	1500
	~	Dollar/Square Meter
	~	Cost for 1 square meter of new highway bridge.
	|

New Mileage Unit Cost=
	1.5e+006
	~	Dollar/Lane Mile
	~	Unit cost for 1 lane mile of new highway.
```

```
	|

"Bridge Fund Proportional/Manual Allocation Switch"=
	1
	~	Dmnl
	~	1 means the STA allocate bridge fund proportionally. 0 means the STA \
		allocate bridge fund manually based on priority.
	|

"Bridge Fund Required - Fair to Good Repair"=
	Planned Fair Bridge to Good Bridge Repair Quantity*"Bridge Repair Unit Cost - Fair to
Good"
	~	Dollar
	~	Fund required for fair to good bridge repair.
	|

"Bridge Fund Required - New Bridge"=
	Forecasted New Bridge Area Needed*New Bridge Unit Cost
	~	Dollar
	~	Fund required for planned new highway bridge.
	|

"Bridge Fund Required - Poor to Fair Repair"=
	Planned Poor Bridge to Fair Bridge Repair Quantity*"Bridge Repair Unit Cost - Poor to
Fair"
	~	Dollar
	~	Fund required for poor to fair bridge repair.
	|

"Bridge Fund Required - Poor to Good Replacement"=
	Planned Poor Bridge to Good Bridge Repair Quantity*"Bridge Repair Unit Cost - Poor to
Good"
	~	Dollar
	~	Fund required for poor to good bridge replacement.
	|

Total Bridge Fund Required=
	"Bridge Fund Required - Fair to Good Repair"+"Bridge Fund Required - New
Bridge"+"Bridge Fund Required - Poor to Good Replacement"
	+"Bridge Fund Required - Poor to Fair Repair"
	~	Dollar
	~	Required bridge fund for all capital outlay.
	|

"Road Fund Required - Poor to Fair Repair"=
	Planned Poor Road to Fair Road Repair Quantity*"Road Repair Unit Cost - Poor to Fair"
	~	Dollar
	~	Amount of fund required for planned poor to fair road repair.
	|

"Proportional % Bridge Fund Allocated to Fair to Good Repair"=
```

```
	ZIDZ ("Bridge Fund Required - Fair to Good Repair",Total Bridge Fund Required)
	~	Dmnl
	~	Percentage of bridge fund allocated to fair to good repair. Determined \
		proportionally based on requirement.
	|

"Bridge Repair Unit Cost - Fair to Good"=
	520
	~	Dollar/Square Meter
	~	Cost for repairing 1 square meter of highway bridge from fair condition to \
		good condition.
	|

Total Road Fund Required=
	"Road Fund Required - Fair to Good Repair"+"Road Fund Required - New
Mileage"+"Road Fund Required - Poor to Fair Repair"\
		+"Road Fund Required - Poor to Good Repair"
	~	Dollar
	~	Required road fund for all capital outlay.
	|

"Manual % Road Fund Allocated to Fair to Good Repair"=
	0.25
	~	Dmnl
	~	Percentage of road fund allocated to fair to good repair. Determined \
		manually based on priority.
	|

"Proportional % Bridge Fund Allocated to Poor to Good Repair"=
	ZIDZ("Bridge Fund Required - Poor to Good Replacement",Total Bridge Fund Required)
	~	Dmnl
	~	Percentage of bridge fund allocated to poor to good repair. Determined \
		proportionally based on requirement.
	|

"Proportional % Road Fund Allocated to New Mileage"=
	"Road Fund Required - New Mileage"/Total Road Fund Required
	~	Dmnl
	~	Percentage of road fund allocated to new mileage. Determined \
		proportionally based on requirement.
	|

"Proportional % Road Fund Allocated to Poor to Fair Repair"=
	"Road Fund Required - Poor to Fair Repair"/Total Road Fund Required
	~	Dmnl
	~	Percentage of road fund allocated to poor to fair repair. Determined \
		proportionally based on requirement.
	|

"Proportional % Road Fund Allocated to Poor to Good Repair"=
	"Road Fund Required - Poor to Good Repair"/Total Road Fund Required
```

```
	~	Dmnl
	~	Percentage of road fund allocated to poor to good repair. Determined \
		proportionally based on requirement.
	|

"Road Fund Required - Poor to Good Repair"=
	Planned Poor Road to Good Road Repair Quantity*"Road Repair Unit Cost - Poor to
Good"
	~	Dollar
	~	Amount of fund required for planned poor to good road repair.
	|

"Manual % Bridge Fund Allocated to Poor to Good Repair"=
	0.25
	~	Dmnl
	~	Percentage of bridge fund allocated to poor to good repair. Determined \
		manually based on priority.
	|

"Road Fund Proportional/Manual Allocation Switch"=
	1
	~	Dmnl
	~	1 means the STA allocate road fund proportionally. 0 means the STA \
		allocate road fund manually based on priority.
	|

"Road Repair Unit Cost - Poor to Good"=
	1e+006
	~	Dollar/Lane Mile
	~	The cost for reconstructing 1 lane mile of highway.
	|

"Fund Gap - Bridge Capital Outlay"=
	Total Bridge Fund Required-Available Bridge Fund
	~	Dollar
	~	The difference between required funding level and available funding level.
	|

Bridge Fund Adjustment Time=
	1e+011
	~	Month
	~	Time required to adjust monthly bridge fund.
	|

"Manual % Bridge Fund Allocated to Fair to Good Repair"=
	0.25
	~	Dmnl
	~	Percentage of bridge fund allocated to fair to good repair. Determined \
		manually based on priority.
	|
```

```
"% Retiring Bridge to Be Replaced"=
        50
        ~       Dmnl
        ~       At the end of this month, some of the existing poor bridge will become \
                undrivable without repair or reconstruction. The STA determines what \
                percentage of these bridge is to be reconstructed or repaired.
        |

Good Bridge Gap to Be Filled by Repairing=
        MAX(Forecasted Good Bridge Gap-Forecasted New Bridge Area Needed, 0 )
        ~       Square Meter
        ~       A portion of the good bridge gap can be filled my building new bridge \
                area. The rest need to be filled by repairing existing bridge area.
        |

"Poor Bridge Becoming Undrivable w/o Repair"=
        Poor Bridge/"Average Bridge Degrade Time - Poor to Retire"*TIME STEP
        ~       Square Meter
        ~               |

Target Fair and Better Road=
        Target Road Capacity*Target Fair and Better Road Percentage
        ~       Lane Mile
        ~       Real time target amount (in lane miles) of highway receiving "good" or \
                "fair" ratings.
        |

Forecasted Target Good Bridge Percentage=
        Target Good Bridge Percentage+desired good bridge percentage increment*TIME STEP
        ~       Dmnl
        ~       The forecasted target good bridge percentage at the end of the planning \
                period.
        |

Forecasted Target Good Road=
        Forecasted Target Capacity*Forecasted Target Good Road Percentage
        ~       Lane Mile
        ~       The amount of good lane mileage at the end of this planning period.
        |

Forecasted Target Good Road Percentage=
        Target Good Road Percentage+desired good road percentage increment*TIME STEP
        ~       Dmnl
        ~       The target good road percentage at the end of the planning period.
        |

Forecasted Target Total Bridge Area=
        Forecasted Target Capacity*Highway Bridge Area to Lane Mile Ratio
        ~       Square Meter
        ~       The target bridge area at the end of this planning period.
        |
```

```
Target Fair and Better Bridge=
          Target Total Bridge Area*Target Fair and Better Bridge Percentage
          ~          Square Meter
          ~          Real time target amount (in square meters) of highway bridge area \
                     receiving "good" or "fair" ratings.
          |

Forecasted Target Fair and Better Road Percentage=
          Target Fair and Better Road Percentage+desired fair and better road percentage increment\
                     *TIME STEP
          ~          Dmnl
          ~          The target fair and better road percentage at the end of this planning \
                     period.
          |

Target Good Bridge Percentage= INTEG (
          desired good bridge percentage increment,
                     Good Bridge Percentage)
          ~          Dmnl
          ~          Real time target good bridge percentage.
          |

Forecasted Target Good Bridge=
          Forecasted Target Total Bridge Area*Forecasted Target Good Bridge Percentage
          ~          Square Meter
          ~          The amount of good bridge area at the end of this planning period.
          |

Target Good Bridge=
          Target Total Bridge Area*Target Good Bridge Percentage
          ~          Square Meter
          ~          Real time target amount (in square meter) of bridge area receiving "good" \
                     ratings.
          |

Target Fair and Better Road Percentage= INTEG (
          desired fair and better road percentage increment,
                     Fair and Better Road Percentage)
          ~          Dmnl
          ~          This is the real-time target good and fair combined road percentage.
          |

Target Total Bridge Area=
          Target Road Capacity*Highway Bridge Area to Lane Mile Ratio
          ~          Square Meter
          ~          Real time target bridge deck area assuming a constant bridge area to road \
                     capacity ratio.
          |

Initial Total Bridge Area=
```

```
          5.26133e+006
          ~         Square Meter
          ~         The total area of highway bridge decks on 01-01-2015.
          |

Good Bridge= INTEG (
          add new bridge area+"bridge repair rate - fair to good"+bridge replacement rate-"bridge
degrade rate - good to fair"\
                    ,
                    "Initial (2015) Good Bridge")
          ~         Square Meter
          ~         This stock holds the amount of bridge area in good condition in the state \
                    highway system.
          |

Fair Bridge= INTEG (
          "bridge degrade rate - good to fair"+"bridge repair rate - poor to fair"-"bridge degrade rate
- fair to poor"\
                    -"bridge repair rate - fair to good",
                    "Initial (2015) Fair Bridge")
          ~         Square Meter
          ~         This stock holds the amount (square meters) of bridge deck in fair \
                    condition in the state highway system.
          |

Poor Bridge= INTEG (
          "birdge degrade rate - fair to poor"-"bridge repair rate - poor to fair"-bridge replacement
rate\
                    -bridge retire rate,
                    "Initial (2015) Poor Bridge")
          ~         Square Meter
          ~         This stock holds the amount (square meters) of bridge deck in poor \
                    condition in the state highway system.
          |

Bridge Area Gap=
          Target Total Bridge Area-Current Total Bridge Area
          ~         Square Meter
          ~         The difference between target total bridge area and the actual bridge area.
          |

Highway Bridge Area to Lane Mile Ratio=
          Initial Total Bridge Area/Initial Total Road Capacity
          ~         Square Meter/Lane Mile
          ~         The ratio between total bridge area and total highway lane miles on \
                    01-01-2015
          |

Good Bridge Percentage=
          Good Bridge/Current Total Bridge Area
          ~         Dmnl
```

```
	~	The percentage of the current bridge area (in square meters) that are \
		rated as good.
	|

"% Good bridge Gap to Be Filled by Replacing Poor Bridge"=
	0
	~	Dmnl
	~	This is the portion of the good bridge gap that is going to be filled by \
		replacing poor bridge. This value is determined by the STA. Although \
		replacing poor bridge is more expensive than repairing the same amount of \
		fair bridge into good bridge, it changes the age structure of the entire \
		bridge capacity and may have long term benefits. After determining how \
		much poor bridge the STA is going to replace to fill the good bridge gap, \
		the rest of the gap need to be filled by repairing fair bridge.
	|

"Average Bridge Degrade Time - Fair to Poor"=
	240
	~	Month
	~	This is the average time for fair bridges to degrade into poor bridges \
		without repair.
	|

"Average Bridge Degrade Time - Good to Fair"=
	360
	~	Month
	~	This is the average time for good bridges to degrade into fair bridges \
		without repair.
	|

"Average Bridge Degrade Time - Poor to Retire"=
	120
	~	Month
	~	This is the average time for poor bridges to degrade into retired bridges \
		without repair.
	|

Current Total Bridge Area=
	Good Bridge+Fair Bridge+Poor Bridge
	~	Square Meter
	~	This is the current total bridge area owned by the State Transportation \
		Agency..
	|

desired fair and better bridge percentage increment=
	0
	~	Dmnl/Month
	~	This is the desired change in fair and better bridge percentage per month.
	|

desired good bridge percentage increment=
```

```
	0
	~	Dmnl/Month
	~	This is the desired change in good bridge percentage per month.
	|

Fair and Better Bridge Percentage=
	(Good Bridge+Fair Bridge)/Current Total Bridge Area
	~	Dmnl
	~	The percentage of the current bridge area (in square meters) that are \
		rated as fair or better.
	|

Forecasted Target Fair and Better Bridge Percentage=
	Target Fair and Better Bridge Percentage+desired fair and better bridge percentage
increment\
		*TIME STEP
	~	Dmnl
	~	The target fair and better bridge percentage at the end of this planning \
		period.
	|

Forecasted Target Fair Bridge=
	Forecasted Target Total Bridge Area*Forecasted Target Fair and Better Bridge Percentage\
		-Forecasted Target Good Bridge
	~	Square Meter
	~	Forecasted Target amount of fair bridge area at the end of this planning \
		period.
	|

"bridge degrade rate - good to fair"
	=Good Bridge/"Average Bridge Degrade Time - Good to Fair"
	~	Square Meter/Month
	~	This is the amount of good bridge degrading into fair bridge during each \
		time step.
	|

bridge retire rate=
	MAX( Poor Bridge/"Average Bridge Degrade Time - Poor to Retire"-bridge replacement
rate\
		-"bridge repair rate - poor to fair" , 0 )
	~	Square Meter/Month
	~	The amount of poor bridge becoming completely undrivable during this \
		planning period.
	|

Target Fair and Better Bridge Percentage= INTEG (
	desired fair and better bridge percentage increment,
		Fair and Better Bridge Percentage)
	~	Dmnl
	~	This is the real-time target fair and better bridge percentage.
	|
```

```
Target Road Capacity= INTEG (
        increase target road capacity,
                Initial Total Road Capacity)
        ~       Lane Mile
        ~       This stock holds the planned road capacity (in lane miles) administered by \
                the state transportation agency, assuming a steady increase rate.
        |

"% Retiring Road to Be Reconstructed into Good Road"=
        20
        ~       Dmnl
        ~       At the end of this month, some of the existing poor road will become \
                undrivable without repair or reconstruction. The STA determines what \
                percentage of these road is to be reconstructed or repaired.
        |

Planned Poor Road to Good Road Repair Quantity=
        "Poor Road Becoming Undrivable w/o Repair"*"% Retiring Road to Be Reconstructed into
Good Road"\
                /100
        ~       Lane Mile
        ~       To increase the amount of good road by repairing, STAs can either repair \
                fair road or reconstruct poor road.
        |

"Poor Road Becoming Undrivable w/o Repair"=
        Poor Road/"Average Road Degrade Time - Poor to Retire"*TIME STEP
        ~       Lane Mile
        ~               |

road retire rate=
        MAX( Poor Road/"Average Road Degrade Time - Poor to Retire"-"road repair rate - poor
to good"\
                -"road repair rate - poor to fair" , 0 )*0
        ~       Lane Mile/Month
        ~       The amount of poor road becoming completely undrivable during this \
                planning period.
        |

Target Good Road Percentage= INTEG (
        desired good road percentage increment,
                Good Road Percentage)
        ~       Dmnl
        ~       This is the real-time target good road percentage.
        |

Road Capacity Gap=
        Target Road Capacity-Current Total Road Capacity
        ~       Lane Mile
        ~               |
```

```
Forecasted Target Capacity=
        Target Road Capacity+increase target road capacity*TIME STEP
        ~       Lane Mile
        ~       The target road capacity at the end of this planning period.
        |

Forecasted Target Fair Road=
        Forecasted Target Capacity*Forecasted Target Fair and Better Road Percentage-Forecasted
Target Good Road
        ~       Lane Mile
        ~       Forecasted Target amount of fair lane mileage at the end of this planning \
                period.
        |

desired good road percentage increment=
        0
        ~       Dmnl/Month
        ~       This is the desired change in good road percentage per month.
        |

Target Good Road=
        Target Road Capacity*Target Good Road Percentage
        ~       Lane Mile
        ~       Real time target amount (in lane miles) of highway receiving "good" \
                ratings.
        |

desired fair and better road percentage increment=
        0
        ~       Dmnl/Month
        ~       This is the desired change in fair and better road percentage per month.
        |

"road degrade rate - good to fair"=
        Good Road/"Average Road Degrade Time - Good to Fair"
        ~       Lane Mile/Month
        ~       This is the amount of good road degrading into fair roads during each time \
                step.
        |

"road degrade rate - fair to poor"=
        MAX( Fair Road/"Average Road Degrade Time - Fair to Poor"-"road repair rate - fair to
good"\
                 , 0 )
        ~       Lane Mile/Month
        ~       The amount of fair road degrading into poor road during each time step.
        |

Fair and Better Road Percentage=
        (Good Road+Fair Road)/Current Total Road Capacity
```

```
	~	Dmnl
	~	The percentage of the current road capacity (in lane miles) that are rated \
		as fair or better (International Roughness Index less than 170 in/mile).
	|

Good Road Percentage=
	Good Road/Current Total Road Capacity
	~	Dmnl
	~	The percentage of the current road capacity (in lane miles) that are rated \
		as good (International Roughness Index less than 95 in/mile).
	|

Current Total Road Capacity=
	Good Road+Fair Road+Poor Road
	~	Lane Mile
	~	This is the current total lane miles of highway administered by the state \
		transportation agency.
	|

increase target road capacity=
	Target Road Capacity*Planned Road Capacity Increase Rate
	~	Lane Mile/Month
	~	This is the increase in road capacity during each time step.
	|

Planned Road Capacity Increase Rate=
	0.000228
	~	Dmnl/Month
	~	This is the planned road capacity increase rate. 0.0002 is the test value \
		in the generic model. For Kentucky, assuming road capacity increases at \
		the same rate as it has been during the period of 2000-2015, the value of \
		this variable is approximately 0.0228%.
	|

Poor Road= INTEG (
	"road degrade rate - fair to poor"-"road repair rate - poor to fair"-"road repair rate - poor to
good"\
		-road retire rate,
		"Initial (2015) Poor Roads")
	~	Lane Mile
	~	This stock holds the amount (lane miles) of roads in poor condition in the \
		state highway system.
	|

"Average Road Degrade Time - Good to Fair"=
	144
	~	Month
	~	This is the average time for good roads to degrade into fair roads without \
		maintenance work.
	|
```

```
"Average Road Degrade Time - Poor to Retire"=
          96
          ~         Month
          ~         This is the average time for poor roads to degrade into retired roads \
                    without maintenance work.
          |

"Average Road Degrade Time - Fair to Poor"=
          120
          ~         Month
          ~         This is the average time for fair roads to degrade into poor roads without \
                    maintenance.
          |

Fair Road= INTEG (
          "road degrade rate - good to fair"+"road repair rate - poor to fair"-"road degrade rate - fair
to poor"\
                    -"road repair rate - fair to good",
                    "Initial (2015) Fair Roads")
          ~         Lane Mile
          ~         This stock holds the amount (lane miles) of roads in fair condition in the \
                    state highway system.
          |

Good Road= INTEG (
          add new lane mileage+"road repair rate - fair to good"+"road repair rate - poor to good"\
                    -"road degrade rate - good to fair",
                    "Initial (2015) Good Roads")
          ~         Lane Mile
          ~         This stock holds the amount (lane miles) of roads in good condition in the \
                    state highway system.
          |

********************************************************
          .Control
********************************************************~
                    Simulation Control Parameters
          |

FINAL TIME  = 300
          ~         Month
          ~         The final time for the simulation.
          |

INITIAL TIME  = 0
          ~         Month
          ~         The initial time for the simulation.
          |

SAVEPER  =
      TIME STEP
```

```
	~	Month [0,?]
	~	The frequency with which output is stored.
	|

TIME STEP  = 1
	~	Month [0,?]
	~	The time step for the simulation.
	|

\\\---/// Sketch information - do not modify anything except names
```

APPENDIX B EXOGENOUS MODEL PARAMETER VALUES

Table B.1: Exogenous Model Parameter Values for the Generic Model and the KY Case Model

Variable Name	Unit	Generic Model Value	KY Model Value
% EIT quit/fired	Dmnl/Month	0.03	0.03
% Engineer Gap to Be Filled by Hiring EIT	Dmnl	60	90
% Engineer Gap to Be Filled by Hiring Licensed Engineer	Dmnl	30	10
% Engineer Gap to Be Filled By Hiring Senior Licensed Engineer	Dmnl	10	0
% Entry Level Technician Quit/Fired	Dmnl/Month	0.1	0.1
% Licensed Engineer Quit/Fired	Dmnl/Month	0.2	0.2
% Mid-Level Technician Quit/Fired	Dmnl/Month	0.5	0.5
% Retiring Bridge to Be Rehabilitated	Dmnl	50	50
% Retiring Bridge to Be Replaced	Dmnl	50	50
% Retiring Road to Be Reconstructed into Good Road	Dmnl	50	20
% Retiring Road to Be Repaired into Fair Road	Dmnl	50	80
% Senior Licensed Engineer Quit/Fired	Dmnl/Month	0.1	0.1
% Senior Technician Quit/Fired	Dmnl/Month	1	1
% Technician Gap to Be Filled by Hiring Entry Level Technicians	Dmnl	60	90
% Technician Gap to Be Filled by Hiring Mid-Level Technician	Dmnl	30	10
% Technician Gap to Be Filled By Hiring Senior Technician	Dmnl	10	0
2015 Senior Licensed Engineer Average Time Served	Month	60	72
2015 Senior Technician Average Time Served	Month	72	96
Average Bridge Degrade Time - Fair to Poor	Month	240	240
Average Bridge Degrade Time - Good to Fair	Month	360	360
Average Bridge Degrade Time - Poor to Retire	Month	120	120
Average Road Degrade Time - Fair to Poor	Month	120	120
Average Road Degrade Time - Good to Fair	Month	144	144
Average Road Degrade Time - Poor to Retire	Month	96	96
Bridge Fund Adjustment Mode Switch	Dmnl	1	1
Bridge Fund Adjustment Time	Month	24	1.00E+11
Bridge Fund Change Rate	Dmnl/Month	0	0
Bridge Fund Limit Switch	Dmnl	1	1
Bridge Fund Proportional/Manual Allocation Switch	Dmnl	1	1
Bridge Repair Unit Cost - Fair to Good	Dollar/Square Meter	520	520
Bridge Repair Unit Cost - Poor to Fair	Dollar/Square Meter	884	884

Variable Name	Unit	Generic Model Value	KY Model Value
Bridge Repair Unit Cost - Poor to Good	Dollar/Square Meter	1300	1300
Consulting Engineer Productivity Factor	Eqv Person/Person	2	2
Consulting Engineer Switch	Dmnl	1	1
Consulting Engineer Wage	Dollar/(Month*Person)	8000	8000
Consulting Technician Productivity Factor	Eqv Person/Person	2	2
Consulting Technician Switch	Dmnl	1	1
Consulting Technician Wage	Dollar/(Month*Person)	5166	5166
desired fair and better bridge percentage increment	Dmnl/Month	0	0
desired fair and better road percentage increment	Dmnl/Month	0	0
Desired Fraction of Engineer Gap to Be Filled by New Hire	Dmnl	1	1
Desired Fraction of Technician Gap to Be Filled by New Hire	Dmnl	1	1
desired good bridge percentage increment	Dmnl/Month	0	0
desired good road percentage increment	Dmnl/Month	0	0
EIT Average Salary	Dollar/(Month*Person)	3000	3000
EIT Productivity Factor	Eqv Person/Person	0.5	0.5
Engineer Productivity - Bridge Fair to Good Repair	Dollar/Eqv Person	170000	126362
Engineer Productivity - Bridge Poor to Fair Repair	Dollar/Eqv Person	178000	132200
Engineer Productivity - Bridge Poor to Good Repair	Dollar/Eqv Person	34000	25561
Engineer Productivity - New Bridge Area	Dollar/Eqv Person	13000	9648
Engineer Productivity - New Mileage	Dollar/Eqv Person	65000	48373
Engineer Productivity - Road Fair to Good Repair	Dollar/Eqv Person	296000	219464
Engineer Productivity - Road Poor to Fair Repair	Dollar/Eqv Person	271000	201160
Engineer Productivity - Road Poor to Good Repair	Dollar/Eqv Person	83000	61853
Entry Level Technician Average Salary	Dollar/(Month*Person)	2083	2083
Entry Level Technician Productivity Factor	Eqv Person/Person	0.5	0.5
FINAL TIME	Month	300	300
Formerly Retired Engineer Back Hire Switch	Dmnl	N/A	1
Formerly Retired Technician Back Hire Switch	Dmnl	N/A	1
Fraction of Formerly Retired Engineers Returning to the Agency	Dmnl	N/A	0.15

Variable Name	Unit	Generic Model Value	KY Model Value
Fraction of Formerly Retired Technicians Returning to the Agency	Dmnl	N/A	0.15
Initial % Funding Level for Bridge Work	Dmnl	100	80
Initial % Funding Level for Road Work	Dmnl	100	80
Initial EIT	Person	192	261
Initial Entry Level Technician	Person	258	478
Initial Fair and Better Bridge Percentage	Dmnl	78	78
Initial Fair and Better Road Percentage	Dmnl	90	90
Initial Good Bridge Percentage	Dmnl	74	74
Initial Good Road Percentage	Dmnl	50	50
Initial Licensed Engineer	Person	288	590
Initial Mid-Level Technician	Person	430	1705
Initial Senior Licensed Engineer	Person	479	324
Initial Senior Technician	Person	1030	361
INITIAL TIME	Month	0	0
Initial Total Bridge Area	Square Meter	5440000	5260000
Initial Total Road Capacity	Lane Mile	60000	63100
Licensed Engineer Average Salary	Dollar/(Month*Person)	4000	4000
Licensed Engineer Productivity Factor	Eqv Person/Person	1	1
Manual % Bridge Fund Allocated to Fair to Good Repair	Dmnl	0.25	0.25
Manual % Bridge Fund Allocated to New Mileage	Dmnl	0.25	0.25
Manual % Bridge Fund Allocated to Poor to Fair Repair	Dmnl	0.25	0.25
Manual % Bridge Fund Allocated to Poor to Good Repair	Dmnl	0.25	0.25
Manual % Road Fund Allocated to Fair to Good Repair	Dmnl	0.25	0.25
Manual % Road Fund Allocated to New Mileage	Dmnl	0.25	0.25
Manual % Road Fund Allocated to Poor to Fair Repair	Dmnl	0.25	0.25
Manual % Road Fund Allocated to Poor to Good Repair	Dmnl	0.25	0.25
Mid-Level Technician Average Salary	Dollar/(Month*Person)	2583	2583
Mid-Level Technician Productivity Factor	Eqv Person/Person	1	1
New Bridge Unit Cost	Dollar/Square Meter	1500	1500
New Mileage Unit Cost	Dollar/Lane Mile	1500000	1500000
Planned Road Capacity Increase Rate	Dmnl/Month	0.0002	0.000228
Road Fund Adjustment Mode Switch	Dmnl	1	1
Road Fund Adjustment Time	Month	24	1.00E+11
Road Fund Change Rate	Dmnl/Month	0	0
Road Fund Limit Switch	Dmnl	1	1

Variable Name	Unit	Generic Model Value	KY Model Value
Road Fund Proportional/Manual Allocation Switch	Dmnl	1	1
Road Repair Unit Cost - Fair to Good	Dollar/Lane Mile	450000	450000
Road Repair Unit Cost - Poor to Fair	Dollar/Lane Mile	600000	600000
Road Repair Unit Cost - Poor to Good	Dollar/Lane Mile	1000000	1000000
Senior Licensed Engineer Average Salary	Dollar/(Month*Person)	5833	5833
Senior Licensed Engineer Maximum Service Time	Month	120	120
Senior Licensed Engineer Productivity Factor	Eqv Person/Person	2	2
Senior Technician Average Salary	Dollar/(Month*Person)	2917	2917
Senior Technician Maximum Service Time	Month	144	144
Senior Technician Productivity Factor	Eqv Person/Person	2	2
Technician Productivity - Bridge Fair to Good Repair	Dollar/Eqv Person	57000	43022
Technician Productivity - Bridge Poor to Fair Repair	Dollar/Eqv Person	89000	67513
Technician Productivity - Bridge Poor to Good Repair	Dollar/Eqv Person	19000	14504
Technician Productivity - New Bridge Area	Dollar/Eqv Person	9000	6844
Technician Productivity - New Mileage	Dollar/Eqv Person	45000	34311
Technician Productivity - Road Fair to Good Repair	Dollar/Eqv Person	99000	74720
Technician Productivity - Road Poor to Fair Repair	Dollar/Eqv Person	136000	102732
Technician Productivity - Road Poor to Good Repair	Dollar/Eqv Person	46000	35098
Time Required for EIT to Obtain License	Month	48	48
Time Required for Entry Level Technicians to Gain Experience	Month	36	36
Time Required for Licensed Engineer to Gain Experience	Month	72	72
Time Required for Mid-Level Technician to Gain Experience	Month	60	60
Time Required to Hire EIT	Month	1	1
Time Required to Hire Entry Level Technicians	Month	1	1
Time Required to Hire Licensed Engineer	Month	2	2
Time Required to Hire Mid-Level Technician	Month	1	1
Time Required to Hire Senior Licensed Engineer	Month	3	3
Time Required to Hire Senior Technician	Month	2	2
TIME STEP	Month	1	1
Workforce Budget Restraint Switch	Dmnl	1	1
Workforce Restraint Switch	Dmnl	1	1

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VITA

Name

Ying Li

Education

August, 2009 --- Present

Doctoral Student in Construction Engineering and Project Management

Department of Civil Engineering

University of Kentucky

September 2005 --- July, 2009

B.S. in Construction Management

College of Economics and Management

Tongji University, Shanghai, China