Parametric Model for Assessing Factors that Influence Highway Bridge Service Life

By

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ABSTRACT

Infrastructure management must move from a perspective that may singularly emphasize facility condition assessment to a broader view that involves nonphysical factors, which may substantially impact facility performance and shorten its service life. Socioeconomic, technological, regulatory, and user value changes can substantially increase the service expectations of existing facilities. Based on a theoretical framework drawn from prior work, this research develops a new approach to model infrastructure performance and assess factors that influence the remaining service life of highway bridges. Key parameters that impact the serviceability of highway bridges are identified and incorporated into a system dynamics model. This platform supports parametric scenario analysis and is applied in several cases to test how various factors influence bridge service life and performance. This decision support system provides a new approach for modeling serviceability over time and gives decision-makers an indication of: (a) the gap between society's service expectations and the service level provided and (b) the remaining service life of a highway bridge.

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1. INTRODUCTION

Bridges have attracted substantial attention throughout history. Many, like the Brooklyn Bridge, are hailed as engineering marvels. Some, like the Tacoma Narrows Bridge and the bridge over I-35 in Minnesota, are notorious for their catastrophic collapses. This latter category, rather correctly, has focused the engineering community's attention upon bridge safety, condition assessment, and management. A bridge, however, is far more than a structural system. It is a link within a transportation corridor that must meet the demands of its users and society. Thus, bridge lifecycle management must balance supply and demand conditions.

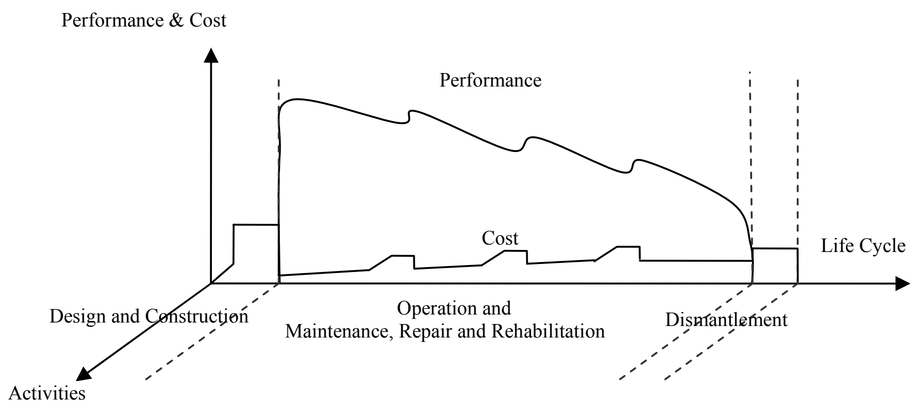


Figure 1-1, Bridge Life Cycle Management

Figure 1-1 provides the needed perspective of bridge life cycle management. A bridge will undergo design, construction, operation and maintenance, until decommissioning. These activities necessitate continuous investments to keep a bridge functional to provide adequate service to its users since various factors will influence a bridge's performance. These factors are both physical and non-physical, and the intent of this thesis is to develop a model that will allow decision-makers to better understand how these factors influence a bridge's performance and service life.

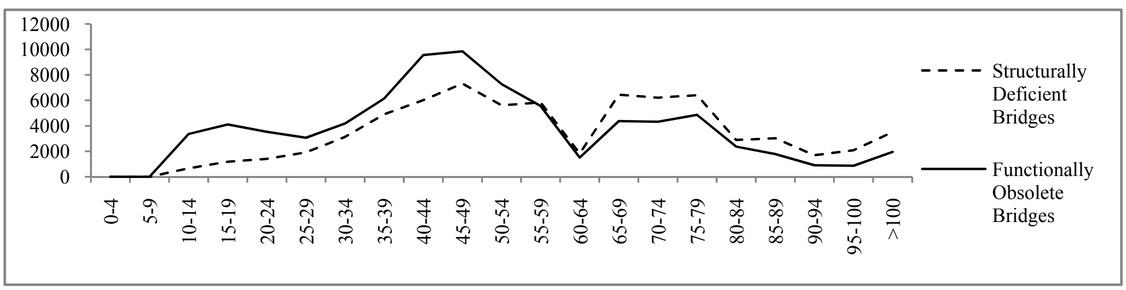
1.1 Background

Highway bridges, like other infrastructure facilities, are experiencing increasing demands in an environment where resources for their management are limited. In 2007, 599,177 bridges over 20 feet in length were in service on public roads in the United States, carrying nearly 4 billion vehicles per day. According to the National Bridge Inventory (NBI), 25.32 percent of these bridges were classified as structurally deficient or functionally obsolete:

Structurally Deficient. This classification is given to a bridge that is restricted to light vehicles, or requires immediate rehabilitation to remain open due to deterioration of structural components. A restricted-use structurally deficient bridge is not necessarily unsafe and strict observance of the posted allowable traffic load and vehicle speed will generally provide adequate safeguards for those using the bridge.

Functionally Obsolete. This classification is given to a bridge on which the deck geometry, load carrying capacity (comparison of the original design load to the current state legal load), clearance, or approach roadway alignment no longer meet criteria for the system of which it is an integral part. A functionally obsolete bridge is not necessarily broken, worn out, dysfunctional, or unsafe for all vehicles; rather, the antiquated, out of date design prevents the facility from accommodating current traffic volumes and modern vehicle sizes and weights.

a). Deficient Bridge Counts by Year Built



b). Deficient Bridge Percentages by Year Built

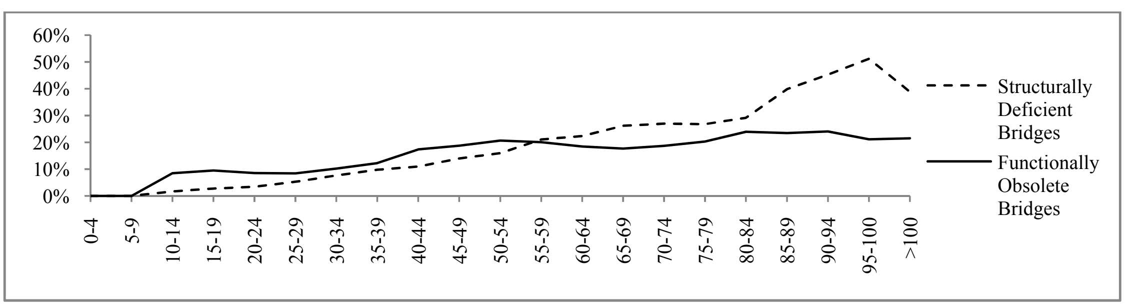


Figure 1-2, National Bridge Deficiency, Data from FHWA (2007)

Figure 1-2 generated from the 2007 NBI data discloses that functionally obsolete bridges are approximately equal to structurally deficient bridges by age. Bridges built in the past 50 years are more functionally obsolete than structurally deficient by both bridge counts and percentages. Based on the 1992 NBI data, Kenneth and Basile (1995) identified eight dominant deficiencies with deck geometry standing out as the most common deficiency. With the 2005 NBI data, Chang and Garvin (2008) also presented similar results based on the updated bridge survey. Figure 1-3 depicts the findings from both these studies.

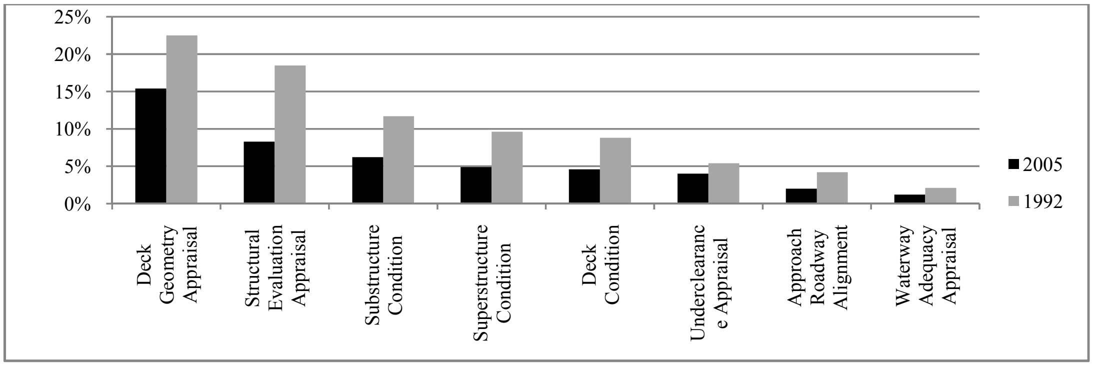


Figure 1-3, Bridge Deficiency, Data from Kenneth & Basile (1995) and Chang & Garvin (2008)

In the above figure, deck geometry appraisal and structural evaluation appraisal count as the most prominent factors for bridge deficiencies, thus the situation in the past decade has not fundamentally changed. A bridge may be structurally deficient because it was designed for a lighter load, thereby reflecting antiquated standards, or it may be the result of advanced deterioration that has reduced load-carrying capacity. Further analysis by Chang (2007) reveals that of the 47,648 bridges with structural evaluation appraisal deficiencies in 2005, 16,722 can be considered to be condition-based, since they have either a superstructure or substructure condition rating that is less than or equal to 3. The remaining 30,752 bridges are deficient based on load rating. Therefore, a majority of the structural deficiencies result from factors other than physical condition.

1.2 Research Motivation

Lemer (1996) presented a framework that helps to explain the findings presented in the previous section. Figure 1-4 conceptually illustrates that any facility's performance is a function of supply, demand, and exogenous factors. The service supplied tends to degrade with time while the service demanded is influenced by factors like regulatory changes that can cause jumps in service demand.

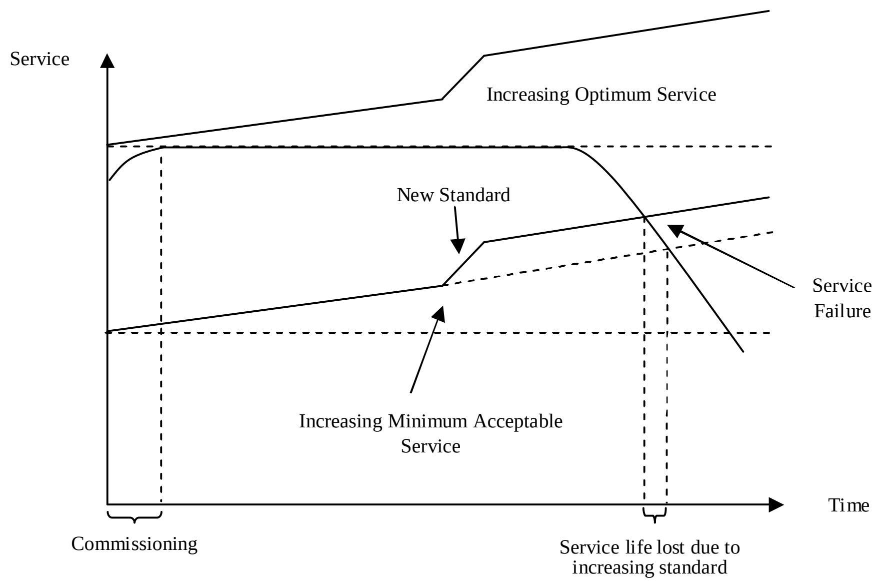
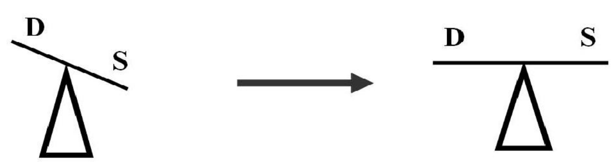


Figure 1-4, Increasing Standard and Policy Change on Performance, Modified from Lemer (1996)

The functional deficiencies found in the studies of the NBI data cited previously provide concrete examples of Lemer's theory that a facility's serviceability is a function of both physical and non-physical factors.

In general, past work emphasizes mainly the "supply side" of the situation as in Figure 1-5a.



a) Emphasizing service supply b) Balance between service and demand

Figure 1-5, Changing Point of View on Serviceability Research

Many models focus upon the "supply", i.e. the attributes or components of the asset itself. In other words, these models answer questions such as 'what is the status or condition of a bridge's deck structures?' Few, if any, balance this with an assessment of the "demand" for the asset. Current models cannot answer questions such as 'how many heavy-load trucks use a bridge annually and what impact do these users have upon bridge performance?' This perspective is important when trying to model the performance or serviceability of an infrastructure asset. Without it, we can only determine what service the asset can provide, and we cannot determine whether this service is obsolete or not. This research plans to reach a “balance” between the supply and demand as depicted in Figure 1-5b.

1.3 Research Objectives

There are four objectives of this research:

1. Explore the serviceability of infrastructure broadly beyond the perspective of the physical limit state by examining the relationship between service supply and demand, and how these two aspects play their roles in the performance of highway bridges.
2. Introduce an approach that balances management attention on both supply and demand sides into performance evaluation and utilize system dynamics as the modeling platform.
3. Emphasize the importance of non-physical factors upon serviceability. This research should prompt decision makers to at least consider these factors and motivate them to collect historical data regarding regulatory, economic, and user demand as important elements of infrastructure management.
4. Build a parametric model to assess factors that influence highway bridge performance. Such a platform provides an environment to numerically estimate the future performance and serviceability of an existing highway bridge by assigning proper values to those related physical and nonphysical factors.

This research concentrates on those bridges that serve as critical links in an urban area instead of common parts of highway corridors. Local transportation and economics are sensitive to the performance of such links, which may result in extra costs by waiting, detouring, and more accidents (Brito and Branco, 1997).

1.4 Research Design

As shown in Figure 1-6, this research starts with a proposition, follows a step-wise exploratory process, and concludes through confirmation of a final model. The approach includes introducing a founding theory, defining a conceptual model, identifying the predominant factors, constructing a model prototype, calibrating the model for specific case bridges, and validating and verifying (V&V) the working model. The final product is a development framework and case-specific models.

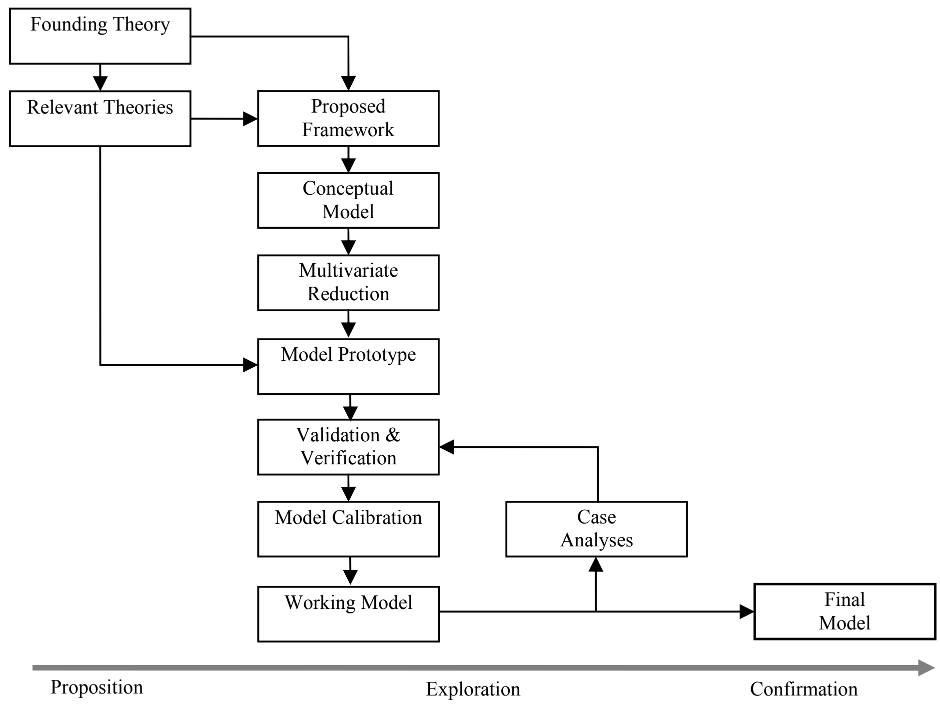


Figure 1-6, Research Approach

1. A founding theory is the backbone of this research. First, it forwards a proposition of broader understanding of infrastructure performance. Second, it directs the literature review. Third, it supplies the initial framework of this research.
2. Directed by the founding theory, a comprehensive literature review covers several necessary theories to complete and expand the framework. This step not only provides supportive knowledge, but also identifies the shortcomings of current methodologies.
3. A proposed framework about infrastructure performance theory supplies a new perspective of infrastructure performance. It embodies the initial proposition by emphasizing the service supply, service demand, as well as several critical nonphysical factors.
4. Based upon the proposed framework, a conceptual model formulates the fundamental logical and mathematical relationships by combining the most predominant components as cornerstones for simulation.

5. Multivariate reduction is a statistical technique to identify the predominant variables that can keep most of the information from the original collected data set with a reduced data size. The framework enumerates the potential decision factors related to the infrastructure performance. However, some variables may not be sensitive to the performance evaluation and may distract the research. An analytical examination, as well as statistical tests, help to focus the further modeling process.
6. A prototype is an initial model with a clear structure that combines all predominant components as cornerstones for simulation. Basically, the model is able to simulate the evolution of service supply and demand as well as the facility performance gaps under different decision making policies.
7. Modeling V&V is a requisite in a modeling process to improve the model's credibility. V&V underpins the model structure and parameter values as well as tests the correspondence between the simulation results and reality. This step will adopt particular V&V techniques for system dynamics modeling.
8. A calibration process will refine the model prototype of the model structure and parameters to a more specific situation. The modeling process will center upon bridges that serve as significant links between travel destinations.
9. A working model is the point of commencement for an iterative process of case-based analysis and model validation & verification.
10. A set of case analyses will observe, in particular, how non-physical factors influence bridge performance historically. This step will improve and balance the model structure. This process will help to expand and confirm the working model and advance it toward a final one.
11. The research will conclude with a final, confirmed model that is a result of the previous steps. The final model will have transformed the founding theory of infrastructure performance into operable case-specific model that enhances infrastructure decision-making.

1.5 Organization

This dissertation includes eight chapters. Chapter One is an introduction about research background, motivation, objectives, and design. Chapter Two starts with the founding theory and forwards a further definition of infrastructure performance in terms of several performance gaps. Chapter Three is a comprehensive literature review focused upon three particular aspects, service supply, service demand, and performance evaluation. Chapter Four describes how to select the significant model variables by literature review and statistical tests. Chapter Five explains the details of developing the model in system dynamics. Chapter Six conducts a systematic validation and verification process to improve the model's credibility. Chapter Seven presents the application of the model in three case analyses. Chapter Eight concludes the work and gives several suggestions for future research.

2. FOUNDING THEORY

The founding theory forwards a proposition of broader understanding of infrastructure performance. It sets up an initial framework and directs the related literature review. This section characterizes Lemer's (1996) ideas about facility obsolescence as "Infrastructure Performance Theory", which is the founding theory of this research. Additionally, to operationalize this conceptual framework, this research tentatively expands the founding theory with three gaps as critical indicators for later quantitative analysis.

2.1 Infrastructure Performance Theory

Lemer's Infrastructure Performance Theory provides a foundation for the measurement of facility performance. In his observations, infrastructure performance is a function of service supply and demand. Neither of these two sides is constant over time. A facility's design establishes the initial conditions and functions. The physical status generally deteriorates under usage, while the functional standing becomes obsolete with increasing expectations. From the perspective of life cycle management, continuous investment in the form of maintenance will defer the deterioration, whereas rehabilitation or upgrade will restore the facility to its original condition or counteract its obsolescence. Evaluation of supply and demand requires interdisciplinary knowledge in five areas: serviceability assessment; physical deterioration; mobility expectation; maintenance, repair and rehabilitation (MR&R); and other nonphysical factors that influence facility performance.

Lemer introduced a framework for understanding infrastructure obsolescence and the mechanisms by which it occurs. Obsolescence is a critical concern throughout a facility's entire life cycle, reflecting changed experience regarding the function, profitability, or other dimensions of performance that a facility is expected to provide. Conceptually, the performance of a facility is the relation between its structural integrity and usage. First, performance of infrastructure certainly depends upon the physical condition of a facility. Materials will deteriorate naturally with time and degrade from the original strength and functions. Service life clearly ends when the structure or the main components fail, which can be depicted as Figure 2-1.

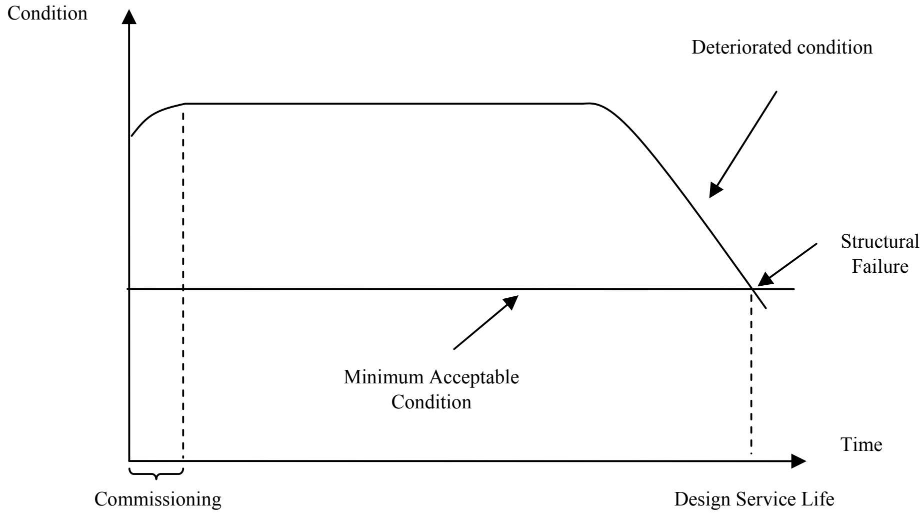


Figure 2-1, Structural Failure, Modified from Lemer (1996)

The research community (some examples cited later) has given a tremendous amount of attention to understanding and forecasting the deterioration curve.

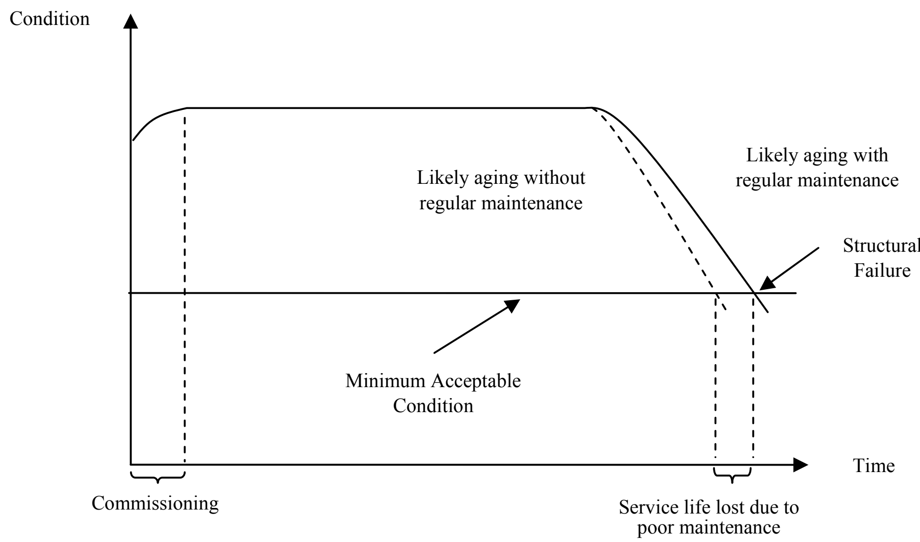


Figure 2-2, Maintenance Practice Influence on Performance, Modified from Lemer (1996)

Maintenance also plays a significant role in a facility's performance. Regular maintenance is likely to slow the process of deterioration; however, budget limitations and other factors, such as a passive/reactive approach, often constrain the amount of maintenance done. In the case of inadequate maintenance, the asset degrades more quickly as shown in Figure 2-2.

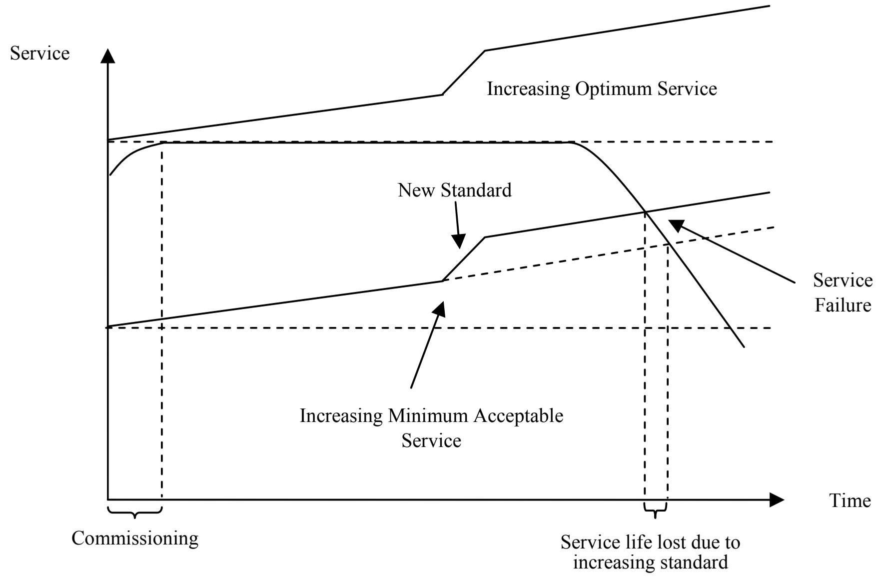


Figure 2-3, Increasing Standard and Policy Change on Performance, Modified from Lemer (1996)

Figure 2-3 presents a much broader conception of facility performance. This figure introduces several important notions. First, an asset has both an "optimum" Level of Service and a "minimum" acceptable Level of Service. Second, these levels are likely to change over time as expectations change or as standards change. The "jump" in the figure illustrates the situation where a new industrial standard or regulation is imposed, so both the optimum and the minimum levels respond to this change. In this case, service life would be lost if the responsible decision makers did not improve the asset's functions or properties to comply with the new standard. In contrast to the two former situations, obsolescence shortens the service life independently from the effects of deterioration. Generally, a facility's performance is highly dependent on an asset's structure, materials, management, usage, and maintenance, as well as user demands and regulations, all of which together comprise the performance parameters of an infrastructure facility.

Lemer posited obsolescence results from the change in the requirements or expectations regarding the use of a particular facility. He grouped the factors that cause obsolescence into four categories: technological change, regulatory changes, economic or social change, and changes in human behavior. Lemer postulated that the performance of a constructed asset is a function of factors of supply and demand as well as time as shown in Formula(2.1):

$$Performance = P(S_j, D_j, t) \tag{2.1}$$

Where S_j = supply vector of services j that the infrastructure facility or system provides to various groups; D_j = demand vector of services j that various groups require of an infrastructure facility or system; t = time. The supply of services, S_j, is characterized or predicted as a function of design and operational characteristics of the facility.

The performance in general has dimensions of effectiveness, reliability, and cost. Effectiveness is the degree to which the infrastructure accomplishes the tasks to meet the demands. Reliability is the probability that effectiveness will be sustained at acceptable levels for an extended period of time. Cost is measured throughout the lifecycle of a facility.

By defining expected performance and minimum performance, Lemer forwarded a theoretical measure of the service life as an inequality:

$$P(S_j, D_j, t) < P^F \tag{2.2}$$

Where P^F is the minimum acceptable performance.

$$P^F = P^F(E_k, t) \tag{2.3}$$

Where E_k = exogenous factors, such as technology and economics that influence expectations about infrastructure performance. The rise in expectations and failure criteria is generally the source of obsolescence, and the cause of service life reduction.

$$E[P(t = T^0 \mid X_i, D_j)] < P^F(t = T^0 \mid E_k) \tag{2.4}$$

Where T^0 is the time that obsolescence begins. The right hand in the inequality is the "Expectations Function", which normally increases with E_k. In other words, the slope of expectation curve is greater than zero.

$$\frac{dP^F}{dt} > 0 \tag{2.5}$$

This research is geared toward providing a framework to support this type of broader conception of infrastructure performance. The expectation is that the framework developed will help to answer such questions as: 1) how does economic development change the demands for more occupancy, capacity and modern functions? 2) how do environmental policies or regulations influence expectations? 3) how does the pace of technological change impact a facility and the service it provides? Answering these questions is not easy; however, a thorough understanding of serviceability requires that both physical and non-physical factors be considered.

2.2 Expansion of Infrastructure Performance Theory

Figure 2-4 succinctly represents the important concepts from Lemer's theory while also introducing some new ones.

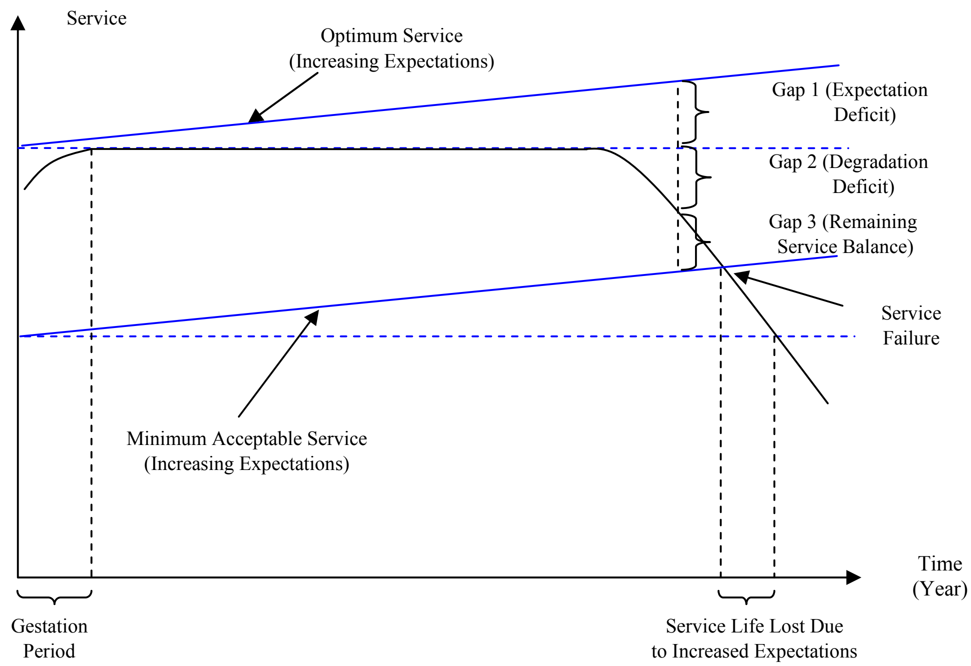


Figure 2-4, Proposed Framework

The horizontal dashed line in Figure 2-4 represents the expectation or demand for which an infrastructure asset is originally designed. The infrastructure asset is constructed or supplied to presumably meet this expectation after some gestation period where "kinks" in the system are worked out. The asset maintains this level of supply, as represented by the solid line, over time until normal deterioration begins to degrade the level of supply. If expectations remain the same over time, then service failure will occur when the supply has degraded to the point of minimum expectation. Typically, expectations, however, change over time as illustrated by the upward sloping solid lines. Thus, service failure occurs sooner than originally predicted because expectations have risen. These notions introduce three "gaps". Gap 1 is an expectation deficit, which illustrates the difference between original demand and current demand. Gap 2 is a degradation deficit, which illustrates the difference between original demand and current supply. Gap 3 is a remaining service balance, which illustrates the difference between current supply and minimum expectation. This figure illustrates the central idea of the proposed framework and introduces potential measures of changes in performance.

Gaps are the differences between the supply and demand curves. To quantify these gaps, we can measure the "distances" between the points on these curves at a certain time. $D_{optimum}$ is the expectation of users over any demand factors while S_{Design} is the supplied service by the design that is intended to meet the corresponding demand factors. We can define

$$Gap_1 = D_{Optimum}(t) - S_{Design} \tag{2.6}$$

Where Gap_1 is the expectation deficit; $D_{Optimum}(t)$ represents user expectations and demands over time while S_{Design} represents the service supplied that results following facility planning, design, and construction.

$$Gap_2 = S_{Design} - S(t) \tag{2.7}$$

Where Gap_2 is the degradation deficit; and S(t) is current service supplied by the facility.

$$Gap_3 = S(t) - D_{\min}(t) \tag{2.8}$$

Where Gap_3 is the remaining service balance; $D_{min}(t)$ is the minimum acceptable performance over time.

A facility is generally designed with excess capacity, which will be consumed over time. For example, a highway may be wide enough to easily accommodate all current traffic while becoming congested later. Wastewater pipelines may be initially sufficient and later become inadequate with increasing residents. After reaching its design capacity, such facilities may incur additional in-use costs or intangible operating costs. Figure 2-5 illustrates the relationship between a transportation facility's performance, design capacity, and its operational cost.

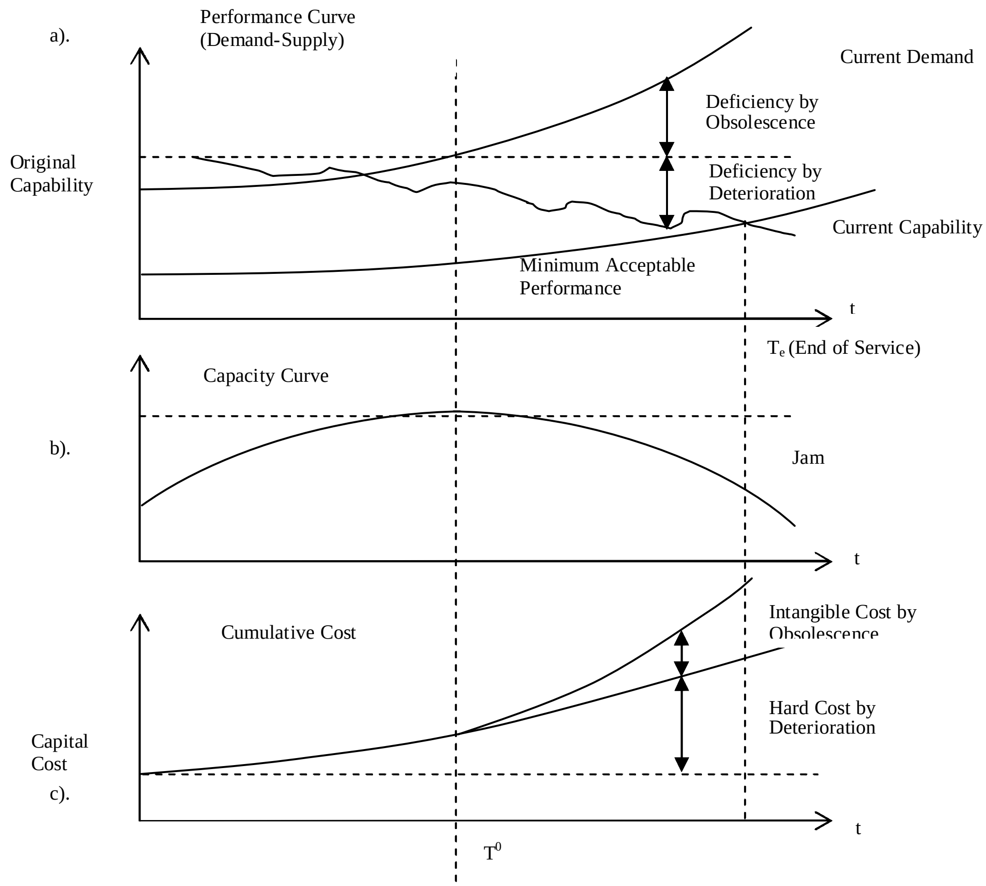


Figure 2-5, Life Cycle Cost and Facility Performance

Obsolescence begins to occur when the capability of the facility is lower than the demand. Excessive demand relative to service supply will reduce the efficiency and induce additional cost. Figure 2-5 a) shows the increasing demand and decreasing capability. After time T^0, current demand surpasses the original design performance, resulting in deficiency caused by obsolescence. This time T^0 in the capacity curve Figure 2-5 b) reflects the start of over utilization, as well as the appearance of intangible costs from obsolescence in Figure 2-5 c) At time T_e, the facility's performance decreases to the minimum acceptable level. The facility will have accumulated substantial cost due to excess usage and poor performance.

3. LITERATURE REVIEW

The former chapter provides a basic logic of performance evaluation for infrastructure facilities and a foundation to build upon. A highway bridge has its special properties that define its performance and service life. To make the theoretical framework introduced operational for highway bridges, this research must establish means to quantify S(t) and D(t) as well as methods to measure the performance "gaps". Figure 3-1 illustrates topical areas that are relevant to achieve this. The literature surveyed covers the topics depicted.

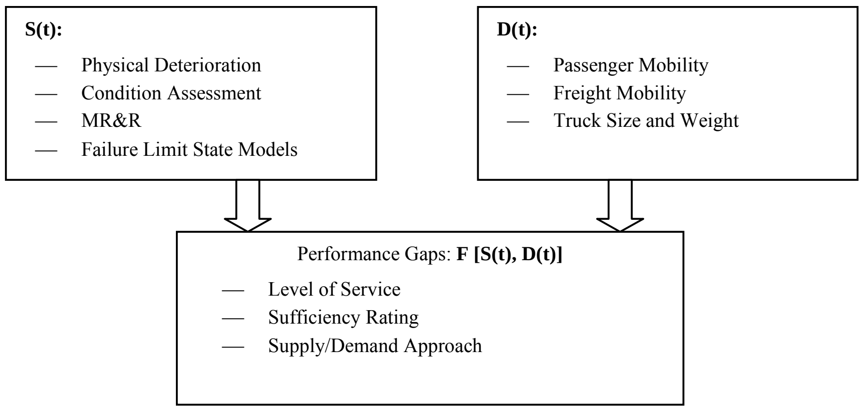


Figure 3-1, Required Literature on Supply/Demand Approach for Performance Evaluation

3.1 Service Supply – S(t)

3.1.1 Physical Deterioration

Ronald and Valery (2004) stated "*Fundamental to the prediction of remaining service life is the forecasting of deterioration rates. Choosing a design service life is the first step. The second step is predicting how the structure will measure up to the design service life under the complex interaction of many variables involved in material degradation over time.*"

The Markov chain method is a widely used stochastic technique for predicting physical component condition over multiple periods with transition probability matrices. This technique is employed in Pontis, the most widely utilized bridge management system in the Unite States. It is based on the assumption of the Markovian process that the "future" only depends on "today", without relation to "yesterday"(Ross, 2000). To apply a Markov chain approach, this assumption must be examined first by certain tests, such as a simple frequency analysis, a chi-square statistical test (Abraham and Iseley, 2001). The Markov chain method employs a transition matrix that defines a set of probabilities about a component's condition changing from one state to another. If no repairs or rehabilitation is done, the component's condition will worsen. The main difficulty in applying the method is establishing the transition matrix. Unlike the real situation where most deterioration processes are continuous, modelers need to divide the whole life cycle into discrete condition states. The number of divisions depends on facility stability, environmental influences and subjectively determined intervals. The shorter the interval, the more accurate the results should be. A practical way is for the intervals to coincide with the periodic inspections of the component. Estimation of the transition matrix entries normally use the maximum likelihood method with synthetic records (Takyi and Lence, 1995), the ordered probit technique (Madanat et al., 1995), or Poisson regression(Madanat and Ibrahim, 1995), etc.

Conventional Markov chain analysis is a stationary process. To break free of this limitation, some researchers also recommend a non-stationary process, or semi-Markov chain method. Destefano and Grivas (1998) described a state increment prediction methodology in which a specified probabilistic distribution function is employed to predict the future conditions of bridge elements. The state increment model assumes that a transition probability depends on the time spent in an initial state. It is a memory process in which the probability of future deterioration relies not only on the current condition, but also on historic information. Guignier and Madanat (1999) also recommended age dependent transition matrices to achieve better results. Nevertheless, this substantially increases the amount of data collection and statistical tests required.

Other research has investigated the impacts of factors, such as severe environment, heavier traffic, and poor maintenance upon deterioration. For instance, Dadson and de la Garza (2002) proposed a statistical approach to test the relationship between the service lives of highway bridge components/protective systems and climatic regions. The results reveal that in most areas in Virginia, infrastructure service life is significantly correlated with the topography and weather conditions. They suggested assigning environmental level, i.e. benign, low, worse, severe, as a decision factor in infrastructure management.

3.1.2 Condition Assessment

The common way to track bridge condition is visual inspection of its systems and components. Inspections perform tasks of verifying the inventory; identifying potential hazards and scheduling remedial action; rating the conditions of structural elements or components in terms of departures from the presumed as-built state and describing them in details corresponding to their gravity; and rating the load-bearing structural capacity (Yanev, 2007). Based on such firsthand information, condition assessments determine present and future maintenance and repair needs. Yanev (2007) generalized two types of inspection processes, rating/descriptive and defect/action. The rating/descriptive method determines needs based on observed conditions. The defect/action method merges the assessment and decision stages and limits the findings to predefined response options. Comparatively, the rating/descriptive evaluation system uses the declarative knowledge representation, whereas the defect/action system employs a procedural representation.

As one of the routine management activities, inspection requires established inspection and rating procedures, qualified inspectors, proper scheduling, and a reliable inventory. The National Bridge Inspection standards, implemented by the Federal Highway Administration in the early 1970's, establish specifications for the inspection and inventory of bridges with a typical two-year cycle. Inspection information is collected through this program and recorded in the NBI database. State transportation agencies rate bridges using an "inventory rating" or an "operating rating" approach to determine when use by certain vehicles should be prohibited. The inventory rating is more conservative than the operating rating, requiring a greater margin of safety (55 percent of yield stress as opposed to 75 percent of yield stress for the operating rating).

3.1.3 Maintenance, Repair and Rehabilitation

3.1.3.1 General Overview

MR&R at prescribed intervals aims to minimize the facility downtime and preserve continuous use. In the infrastructure industry, *maintainability* is defined as the ability of a facility to be retained in or restored close to its original conditions by appropriate actions (Chew et al., 2004). Maintenance policy reflects the managerial issues of the facility agency, such as budgeting, evaluation standard, and maintenance practices.

Maintenance can be scheduled ahead or reactive to the need, which infers a comparison between preventive and passive maintenance. The preventive actions are carried out at premature stage of deterioration to avoid higher cost of passive maintenance when it is urgent. Passive maintenance tends to defer the activities subject to optimization process in order to minimize the cost of individual bridge within one maintenance circle. However, the adverse side is that an increasing backlog of deferred maintenance increases the crisis proportions on the interstate and primary highways. Advocating preventive maintenance can reduce the life cycle cost by invest less but earlier and provide a constant service to the public.

MR&R indicates the magnitude of cost and duration of each action to keep or recover a bridge condition. The effects of maintenance actions can be classified as: 1) improvement of current condition, 2) delay in deterioration occurrence, and 3) reduction of deterioration rates. MR&R policy defines the fundament of decision making under certain circumstances defined by the bridge agency. Besides of "do nothing", all other alternatives consume resources from both administration and user. Optimization is widely used to allocate these resources, such as budget and time along the life cycle for individual bridge at the project level and among bridges at the network level. A project-level implementation stressing discipline and accountability is at least as essential as an enlightened network-level optimization (Yanev, 2007).

3.1.3.2 MR&R at A Network Level

Highway bridges are normally managed within a local bridge network in conformity with their collective service to a community. The main purpose of network management is to prioritize the portfolio components and optimize the utilization of the limited resources in a prescribed interval. "*The differences reflect the larger scope and broader considerations of the former and the greater significance of technical detail in the latter… Project-level management supplies services and demands funding, whereas the network level provides funding and demands accountability*"(Yanev, 2007). Current highway bridge management systems are designed at the network level, by which bridge agencies are able to manage all these facilities by allocating limited resources to achieve optimal performance of the whole network.

Prioritization employs condition or performance indexes, such as Sufficiency Rating and Level of Service, to rank the competing bridges with a local network and focus on the most critical bridges. This type of technique has been incorporated in industrial practice of current bridge management systems. Optimization provides more opportunity to achieve multiple purposes by meeting certain constraints.

Frangopol and Liu (2007) used stochastic dynamic programming procedure for multiobjective optimization of bridge network maintenance planning that involves a group of existing highway bridges with various remaining service lifetimes and different reliability importance factors to the bridge network. There are basically two phases: The phase I identifies the optimal maintenance for each bridge with minimum life-cycle maintenance costs by Monte Carlo simulation. In phase II, maximum bridges can obtain portioned annual budgets according to individual optimal maintenance plan. The ultimate goal is identification of the most efficient combinations of available maintenance actions applied to all bridges in a highway network. Wu (2008) modeled with generic algorithm to identify optimal strategies for maintenance and repair of a bridge network with the threefold objectives of maximizing bridge service life, minimizing maintenance and repair costs, and minimizing user travel time delay.

Devulapalli (2002) developed a policy analysis tools by discrete event simulation to expand the functions of Points. Functionally, this tool provides user a platform to observe evolvement of network performance under various policy scenarios. With given cost and deterioration data recorded, a policy analysis tool targets to compare different policies and determines the best policy of priority setting and optimization of funds allocation. Discrete event simulation can effectively handle probabilistic distributions of data to capture all the inherent uncertainty to a more reasonable level of reality simulation than deterministic tools.

3.1.4 Failure Limit State Modeling

Predicting the failure limit state over a prescribed period is an important area of research, which is designed primarily to model the interaction between the physical system and its environment.

The factor method is an approach in which reference service life is multiplied by a series of modifying factors that relate to the specific conditions of the case. Comprehensive work has been done on the subject by the International Council for Research and Innovation in Building and Construction (CIB, 2004) and International Standard Organization (ISO15686-2, 2001). The factor method multiplies the reference service life by the modifying factors that are likely to affect service life. Reference service life is a documented period in years for which the component or assembly can be expected to last in a reference case under general service conditions. Reference service life may be determined from the facilities of a comparable manufacturer or through previous experience or observation of similar construction in similar conditions. The modifying factors represent the deviation from the assumed conditions used to establish the reference service life. They generally include the quality of components, the design level, the work execution level, the indoor environment, the outdoor environment, the maintenance level, and in-use conditions.

The result of the factor method is deterministic. Moser and Edvardsen (2002) proposed the engineering method which assigns probability density functions to the factors, such as normal or lognormal distributions. The engineering method modifies the factor method towards taking a more scientific approach and defines the level of complexity of models and type and amount of data to be used in an engineering design method. The factor method is one of the industry recommended (ISO15686-2, 2001) methods of service life prediction for infrastructure facilities.

The reliability method predicts the service life of a facility (or component) by the hazard function based on probability theory. The design provision of the Load and Resistance Factor Design (LRFD) uses factors developed from reliability theory (AASHTO, 2004). It reaches the system level by utilizing logical relations of parallel, series, or combinations among components or subsystems, instead of a linear relation as in the condition assessment techniques. Akgűl and Frangopol (2003) pointed out a reliability analysis requires the formulation and identification of various potential collapse modes and their combinations into a single assessment for a system. Time-dependent reliability analysis (Ellingwood and Mori, 1997) takes into account the stochastic nature of past and future loads due to operating conditions and the environment, randomness in strength, and degradation resulting from environmental stressors. Liu and Frangopol (2005) further forwarded a concept of the time-dependent bridge network reliability and bridge reliability importance factor, which include traffic capacity and impacts of bridge maintenance activities on economy, environment, and society. The main advantage of this methodology is the development of a closed function expressing the structure reliability which considers the time dependency of structural strength degradation.

The above physically oriented methods embody several of the past approaches to performance evaluation. These physical predictors supply the tools to estimate a good portion of the supply side, but this addresses only one of the two components in the service relationship. Although these processes require usage condition for physical performance estimation, they usually treat the demand vectors as constants. This will unbalance the relationship and cannot correctly or efficiently predict the service life under a more comprehensive scenario in which changes in the demand side can cause severe obsolescence.

3.2 Service Demand – D(t)

Service demand of transportation facilities is principally an issue of traffic mobility, which can further be divided into passenger mobility and freight mobility.

3.2.1 Passenger Mobility

Satisfaction with future mobility is the target of sustainable development of transportation infrastructure systems. Traffic demands are the results of a wide range of social and economic variables, such as population, economics, land use, and the available transportation network. Within the rational planning framework, transportation forecasts have traditionally followed the sequential four-step model or urban transportation planning procedure, first implemented on mainframe computers in the 1950s at the Detroit Area Transportation Study and Chicago Area Transportation Study (Meyer and Miller, 2000). Now, urban travel demand forecasting has evolved from an aggregate level to agent models which allow analysis of individual pedestrian or vehicles.

The four-step method starts from the traffic demand side and assigns potential trips according to the availability of the traffic supply side at the urban level. For a given bridge, the traffic performance depends on the traffic between the zones that it may serve and its relative capability compared with alternative routes.

Oppenheim (1994) gives a description of the four step method for urban travel demand modeling. The first step in the method is trip generation. Passenger trips are classified as Home Based Work (HBW), Home Based Other (HBO), and Non-Home Based (NHB). By dividing an urban area into uniform zones, the model estimates the number of person or motorized trips to and from each traffic zone. With disaggregate data, the model generates trip production and trip attraction and balances these numbers for all zones for the further aggregate prediction. The second step is trip distribution. The number of trips out from one zone to another is the total number of trips generated in an area multiplied by the ratio of trip attraction of to the target zone to all destination zones. The third step is mode choice. It is the process of splitting the person trips into specific modes according to the characteristics of travelers, trips, and modes. Travel time and travel cost determine the trip interchanges among available modes. The last step in the method is the assignment of zonal origin-destination flows to transportation routes, based on the factors that affect route choice. This process requires information of traffic network geometry, which directly connects with transportation supply.

A passenger normally makes his or her transportation decision by comparing factors among the affordable modes. Common passenger traffic modes include automobile, public transit, railroads, aviation, marine, pedestrians and bicyclists. Automobiles supply more flexibility and convenience than other modes, especially for suburban development. The 1995

National Personal Transportation Study (FHWA, 1995a) showed that 74% of people drove to work alone. Other modes represent a significantly smaller portion of the mode choice, with 12% of commuters ridesharing, 7% using public transit, and 7% biking or walking. Commuter rail and intercity passenger rail service can offer reliable transportation service at a cost per passenger mile that is lower than most other modal choices. However, transit or rail is not well suited for distributing passengers in low-density areas.

There are several mode choice techniques that vary by complexity, data, and application. Most of them require certain combination of the following inputs: person trip tables for each trip purpose (HBW, NHB, and HBO), characteristics of the trips, the traveler, and the available mode choices. Decisive factors include the relative cost and time for making the trip by each mode, person/trip/land use characteristics, person/household characteristics (automobile ownership, income), trip characteristics (trip purpose, trip chaining, time, length), mode characteristics (congestion, cost, frequency, connectivity), and land use characteristics (sidewalk or pedestrian facilities, mixture of uses at both ends of trip, distance to transit, parking availability and cost).

At the disaggregate level, the common method of modal choice is to compare the utilities of two modes in terms of travel times and costs. The behavior of travelers reflects the actual choice process at the consumer level.

To account for personal behavior, the model can incorporate independent variables, such as income and ownership of an automobile. This method collects interview information for traveler's past behavior and uses statistical analysis to determine the relative weight. There are two deficiencies in regression: 1) errors are not normally distributed, 2) the variance of the error term is not constant. All these violate the multiple regression assumptions. In addition, it may lead to unbounded probabilities (<0.0 or >1.0) for extreme values of travel cost or travel time (Hobeika, 2006). An improved approach is logit transformation. It is convenient to make modal choice with the given utility of each traffic mode by the ratio of the individual utility and the sum of all modes'. Ahmed (1996) compared the logit and probit models with several case analyses based on criteria such as consistency, significance of the model's coefficients, goodness-of-fit measures, outlier analysis, and market segment test. He concluded that the logit models are superior to probit ones.

Normally, mode choice is the decision of the traveler. However, the facility agencies have certain methods to influence mode choice, such as high-occupancy vehicle facilities, parking availability, transit fare changes, increasing transit frequency, or increasing transit coverage. Even though not directly influencing the traveler's choice, these methods change the properties of certain modes in terms of their usage cost, travel time, connectivity, or availability.

3.2.2 Freight Mobility

There are several differences between passenger traffic and freight traffic (Eatough et al., 1998): *Unit of measure,* freight transportation is measured by the number of vehicles, freight volume and weight. With different measures, there are mainly two types of models, commodity-based modeling and vehicle trip-based modeling; *Value of time,* the value of time differs among commodities; *Loading and unloading*, freight requires extensive facilities and equipment for loading and unloading and these processes that are specialized for different commodities; *Type of vehicles,* there are specific purpose vehicles to carry refrigerated goods, liquid, and gas.

Eatough et al. (1998) generalized two types of modeling structure for freight traffic. Their first model follows a structural approach, similar to the four-step model for passenger travel. Freight demand is derived from economic activities and molded by intermodal or intramodal competitive forces and government actions. It involves comprehensive interrelationships among economic activity, production and consumption nodes, distribution or linkages among production and consumption nodes, mode choice and shipment size decisions, vehicle trips, and route assignments. Eatough et al.'s second model follows a direct approach. This is a simplified structural approach in that it usually addresses a specific aspect or component of goods movement rather than estimating the entire freight demand on the transportation system.

Common freight modes include truck, rail, air, waterway, and pipeline. Among all these modes, trucks play a significant role, for most other modes rely on truck traffic to complete the supply chain. By comparing typical freight modes, Bowen and Slack (2007) concluded that trucking is more competitive than other modes especially for short-haul transport. Table 3-1 shows the modal shares in terms of value, weight and ton-km for two recent years. The difference between the 1993 and 2002 measures is not obvious. The trucking mode dominates the domestic movement of freight. Although rail and waterway have a higher percentage of ton-km, the values for these two modes are much lower than for trucks. So, trucking has a greater appeal for higher-value freight. Dividing the ton-km by weight, only truck transport has a result smaller than 1, while all other known modes have bigger results. This reflects the reality that the trip distance of truck transport is shorter than all others because of its flexibility and speed.

Table 3-1, Modal Shares of Commercial Freight in the US (Bowen and Slack, 2007)

Mode	1993			2002		
	Value	Weight	Ton-km	Value	Weight	Ton-km
Truck	65.1%	54.5%	25.6%	63.7%	58.2%	32.1%
Rail	3.9%	11.8%	26.5%	3.7%	12%	27.8%
Water	8.6%	15.9%	24.3%	8.3%	14.8%	16.3%
Air	5.5%	0.1%	0.2%	7.4%	0.1%	0.3%
Pipeline	4.3%	11.9%	16.3%	2.7%	10.5%	16.7%
Multimodal	9.2%	1.7%	4.6%	10.6%	1.3%	5.0%
Other	3.4%	4.0%	2.5%	3.6%	3.2%	1.7%

Rail transportation remains dominant in the carriage of lower-value commodities and overshadows trucking in terms of freight ton-kilometers (FTKs) within North America. The difficulty of expanding the network and related infrastructure keeps rail traffic relatively static. Pipelines accounts for the largest portion of fluid and gas transport. The domestic waterborne freight transport still remains important in terms of tonnage (24.3%), even though the goods have a very low value (8.3%). Miller (2003) predicted that freight traffic in Virginia will significantly increase from 1998 to 2020: truck tonnage will grow by 81%, rail tonnage will grow by 41%, and air tonnage will grow by about 300%. The market share of freight shipped by air, truck, and rail will change as well. In Virginia, rail occupancy of freight will decrease to 26% in 2020 from 30% in 1998. In contrast, the shares for trucking will increase from 64% to 68% for the same period. The market share for air freight will increase from 9% to 12%.

The basic methodologies of freight mode choice are similar to the passenger ones for the model structure. The carriers need consider purchase price, operating costs and likely productivity improvements, and they normally adopt the most cost efficient options. Holguin-Veras (2002) proposed a commercial vehicle choice method in order to compensate for the shortage of approaches on this topic other than the traditional structural method. As discussed previously, truck characteristics can be recognized from their weight, size, and number of axles. He used the load equivalency factors, to define the different types of vehicles. The load equivalency factor is an indication of the number of standard single axle loads that are required to produce the same amount of damage as the actual axle load. To reduce the number of cases, he used three main classes: (1) pick-ups (small trucks), (2) trucks (two and three axle trucks), and (3) semitrailers (one trailer trucks with four to six axles). Hauling distance plays a decisive factor in the market share of each type. The shipment size increases with the capacity of the vehicle. In the American trucking industry, as a consequence of the high level of specialization, there is a hierarchy, with truckload operators doing long-haul movements, and less than truckload operators transporting commodities at the ends of the trip.

Holguin-Veras defined a utility function to distinguish the discrete-continuous mode choice in analyzing the market share of trucking transport. The choice of truck type is a discrete variable, while the shipment size is a continuous variable. Shipment size is a function of: 1) the trip length (km), 2) the binary variables that represent the commodity groups (e.g. prepared food, monumental or building stone, natural sands, or fuel), and 3) the type of economic activities taking place at the ends of the trip (retail, wholesale, or other). Statistical analysis of the shipment size model presents several properties: 1) high unit weight commodities have positive marginal rates since they are usually transported in bulk. Shippers tend to transport these commodity groups in relatively large shipments. 2) The slope of the shipment size functions is smaller when the flows involve retail activities. 3) Adding economic activities at the trip ends is important in his model and increases the determination coefficient from 0.24 to 0.44.

Given the fact that the mode choice depends on the shipment size, he specified the vehicle choice sets for different shipment sizes. If the shipment size is smaller than 3 tons, the choice set can comprise all three vehicle classes. From 3 tons to 15 tons, trucks and semitrailers are considered. Above 15 tons, only semitrailers are considered. This creates an instrumental variable, which is a proxy for the actual shipment size for the utility function.

In real data analysis with the utility function, he used only one variable for Z_i, unit cost per ton C, since the unit costs estimating the amount of resources are associated with using a particular vehicle. Instead of directly using y_i, he defined a difference variable between the centering parameter (average legal payload of the vehicle class) and the estimated shipment size. Large differences between shipment size and the centering parameter would make the vehicle less likely to be selected. Then he got the utility functions for three vehicle classes, which would be used for policy analysis. In his analysis, we find that the key variables to freight mode choice are unit cost, trip distance, and the type of commodity being transferred.

Intermodalism is a concept based on the fact that no single mode (rail, automobile, etc.) can fully serve all trips. Therefore, transportation system should provide modal alternatives for travelers and connections between modes. To connect different modes, transfer points receive much attention because they are often the critical bottlenecks in the freight system. Passenger intermodalism includes parking and drop-off facilities around a rail station or airport, transit connections, and trip information services. Freight intermodalism includes the freight traffic on different modes and the transferring procedures.

3.2.3 Truck Size and Weight

In freight transportation, trucks deliver 90 percent of the value of U.S. freight, and trucking charges are more than $610 billion a year (Samuel et al., 2002). Since 1970, truck travel in the Unites States measured in vehicle miles of travel (VMT) has increased by 216%, whereas the population has increased by only 33% (Chang and Garvin, 2006). The physical and operating characteristics of the trucks are primarily determined by the regulations governing their sizes and weights, the extent of their enforcement, the characteristics of freight, and technology in the motor vehicle manufacturing industry.

One of the most comprehensive researches about trucking is the *Comprehensive Truck Size and Weight Study* by the U.S. Department of Transportation (USDOT, 2000). Another valuable resource is *Effect of Truck Weight on Bridge Network Costs* by National Cooperative Highway Research Program (NCHRP, 2003). These reports attempt to quantify the impacts on the infrastructure and freight traffic by the changes of federal Truck Size and Weight (TS&W) limits.

In calculating the truck weight influence, axle weight and distances between axles are basic arguments to measure truck load spectra. The Federal law includes the following four basic weight limits for trucks traveling on the Interstate System, i.e. 89 kN (20,000 lbs) for single axles, 151 kN (34,000 lbs) for tandem axles. A maximum gross vehicle weight of 356 kN (80,000 lbs). Application of the Federal Bridge Formula for other axle groups up to the maximum of 356 kN (80,000 lbs) gross vehicle weight.

Changes in the Nation's TS&W limits, which determine the maximum payload that vehicles may carry, influence motor carrier productivity. For high density freight such as farm products and natural resources, a vehicle's maximum payload is controlled by truck weight limits. For low density freight, vehicle size limits constrain payload instead of weight limits. In general, increases in TS&W limits would increase the tonnage and/or volume of freight that may be carried per vehicle per trip. Consequently, fewer trips would be required to carry the same amount of freight, decreasing VMT and reducing trucking costs. Alternatively, more restrictive TS&W limits would increase trips, VMT, and trucking costs (USDOT, 2000).

Bridge stresses caused by vehicles depend on gross vehicle weight and the distances between the axles. Trucks with equal weight but different wheelbases produce different bridge stresses: the shorter the wheelbase, the greater the stress. Changes in the nature and frequency of freight traffic create a number of challenges to existing bridges. Heavy trucks are more critical than normal automobiles because of their concentrated higher load and bigger dimension. The effects on the bridges produced by the truck loads are functions of the structural dimensions and material properties of the bridges such as the distances between the girders, the deck stiffness, and the lengths of the spans of the bridge.

The federal truck size and weight regulations designed to protect bridges is based upon the bridge formula.

$$W = 500[LN/ (N-1) + 12N + 36] \tag{3.1}$$

Where W = overall gross weight on any group of two or more axles to the nearest 500 lbs; L = distance in feet between extreme of any group of two or more consecutive axles; and N = number of axle groups under consideration.

This equation was designed to avoid overstressing HS-20 bridges by more than 5% and H-15 bridges by more than 30% (Ghosn, 2000). As noted, design loadings incorporate significant margins of safety such that even the 30 percent overstress allowed on H-15 bridges does not put that bridge in danger of sudden failure (USDOT, 2000). Adopted in 1975, the bridge formula protects bridges by restricting the maximum weight allowed on any group of consecutive axles based upon the number of axles in the group and the distance from the first to the last axle. The bridge formula reflects the fact that loads concentrated over a short distance are generally more damaging to bridges than loads spread over a longer distance. It allows additional gross weight as the wheel base lengthens and the number of axles increases.

A change in truck weight limits will alter the truck-weight frequency distributions, or truck load spectra by vehicle type. Chang and Garvin (2006) pointed out that the overloads cause both short-term challenges related to strength and longer-term challenges related to serviceability. The immediate concern posed by overload vehicles is the risk of member or system failure caused by an overstress in bridge members. The long-term concern involves fatigue damage resulting from the cumulative effect of repeated loadings. For example, it has been reported (NCHRP, 2003) that for steel bridge members a 10 percent increase in effective truck weight causes about a 33 percent increase in fatigue damage.

3.3 Performance Evaluation – F[S(t), D(t)]

As postulated, the performance of a highway bridge is a function of supply and demand factors. Measures of bridge performance that incorporate this notion include serviceability assessment, Level of Service, Sufficiency Rating, and an approach of service supply and demand.

In structural engineering, serviceability refers to the failure limit state (Stewart, 1996, Veras, 1997, Li et al., 2004). A serviceable structure is one that performs satisfactorily, not causing any discomfort or perceptions of unsafety for the occupants or users of the structure (*LRFD Steel Design, Second Edition).* However, a more comprehensive definition is needed for this research. A broader understanding was given by Lemer (1971), "Serviceability is the degree to which a system of constructed facilities provides adequate service to the user, from the user's point of view." With this definition, it requires not only conditional soundness, but also functional adequacy. A serviceable structure must perform satisfactorily under normal service loads without causing discomfort to the users or disrupting the functions of the structural system. For example, a suspended bridge may still be structurally stable, but swing with observable amplitude as property of poor aerodynamics. This may cause drivers or pedestrians discomfort or a perception of unsafe conditions.

Lemer (1971) suggested estimating serviceability as the probability that the user will judge service to be satisfactory, or the fraction of users finding service to be adequate. For example, the roughness of highway pavement will be perceived by the user as vibration and noise in the vehicle, which promote a feeling of discomfort. This feeling, among other variables, can be used to judge the adequacy of the pavement. The serviceability of the as-built structure is quantified to a degree in terms of traffic type, capacity, and average traveling speed (Yanev, 2007). With unchanged structural condition, bridge serviceability can decline due to increasing traffic demand. Then, serviceability forecasts must anticipate the physical degradation and the transportation need.

3.3.1 Bridge Performance Measures

Various indicators are designed to quantify highway bridge performance, such as Level of Service, Sufficiency Rating. These variables have included a broader scope of arguments than some pure condition indexes, such as what designed for BUILDER Engineered Management Systems (Uzarski and Burley, 1997). Table 3-2 lists current highway bridge performance measures their applications generalized in the NCHRP Report 590. Since all these performance measures are well defined, they are easily calculated with given data. They have different emphases and reflect bridge performance from different aspect. Their choices depend on the application by the bridge agency, who can exhibit its own preference. An automatic though is whether it is helpful to combine some of these measures in a certain way. However, their various scales and dimensions prevent a direct sum of these factors.

Table 3-2, Performance Measures and Applications (NCHRP, 2007)

Goal	Performance Measures
1. Preservation of Bridge Condition	a) NBI Condition Ratings b) Health Index c) Sufficiency Rating
2. Traffic Safety Enhancement	a) Geometric Rating/Functional Obsolescence b) Inventory Rating/Operating Rating
3. Protection from Extreme Events	a) Scour Vulnerability Rating b) Fatigue/Fracture Criticality Rating c) Earthquake Vulnerability Rating d) Other Disaster Vulnerability Rating (Collision, Overload, Human-Made)
4. Agency Cost Minimization	a) Initial Cost b) Life-Cycle Agency Cost
5. User Cost Minimization	a) Life-Cycle User Cost

Condition ratings give the primary measures of bridge carrying ability. There are a rich collection of literature, such as NBI condition rating (FHWA, 1995b), bridge health index (Shepard and Johnson, 2001), inventory rating (FHWA, 1995b), operating rating (FHWA, 1995b), and vulnerability ratings (NCHRP, 2007). However, this type of evaluation methods compares the current condition with its design load or capacity, but not takes into account of user's demand. Therefore, this section highlights Level of Service and Sufficiency Rating that identify the relationship between the facility and user.

3.3.1.1 Level of Service

For transportation facilities, Level of Service is a quality measure describing operational conditions within a traffic stream, generally in terms of such service measures as speed and travel time, freedom to maneuver, traffic interruptions, comfort and convenience. The development of this concept dates back to the 1950s and was first introduced in the Highway Capacity Manual (HRB, 1965) as "a qualitative measure of the effect of a number of factors, which include speed and travel time, traffic interruptions, freedom to maneuver, safety, driving comfort and convenience, and operating costs." Since its appearance, the definition of Level of Service has experienced expansion as well as concentration on certain types of facilities. It is suited to defining different attributes of a certain category, such as safety, user value, and traffic flow. Highway Capacity Manual (TRB, 2000) has a broad range of transportation facilities, such as highways, streets, light rail, and pedestrian facilities. Level of Service is defined as the operational criteria for each type of facility.

Letters from A to F are used to represent the operating conditions and the driver's perception of those conditions from the best to the worst. Performance measures are used to calculate Level of Service and reflect the operating conditions, given a set of roadway, traffic, and control conditions. The primary performance measure determining the Level of Service is called the measure of effectiveness (MOE). Generally, the volume-to-capacity ratio is used as one of the main criteria to quantify the Level of Service of transportation facility.

Factors affecting Level of Service include base conditions, roadway conditions, traffic conditions, and control conditions. The standards for the base conditions are given as good weather, good pavement conditions, users being familiar with the facility, and no impediments to traffic flow. Roadway conditions include geometric and other design elements. Traffic conditions include vehicle type and directional and lane distribution. Control conditions are relevant to interrupted-flow facilities, such as traffic signals, stop signs, yield signs, turn restrictions, and lane use controls.

HCM supplies a framework only for standard conditions, while some special conditions or factors deserve further consideration. One special category in this element is the safety. Old versions of HCM included this term, but it has been removed since 1994 because the real operational measurements used to define Level of Service do not correlate with safety. Since safety is an integral part in facility operation, current research is trying to combine safety with other critical criteria to modify the definition of Level of Service. Lin and Panos (2003) used delay and safety index as a comprehensive Level of Service indicator for signalized intersections. Their model takes account of the vehicle-vehicle conflict and vehicle-pedestrian conflicts as potential risk parameters to combine with delay. Researchers are also exploring other potential influencing factors. Kim et al. (2003) suggested that density-based Level of Service does not reflect a driver's psychological or emotional comfort. They used three other measures: acceleration noise, number of uses and duration of cruise control as a driver convenience, and percent time of following. Chasey et al. (1997) defined a comprehensive Level of Service to include both capacity (Level of Availability) and maintenance (Level of Operations) to overcome HCM's limitation that the physical conditions of facility are always assumed to be good. To deal with tolled facilities, Jack and Haitham (2002) incorporated plaza configuration, usage level of electronic toll collection, and service time in the Level of Service hierarchy.

3.3.1.2 Sufficiency Rating

Differing from the Level of Service which uses only a six-degree scale to describe each stage, the sufficiency rating provides a more structured degree value calculated from different aspects of facility performance. The sufficiency rating for highway bridges was first introduced as a comprehensive evaluation standard in the *Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges* (FHWA, 1995b). It calculates four groups of factors to obtain a numeric assessment which is indicative of bridge sufficiency to remain in service, i.e. structural adequacy and safety (55% of overall rating), serviceability and functional obsolescence (30% of overall rating), essentiality for public use (15% of overall rating), and special reductions (13% of overall rating). It has a percentage value representing the range from an entirely sufficient bridge at 100% to an entirely insufficient (deficient) bridge at 0%. If the bridge agency completes the data collection according to the *Recording and Coding Guide*, there is a convenient method for calculating the sufficiency rating. The federal government uses the Sufficiency Rating in allocating funds for the Highway Bridge Rehabilitation and Replacement (HBRR) Program and in determining eligibility criteria for bridge projects that use these funds. In Tennessee, a bridge with sufficiency rating less than 80 is eligible for rehabilitation and less than 50 is eligible for replacement.

An opposite concept of sufficiency rating is deficiency rating, an alternative criterion index with a rationale that it is a direct reflection of the fact that 40% of the 600,000 highway bridges in the U.S. are deficient (deteriorated or obsolete). Both sufficiency rating and deficiency rating focus on evaluating the whole bridge in lieu of separate evaluations of its components. This allows for prioritization among bridges in a network. The method provides decision makers with a straightforward and simple approach for comparing and ranking their facilities. Applications of either sufficiency or deficiency ratings are comparative, since they stem from the same theoretic basis. As noted by Kenneth and Basile (1995), "condition ratings reflect physical deterioration due to environmental effects and traffic, and appraisal ratings indicate changes in traffic volume, existing load capacities, and compliance with safety standards related to bridge geometry and clearances."

3.3.2 Supply and Demand Approach to Evaluate Performance

A highway bridge may lose its serviceability in two directions, deterioration by decreasing supply or obsolescence by increasing demand. Recent research has started to combine service supply and demand together for infrastructure performance evaluation. Raux (2003) tested the interaction between the supply of public transport services and trip demand through the impact of the levels of fares, service frequencies and public funding. Adey *et al.* (2003) generalized three approaches to measure the highway bridge (highway bridges) performance, i.e., the supply bridge (SB) approach, the supply and demand bridge (SDB) approach, and the supply and demand system (SDS) approach. The supply approach is based solely on the physical conditions of the bridge. The supply and demand approach is based on the ability of an individual bridge to perform adequately, otherwise expected additional user costs occurs on the demand side. Both of these approaches are used in most existing bridge management systems, such as Pontis, Bridgit, and Kuba-MS. The supply and demand system approach considers the scenario that multiple bridges are adversely affected simultaneously at a network level. To combine and compare the service supply and demand, all of these approaches utilize monetary values to represent agency costs and user costs.

In Adey *et al.*'s definitions, supply is the performance of all the bridge in the network and demand is the consequences if an adequate level service is not provided, which are expressed in terms of costs to the users. The negative impacts include the loss of network reliability, restriction in traffic flow capacities, injuries and deaths. A convenient way to count all these effects and normal MR&R activities is transferring all of them into monetary values. User costs can be divided into normal costs incurred under usual travel conditions and additional costs incurred when direct travel is impossible due to reconstruction or weight limit. User costs when travel is possible include travel time costs, vehicle operating costs, and accident costs. User costs when travel is not possible are the losses of the benefits of being able to travel. It is hard to quantify the costs from the demand side, especially those related to human life. An alternative approach can be estimating the loss of production, surveying the populations' willingness to pay, and calculating implicit value derived from community choices in the allocation of resources and behavior of individuals regarding expenditures on protection against road accidents and their consequences.

Table 3-3, Comparison of Three Levels of Approach of Bridge Performance Evaluation

	SB	**SDB**	**SDS**
Factors	Physical conditions of highway bridges.	Conditions of highway bridges and user costs at project level.	Conditions of highway bridges and user costs at network level.
Evaluation Criteria	Minimize the Life Cycle Cost of the whole network.	Minimize the sum of Life Cycle Cost and User Costs at single bridge failure within the network.	Minimize the agency cost and user costs of multiple bridges failures within the network.
Advantage	Emphasizing the supply side of structural integrity, safety, load resistance.	Incorporating user costs in case of a loss of connectivity of the transportation network.	The optimal management strategy is based on the physical condition, additional user costs in case of simultaneous non-operational bridges.
Limits	Not considering demand side.	As per Adey et al. (2003), SDB does not provide an adequate Level of Service of the transportation network as a whole.	Labor intensive for the analysis of simultaneous non-operational bridges.

Rather than actual demands as defined in this research, SDB and SDS use nominal demands or the additional user costs in case of bridge failure. This is an economic approach for the prioritization within a network of allocating limited budget by prioritizing the most urgent expenses to minimize potential loss. In other words, it utilizes the cost benefit ratio for prioritization. However, these methods are unable to account for other potential losses as well as why and when the failures may happen. This research will extend the scope of the demand side by including additional influential factors.

4. SIGNIFICANT SUPPLY AND DEMAND FACTORS

This chapter identifies explanatory factors fitted in the S(t) and D(t) vectors for highway bridges, among which significant variables are selected by statistical tests and literature review.

4.1 Service Supply & Demand of Highway Bridges

4.1.1 Service Supply

A highway bridge over a significant span is typically composed of six subsystems: abutment, pier, girder, deck, approach, tower, and cable (suspension and cable-stayed), with diverse life spans. The main structure (abutment, pier, approach, and tower) usually determines the physical life of the facility. Possibly reinforced, they are seldom replaced entirely. Conversely, deck or pavement and painting can be periodically repaired or replaced.

The various properties of the facility performance as defined in the Formula (4.1) are decomposed according to the supply and demand elements. The vector of decision factors X_j in supply side S (X_j) is

$$X_j = \left(f_{j1,} f_{j2}, f_{j3}, ...\right) \tag{4.1}$$

The *Recording and Coding Guide* (FHWA, 1995b) characterizes a bridge with information about its structure type and material, geometric data, condition and so on. This research categorizes bridge supply vectors using the same division:

S_1— Structure Type and Material

$$\begin{aligned} X_1 = (&f_{StrucMainMaterial}, f_{StrucMainType}, f_{StrucAppMaterial}, f_{StrucAppType}, f_{NumMainSpan}, f_{NumAppSpan}, \\ &f_{DeckType}, f_{DeckWear}, f_{DeckMem}, f_{DeckProt}) \end{aligned} \tag{4.2}$$

$f_{StrucMainMaterial}$ is the main structural material.
$f_{StrucMainType}$ is the type of structure for the main span(s).
$f_{StrucAppMaterial}$ is the approach material.
$f_{StrucAppType}$ is the approach structure type.
$f_{NumMainSpan}$ is the number of spans of the main structure.
$f_{NumAppSpan}$ is the number of spans of the approach.

$f_{DeckType}$ is the type of deck.

$f_{DeckWear}$ is the wearing surface of deck.

$f_{DeckMem}$ is the type of membrane.

$f_{DeckProt}$ is the deck protection.

S_2 — Age and Service

$$X_2 = (f_{Year}, f_{ServOn}, f_{ServUnder}, f_{LnOn}, f_{LnUnder}, f_{Detour}, f_{FuncClass}) \tag{4.3}$$

Where,

f_{Year} is the year built.

f_{ServOn} is the type of service on bridge.

$f_{ServUnder}$ is the type of service under bridge.

f_{LnOn} is the number of lanes being carried by the structure and being crossed over by the structure.

$f_{LnUnder}$ is the number of lanes under the structure.

f_{Detour} is the actual length to the nearest kilometer of the detour length.

$f_{FuncClass}$ is the inventory route functional classification.

S_3 — Geometry

$$\begin{aligned} X_3 = (&f_{MaxSpanLength}, f_{StruLength}, f_{RdwayWidth}, f_{DeckWidth}, f_{AppWidth}, f_{Skew}, \\ &f_{InventVerClear}, f_{InventHorClear}, f_{MinVerClearOver}, f_{MinUnderClear}) \end{aligned} \tag{4.4}$$

Where,

$f_{StruLength}$ is the length of the maximum span.

$f_{StruLengh}$ is the length of the structure.

$f_{RdwayWidth}$ is the most restrictive minimum distance between curbs or rails on the structure roadway.

$f_{DeckWidth}$ is the out-to-out deck width.

$f_{AppWidth}$ is the normal width of usable roadway approaching the structure.

f_{Skew} is the skew angle between the centerline of a pier and a line normal to the roadway centerline.

$f_{InventHorClear}$ is the total horizontal clearance for the inventory route.

$f_{MinVerClearOver}$ is the actual minimum vertical clearance over the bridge roadway, including shoulders, to any superstructure restriction.

$f_{MinUnderClear}$ is the minimum vertical clearance from the roadway or rail track beneath the structure to the underside of the superstructure.

S_4— Navigation

$$X_4 = (f_{NavControl}, f_{PierProt}, f_{NavVerClear}, f_{NavHorClear}) \tag{4.5}$$

Where,

$f_{NavControl}$ indicates whether requires navigation control.

$f_{PierProt}$ is the presence and adequacy of pier or abutment features.

$f_{NavVerClear}$ is the minimum vertical clearance for navigation.

$f_{NavHorClear}$ is the minimum horizontal clearance for navigation.

S_5 — Physical Condition

$$X_5 = (f_{DeckCon}, f_{SupStruc}, f_{SubStruc}, f_{Culvert}, f_{ChannelProt}) \tag{4.6}$$

Where,

$f_{DeckCon}$ is the overall condition rating of the deck.

$f_{Supstruc}$ is the physical condition of all super structural members.

$f_{Substruc}$ is the physical condition of piers, abutments, piles, fenders, footings, or other components.

$f_{Culvert}$ is the alignment, settlement, joints, structural condition, scour, and other items associated with culverts.

$f_{ChannelProt}$ describes the physical condition of channel and protection.

S_6 — Load Rating and Posting

$$X_6 = (f_{DesignLoad}, f_{OperRateMethod}, f_{OperRate}, f_{InventRateMethod}, f_{InventRate}, f_{Post}) \tag{4.7}$$

Where,

$f_{DesignLoad}$ is the designed live load.

$f_{OperRateMethod}$ is the load rating method for the Operating Rating.

$f_{OperRate}$ is the operating rating that will result in the absolute maximum permissible load level.

$f_{InventRateMethod}$ is the load rating method for the Inventory Rating.

$f_{InventRate}$ is a load level which can safely utilize an existing structure for an indefinite period of time.

f_{Post} is operating rating to maximum legal load when necessary.

S_7 — Appraisal

$$X_7 = (f_{StrucEval}, f_{DeckGeom}, f_{UnderClear}, f_{WaterwayAdq}, f_{AppAlign}, f_{Safety}, f_{Scour}) \tag{4.8}$$

Where,

$f_{StrucEval}$ is the condition rating based on subsystem rating and traffic flow.

$f_{DeckGeom}$ is the curb-to-curb or face-to-face of rail bridge width and the minimum vertical clearance over the bridge roadway.

$f_{UnderClear}$ is Vertical and horizontal underclearances through roadway to the superstructure or substructure.

$f_{WaterwayAdq}$ is the evaluating waterway adequacy with respect to passage of flow.

$f_{ApprAlign}$ is the adequacy of the approach roadway alignment.

f_{Safety} is the bridge safety features, i.e. railing, transitions, approach guardrail, approach guardrail ends.

f_{Scour} indicates the current status of the bridge regarding its vulnerability to scour.

4.1.2 Service Demand

"*The most expedient bridge is the structure that best satisfies the requirements of transport, passing capacity, and most traffic comfort conditions, has the minimum cost, and may be erected in the shortest time*" (Troitsky, 1994). Society "demands" certain levels of safety, ride quality, and passing ability from its highway bridges to satisfy its requirements. A highway bridge's main function is to move traffic across it and to allow traffic to pass under it. "Traffic on" refers to all functions and safety related to traffic moving across the bridge. "Traffic under" refers to the traffic moving under the bridge. Under traffic is not a function of the bridge, for a bridge does not support under traffic directly. However, a bridge may become a bottleneck for the traffic system due to insufficient service to either traffic on or under it, which may provide reason to replace an existing bridge. Thus, an inadequate "under" condition may necessitate a change even if upper functions still work well. The four attributes in Figure 4-1 are proxies for the demands of users and society. Each attribute includes a group of components that facilitates the satisfaction of the demands from user and society.

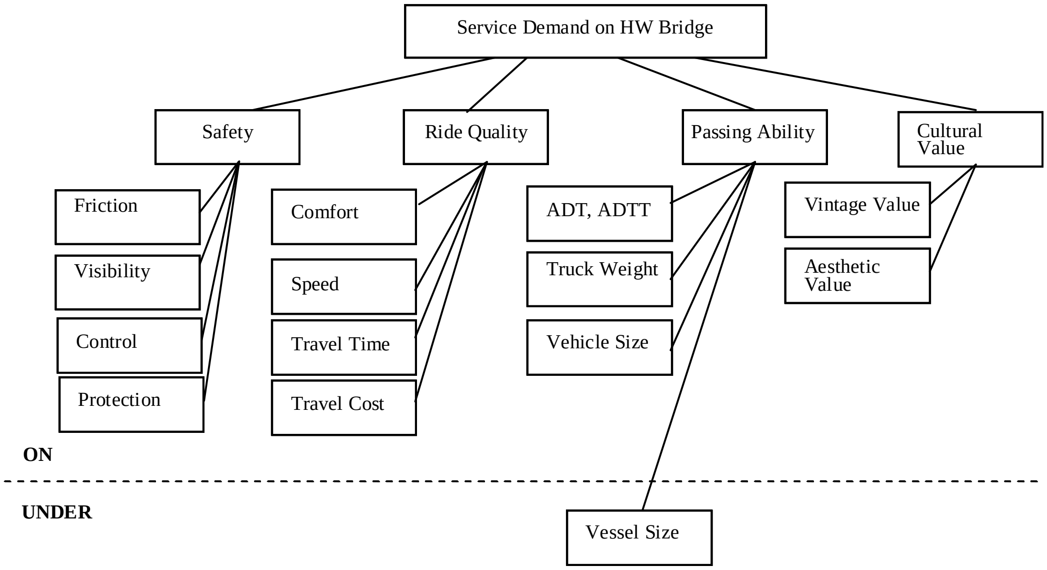


Figure 4-1, Hierarchy of Highway Bridge Service Demand

Safety

The first set in the hierarchy is safety, which ranks at the highest position in management decisions. Bridges spanning over the river, gulf, or gorge make them important linkages as well as pretty dangerous. There are numbers of catastrophic collapses in different countries during different eras, no matter which type of structure they are. Bridge of Angers, France, collapsed for the reason of resonance of soldiers in 1850. Tacoma Narrows Bridge, USA collapsed from aerodynamic “self-excitation” by the wind in 1940. Even though bridge design and construction standards and practices have progressed, failures till occurs. In 2007, the I-35W Mississippi River Bridge collapsed suddenly in rush hour with hundreds of vehicles involved. Safety of highway bridges includes pavement/deck friction to prevent skidding (especially with snow), protection by railing and parapet, control system, security measure and so on.

Ride quality

Ride quality or rideability (Lemer, 1971) is an important set of criteria from the riders on how content they are when traveling on the facility. Usually, it is designed as an index system to reflect how comfortable travel is from the driver’s perspective. As for bridge design, low gradient to increase maneuver and visibility, straight or curved approaches, clear signs and smooth pavement can make the ride on bridges comfortable and easy. Otherwise steep gradient and small radii of the approaches are particularly dangerous for traffic.

Passing Ability

Bridges usually are choke points for certain over size or heavy vehicles. Limits of weight and clearance between lower highway or waterway can lead to the replacement of existing bridges. Passing ability of bridges includes upper part and under part, which are fixed by the structure. Mobile bridges can lift or rotate their structures and enlarge their openings to relieve clearance limits. Usually, the designed serviceability will satisfy certain period of demand on the base of prediction. However, increasing traffic loads can wash out obsolete bridges that were unable to support heavier traffic. Passing ability is critical for the serviceability, and may result in the replacement of the existing bridges. For example, in 2005, the old Cooper River Bridges were replaced by a new 8 lane bridge with 36 feet additional clearance to allow large cargo ships to the port of Charleston.

Cultural Value

Aesthetics may defer the replacement of the bridge and attract more attention from the government and its citizens. Large scale bridges are landmarks of urban area for a long time. This most subjective value of bridges differentiates them from other normal transportation facilities. Long history of the bridge and contribution to the local economics bring another subjective importance, vintage value, to keep historic bridges. Roman aqueduct, the Pont du Gard, in France and other arch bridges still stand well for more than 2000 years to show these earliest bridge engineering works. Some 100-year bridges are still working well only with tremendous fund to rehabilitate them to afford current loads.

The demand vectors are therefore defined as:

D_1 — Safety

$$Y_1 = (f_{Friction}, f_{Visibility}, f_{Control}, f_{Protection}) \tag{4.9}$$

Where,

$f_{Friction}$ is the friction rating of the deck.
$f_{Visibility}$ is the navigation bridge visibility.
$f_{Control}$ is the signal or management measurements for traffic safety.
$f_{Protection}$ is the structural requirement, such as non-mountable median.

D_2 — Ride Quality

$$Y_2 = (f_{Comfortableness}, f_{TrafficSpeed}, f_{Time}, f_{Cost}) \tag{4.10}$$

Where,

$f_{Comfortableness}$ is the passenger feeling of passing the crossing.

$f_{TrafficSpeed}$ is whether substantial traffic speed reduction by passing the bridge

f_{Time} is the traffic time on the facility.

f_{Cost} is the traffic cost to pass the bridge.

D_3 — Passing Ability

$$Y_3 = (f_{ADT}, f_{ADTT}, f_{TruckWeight}, f_{VehicleSize}, f_{VesselSize}) \tag{4.11}$$

Where,

f_{ADT} is the average daily traffic volume for the inventory route.

f_{ADTT} is the percentage of truck traffic in the ADT.

$f_{TruckWeight}$ is the legal truck weight.

$f_{VehicleSize}$ is the maximum vehicle size need pass on the bridge.

$f_{VesselSize}$ is the maximum vessel size need pass under the bridge.

D_4 — Cultural Value

$$Y_4 = (f_{HistoricVal}, f_{AestheticVal}) \tag{4.12}$$

Where:

$f_{HistoricVal}$ is the vintage value

$f_{AestheticalVal}$ is the aesthetic value of the bridge.

4.2 Predominant Variable Identification

Previously, 7 supply vectors and 4 demand vectors with regard to highway bridge performance were defined. The reduction of the factors within these vectors is necessary to develop a viable model, but this reduction should not come at the expense of model credibility.

Simulation provides an instrument to numerically estimate reality. To measure a facility's performance, the modeling process would consider all initial variables then concentrate on the critical ones. This will not only save effort in later data collection, but also emphasizes the benefits of modeling. However, an arbitrary selection of critical variables may reduce confidence in the model. Statistical tests are suitable for variables with historical or cross-sectional data. All supply vectors and some demand variables are defined in the NBI with which historic data are available. Other demand variables are not recorded systematically. Additional literature review is necessary for their identification.

4.2.1 Canonical Discriminant Analysis

In the realm of multivariate data analysis, dimensionality reduction techniques allow the original data size to be presented in a subspace with smaller dimensions. This section gives a framework for structuring multivariate data analysis to statistically identify the predominant variables in highway bridge performance evaluation. The central procedure is canonical discriminant analysis (CDA). Based on the work of Klecka (1980) and Khattree and Naik (2000), three considerations for a CDA process are generalized to briefly illustrate how to define discriminant functions and reduce the dimension of the original data vectors without losing the statistical significance in a smaller subspace. From a large number of possibly correlated characteristics on which measurements are taken, CDA attempts to determine only a few new variables that can help describe the differences among various populations. These new variables are obtained as certain linear combinations of original measurements and are termed canonical variables. Theoretically, there are three considerations of CDA process.

The first consideration in the analysis is the canonical discriminant variable, which is defined by a canonical discriminant function which is a linear combination of the discriminating variables.

$$df_{km} = u_0 + u_1 X_{1km} + u_2 X_{2km} + \ldots + u_p X_{pkm} \tag{4.13}$$

Given two or more groups of observations with measurements on several quantitative variables, CDA derives a linear combination of the variables that has the highest possible multiple correlation with the groups. The variable defined by the linear combination of predominant variables is the first canonical variable. The second canonical correlation is obtained by finding the linear combination uncorrelated with the first canonical variable that has the highest possible multiple correlation with the groups. The process of extracting canonical variables can be repeated until the number of canonical variables equals the number of original variables or the number of classes minus one, whichever is smaller.

Klecka (1980) suggested a stepwise procedure to select the most useful discriminating variables in either a forward or a backward direction. The set of variables that makes up each class is assumed to be multivariate normal in distribution with a common covariance matrix. A forward stepwise procedure begins by selecting the individual variable that provides the greatest univariate discrimination and continuing with additional variables, one by one, which contribute a sufficient increment. The backward stepwise procedure begins with all variables being included and casts out those lacking significant influence on the total discrimination.

The second consideration is the number of canonical variables to be included. This is a critical question since the basic interest of CDA is the dimensionality reduction of the original data. The minimum number of canonical variables included should adequately describe the original information.

To answer this question requires testing a series of hypotheses:

$$H_0^{(j)}: \lambda_j = \lambda_{j+1} = \ldots = \lambda_r = 0, \text{ for } j=1,2,\ldots, r \tag{4.14}$$

The answer reaches the minimum number of important canonical variables as soon as $H_0^{(j)}$ is accepted. For example, suppose $H_0^{(1)},\ldots, H_0^{(j-1)}$ are all rejected, but $H_0^{(j)}$, j=1,…,r+1, is accepted. Then only (j-1) canonical variables $v_1,\ldots,v_{j-1}$ are sufficient to describe the data and hence the appropriate smallest dimension of the space in which the data can be presented is (j-1).

The third consideration in the analysis is which statistical tests are necessary. The first canonical correlation should be at least as large as the multiple correlations among the groups and any of the original variables. But for other canonical variables, there are several instruments can help to measure statistical significance of each canonical variable.

1. The relative percentage. For each discriminant function (variable), its relative magnitude to the total discriminating power can be interpreted by the relative percentage of its eigenvalue λ_i. The calculation is the ratio of one eigenvalue of one function to the sum of all

eigenvalues of the functions. This percentage reflects the relative importance of each function's or variable's capability to explain the total variance.

2. The canonical correlation. Another way to judge the substantive utility of a discriminant function (variable) is examining the canonical correlation coefficient. Obviously, this test relates directly to the Canonical Correlation Analysis. Normally, a high coefficient indicates that a strong relationship exists between the groups and the discriminant function.

3. Wilk's Lambda. Rather than testing the function (variable) itself, the statistical significance of the discriminant functions can also be revealed by the residual discrimination in the system prior to deriving that function. If the residual discrimination is too small, then it is meaningless to derive any more functions. Wilk's lambda is a multivariate measure of group differences over several discriminating variables. If the residual discrimination is significant, then one proceeds to derive the next function. Otherwise, additional functions will not contribute to the explanation of the problem.

To apply CDA, some of the popular statistics software tools supply the necessary functions, e.g. CANDISC procedure in SAS, or automated version of CDA in SPSS. In SAS, the CANDISC procedure performs a canonical discriminant analysis and performs both univariate and multivariate one-way analyses of variance (one-way MANOVA). The CANDISC procedure produces two output data sets: one contains the canonical coefficients and the other contains scored canonical variables. Given a classification variable and several quantitative variables, the CANDISC procedure derives canonical variables, which are linear combinations of the quantitative variables that summarize between-class variation in much the same way that principal components summarize total variation. It is customary to standardize the canonical coefficients so that the canonical variables have means that are equal to zero and pooled within-class variances that are equal to one. CANDISC displays both standardized and non-standardized canonical coefficients as well as correlations between the canonical variables and the original variables as well as the class means for the canonical variables.

The NBI data are first divided into strata based on the similarity of different types of highway bridges. By applying CDA tests, 27 entries are selected from the original 46 variables.

The STEPDISC Procedure

Stepwise Selection: Step 41

Statistics for Removal, DF = 18, 12818

Variable	R-Square	F Value	Pr > F
Bypass_Detour_Length	0.0176	12.74	<.0001
Functional_Class_Of_Inventory_Rt	0.0119	8.56	<.0001
Year_Built	0.0101	7.28	<.0001
Lanes_On_Structure	0.0263	19.21	<.0001
Lanes_Under_Structure	0.0066	4.74	<.0001
Average_Daily_Traffic	0.0103	7.38	<.0001
Design_Load	0.0086	6.15	<.0001
Approach_Roadway_Width	0.0027	1.95	0.0092
Navigation_Vertical_Clearance	0.1941	171.56	<.0001
Navigation_Horizontal_Clearance	0.2551	243.88	<.0001
Kind_of_Material_Design	0.2461	232.43	<.0001
Bridge_Roadway_Width_Curb_To_Cur	0.0559	42.20	<.0001
Minimum_Vertical_Underclearance	0.0119	8.56	<.0001
Minimum_Lateral_Underclearance	0.0479	35.83	<.0001
Deck	0.1091	87.18	<.0001
Superstructure	0.1920	169.17	<.0001
Substructure	0.2957	299.01	<.0001
Method_Used_To_Determine_Operati	0.0159	11.47	<.0001
Operating_Rating	0.0228	16.59	<.0001
Method_Used_To_Determine_Invento	0.0148	10.72	<.0001
Inventory_Rating	0.0219	15.93	<.0001
Structural_Evaluation	0.1646	140.33	<.0001
Deck_Geometry	0.0287	21.02	<.0001
Bridge_Posting	0.0434	32.30	<.0001
Waterway_Adequacy	0.0134	9.71	<.0001
Approach_Roadway_Alignment	0.0071	5.10	<.0001
Average_Daily_Truck_Traffic	0.0126	9.07	<.0001

No variables can be removed.
No further steps are possible.

Appendix A gives a complete procedure of the CDA test and SAS codes.

4.2.2 Significant Variables Identified in Literature Review

With the NBI data, the CDA test selects a group of significant variables to measure bridge service supply. This section analyzes why these factors mostly influence a bridge performance and identifies other important variables that are not recorded in the NBI so could not be included in the statistical analysis.

4.1.1.1 Critical Supply Variables

For the supply variable selection, the observations of Kenneth and Basile (1995) and Chang and Garvin (2006) discussed previously provide a rational foundation for identification of the significant factors. Over a ten year span, the leading reasons for highway bridge deficiencies remain similar as shown in Figure 1-3. Those eight factors are clearly important to assessing highway bridge performance.

$$S' = \left(f_{DeckGeom}, f_{StrucEvalu}, f_{SubStruc}, f_{SupStruc}, f_{DeckCon}, f_{UnderClear}, f_{WaterAdeq}, f_{AppAlign} \right) \tag{4.15}$$

In addition, recent work also indicates that managerial issues play a critical role in facility service life. Chang and Garvin suggested that alternative levels of operating/performance standards can substantially change the potential remaining service life of a given bridge via differing load allowances and the corresponding fatigue rate.

Using this observation, we introduce a management vector, M', that includes operating standards and other relevant factors. Maintenance and repair funding and strategies will also certainly impact service life. Operating standards and posting are defined by management policies which directly influence the fatigue rate.

$$M' = \left(f_{EvaluationCriteria}, f_{Posting}, f_{Budget}, f_{Maintenance} \right) \tag{4.16}$$

4.1.1.2 Demand Side

The changing demand may significantly shorten the remaining service life of a given facility by accelerating the physical deterioration and causing functional obsolescence. We suggested earlier measuring the highway bridge demand using five vectors, i.e. safety, ride quality, structural integrity, passing ability, and cultural value.

In the NBI, the appraisal variables, such as structural evaluation and deck geometry are calculated by comparing both traffic supply and demand. Based on the given load, geometric and traffic demand rating, a single digit is assigned for each variable under different average daily traffic, ADT, as shown in Table 4-1 and Table 4-2.

Table 4-1, Structural Evaluation (FHWA, 1995b)

Structural Evaluation Rating Code	Inventory Rating		
	Average Daily Traffic (ADT)		
	0-500	501-5000	>5000
9	>32.4 (MS18)	>32.4 (MS18)	>32.4 (MS18)
8	32.4 (MS18)	32.4 (MS18)	32.4 (MS18)
…	…	…	…

Table 4-2, Deck Geometry Rating by Comparison of ADT (NBI 95)

Deck Geometry Rating Code	Bridge Roadway Width 2 Lanes; 2 Way Traffic					
	ADT (Both Directions)					
	0-100	101-400	401-1000	1001-2000	2001-5000	>5000
9	>9.8	>11.0	>12.2	>13.4	>13.4	>13.4
8	.8	11.0	12.2	13.4	13.4	13.4
7	8.5	9.8	11.0	12.2	13.4	13.4
…	…	…	…	…	…	…

ADT is a critical entry for both appraisals and certainly belongs in the demand vector. Compared with passenger vehicles, heavy trucks have more influence on the performance of the facility for their concentrated higher loads and dimensions. The difference between the Federal and state laws and even adjacent countries cause a discrepancy between the load limit and the real weight of trucks. Overloading a structure will typically generate a higher fatigue rate, which can shorten bridge service life. Another source of pressure comes from the need to comply with the North American Free Trade Agreement. Two variables ADTT and posting (in the management vector) are directly correlated with heavy truck traffic and are also included in the vector.

Among the expected five demand vectors, some variables are not recorded in the NBI data, such as Friction, Visibility, and Control. Some of the variables are viewed as less critical to performance, such as toll and vintage value. Presumably, these variables can be safely removed from the demand side. The last entries of the demand vector keep the traffic on and traffic under related with their load and geometric requirement.

$$D' = \left(f_{ADT}, f_{ADTT}, f_{TruckWeight}, f_{VesselSize}, f_{GovReg} \right) \tag{4.17}$$

4.2.3 Predominant Variables of HWB Performance

From both statistical analysis and literature review, the supply and demand vectors can be synthesized together as the main factors in modeling process. The predominant variables are selected as listed in Table 4-3.

Table 4-3, Significant Variables Selected

Service Supply Variables	Service Demand Variables	Managerial Variables
Bypass Detour Length	Average Daily Traffic	Evaluation Criteria
Functional Class Of Inventory Rating	Average Daily Truck Traffic	Posting
Year Built	Truck Weight	Budgeting
Lanes On Structure	Vessel Size	Maintenance Policy
Lanes Under Structure	Government Regulation	
Design Load		
Approach Roadway Width		
Navigation Vertical Clearance		
Navigation Horizontal Clearance		
Kind of Material Design		
Bridge Roadway Width Curb To Cur		
Minimum Vertical Underclearance		
Minimum Lateral Underclearance		
Deck Condition		
Superstructure Condition		
Substructure Condition		
Method Used To Determine Operating Rating		
Operating Rating		
Method Used To Determine Inventory Rating		
Inventory Rating		
Structural Evaluation		
Deck Geometry		
Bridge Posting		
Waterway Adequacy		
Approach Roadway Alignment		

5. MODEL DEVELOPMENT

To be efficient, the model prototype is divided into 11 modules, each of which can carry out separate functions and interchange information with other modules to form a feedback system. Figure 5-1 illustrates a schematic framework that lays out all modules and their connections by highlighting the exchange of key variables (depicted by arrows in the graphic). Basically, modules at lower levels generate results as inputs for modules at a higher level. For example, the Socioeconomics Module generates values of two variables, *Population* and Local_*Industrial_Output*[1] as the key inputs for the Passenger Traffic Demand Prediction (TDP) Module and the Freight TDP Module. Then, these two modules predict *Average_Daily_Traffic* and *Average_Daily_Truck_Traffic* on the bridge of interest and deliver this information to the Performance Evaluation Module. In the other direction, *Local_Industrial_Output* and information from other modules are fed into the Financing Module which generates *Investment_in_the_LHWBN* (Local Highway Bridge Network). Consequently, this information will be used by other modules until reaching the Performance Evaluation Module.

To illustrate the model's logic, the schematic framework numbers each module relative to the overall model's flow. The following are brief descriptions of these 11 modules:

1. The Socioeconomics Module simulates the evolvement of local population and economic development. Population can be simplified as a self-evolution process with parameters of birth, death, and immigration rates. However, this module emphasizes that the local economics and industrial output rely on the capacity and condition of the local transportation system. The outputs of this module are *Population* and *Local_Industrial_Output* for the Financing Module, the Passenger TDP Module, and the Freight TDP Module.
2. The Government Regulation Module simulates the potential changes of government regulations for both highway traffic and bridge management. This module enumerates two concrete regulations, the truck weight regulation and speed limits regulation for highway traffic. The potential deregulation of truck weight as per the North American Free Trade Agreement (NAFTA) may allow increased weight limits for the trucking industry. Average speed limits may also change along with urban development. As for

[1] Vensim allows long variable names. Except for commonly recognized abbreviations, this model names its variable with full length words or phrases in italics to increase readability.

the potential regulatory changes on highway bridges, this module provides a general process that forecasts future mandatory improvement regulations with dimensions of their frequency and potential costs. The outputs of this module are *Truck_Weight_Regulation, Mandatory_Improvement_of_Bridges, and Speed_limits_ Regulation* for the Passenger TDP Module, the Freight TDP Module, and the Upgrade Module.

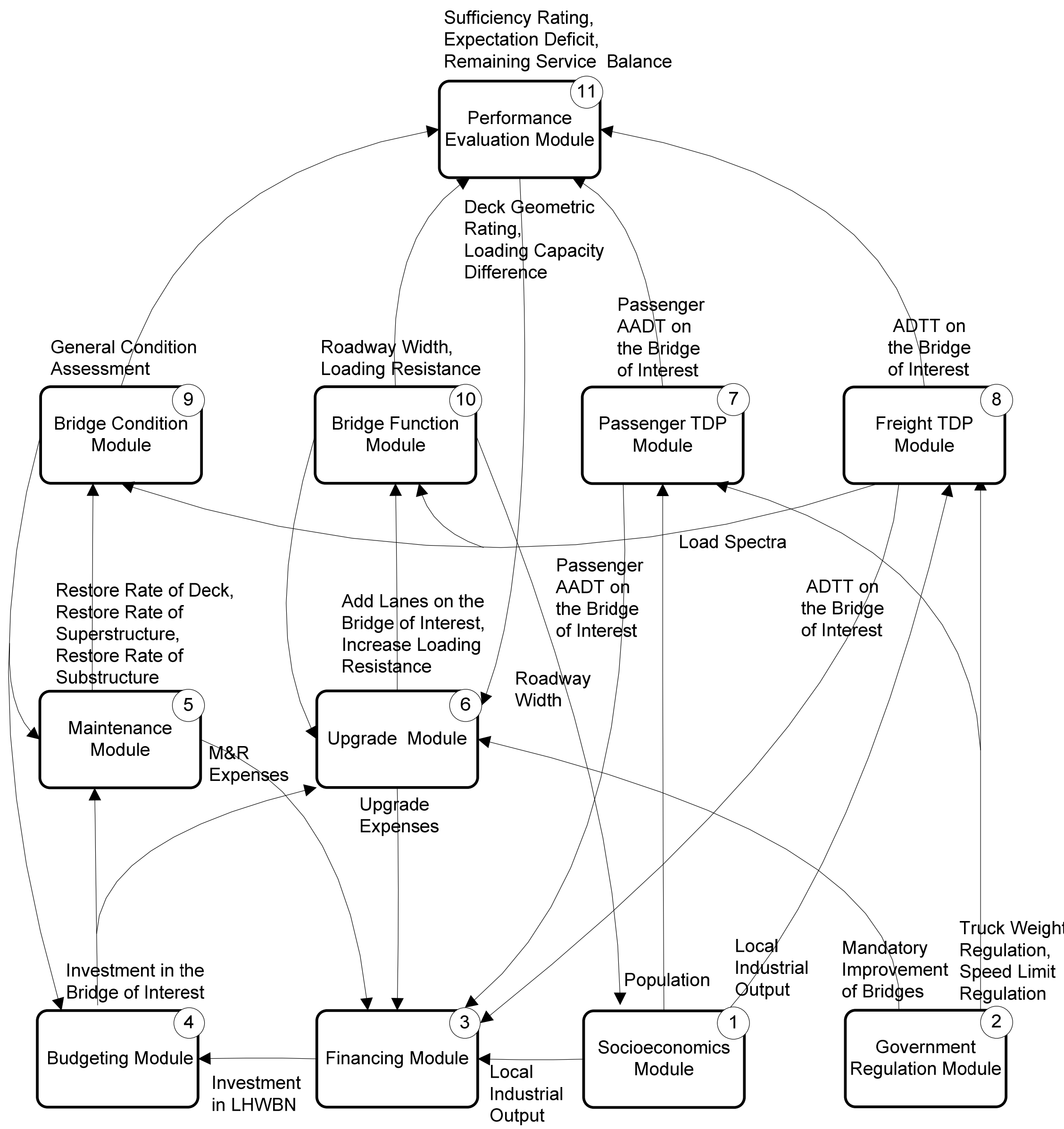


Figure 5-1, Schematic Framework

3. The Financing Module simulates the financing procedure for the LHWBN. This module includes five potential financial resources for highway bridges, i.e. state funds, federal funds, loans, user fees, and dedicated taxes. The federal and state funds provide

the fundamental financial resources for the whole LHWBN. Loans from banks, user fees, or dedicated taxes can be options when there are not sufficient funds. The output of this module is *Investment_in_LHWBN* for the Budgeting Module.

4. The Budgeting Module simulates the budget allocation procedure among the LHWBN. It prioritizes all bridges in the network based on the conditions and replacement costs of bridge components. Then, the bridge of interest receives budgetary allocations as part of *Investment_in_LHWBN.* The output of this module is the *Investment_in_the_ Bridge_of_Interest* for the Maintenance Module and Upgrade Module.

5. The Maintenance Module simulates the decision-making for bridge maintenance and repair (M&R). Preset with certain decision rules, this module generates possible M&R activities by evaluating the current condition of each subsystem and the related available budget. The key parameters are *Aggregate_Condition_Assessment, Investment_in_the_Bridge_of_Interest.* The outputs of this module are *Restoration_ Rate_of_Deck, Restoration_Rate_of_Superstructure,* and *Restoration_Rate_of_ Substructure* for the Bridge Condition Module.

6. The Upgrade Module simulates the decision-making for bridge upgrade. Generally, a highway bridge may be upgraded if its original design has the capacity for future expansion. Either under mandatory requirement or with financial allowance, the bridge of interest may be upgraded if it is more economical than building a new bridge. The key parameters in this module include *Mandatory_Improvement_of_Bridges*, *Investment_in_the_Bridge_of_Interest*, *Roadway_Width*, *Loading_Resistance, Deck_ Geometric_Rating,* and *Loading_Capacity_Difference*. The outputs are *Add_Lanes_ on_the_Bridge_of_Interest* and *Increase_Loading_Resistance* for the Bridge Function Module.

7. The Passenger Traffic Demand Prediction (TDP) Module simulates the passenger traffic flow within the local area. This module generates the passenger traffic flow on the bridge of interest by the Four-Step Method. With a simplified form, this module only requires estimations of the two zones on the ends of the bridge. Three common traffic modes compete for the traffic by utility functions by specifying their travel costs and average travel time. The key output is *AADT_on_the_Bridge_of_Interest* for the Performance Evaluation Module and Financing Module.

8. The Freight TDP Module simulates the freight traffic on the bridge of interest. This module assumes a similar framework as the Passenger TDP Module. There are also

three types of traffic vehicles for the mode choice based on the utility functions calculated by travel costs and time. The key parameter is *Local_Industrial_Output*. The output is *ADTT_on_the_Bridge_of_Interest* for the Performance Evaluation Module and Financing Module.

9. The Bridge Condition Module simulates bridge physical conditions at a subsystem level. This module uses the Markov chain to estimate the deterioration rate of bridge subsystems. Designed as an index, the physical condition of a subsystem drops from the original value by subtracting the deterioration rate. M&R (or upgrade) counteracts deterioration by adding a restoration rate to the index. Since these two proceedings are not equivalent in their frequencies and magnitudes, the physical condition index generally decreases but fluctuates during the bridge life cycle. The outputs of this module are *Aggregate_Condition_Assessment* for the Performance Evaluation Module and the Budgeting Module.

10. The Bridge Function Module simulates the functional aspects of the bridge of interest. It has a simple scheme as a recorder of several critical variables, *Roadway_Width* and *Loading_Resistance,* etc. They are predetermined by the original structure materials and can be improved by the upgrade activities. These variables will be used for the Performance Evaluation Module.

11. The Performance Evaluation Module estimates bridge performance with three measures by gathering information from both bridge condition/function and traffic on the bridge of interest. The first measure is sufficiency rating, which comprehensively reflects the bridge serviceability. The other two measures are designed as performance gaps according to the Infrastructure Performance Theory (Lemer, 1996). The first gap, *Expectation_Deficit*, measures the difference between the expected performance and the current performance. The second gap, *Remaining_Service_Balance*, measures the difference between the current performance and the minimum acceptable performance. To answer the research question, bridge service life can be estimated with these measures from a variety of levels, ranging from a long-term, higher standard of service to a short-term, lower standard of service.

5.1.1 Socioeconomics Module

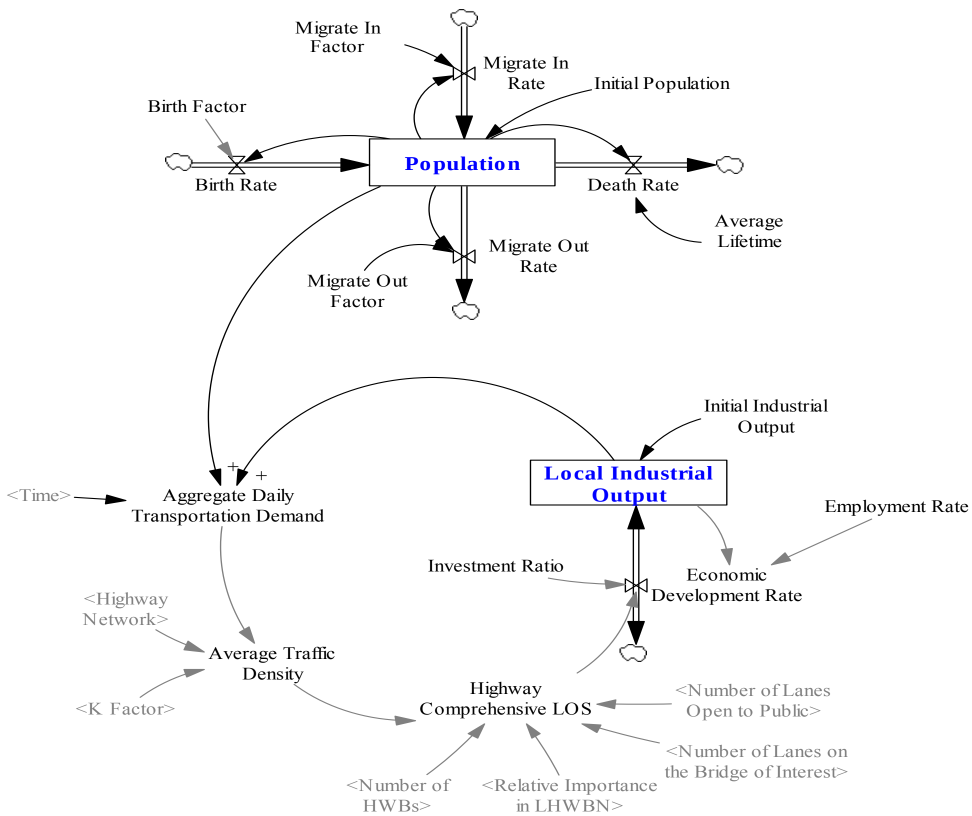


Figure 5-2, Socioeconomics Module[2]

As depicted in Figure 5-2, this module borrows two molecules (block structures) from past work, *Population* (Kim, 1998) and *Local_Industrial_Output* (Dodder et al., 2004). *Population* evolves by natural growth and migration. *Local_Industrial_Output* measures *Economic_Development_Rate* with respect to *Highway_Comprehensive_LOS*.

5.1.2 Government Regulation Module

As an exogenous factor, government regulation has a twofold effect, on traffic demand as well as bridge function and its service supply. On the demand side, regulations are issued to relieve transportation congestion, cut down environmental pollution, or reduce traffic accidents. For example, Transportation Demand Management (TDM) has proven effective where increasing transportation supply seems ineffective or financially infeasible. To increase the passenger carrying capacity of the current system, the local government can encourage motorists to use High Occupancy Vehicle (HOV) lanes, shift their trips out of rush hours, and

[2] Vensim uses angle brackets for shadow variables that are already defined elsewhere in the model or within the module schematic.

take public transportation. For freight traffic, regulations are issued to create uniformity in vehicle size to relieve traffic load on highway systems and to increase safety. These regulations include Longer Combination Vehicles (LCV) and other Truck Size & Weight (TS&W) standards. On the supply side, the mandatory regulations may cover the design load standard, environmental protection, and safety.

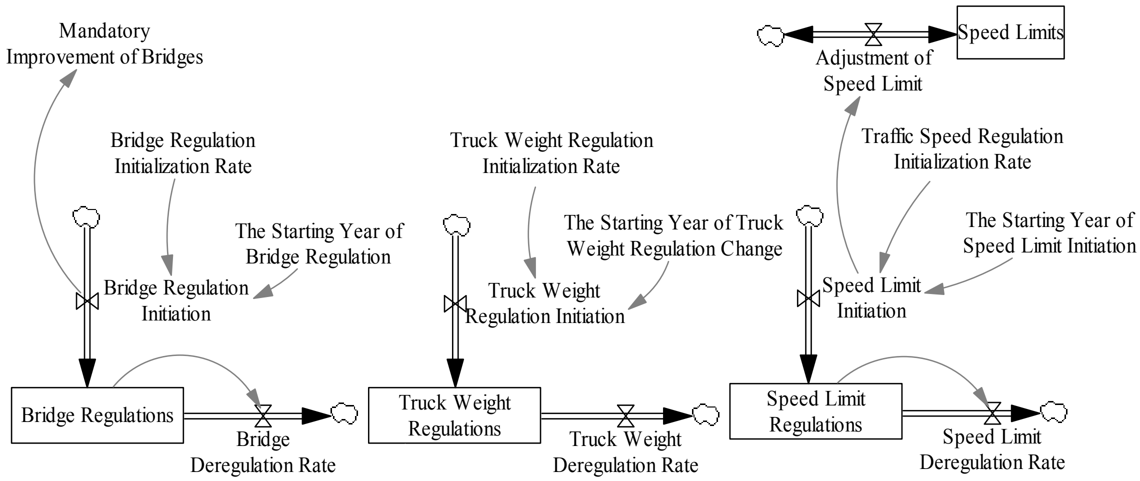


Figure 5-3, Government Regulation Module

A causal loop or government regulation may start from the initialization of a regulation, and then experience a period of time of formalization, and issue a new regulation. Because some of these regulations increase the social benefits by sacrificing economic efficiency, there is also a tendency to rescind these regulations. The module will also consider deregulation for the sake of performance of economic sector. The deregulation process indeed follows the same loop and just counteracts the former regulation process. Figure 5-3 depicts the Government Regulation Module in three parts, regulations on a bridge, regulations on freight traffic and regulations on speed limit. For each type of regulation, a stock variable accumulates all new initialized regulations and releases those deregulated ones. Therefore, this module generates three types of effects, i.e. mandatory improvement of a bridge, truck weight requirement, and speed limits. Measured by frequency and magnitude, this module creates regulation changes as a discrete event inputting to other modules.

5.1.3 Financing Module

Life cycle investment in maintenance and upgrades affords a bridge the necessary resources to counteract deterioration and obsolescence. First, project financing discloses the financial independence of the bridge within its life cycle. Then, budget allocation reveals the insufficiency of the federal and state resources for the infrastructure industry. The financial resources in this module come from five sources: federal funds, state funds, local funds (e.g. dedicated tax), loans from banks, and user fees (Figure 5-4).

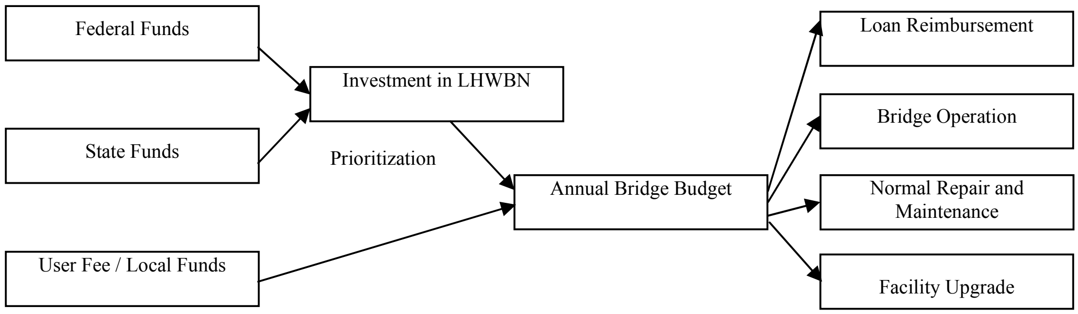


Figure 5-4, Cash Flows to the Bridge

Figure 5-5 illustrates details of the Financing Module. The double lines illustrate the cash flows, showing their directions by the arrows. The single lines link all related parameters with the change rate variables shaped as valves, which control the volumes of the cash flows. A variable with a box is a stock value, which accumulates all changes from the flow-in and flow-out connecting to it. For example, *Investment_in_LHWBN* receives an annual transportation budget from the federal fund and state fund. At the project level, alternative financing resources include loans, user fees and special taxes collected for the bridge. Since this model simulates the remaining service life, it simplifies the project account and bank for reimbursement of the initial construction loan only. Net income will cover maintenance before paying off the loan. The remaining balance of the annual loan payment comes from the *Investment_in_LHWBN.* Generally, state funds are the main resources for the bridge management. Federal funds are strictly limited, with the exception being when the bridge qualifies for the *HWB_Replacement_and_Rehabilitation_Program*.

To estimate *Cumulative_Cost* of different scenarios, the model needs sum the construction cost and all annual costs as the present value. The module first cumulates all annual costs. At year i+1,

$$Cumulative\_Cost_{i+1} = Cumulative\_Cost_i \times (1 + Discount\_Rate) + Annual\_Cost_i \tag{5.1}$$

Where

$$\begin{aligned} &Annual\_Cost_i = Annual\_M\ \&\ R\_Cost_i \\ &+ Annual\_Operating\_Cost_i + Annual\_Upgrade\_Cost_i \end{aligned} \tag{5.2}$$

In the last year N, the module calculates *Cumulative_Cost* by discounting the last year value to the present and adds *Original_Construction_Cost.*

$$Cumulative\_Cost = Cumulative\_Cost_N \times (1 + Discount\_Rate)^{-N} + Construction\_Cost \tag{5.3}$$

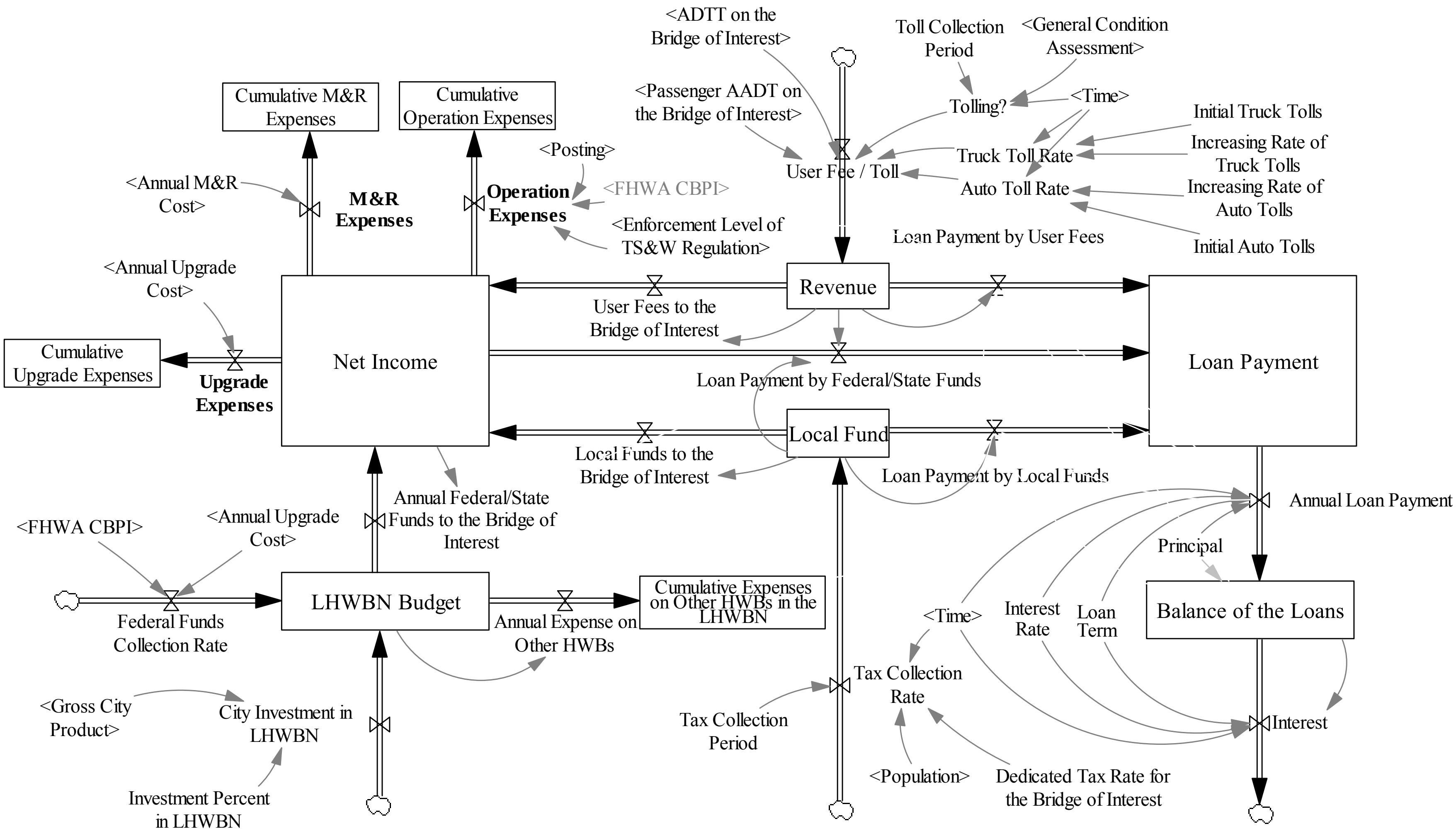


Figure 5-5, Financing Module

5.1.4 Budgeting Module

Federal and state funds reach a budget pool for the LHWBN first. A typical bridge management system (BMS), such as Points, normally prioritizes funds within the budget pool at the bridge component/subsystem level, according to their replacement costs, physical conditions, and *Relative_Importance_in_LHWBN* (Figure 5-6). In the calculation of replacement cost, inflation and other economic factors in the construction industry are comprehensively estimated by the FHWA Composite Bid Price Index (CBPI) (Wilmot and Cheng, 2003).

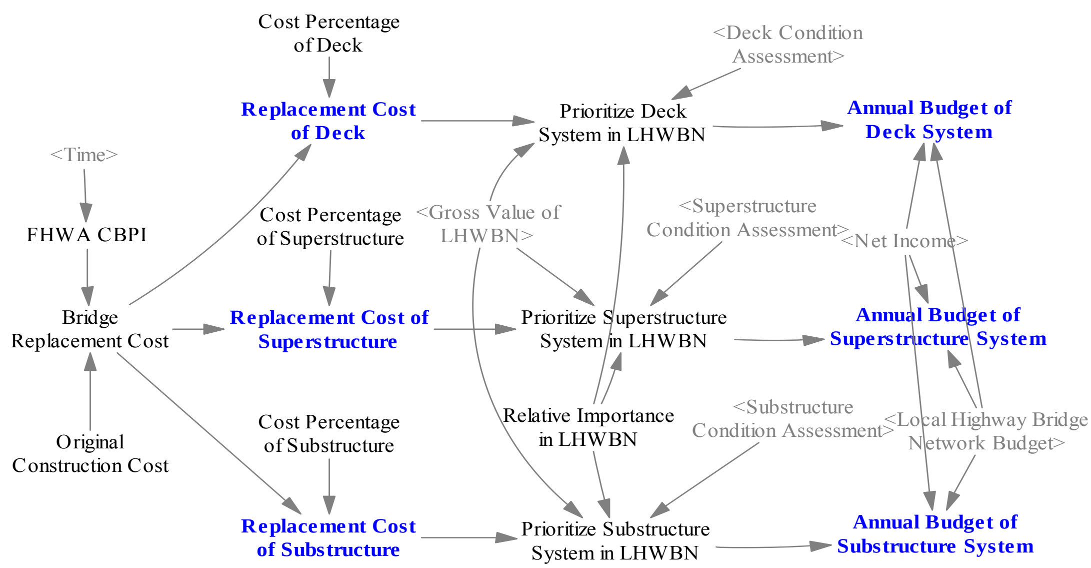


Figure 5-6, Bridge Budget Prioritization

In budget prioritization, the variable *Prioritize_Deck_System_in_LHWBN* is defined as follows. To be clear, all definitions of model variables are framed.

Prioritize Deck System in LHWBN

$$= \text{XIDZ}^{3}(1, \textit{Deck Condition Assessment}, 1) * \textit{Replacement Cost of Deck} / \textit{Gross value of HWBs} * \textit{Relative Importance in LHWBN} \quad (5.4)$$

[3] XIDZ(A,B,X) is a Vensim function, returning A divided by B. If B is zero, then returns X. XIDZ is normally used to express some limit of A/B, as B approaches 0.

5.1.5 Passenger TDP Module

It is desirable to apply an agent model platform in dealing with geometric information at the network level, such as the TRANSIM System. Meanwhile, system dynamics is not designed as a tool in this arena. Hence, a system dynamics model need make an appropriate approximation in applying the four-step method for traffic demand prediction. At the project level, required data collection along with geometric boundary information is saved into two zones, the left bank and right bank linked by the bridge of interest (Figure 5-7).

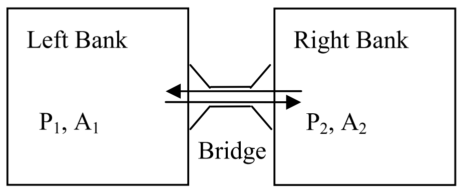


Figure 5-7, Bridge as A Critical Link

In trip generation, passenger trips are balanced between trips generated and attracted. This module does not analyze trip distribution since there are only two zones. Commuters are assumed to choose modes from mass transit, driving alone, and carpooling based on the mode cost and travel time. To avoid geometric information, such as length of links and node distribution, this model defines a LOOKUP[4] function imported directly from agency's transportation planning. Figure 5-8 is the layout of Passenger TDP Module based on a four-step procedure. It is only in step 4 that the researched bridge's capacity is used to compete with other alternatives to calculate the traffic assignment.

[4] LOOKUP in Vensim provides a one dimension table for variable value with a nonlinear relation to the input value.

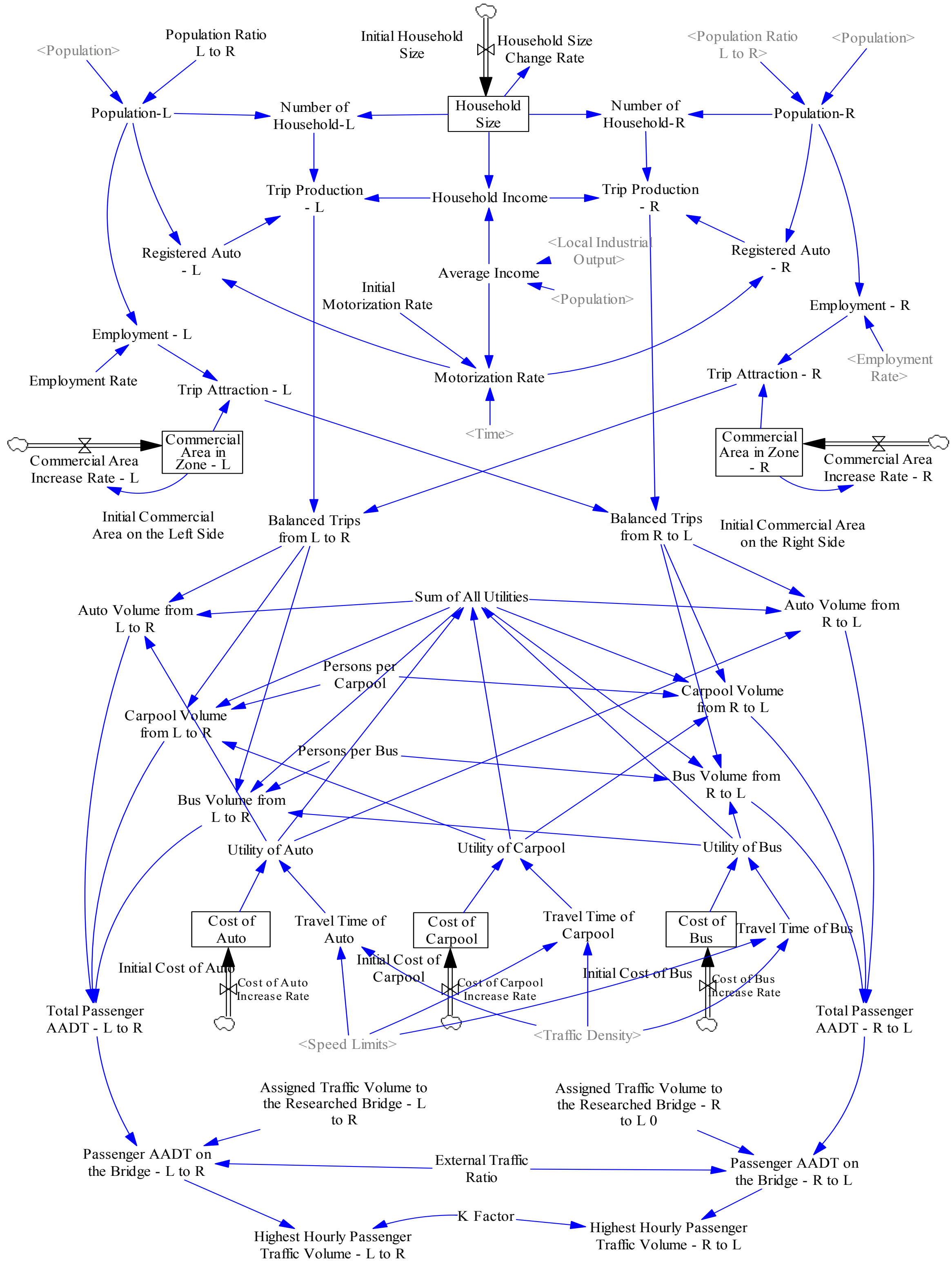


Figure 5-8, Passenger Trip Generation by the Four-Step Method

5.1.6 Freight TDP Module

In the calculation of live load, heavy trucks are a more critical factor than passenger vehicles. Freight traffic imposes a severe fatigue effect on bridges in terms of the number of daily truck traffic as well as these trucks' sizes and weights. Estimating the number of daily freight traffic has a similar framework as the passenger traffic module. The freight traffic generation has a direct relation with *Local_Industrial_Output* generated by the Socioeconomics Module. Mode choice is the competitive result based on a comparison of the attractiveness of each type of trucks of their costs and travel time. Figure 5-9 presents the module structure of traffic demand generation, modal choice, and trip assignment. The module output is the average daily truck traffic on the bridge of interest.

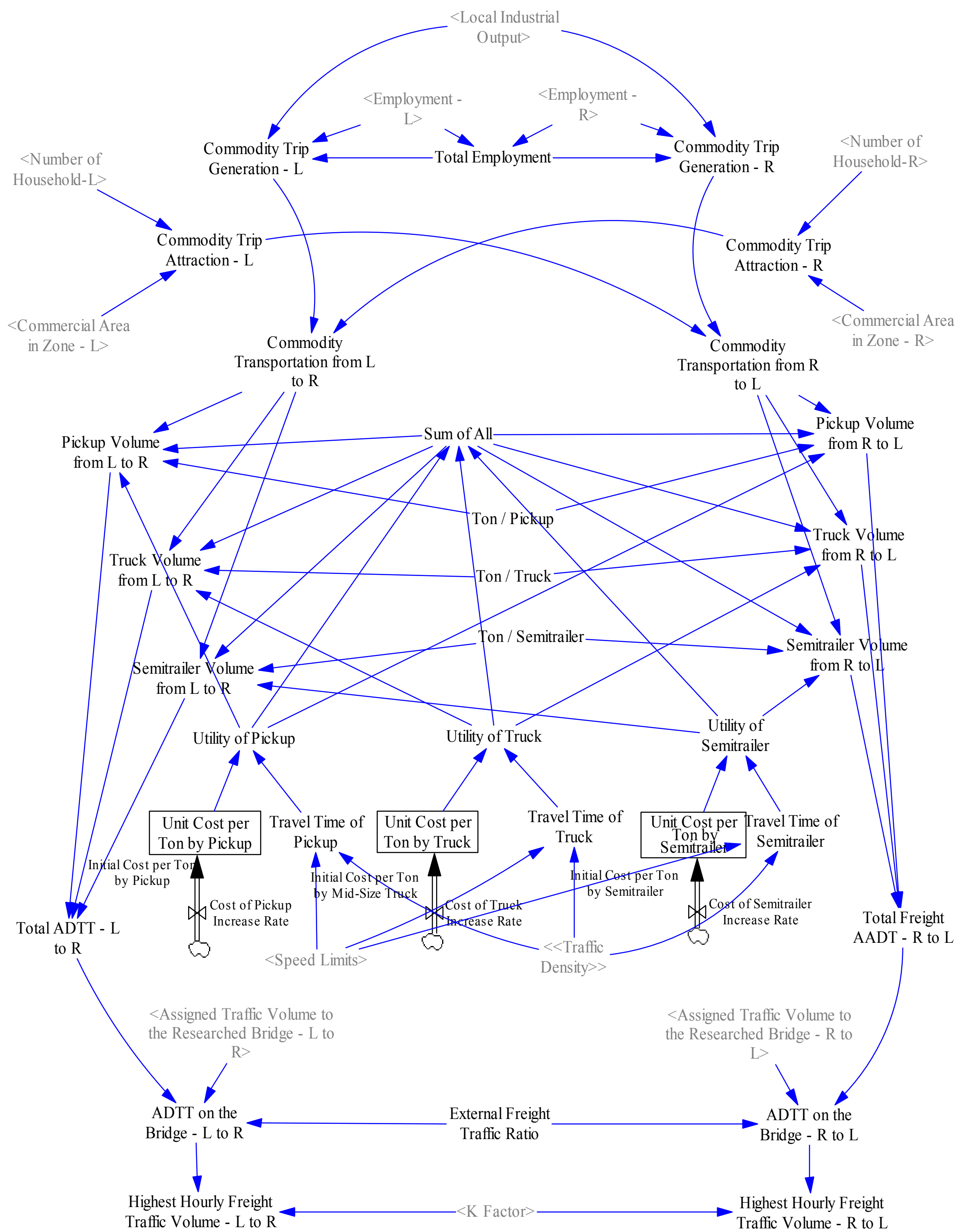


Figure 5-9, Freight TDP by the Four-Step Method

5.1.7 Maintenance Module

Maintenance and repair activities partially or fully restore the physical condition as a positive inflow to a stock variable, physical condition. The restoration rate depends on the current physical condition and type of repair activities conducted on the bridge. In the model setting, bridge maintenance at a lower level is deemed essential, while other needs are subjected to budget limits and may ultimately be deferred to later periods. Thereby, this module determines the compulsory actions to minimize maintenance backlog with available budget before bridge reaching premature replacement or its close.

M&R decision is a function of Condition Assessment, Potential Available Budget, and Threshold of Preventive Maintenance. First, the function calculates the ratio of available budget to the adjusted total construction cost. Then, a M&R Restoration Vector transfer this ratio into an allowable M&R action by a LOOKUP function as shown in Figure 5-10. The input lists the ratio of the available budget to the replacement cost of the subsystem. The output gives the maximum restoration rate within the given budget. This LOOKUP is critical for the decision regarding repair action. Its value should be adjusted by the subsystem materials and structure type.

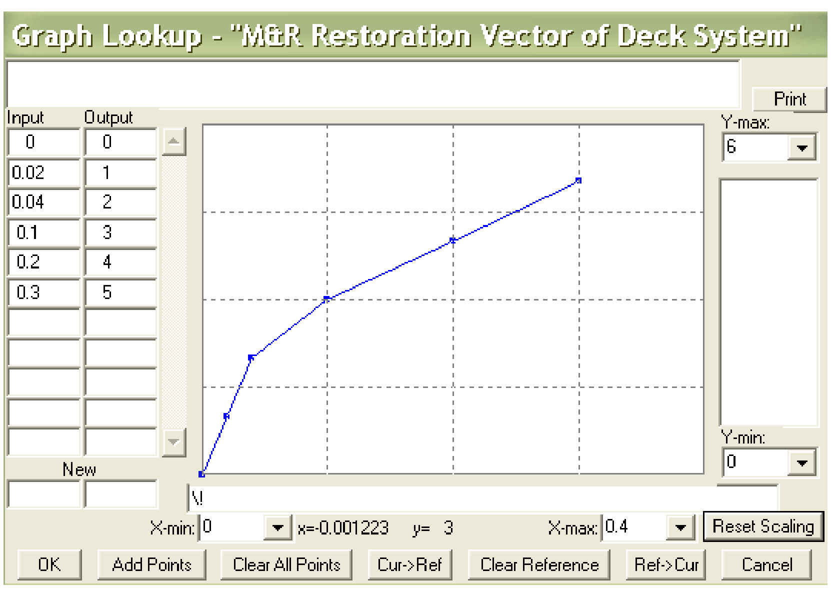


Figure 5-10, M&R Restoration Vector of Deck System

Table 5-1 gives an example of a bridge with a serious condition that may be restored to a better condition based on varying level of investment. To activate M&R action, the available budget must be at least 2% of the subsystem replacement cost to restore bridge condition by 1 degree. The more money available, the higher the restoration rate possible in one repair cycle.

Table 5-1, Effect of M&R Activity with Current Condition Rating

M&R Cost as a Percentage of the Replacement Cost of Deck System	M&R Effect
30%	Restore 5 degrees, which is "VERY GOOD"
20%	Restore 4 degrees, which is "GOOD"
10%	Restore 3 degrees, which is "SATISFACTORY"
4%	Restore 2 degrees, which is "FAIR"
2%	Restore 1 degree, which is "POOR"
	Current condition "SERIOUS"

The maximum *Restoration_Rate_of_Deck* can be the difference between excellent and current condition, which brings the deck system back to the original condition if management replaces all decks. It can take an intermediate value from 1 to the maximum possible improvement value.

Each subsystem has its own deterioration rate. Correspondingly, their M&R frequencies may differ from each other, which necessitates sorting the decision making into three separate module sections. The decking system undergoes direct contact with traffic and experiences a fast deterioration rate. Superstructure ranks in second place in rate of deterioration and substructure normally can hold a relative steady condition thanks to a normally high design safety factor. This module will first evaluate the possibility of replacing the decking system. By comparing with the *Threshold_of_Preventive_Maintenance*, the module should tell whether it is possible to repair the deck by examining a comparison between part or whole subsystem replacement cost and the annual available budget. Instead of the whole bridge, each subsystem will compete with other components for a portion of budget at a network level. Figure 5-11 illustrates a module section of deck maintenance.

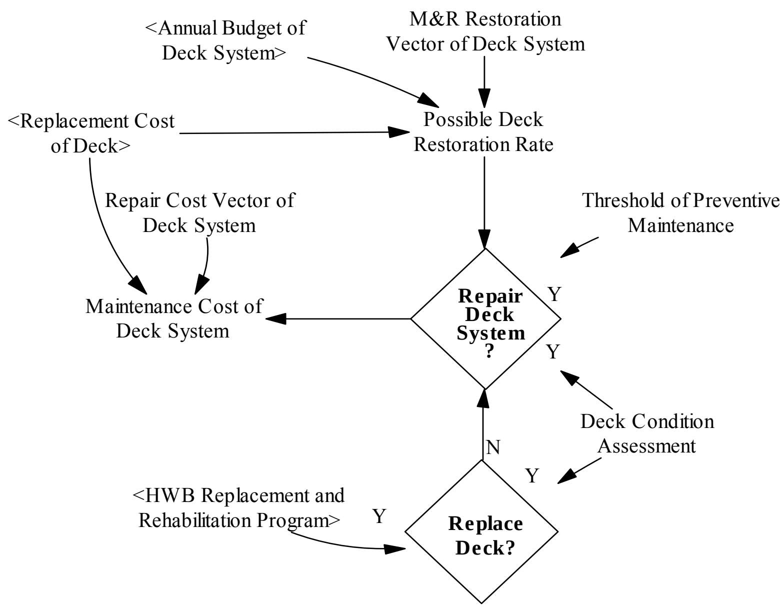


Figure 5-11, Deck Subsystem Maintenance Section

The effect of maintenance depends on the subsystem condition, budget, and anticipated preventive maintenance during the period of operation. For example, *Replace_Deck_System* is evaluated first for the possibility of replacement.

Replace Deck System?
= IF THEN ELSE
(
Deck Condition Assessment<=2:AND:*HWB Replacement and Rehabilitation Program*=1,
1,
0
) (5.5)

If it is not possible to replace the deck, this module executes *Repair Deck System* to check how much of the original condition could be restored by repairing the deck.

Repair Deck System?
= IF THEN ELSE
(
"*Replace Deck?*"=0:AND:*Possible Deck Restoration Rate*>=1:AND:*Deck Condition Assessment*<=*Threshold of Preventive Maintenance*,
Possible Deck Restoration Rate ,
0
) (5.6)

Superstructure and substructure subsystems are model similarly. The Maintenance Module examines how management deals with evaluation criteria and helps to generate decisions. To objectively predict the service life of a given bridge, these M&R activities should follow the normal practice of the bridge agency.

5.1.8 Upgrade Module

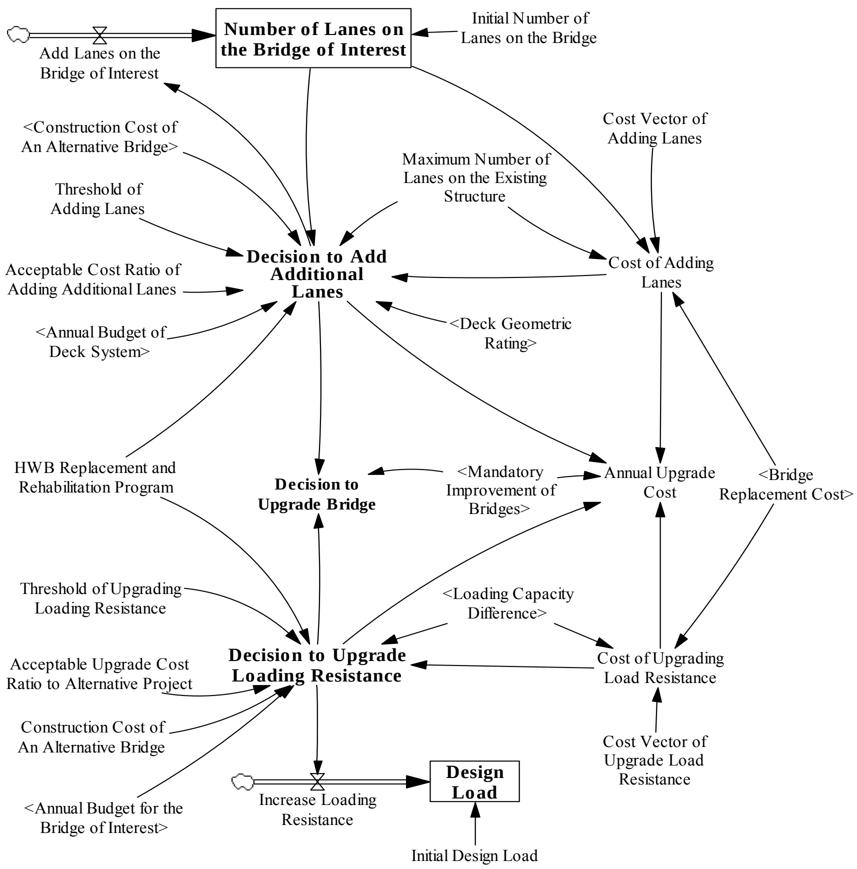


Figure 5-12, Bridge Update Decision Module

A few bridges were designed initially with a view to future expansion, such as the George Washington Suspension Bridge, designed to accommodate an extra deck, and the Salazar Bridge, designed to have two train tracks added (Buckland, 2002). In many cases, strengthening and widening may not be economical compared to replacement, especially for those bridges on the primary highways (TRB, 1990). Designed to bring deficient facilities into compliance with updated codes, regulations, and traffic demand, the Upgrade Module does not intend to relieve current situation of deficient bridges widely existing.

Thresholds of upgrading bridge loading capacity and expanding number of lanes play critical roles in bridge upgrade. It is not possible to place an upgrade order without meeting all these standards first. Pooled together, they successfully tell whether further recapitalization of an existing asset is desirable or not. They vary to account for the range of values that may be acceptable to a given organization. For instance, the U.S. Army's Assistant Chief of Staff for Installation Management establishes management control points for the recapitalization of Army facilities at 50% of the replacement value of a building (Wooldridge, 2002). Model can adjust the related acceptable replacement ratio to such percentage as well.

Upgrading the bridge function is separated from general M&R activities. Upgrade activities provides an option for responding to changes in technologies, regulations, and user values, which in whole are indicative of bridge obsolescence and capitalized in monetary values. Figure 5-12 illustrates two types of upgrade actions for a bridge, adding lanes and increasing load resistance. Similar to the Maintenance Module, a possible upgrade depends on the available budget as well as demands indicators, such as *Deck_Geometric_Rating* and *Loading_Capacity_Difference*. In addition, an alternative project should be included by setting thresholds of *Acceptable_Cost_Ratio_of_Adding_Additional_Lanes, Acceptable_ Upgrade_Cost_Ratio_to_Alternative_Project* as a percentage of these upgrade activities to a new bridge.

When technically practical and economically feasible, a bridge upgrade should attempt to improve widths to match, or provide an improved degree of consistency with the approach roadway width. However, rehabilitation widths not matching the approach roadway are not considered non-standard unless they do not meet the minimum requirement. To add more lanes or increase the loading resistance, the related cost should be both under the budget limit and meet economic requirements relative to an alternative project. For example, improving bridge loading capacity to meet an updated freight vehicle load limit, Moses (1989) estimated relative costs for new bridges by the design load (Table 5-2).

Table 5-2, Relative Costs of Bridge Upgrade (Moses, 1989)

Bridge Type	**Upgrade from HS-20 to HS-25 (%)**	**Upgrade from HS-20 to HS-30 (%)**
Slabs	105%	110%
T-beam	108%	116%
Precast I-beam	103%	106%
Steel girder	106%	112%

In the module, *Construction_Cost_of_an_Alternative_Bridge* requires the bridge engineer's estimation as an input variable for the convenience of scenario analysis in the related GUI.

Decision to Add Additional Lanes

= IF THEN ELSE (

Threshold to Add Lanes>=*Deck Geometric Rating*

:AND:

Acceptable Cost Ratio of Adding Additional Lanes>*Cost of Adding Lanes*/*Construction Cost of An Alternative Bridge*

:AND: (5.7)

Cost of Adding Lanes<=(*Budget of Deck System* +*HWB Replacement and Rehabilitation Program***Cost of Adding Lanes*),

min(2,*Maximum Number of Lanes on the Existing Structure*-*Number of Lanes on the Bridge*),

0

)

Decision to Upgrade Loading Resistance

= IF THEN ELSE (

Threshold to Upgrade Loading Resistance<Loading capacity difference

:AND:

Acceptable Upgrade Cost Ratio to Alternative Project>Cost of Upgrading Loading Resistance/Construction Cost of An Alternative Bridge (5.8)

:AND:

Cost of Upgrading Loading Resistance<=(*Budget of Deck System +HWB Replacement and Rehabilitation Program*Cost of Upgrading Loading Resistance*),

Loading capacity difference,

0

)

This module allows the decision maker to adopt a different management policy by setting thresholds of preventive maintenance, bridge upgrade as well as usage allowance under limited resources. It plays a central role on bridge's performance and service life on the service supply side. From the performance aspect, upgrading a bridge by increasing load capacity or widening deck does alleviate problems current related to traffic demand.

5.1.9 Bridge Condition Module

Condition assessment is used to benchmark the relative condition of facilities, to trigger maintenance and repair events, and to signal the current state of serviceability and adequacy (Wooldridge, 2002). This module simulates deck condition, superstructure condition, and substructure condition with separate deterioration transition matrices to measure the pace of strength being lost annually. The Markov transition matrixes are estimated either from the historic data or under typical usage rate and environment. Because this model uses 1 year as the steps which is normally shorter than the transition period between two physical states, the matrix can assume a semi diagonal form with continuous states.

$$P = \begin{bmatrix} p_9 & 1-p_9 & 0 & \cdots & 0 \\ 0 & p_8 & 1-p_8 & \cdots & 0 \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ 0 & 0 & \cdots & p_1 & 1-p_1 \\ 0 & 0 & 0 & \cdots & 1.0 \end{bmatrix} \tag{5.9}$$

In Equation(5.9), 1-Pi (i=0, …, 9) is the probability of shifting from the current state to a lower one. In Vensim, the transition matrix is replaced with a LOOKUP function (Figure 5-13). The input is current subsystem condition. The output is the probability, Pi, of which the subsystem keeps the same level.

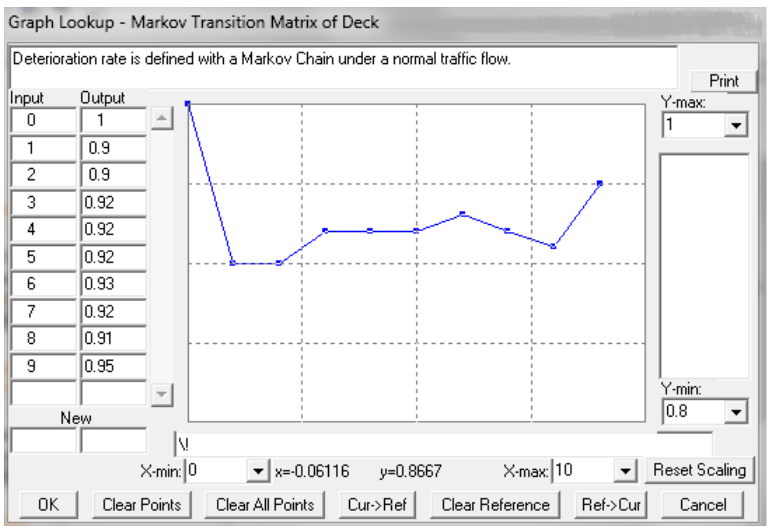


Figure 5-13, Markov Chain Matrix as a LOOKUP in the System Dynamics Model

Since the transition matrix only supplies the deterioration probabilities under common usage, it is necessary to adjust the probability to account for the fatigue rate, which is a result of loading distribution on the bridge. Therefore, the Markov chain herein is not stationary, so it requires developing a nonstationary transition matrix from the given transition matrix by taking account of the relevant changing factors, i.e. freight traffic in the model. Within the total remaining fatigue cycles, the probability of deterioration is assumed independent of the probability of fatigue damage.

$$p'_i = p_i \cdot (1-q) \tag{5.10}$$

Where p'_i is the conditional probability of a nonstationary transition matrix, q is the probability of relative fatigue damage caused by the increase of truck traffic against the past. The probability of deteriorating to a lower state in the following year is $1-p'_i = 1-p_i \cdot (1-q)$.

Deterioration_Rate_of_Deck is calculated by inverse transformation with a RANDOM UNIFORM[5] (lower bound, upper bound, seed) function in Vensim.

Deterioration Rate of Deck

= IF THEN ELSE (

IF THEN ELSE(RANDOM UNIFORM(0, 1 , 3)<(1-Markov Transition Matrix of Deck(Physical Condition of Deck)*(1-Annual Bridge Fatigue Damage)),

1 ,

0

) (5.11)

Physical Condition of Deck is a function of *Deterioration Rate of Deck* and *Restoration Rate of Deck.* The initial physical condition of the deck is set with a default value, 9, expressing an excellent condition.

Physical Condition of Deck

= INTEG[6] (Restoration Rate of Deck-Deterioration Rate of Deck, 9) (5.12)

In measuring traffic demand, the unit vehicle weight or practical maximum gross vehicle weight (PMGVW) is critical for loading spectra. The federal bridge formula restricts the maximum weight allowed on any group of consecutive axles based on the number of axles in the group and the distance from the first to the last axle. There are two bridge

[5] RANDOM UNIFORM (min, max, seed) is a Vensim function which generates a stream with a uniform distribution.

[6] INTEG (rate, initial value) is a Vensim function to define a stock variable, returns the integral of the rate. The initial value is the value of the variable on the left-hand side of the equation at the start of the simulation.

responses in evaluating the effect of deterioration: corrosion and fatigue. Corrosion refers to natural breaking down due to chemical reactions with the environment, while fatigue measures the cumulative damage by long term loading cycles.

Figure 5-14 illustrates a model section with causal relations among freight traffic, regulation and fatigue rate.

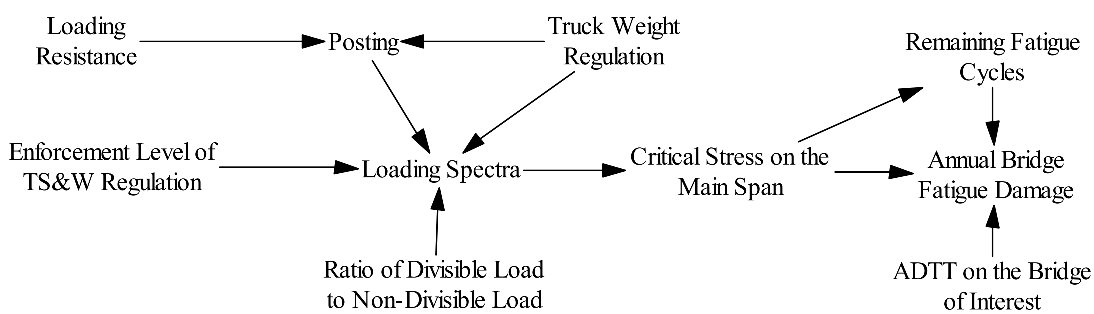


Figure 5-14, Freight Traffic and Fatigue Damage Rate

A change in truck weight limits will lead to a change in truck-weight frequency distributions, and thus it is important to accurately predict the resulting truck load spectra in order to estimate the remaining bridge service life. There are two critical variables defined in this model section, *Loading_Spectra* and *Bridge_Fatigue_Rate.* Load and fatigue evaluations are specially designated to certain types of bridges. Commonly used references include *Guide Specifications for Fatigue Evaluation of Existing Steel Bridges* (AASHTO, 1990), *LRFD Bridge Design Specifications* (AASHTO, 1998). Cohen *et al.* (2003) also emphasized the difference between divisible and indivisible commodities and related truck load shift. Chang (2007) evaluated load spectra by using the top 20% of trucks with site-specific data according to the new LRFR standard (AASHTO, 2003). He also introduced the level of enforcement into his analyses to assess the effect of illegally overloaded trucks. Both of these works pointed out that 5-axle trucks are more statistically significant to bridge deterioration than other types of trucks.

As per Chotickai and Bowman (2006), Weight in Motion (WIM) sensors have been extensively used in recent years by highway and bridge engineers to monitor truck traffic. A WIM system can be used to measure vehicle gross weights, axle weights, and axle spacings of the actual truck traffic. In contrast to the difficulties posed in the subjective measure of bridge physical condition, this module assumes that the agency is able to collect effective data of freight traffic for evaluating bridge loading spectra and fatigue rate.

To simplify the modeling procedure, *Loading_Spectra* is defined as a function of *TS&W_Regulation* (here, it refers to the federal truck weight limit), *Ratio_of_Divisible_Load_to_Non-Divisible_Load,* and *Enforcement_of_TS&W_Regulation.* Enforcement level is defined as the mean truck weight in Chang and Garvin's (2006) work. For example, if a rating truck has a mean weight of 89.9 kips and a standard deviation of 16.1 kips with a sample size of 7,035 trucks, then a presumed enforcement level of 110 kips would require the redistribution of 581 trucks, or 8.2% of the sample. USDOT (2000) estimates that there were an average of 0.6% of trucks overloaded during 1985 to 1995. Hence, enforcement level in this model is simplified as a factorial to calculate the percentage decided by the bridge manager. The higher the enforcement level, the more trucks are under control and more operation expenses are incurred.

Given the gross vehicle weight (GVW) histogram, fatigue analysis usually calculates the effective gross weight of fatigue truck (Zhou, 2006). By using LRFD, the worst case that has the highest loading factor is identified as the side by side situation (NCHRP, 2003), where the live load factor is defined as

$$\gamma_L = 1.8\frac{2W^* + 1.41 t_{ADTT}\sigma^*}{240} \tag{5.13}$$

Where W^* is the average truck weight for the top 20 percent of the truck weight histogram (TWH), σ^* is the standard deviation of the top 20 percent of the TWH, t_{ADTT} is a factor depending on the annual average daily truck at the site to quantify the likelihood of having heavy trucks side by side on the bridge.

Comparatively, the live load factor is defined as follows based on LRFR with site-specific data (Chang and Garvin, 2006).

$$\gamma_L = 1.8\frac{W_T}{240}\times\frac{72}{W} \tag{5.14}$$

Where $W_T = R_T + A_T = 2(W^* + t_{ADTT}\sigma^*)$, R_T is the alongside truck weight, A_T is the rating truck weight, W^* and σ^* have same definitions as before, W is the nominal weight of rating vehicle (legal truck or permit truck). Equation (5.14) falls in a range of 2.00 to 3.10 for legal loads under 80kips, which is relatively higher than LRFD method.

Thus, *Loading_Spectra* (Live Load Factor) is defined as a function of legal load or allowable load on the bridge, *Enforcement_Level_of_TS&W_Regulation*.

***Loading Spectra* (*Live Load Factor*)** = (1.33-"*Enforcement Level of TS&W Regulation*"/3)*1.8*(*Along Side Truck Weight + Rating Truck Weight*)*72/240/"*TS&W Regulation*"	(5.15)

The fatigue damage accumulates the repeated stress from each individual truck passage. A linear damage accumulation law as per the Palmgren-Miner's hypothesis is usually assumed (Chotickai and Bowman, 2006, NCHRP, 2003).

$$D = \sum_{i=1}^{k} \Delta D_i \tag{5.16}$$

Where D is accumulated fatigue damage, ΔD is the damage caused by each stress cycle. As a function of *Loading_Spectra* and *ADTT_on_the_Bridge_of_Interest*, *Bridge_Fatigue_Rate* is an important variable to calculate the stepwise deterioration for each subsystem.

Figure 5-15 shows the relationship between the number of load cycles and the magnitude of stress range (S_r) for various types of details.

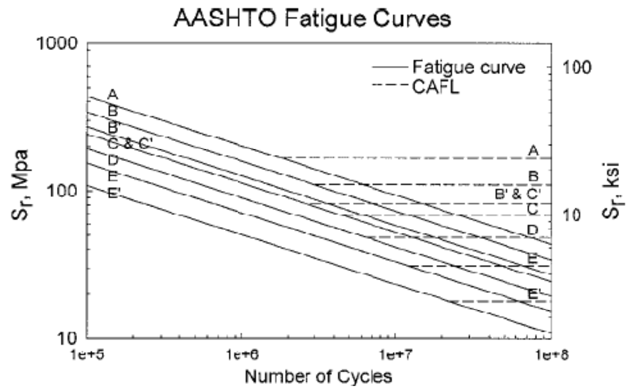


Figure 5-15, AASHTO Fatigue Strength S-N Curves (Zhou, 2006)

S-N curves build the relationship between annual fatigue damage and remaining fatigue life. Instead of using strain gages, the model need identify stress level by analyzing the effect under given *Loading_Spectra* to quantify the influence of freight traffic and related nonphysical factors. A critical element approach as used in Rowatt and Spanos (1998) provides a rational means for addressing the complex cumulative damage process subjected to fatigue loading based on residual strength degradation. Relatively, the subcritical element's failure causes a redistribution of stress within the structure but does not cause failure of the whole system on a global level. The default value is set by the negative moment on the main span of the bridge, which requires adjustment for the bridge of interest.

Annual_Bridge_Fatigue_Damage is defined as a function of *Critical_Stress_on_the_ Main_Span*, *ADTT_on_the_Bridge*, and a LOOKUP function *Remaing_Fatigue_Cycles*. The LOOKUP returns total loading cycles given the stress level based on the S-N curves.

Annual Bridge Fatigue Damage
= *Critical Stress on the Main Span* * *ADTT on the Bridge* * 365 / *Remaining Fatigue Cycles* (*Critical Stress on the Main Span*) (5.17)

The physical condition of a bridge structure describes its in-place state compared to its as-built condition. Figure 5-16 depicts that the condition of each system connects with a deterioration process and restoration process. The stepwise deterioration assumes a deteriorating speed under a given load magnitude and frequency. Simultaneously, the stepwise restoration counteracts such a deterioration process with appropriate maintenance or upgrades. As a stock variable, physical condition is either reduced by the rate of stepwise deterioration or increased by the rate of stepwise restoration. In the model, these rates are directly named as restoration rates or deterioration rates.

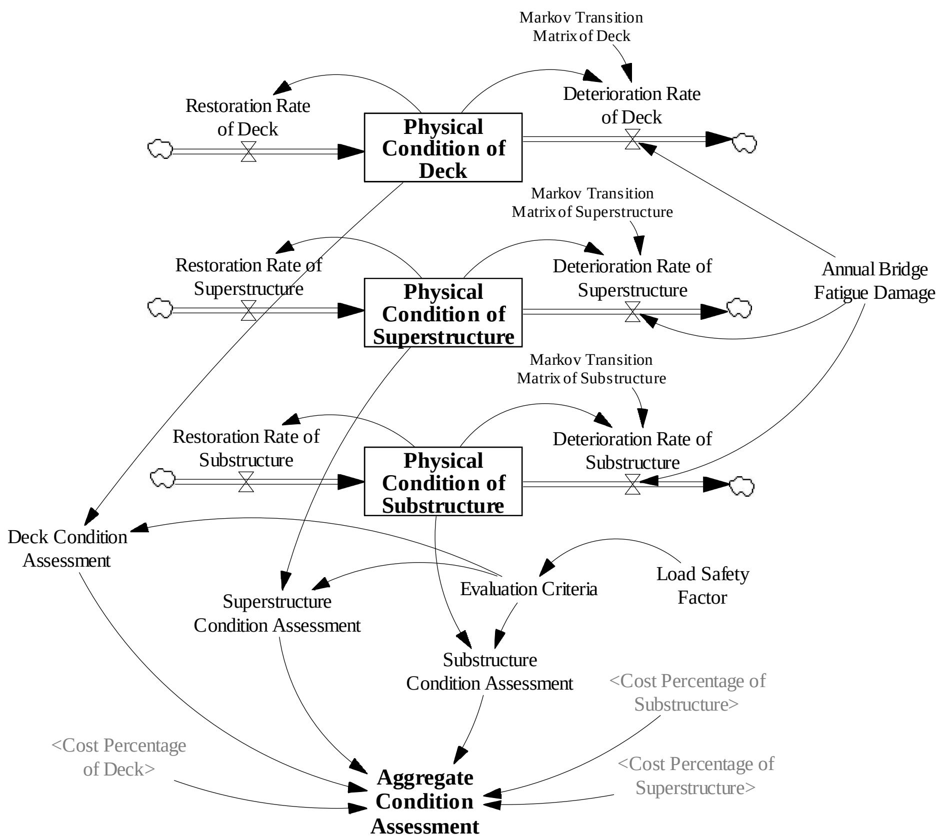


Figure 5-16, Bridge Condition Module

The *Recording and Coding Guide* (FHWA, 1995b) generally emphasizes that condition rating of the bridge subsystems should be independent of each other, since the distinction between these subsystems may not always be clear. Therefore, the conditions of these subsystems are assessed separately for decision making on MR&R activities and budget allocation. In addition, an overall condition assessment value is determined, *Aggregate_Condition_Assessment*, which is the weighted average of the subsystem condition ratings. This value is a proxy for the overall condition of the bridge and provides a single indicator of the physical state. However, this value is typically presented in tandem with the subsystem ratings due to the challenges associated with interpreting a single value.

5.1.10 Bridge Function Module

A bridge function is an attribute of the bridge's designed capacities to satisfy the application purposes of the bridge to its users. Generally, it is fixed by the original design and experiences a process of obsolescence caused by new technology, regulation, or user values. For highway bridges, bridge functions include having capacity to meet demands of AADT, vehicle weight, vehicle geometry, safety, comfortableness, and so on. Administration mainly concerns crossing ability on the bridge as part of the highway system. Additionally, bridge underclearance is also programmed to include the possibility of a good reason to replace a bridge. Hence, the Bridge Function Module here is an aggregate of *Number_of_Lanes_ Open_to_Public*, *Bridge_Roadway_Width*, *Loading_Resistance*, *Vertical_Underclearance,* and *Horizontal_Underclearance.*

Similarly to the situation in which maintenance can restore bridge conditions, upgrade activity counteract obsolescence by improving bridge functions. This model mainly traces the potential of additional lanes, higher loading resistance and their influences on bridge functions. These function indicators are sparsely embedded into other modules as listed in Figure 5-17. It should be notified that *Number_of_Lanes_on_the_Bridge* and *Design_Load* can be updated from the initial designed values by the means of upgrade activities if the original design allows. Expanding underclearance is generally not cost efficient. Hence, the model keeps *Horizontal_Underclearance* and *Vertical_Underclearance* as constants.

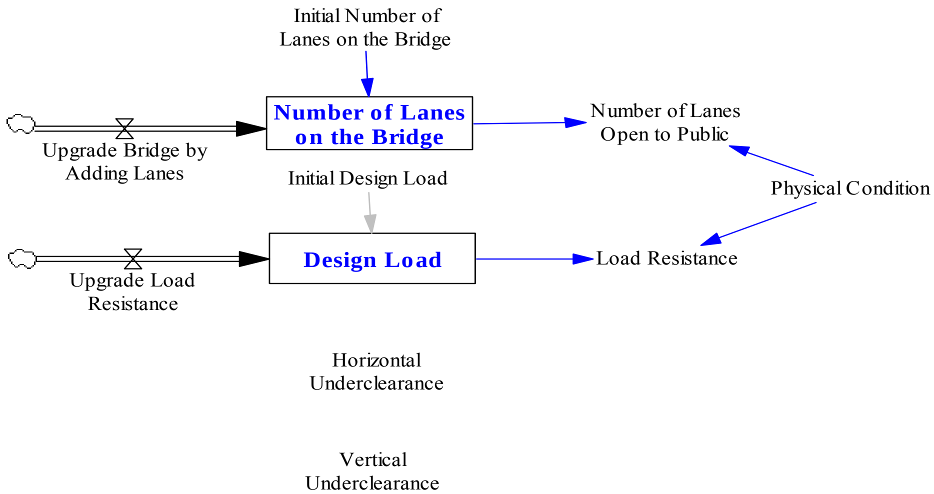


Figure 5-17, Highway Bridge Function Indicators[7]

5.1.11 Performance Evaluation Module

This module will evaluate bridge performance in terms of the Sufficiency Rating and two gaps. The sufficiency rating results a numeric value (0-100) indicating a bridge's sufficiency by calculating *Structural_Adequacy_and_Safety*, *Serviceability_and_ Functional_Obsolescence*, *Essentiality_for_Public_Use*, and *Special_Reductions* (Figure 5-18). The model calculates the sufficiency rating as a comprehensive performance criterion, where a bridge is evaluated as "adequate" with a rating value from 80 to 100, "tolerate" with a rating value from 70-79, "inadequate" with a rating value from 50-69, or "critical" with a rating lower than 59. By feeding NBI data into the model, it is convenient to calculate in which status a bridge falls.

[7] Set as constants, *Horizontal Underclearance, Vertical Underclearance* are individually listed

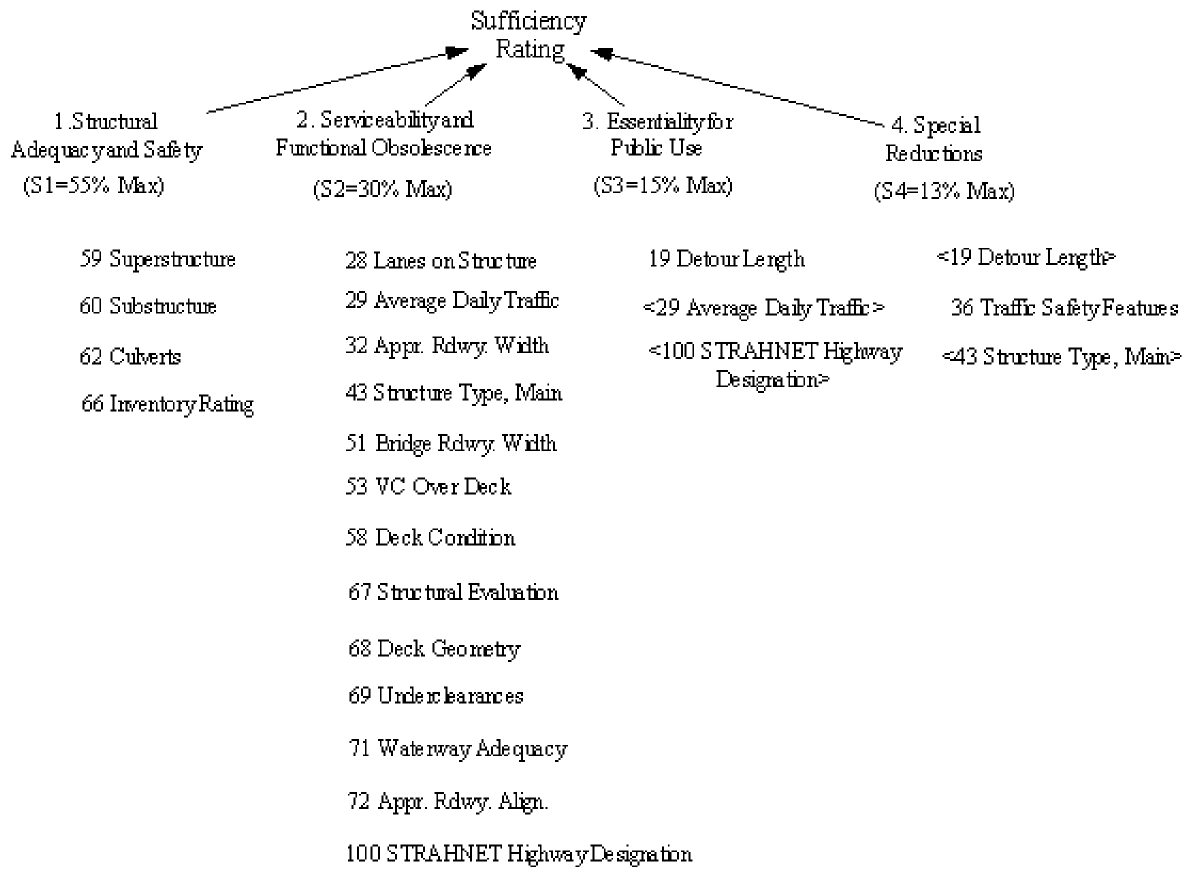


Figure 5-18, Sufficiency Rating

However, there are two types of deficient bridges, structurally deficient and functionally obsolete. A structurally deficient bridge, as defined by the Federal Highway Administration, is one that (1) has been restricted to light vehicles only, (2) is closed, or (3) requires immediate rehabilitation to remain open.

A bridge may be a good candidate for replacement with limited underclearance. Hence, it is necessary to highlight functional aspects of bridge performance in terms of loading limit, deck geometry, and underclearance. The first functional criterion is loading limit, which is measured as the difference between design load and load requirement. The second functional criterion is deck geometry as a function of ADT (both directions) and deck width (curb to curb). Table 5-3 gives the deck geometry rating with different ADT under a given deck width (meter).

Table 5-3, Deck Geometric Rating (FHWA, 1995b)

Deck Geometry Rating Code	Bridge Roadway Width 2 Lanes; 2 Way Traffic						Bridge Roadway Width 1 Lane; 2-Way Traffic	
	ADT (Both Directions)						ADT (Both Directions)	
	0-100	101-400	401-1000	1001-2000	2001-5000	>5000	0-100	>100
9	>9.8	>11.0	>12.2	>13.4	>13.4	>13.4	-	-
8	9.8	11.0	12.2	13.4	13.4	13.4	<4.9	-
7	8.5	9.8	11.0	12.2	13.4	13.4	4.6	-
6	7.3	8.5	9.1	10.4	12.2	13.4	4.3	-
5	6.1	7.3	7.9	8.5	10.4	11.6	4.0	-
4	5.5	6.1	6.7	7.3	8.5	9.8	3.7	-
3	4.9	5.5	6.1	6.7	7.9	9.1	3.4	<4.9
2	Any width less than required for a rating code of 3 and structure is open.							
0	Bridge Closed							

Figure 5-19 illustrates the module for functional obsolescence and underscores two gaps, *Remaining_Service_Balance* and *Expectation_Deficit* in measuring bridge performance from different aspects according to the Infrastructure Performance Theory.

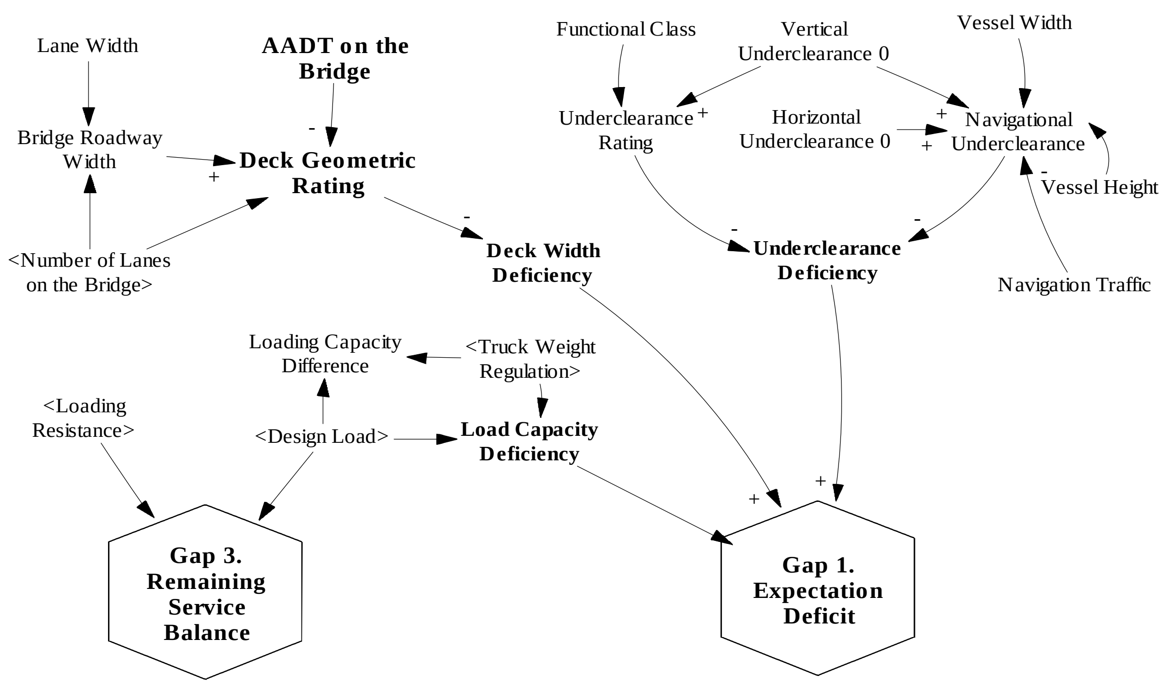


Figure 5-19, Performance Evaluation Module

In simple form, the definitions of the two gaps are designed as an additive index or a relative deficiency.

Gap 1. Expectation Deficit = (*Deck Width Deficiency* + *Load Capacity Deficiency* +*Underclearance Deficiency*)/3	(5.18)

If the design load has a 100% safety margin, the difference between the current *Loading Resistance* under deterioration and half of the *Design Load* measures the remaining load safety margin. Conforming to former indexes, *Gap 3.Remaining Service Balance* is adjusted as a dimensionless figure from 0 to 9.

Gap 3. Remaining Service Balance = 9*(*Loading Resistance*- *Design Load*/2)/*Design Load*	(5.19)

6. MODEL VALIDATION, VERIFICATION, AND CALIBRATION

To obtain a useful model, the main challenge is to connect the realities of the system and industry practice with quantitative descriptions and suitable simplification. Model validation and verification (V&V) has received attention since the first introduction of system dynamics. Forrester (1961) pointed out that a system dynamics model should behave reasonably and be defensible in its details, such as dimensional consistency. Coyle and Excelby (2000) considered that the model boundary should be appropriate and highlighted that a system dynamics model should be correlated with real management practice. Sterman (2000) underlined the use of statistical techniques to check model behavior with historical data.

6.1 Validation and Verification Methods

Simulation is an artificial procedure of human observation and repeated modeling of natural events or social activities. However, limited by the modeler's capabilities, there is not a perfect duplication of the subject itself. Improper model structure and parameters prevent simulation models from accurately mimicking reality, limiting their ability to aid decision-making. Future estimates predicted by the use of an incomplete model are inaccurate representations of the future behavior of the object system. To reach a satisfactory credibility, modelers need to apply V&V to modify the model structure and parameter values, and to test the correspondence between the modeling results and reality. These processes of simulation are not auxiliary and deserve great attention.

Grady (1998) thought V&V as a universal approach to guaranteeing that a complex system design will meet its demands in terms of least cost, best quality, and optimal performance. In his definitions, validation means a process carried out to demonstrate that one or more requirements are clearly understood and that it is possible to satisfy them through design work within the current technological state of the art; verification means a proof process for unequivocally showing that a particular design will or does satisfy the corresponding requirements upon which it is designed. Currently, V&V are more common concepts in software engineering. Validation is a process of ensuring that formal specification is consistent with the user's requirements. Verification can normally be: a static walkthrough, program inspection or a dynamical model test. Specifically, verification means a process of ensuring that the information developed in phase n is traceable to information in phase n-1.

Law (2000) suggested the measures of performance used to validate a model should include those that the decision maker will actually use for evaluating system designs. V&V should be continuously adopted during the modeling process or the life-cycle of a simulation study. Back to the early 1970s, Independent V&V became a mature systems and software engineering discipline in the U.S. Army safeguard system development (Lewis, 1992). This type of model V&V requires an independent department or a group of programmers to work simultaneously with the real design group and audit the software development progress, any potential mistakes, and supply their independent feedback. Goodness-of-fit test is designed to test the hypothesis that a sample of data is distributed following a given probability density function. The test consists of the evaluation of a function of the data, the Goodness-of-fit statistics, and the qualification of this result using the probability distribution of the statistic under the condition that the hypothesis is true (Hameren, 2006). Campolongo *et al.* (2007) generalized sensitivity methods as quantitative variance based methods, defined from the decomposition of the total output variance into the contributions of the input factors. Robinson (2004) suggested validating simulation by white-box with modeling details or black-box with the overall behavior.

V&V can be employed at different modeling stages and at different levels, and this is conveniently compared by putting them into a quadrant framework with two perpendicular axes (Figure 6-1). The horizontal axis represents a continuum of the stages of V&V participation; the vertical axis represents a continuum of the level of the V&V participation. By locating the typical V&V methods in this framework, we can clearly see the scope and depth of each method for the development and application of a certain system.

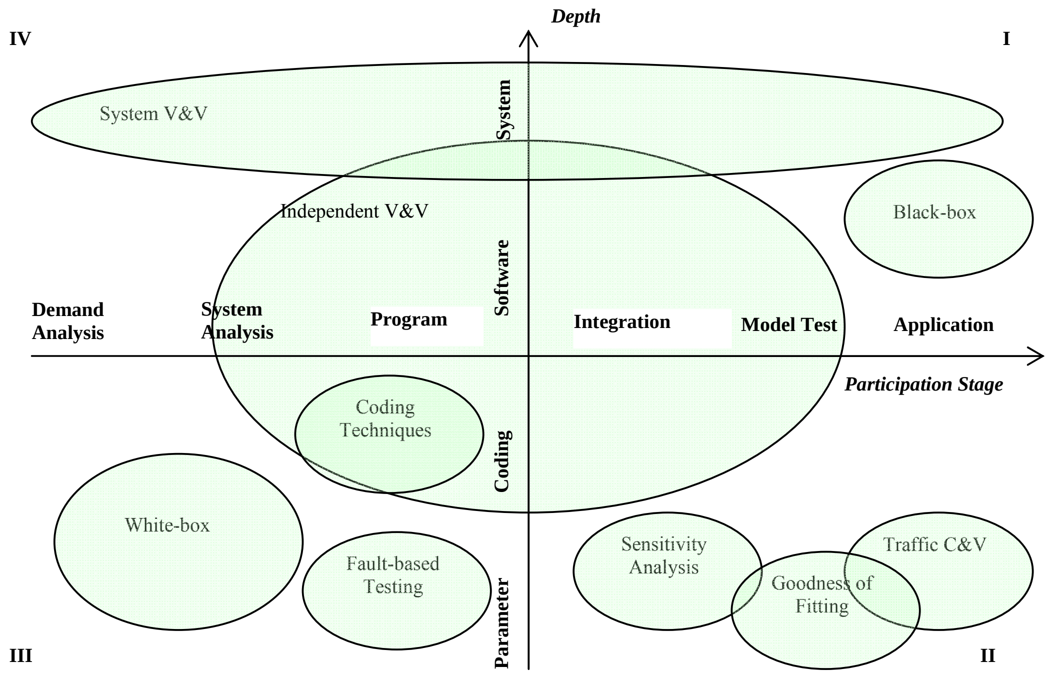


Figure 6-1, Quadrant Frame of V&V Methods

Based on the metric selected, V&V methods examine the degree to which typical methods cover the scope of work.

1) Depth Level: goes from a general system, down to software development, to coding, until parameter adjustment.

2) Participation Stage: V&V may participate in the demand analysis, system analysis, programming, integration of subsystems, testing, and application. The earlier and more broadly V&V is involved in the process, the more influence it has on the final product.

By putting methods into this quadrant frame, one can see that independent V&V has a wider scope of participation, while Traffic Calibration & Validation (C&V) is only a narrow application-level parameter adjustment process of an existing system. The intention here is to identify a method that will cover the system requirements for coding and parameter.

6.2 Validation and Verification Design for This Research

Forrester (1961) placed great emphasis on validation by exploring model details, dimensional consistency, checking model behavior, and using objective and uncontroversial tests. Chasey (1995) tested his model by parameter sensitivity and extreme conditions. Barlas (1996) forwarded the Turing test by checking the difference between randomly sorted outputs from a model and historical behavior. Coyle and Excelby (2000) gave a more comprehensive check list: appropriate model boundary, no gross errors of model behavior, equations and parameters in accord with the real system, consistent model behavior under various condition, etc. Besides the above structured techniques, some researchers still prefer rigorous statistics tests to examine simulation of a system dynamics model. Kleijnen (1995) used statistical techniques of regression analysis and fractional factorials and central composite design to optimize a system dynamics model. Kim (1998) used goodness of fit to test model generated variables and historic data.

This research adopts V&V at three levels: theoretical, methodological, and technical. First, the stepwise process explores the nature of model testing and suggests that the modeling process be recast as an experimental approach to gain credibility in the hypothesis articulated in the model. Then, this research proposes heuristics to guide the testing strategy, and to take advantage of the strengths of a systematical framework at the methodological level. Finally, special designed V&V techniques based on the modeling platform realize the repeating process of testing and calibrating. Additionally, a group of case analyses complete modeling and assist confirmation of the founding theory in the next chapter.

Based on literature review, this research generalizes and employs two groups of V&V techniques:

1). V&V of Model Design:

a) Establish a well defined model structure and appropriate module boundaries.

b) Check model assumptions.

c) Assign proper values of model parameters.

d) Perform dimension consistency test.

2). V&V of Model Performance:

a) Examine module face validity.

b) Conduct sensitivity analysis.

c) Compare the simulation data distribution with historical data. (This technique will be applied in the case analyses phase of the research.)

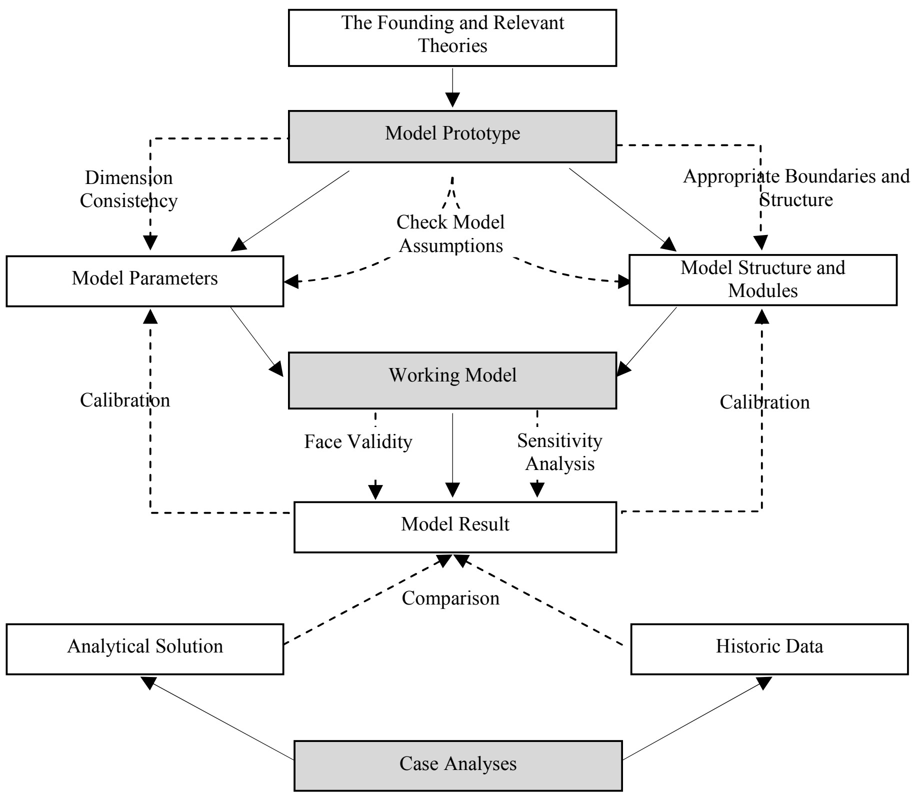


Figure 6-2, A Systematic Procedure for Model V&V

These model V&V techniques should be done in a systematic way and follow a top-down sequence to cover each assumption and parameter. It requires reviewing current work by checking all modules in detail. Face validity examination, sensitivity analysis, and statistical tests help to identify the problem in model assumption and parameters. Especially, face validity test comprehensively presents whether each module can perform in a reasonable way. A module with poor pattern matching consequently requires checking model structure, assumptions and parameters evolved thoroughly. Whenever there is any inappropriate model structure, skeptical assumption, or unsuitable parameter value, that part must be calibrated. Figure 6-2 depicts the V&V process used in this research. All dash lines are V&V steps, which run through the whole modeling and case analysis process. It emphasizes a repeated and systematic way to validate assumptions, parameters, model structures, and simulation result by identifying and reducing of the possible reasons that cause the discrepancy between the simulated output and real data.

6.3 Appropriate Model Structure and Boundaries

Structured programming development is normally beneficial to enhance model quality (reliability, sensitivity to changes, credibility, etc.). Willis (1974) generalized that structured model development is an approach to improve model quality through the use of elemental programming constructs to reach commonly stated improvements: 1)the model is self-documenting, 2) the model is easily understood for testing, maintenance and modification, 3) model has a good provability. In this research, a top-down model development sequence divides the research problem into sub areas. During this procedure, the boundaries of divisions require good clarity to properly address the relationships among all modules. There are several considerations in constructing the model framework and defining a module boundary:

- Whether each module is clearly defined for its function
- Whether the module is relatively independent and performs reasonably
- How to improve readability and transparency of each module
- How to fully utilize the functions of the model development platform

In the modeling development process, the founding theory of this research (Infrastructure Performance Theory) guides the basic function of the overall model. Relevant theories also provide fundamental knowledge for details in constructing each of the modules. The boundary of each module is set to cover the topic relevant to the module. The model framework conforms to this sequence and logic. This is the structured framework that guides module-level development.

However, the same philosophy is applicable and necessary for the next level of model development that is model sections within each module. A deeper level of programming will also touch the functions of the modeling platform. As the programming platform, Vensim 5.7 allows comprehensive logical expressions for a complex simulation. For example, one of the longest variable definitions is *MR&R Decision* (Figure 6-3), which includes multiple inputs and constraints. Comparing codes written in DYNAMO and Vensim, the latter one gives higher flexibility but sacrifices understanding to a certain degree. An aggregate model that links more parameters into one decision variable creates complex logical expressions which increase the difficulty of model validation by incorporating more relations into one equation.

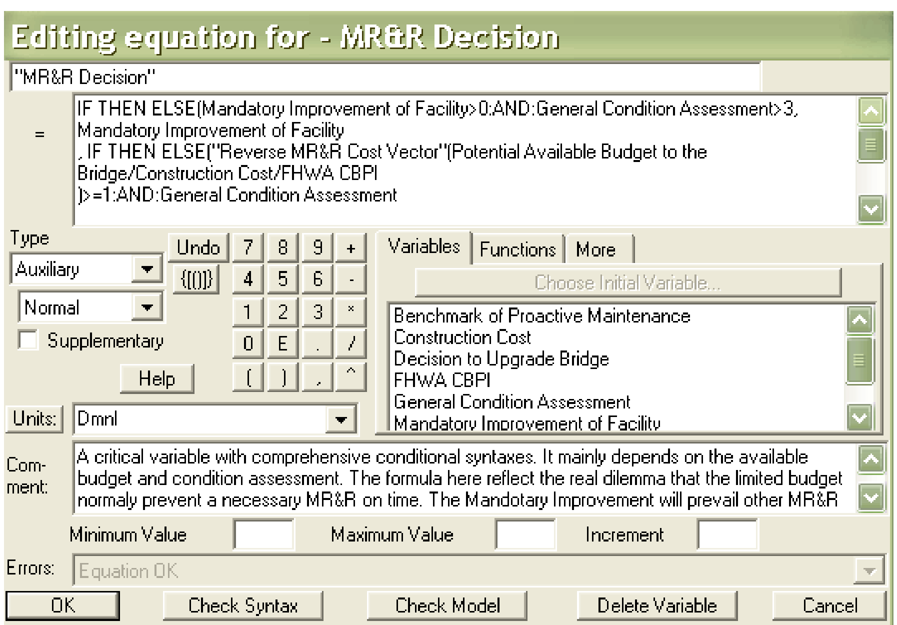


Figure 6-3, Equation Editor in Vensim

To reduce complexity, the model incorporates more causal links and introduces some intermediate variables. For example, three MR&R model sections (Figure 6-5) replace an initial model section of the MR&R Module (Figure 6-4).

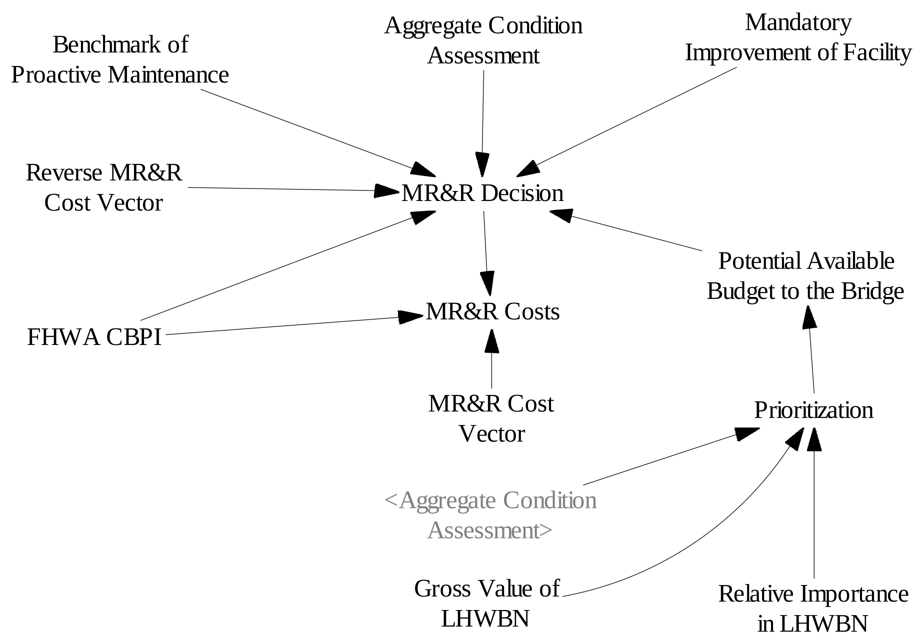
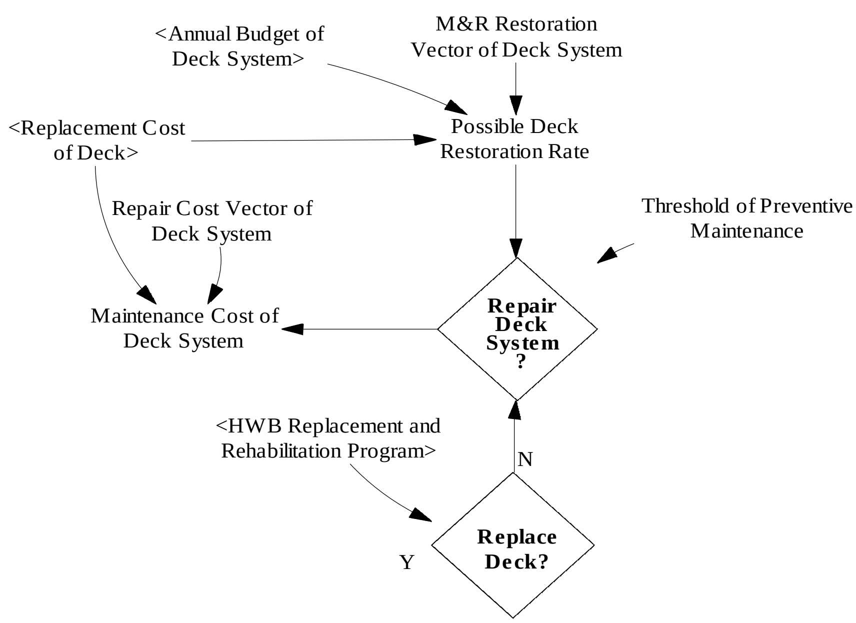


Figure 6-4, Original Section of the M&R Module



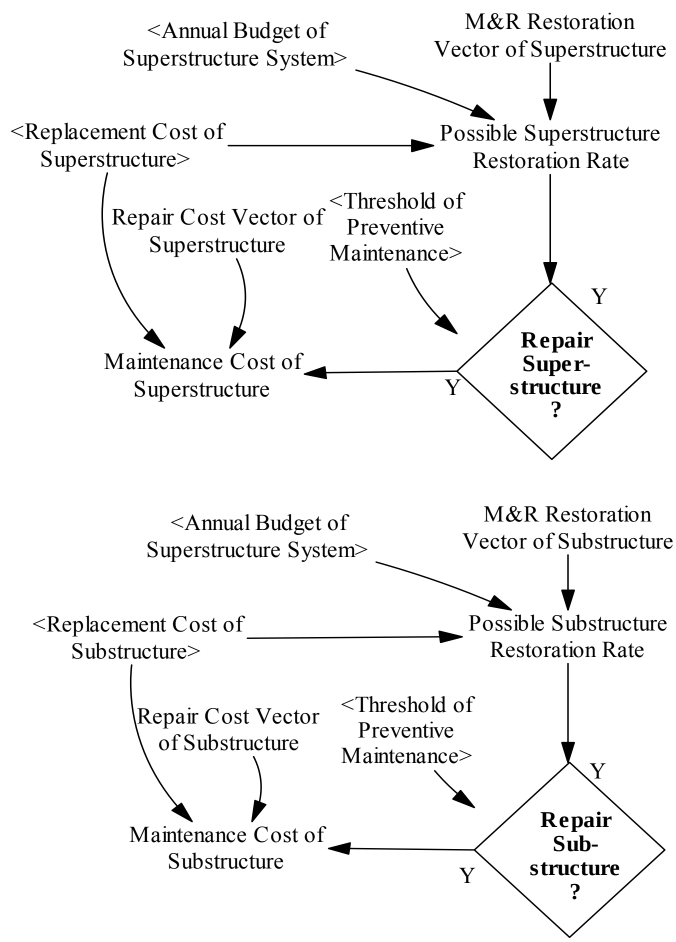


Figure 6-5, Redesigned Module Section of M&R Module

A good model structure not only increases model clarity from its appearance, but also reduces the potential mistakes in the code. The following definition of *MR&R Decision* (corresponding to Figure 6-4) is hard to follow with a two-level "if… then…else" structure as well as complicated logical expressions in the model condition.

```
MR&R Decision
  =IF THEN ELSE
     (
          Mandatory Improvement of Bridges>0
          :AND:
          Aggregate Condition Assessment>3,
                 Mandatory Improvement of Bridges,
                IF THEN ELSE
                     (
                          "Reverse MR&R Cost Vector"(Potential Available Budget to
                          the Bridge / Construction Cost/ FHWA CBPI) >=1
                          :AND:
                          Aggregate Condition Assessment<=Threshold of Proactive
                          Maintenance,                                                    (6.1)
                                  Integer("Reverse MR&R Cost Vector"(Potential
                                  Available Budget to the Bridge/Construction
                                  Cost/FHWA CBPI)),
                                  0
                     )
       )
   *
   IF THEN ELSE
     (
         Decision to Upgrade Bridge>0,
            0 ,
            1
      )
```

The above expression is subsequently replaced by a series of "small" ones with a central component as follows (corresponding to Figure 6-5).

```
Repair Deck System?
  = IF THEN ELSE        (
             "Replace Deck?"=0
             :AND:
             Possible Deck Restoration Rate>=1:AND:Deck Condition                  (6.2)
             Assessment<=Threshold of Preventive Maintenance,
                            Possible Deck Restoration Rate ,
                            0
      )
```

It is important to have well-defined model and appropriate module boundaries. Vensim is powerful, but not necessarily as easy to debug as DYNAMO. When utilizing the current modeling platform, a well defined model framework and clear internal division helps to reach a high model quality.

6.4 Model Assumptions

No matter how a coding technique helps the programming, appropriate assumptions stand out as the fundamental ingredients for a valid model. Model assumptions determine the modeling procedure itself and the credibility of the model functions. Assumption evaluation covers theoretical assumptions of bridge performance, conceptual assumption of each subsystem, and formulation of input data. From the higher level to the lower one, assumptions transform a qualitative format to a quantitative configuration. Model assumptions determine the credibility of the model functions. Correctness and appropriateness of system assumptions stand at the leading point for later structure construction and coding. Assumption checks cover theoretical assumptions of bridge performance, conceptual assumptions in each module, and formulation of input data.

A check of theoretical assumptions requires a system analysis of the fundamental theory and proposed concepts that direct the modeling, as well as the methods used for realizing the model. For instance, to simplify its structure, the original model disregarded the contribution of an individual bridge to urban socioeconomic changes. With this assumption, the model performs reasonably in general. However, it does not perform reasonably under extreme conditions. When the performance of the bridge of interest reaches a low level, Industrial Output still grows at its own rate as shown in Figure 6-6. This presents a challenge when the bridge serves as a critical link for an urban district. For example, the model may lose its validity when it is applied to links, such as the Cooper River Bridge in the City of Charleston or the George Washington Bridge in Manhattan.

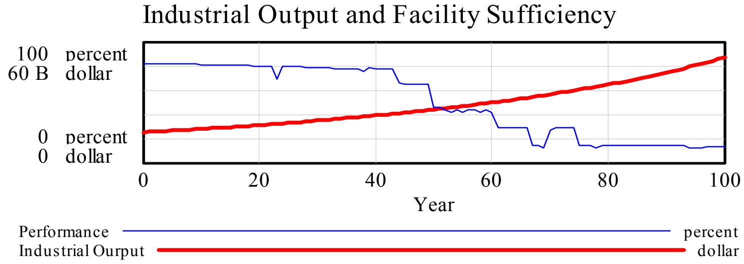


Figure 6-6, Broken Relation between Industrial Output and Bridge Sufficiency

This figure examines the relationship between the *Local_Industrial_Output* and performance of the bridge of interest. However, it is difficult to determine such a causal loop in a working model with complex links. By picking up several key variables from the modules, Figure 6-7 illustrates information flowing from network level to project level. What is missed there is the feedback from performance of the bridge of interest to the performance of the LHWBN, which results in a missing closure of this causal loop.

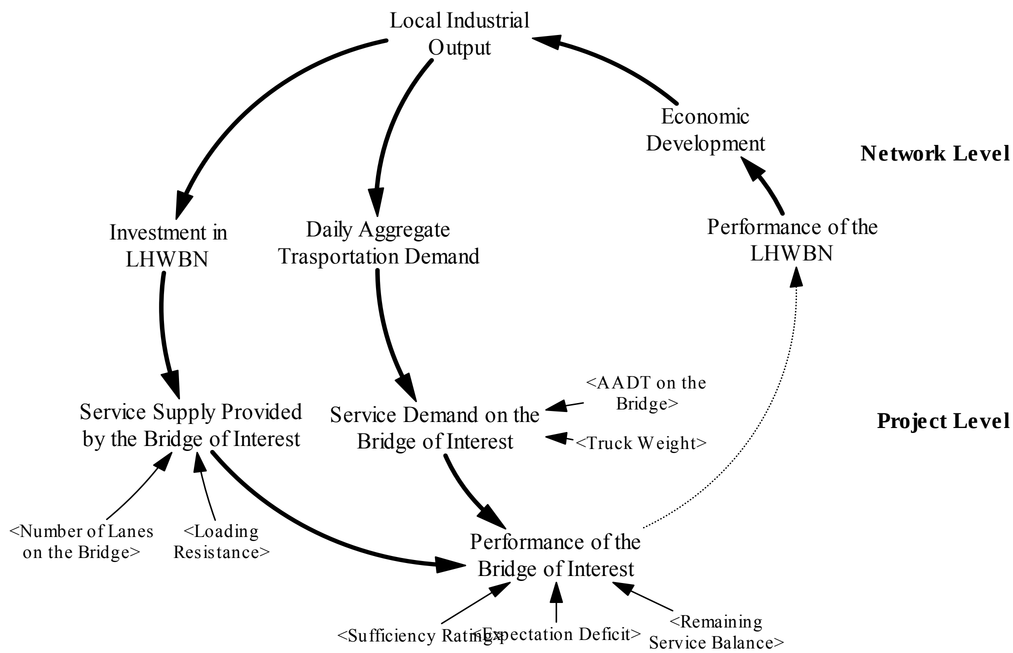


Figure 6-7, Single Way Causal Relation

To work out this dilemma, one needs to reexamine the relation between *Local_ Industrial_Output* or *Economic_Development* and performance of transportation infrastructure network. The questions involved include: how to measure the economic development rate under a given transportation network? How to quantify the network level performance? How to estimate network level performance based on one of its critical facilities? At the network level, Chasey (1995) constructed a causal loop between the highway development and user benefit. He also proposed a concept, Comprehensive Level of Service, for highway maintenance with a combination of both maintenance (Level of Operation) and capacity (Level of availability) indicators. In lieu of separate existence in highway maintenance and operation, these two interdependent factors are quantified into one single index to account for the highway performance. Normally, highway performance is assessed under a normal physical condition (TRB, 2000). Chasey's model examines and reveals that the transportation system requires improved condition to reach a higher level of performance. Later, Kim (1998) expanded the system dynamics model by measuring the highway system (including pavement and bridge subsystems), for which he defined the feedback from the transportation network to industrial output. A sufficient highway system increases productivity and attracts capital investment, which results in a higher industrial output.

The network level model is essential to categorize macro supply and demand, rather than having an unlinked micro factor of supply to demand. Kim's model simulates the bridge network by categorizing bridges into different levels of physical conditions and functions. Comparing to Kim's work, our model concentrates on the condition and function of an individual bridge. The link from the performance of a single project to that of the network level requires additional consideration of the working model. In modern BMS, the budget is prioritized according to the component's conditions within facilities. In the other words, budget will be allocated to the most demanding component among the *LHWBN*. An important bridge located on interstate highway with an average service life will receive more attention and funding for its maintenance. If such a bridge falls into poor condition as in Figure 6-6, either the budget is inadequate or a poor maintenance policy is in place. It is reasonable to conclude that other bridges with average lives under the same administration may fall into poor condition as well. However, it is still difficult to quantify the network condition only from the state of an individual bridge and it is necessary to construct a model at the network level to calculate the average physical condition of a highway system, as seen in models by Chasey (1995) and Kim (1998).

An individual bridge should only be tackled as one cell of the network and only its own capacity counted. Chasey defined Level of Operation as a measure of bridge down time and traffic delay. A bridge loses given capacity by closing part of the lanes to traffic or limiting certain type of vehicles. Figure 6-8 illustrates that either repair, upgrade, or poor condition will lead to a temporary closure of bridge lanes. This explains how a deficient bridge may not undertake traffic demand during its down time.

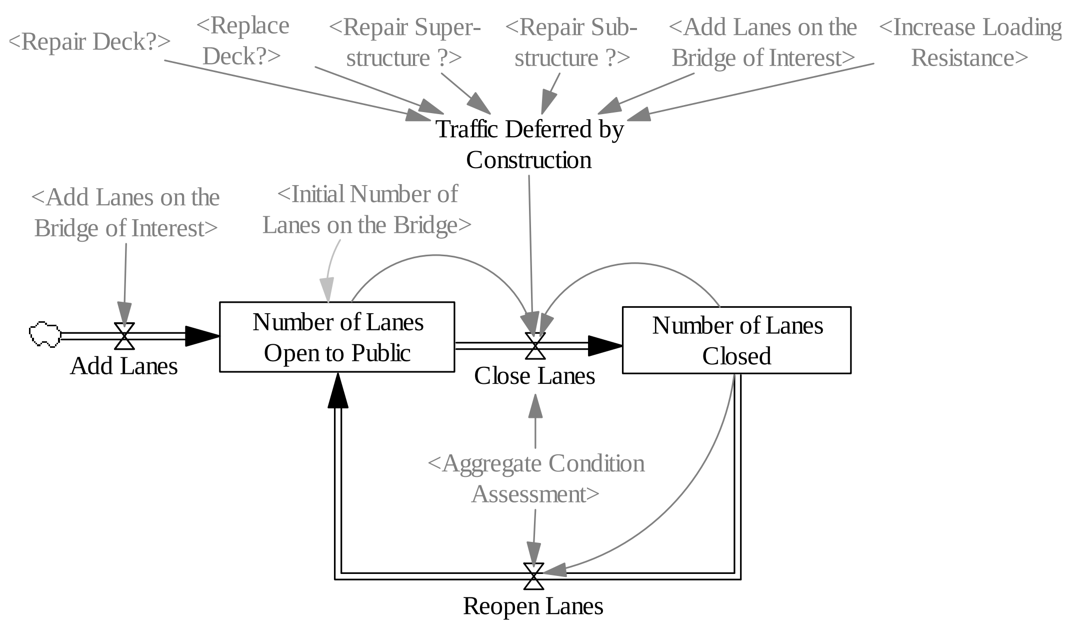


Figure 6-8, Bridge Lanes Open to Public

In Equation(6.3), the Comprehensive LOS is defined as *Average_Traffic_Density* and physical condition of the bridge of interest.

$$Highway\ Comprehensive\ LOS =$$

$$\frac{1+\left(\frac{Number\ of\ Lanes\ Open\ to\ Public}{Number\ of\ Lanes\ on\ the\ Bridge}\right)\times\frac{Relative\ Importance\ in\ HWB\ Network}{Number\ of\ HWB}}{\left(1+\frac{0.6}{Number\ of\ HWB}\right)\times Average\ Traffic\ Density} \quad (6.3)$$

The model above assumes that a transportation system has a depressing effect on economic development. This way, the model basically explains the correlation between local bridge deficiency and the overall performance. The model structure is calibrated as Figure 6-9.

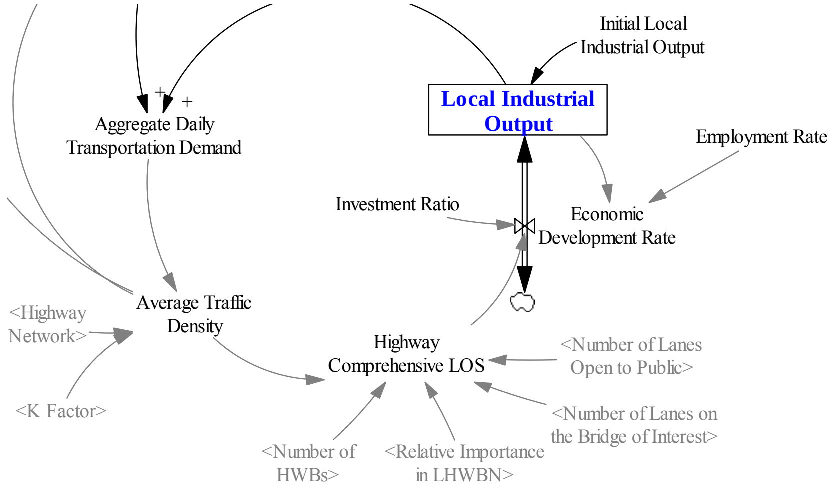


Figure 6-9, Calibrated Industrial Output Module

This adjustment shows the obvious effect for an urban area with fewer bridges. For example, if there are 20 critical bridges in the regional transportation network, the development of Industrial Output will slow down with a worse Sufficiency Rating (Figure 6-10).

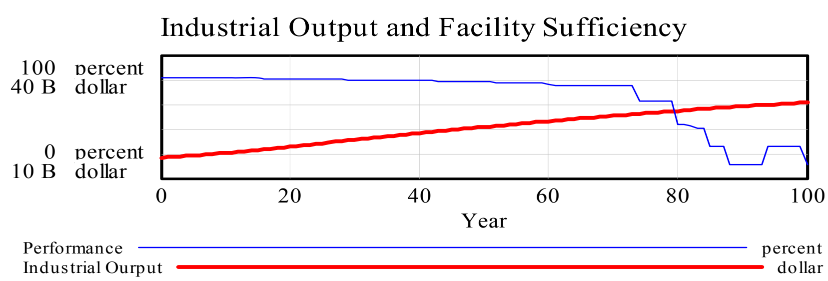


Figure 6-10, *Industrial_Output*and Bridge *Sufficiency_Rating*

Appendix B gives a complete list of all model assumptions, checks and calibration if necessary.

6.5 Model Parameters

Appropriate model parameters are critical for a model's credibility. Values of model parameters can lead the model to different performance. Parameter calibration is equally important as other V&V techniques. Selection of parameters should correspond to the real system and the model should be able to reproduce the system behavior in various conditions.

Depending on the sources, parameters are tested and calibrated in different ways. If a parameter comes directly from other work, literature, or industry codes, the original work will be cited in the variable comment. This type of parameter is assumed correct first. In case of being questionable, other literature will be referred for calibration. Most parameters in the model are case-based, such as *Population, Local_Industrial_Output,* and *Design_Load.* This means current values of these parameters in the model will be replaced in the stage of case analysis. Further V&V and calibration are necessary and repeated for each case analysis.

Different than case based parameters, system parameters are independent of individual cases but decisive to all simulation results. They are critical for the model credibility and deserve special attention. This section will investigate two system parameters, the time horizon of the model and the seeds for random number generation.

6.5.1.1 Time Horizon

First of all, the simulation time horizon is a critical variable for the model result. An effective forecast for conditions at a future time can be made only as far as the past continuity still prevails. Beyond that horizon, uncertainty is increasingly dominant. "*However, the forecast is of little value in a short forecast time horizon because a responding decision will be defeated by the very continuity that made the forecast possible*" (Forrester, 2007).

There is not a standard to choose the time horizon of a prediction model. Chasey (1995) comparatively ran his system dynamics model about comprehensive Level of Service of highways over 10, 15 and 20 years. Kim (1998) built his system dynamics model of a decision support system of highway network with a 20 years horizon. Similarly, Raux (2003) used a forecast horizon as 20 years with an annual time step in his system dynamics model of public transport services. In scenario analysis, 20 years may be long enough to observe deterioration on the supply side and traffic increase on the demand side. And, a shorter time horizon is “safe” for model confidence. However, it is not long enough to cover the change rate of some other exogenous factors. It may take longer time, such as 50 years, for regulatory changes or technology innovation/adoption in the transportation arena. Therefore, it is necessary to show the prediction result with a wider confidence interval to include changes of more nonphysical factors if their inception is uncertain.

In this research, highway bridges are selected as the model subject. Their design service lives are generally 75 to 100 years. Indeed, a number of bridges have already been used for more than one century and are still in service. Unlike pavement with shorter replacement duration, highway bridges require a model with a long time horizon to cover main activities and changes in its life cycle.

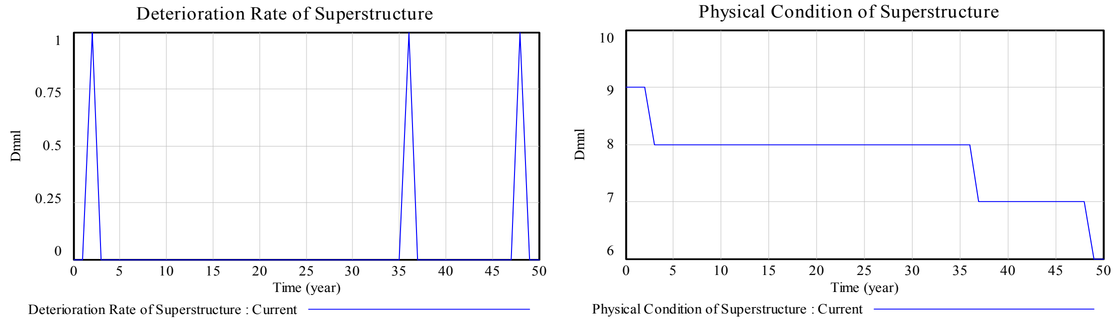
6.5.1.2 Model Seeds

During the model debugging process, the model sometimes shows a strong correlation with the choice of the seed in generating a random variable series. For example, the application of a Markov chain in calculating the physical deterioration rate requires a random normal variable during function inversion. By changing the seed, the Monte Carlo simulation of the deterioration rate of the superstructure presents instability, which impairs the model’s reliability.

Deterioration Rate of Superstructure

```
= IF THEN ELSE
   (
         RANDOM UNIFORM(0, 1 , 0)<Markov Matrix of Superstructure          (6.4)
         (Physical Condition of Superstructure),
               1 ,
               0
   )
```

a). Seed = 0



b). Seed = 3

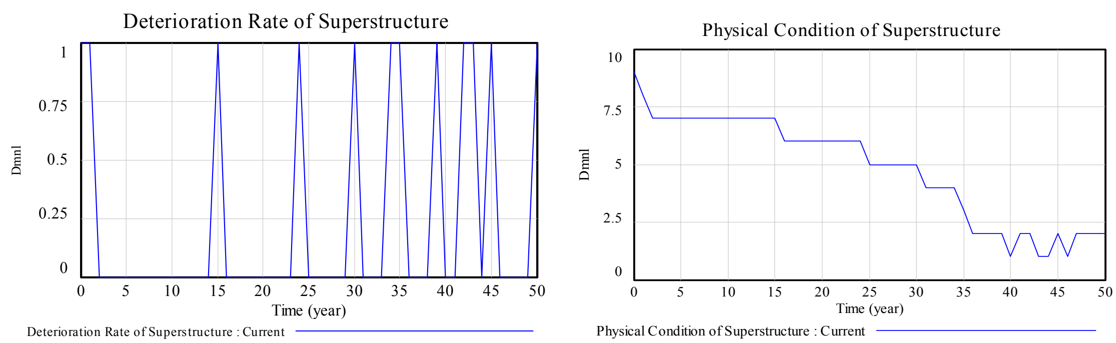
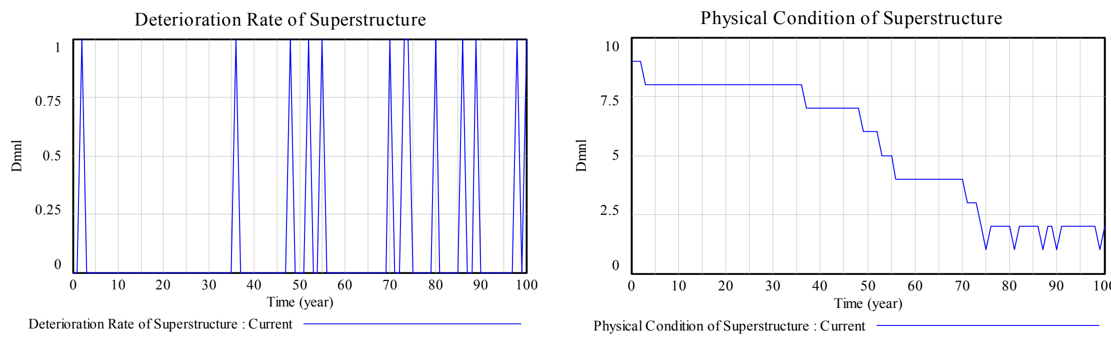


Figure 6-11, Deterioration Rate with Different Seed for the Random Number Generation

By keeping all other parameters same, the model tests different seed values in the RANDOM UNIFORM (min, max, seed) for the superstructure physical deterioration rate with a Markov chain. In most situations, the model presents a reasonable shape as in Figure 6-11 b). In a few cases, the model shows an irrational shape as in Figure 6-11 a). There are several factors that contribute to this instability. The first one is the time horizon. By expanding the simulation period from 50 years to 100 years, model presents more regular shapes for different seeds. The long-term perspective amplifies the condition results by increasing bridge backlog over more periods, which is evident in Figure 6-12. Consequently, this scenario requires significant capital outlay over a long time.

a). Seed = 0



b). Seed = 3

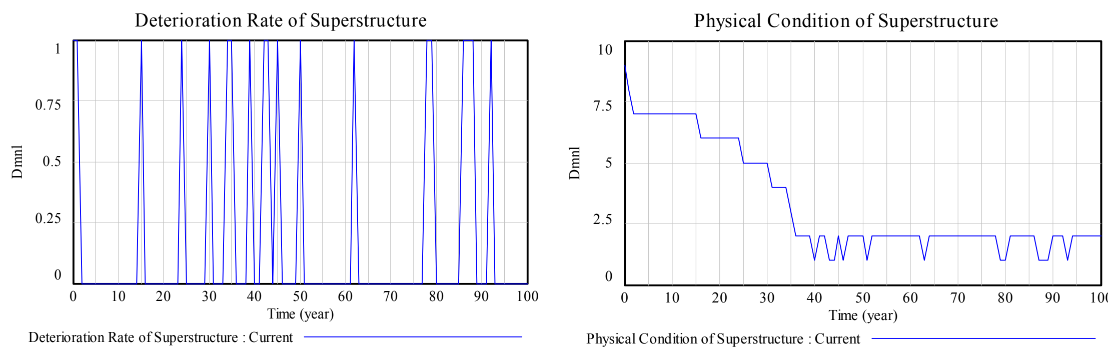


Figure 6-12, Deterioration Rate with Different Seed Value with 100 Years Span

Second, it is important to check the credibility of the method used in the model. Suppose *Deterioration Rate$_i$* is a discrete random variable with a probability mass function (PMF)

$$\text{Deterioration Rate}_i = \begin{cases} 1, \text{ if } 0 \le U \le 1 - p_i \\ 0, \text{ if } 1\text{-}p_i < U \le 1 \end{cases} \tag{6.5}$$

Where *Deterioration Rate$_i$* is the deterioration rate at state i, U~U(0,1), 1-p_i is the probability that a bridge component will deteriorate to the next level as the i$^{\text{th}}$ semi-diagonal entry in the deterioration Markov chain, which is conveniently realized by a LOOKUP function.

Since the model uses MCMC, the deterioration rate of all components are free of historical changes and the model achieves a simple format as Equation(6.6).

$$P\,(\text{Deterioration Rate}_i = 1) = P\,(0 \le U \le 1\text{-p}_i) = 1\text{-p}_i \tag{6.6}$$

Third, there are several principal methods, the inverse transform method, the composition method, and the acceptance-rejection method for generating univariate random variables. All of these methods rely on having a $U\,(0, 1)$ random number generator available (Haugh, 2004), which is RANDOM UNIFORM (min, max, seed) in Vensim. The question is whether Vensim provides a good uniform random number generator. By setting seed equal to 3, the first fifty years show a sharper descending rate than a scenario with a seed value of 0.

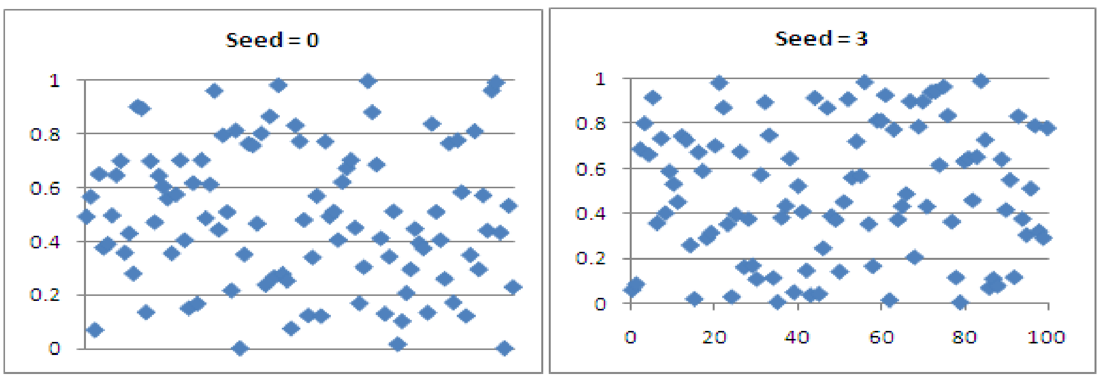


Figure 6-13, RANDOM UNIFORM (0, 1, Seed) Value

The seed setting with 0 has the default noise stream. However, a random uniform plot with the default noise stream is not even with a seed of 3 (Figure 6-13). The working model adopts tested seeds in random variable generation to avoid such special cases, especially for short term simulation. This step is essential for variance reduction in application of Monte Carlo method.

Table 6-1, Selected Seeds for Random Number Generation in Vensim

Seed	Mean μ	Standard Variation σ
3	0.4977	0.2955
5	0.5062	0.2727
8	0.5059	0.2970

Unlike model structure calibration, a model parameter should be calibrated whenever a different type of bridge is analyzed. Among all types of parameters, LOOKUPs preload with default values of critical parameters, such as a transition probability matrix and maintenance cost vectors for each sub bridge system. These values can substantially influence model results and they are case sensitive. It is desirable to calculate a transition matrix from historical data by linear regression method (Madanat et al., 1995) or by non-parametric transition probability (DeStefano and Grivas, 1998). To simplify its application, the model will directly use available matrices from the literature for a steel suspension bridge, a concrete girder bridge, and a steel truss bridge. Then, these parameters will be calibrated based on the bridge type, location, and traffic, which results in a unique transition matrix for a certain type of bridge.

6.6 Sensitivity Analysis

Sensitivity analysis is a critical step of V&V in the model building process to ascertain how a given model output depends on the input parameters (Campolongo et al., 2007). By identifying the sensitive parameters, it is more cost effective to concentrate resources to improve a system dynamics model performance. Additional efforts to increase the precision of estimates of those parameters that are not critical to the model's performance might be unwarranted. Therefore, it is possible to focus on small model partitions for calibration due to obvious direct impact on the outcome, and the confidence intervals for the estimated parameters will be small (Oliva, 2003).

Sensitivity analysis is a quantitative variance based method from the decomposition of the total output variance into the contributions of the input factors. There are three types of sensitivities: numerical, behavior mode and policy sensitivity. For most purposes, behavior mode sensitivity and policy sensitivity are important (Sterman, 2000). Saltelli et al. (2004) generalized modeling sensitivity analysis approaches into Screening Methods, Local Methods, Sampling-Based Methods, Reliability-Based Method, Variance-Based Methods, Bayesian uncertainty estimation, and Monte Carlo Filtering. Sensitivity analysis should complete two basic steps:

1) Identification of calibration parameters. This approach includes identifying relevant impact parameters and determining their acceptable initial ranges. To find the predominant variables in a system, traditional statistical techniques include various kinds of multivariate analysis, such as analysis of variance (ANOVA), multiple analyses of variance (MANOVA), canonical analysis, discriminant analysis, etc. Morris (1991) proposed the elementary effects method by calculating each input with a number of incremental ratios to save time. The "One at a Time" method, local analysis by varying a single variable at a time around the baseline point, is prevailing as a simple process.

2) Combination of feasible variables. Another approach is to combine these selected parameters to find a scenario with the best statistical significance by using site data. Ideal testing include testing of all possible combinations of parameters. Certain technologies are designed to reduce the number of combinations to a practical amount while still reasonably covering the entire parameter surface. In his comprehensive test of types of transportation model, Park et al. (2004) recommend scatter plots, histograms, or animation properties.

In Vensim DSS, sensitivity testing is one of the embedded model V&V tools. Vensim has the capability to do repeated simulations in which model parameters are changed for each simulation. This can be very helpful in understanding the behavioral boundaries of a model and in testing the robustness of model-based policies. A model can contain quite a few assumptions, and these assumptions are known to be uncertain. Instead of changing the assumptions one at a time, Vensim DSS applies Monte-Carlo Simulation or Multivariate Sensitivity Simulation (MVSS) by setting ranges on the uncertain assumptions.

Results in Vensim present multiple scenarios by colorful contours under different probabilities. In his model of preventive maintenance, Kothari (2004) analyzed the sensitivity of cumulative system availability to operational_cycle_10 under 50%, 75%, 95%, 100% chances. The above graph shows that there is a 75% chance that the cumulative system availability over a 1000 week cycle will be between 510 and 890, 95% chance that it will be between 445 and 909. The mean at week 1000 is 673. Sensitivity analysis tests how the model output varying can be apportioned to different sources of variations. Generally, the larger probability allowed, the wider the scope of result.

Given the model structure in this research, sensitivity analysis should focus on the influential parameters and relationships, such as the variation of tolling period and bridge performance. This progress report will underscore two central relationships in performance evaluation:

- Bridge condition deterioration rate by adopting different M&R policies.
- Bridge performance under different financing strategies.

Before sensitivity analysis, it is noted that the physical condition of subsystems show cyclic changes, descending by deterioration and ascending by restoration (Figure 6-14). Sensitivity analysis becomes meaningless if it does not work on a monotonous change.

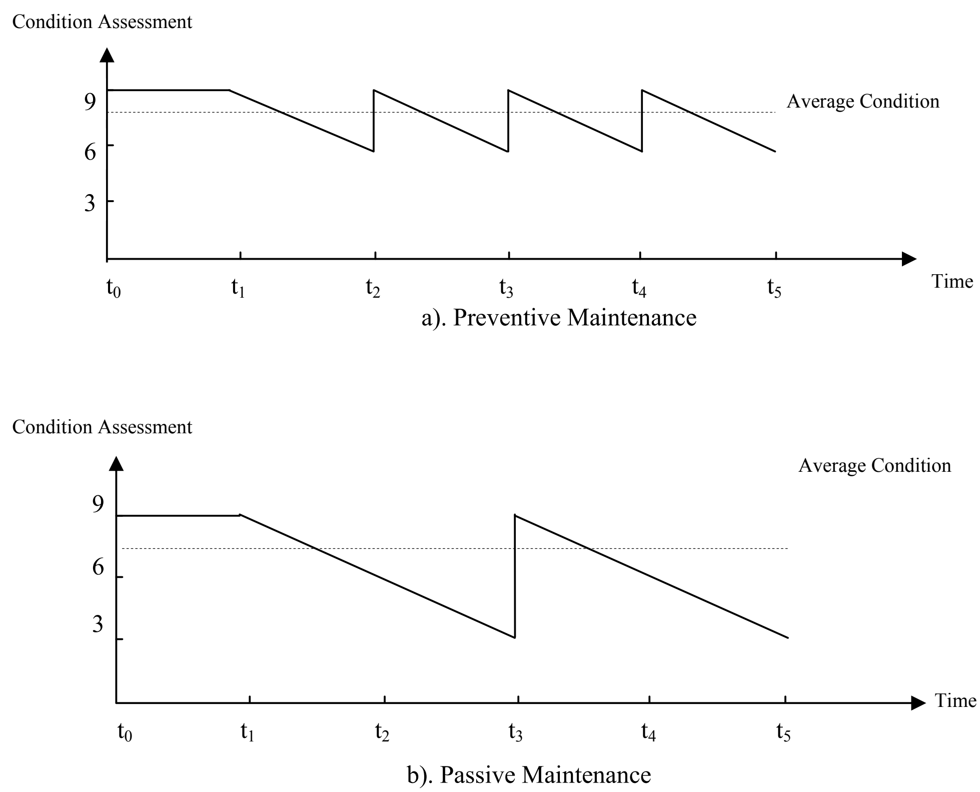


Figure 6-14, Bridge Conditions under Different Level of Maintenance

Conceptually shown in Figure 6-14, the physical conditions are same under two types of maintenance policies after repairing activities at time t_3. However, the bridge average conditions are different. Sensitivity analysis faces such a dilemma to choose an appropriate checking time. To reveal an appropriate relation, it is necessary to transform the variable index into an average value as the testing output.

6.6.1 M&R Activities and Bridge Condition

To initialize the sensitivity analysis, all other actions that may alter the case under consideration must be negated. For example, upgrade activities will also improve the physical condition, which will be set to an inactive mode during this analysis. Since *Average_Physical_Condition* is not a variable in the original model, this test variable is temporarily added into the model for the purpose of sensitivity analysis (Figure 6-15).

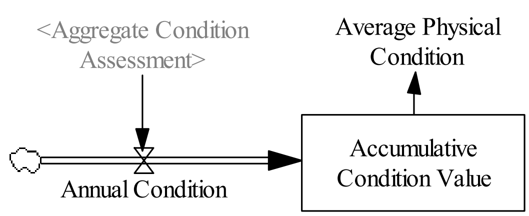


Figure 6-15, *Average_Physical_Condition*

The variable, *Average_Physical_Condition* monotonically decreases with an end value 4.54 at year 100 (Figure 6-16).

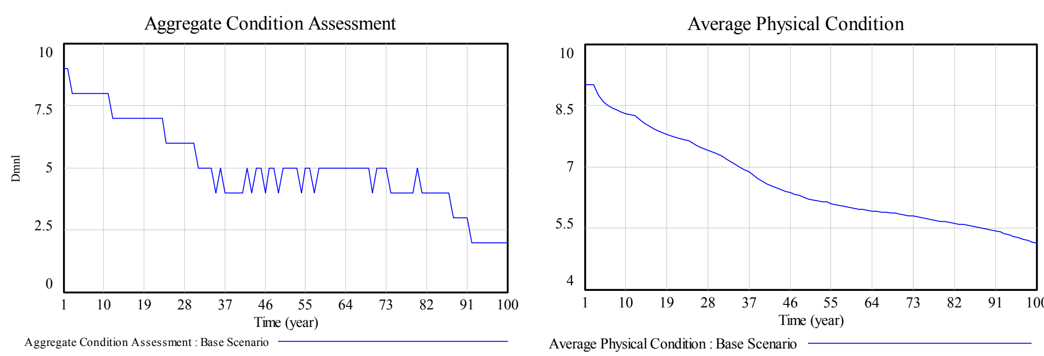


Figure 6-16, Comparison of *Aggregate_Condition_Assessment* and *Average_Physical_Condition*

Table 6-2, Sensitivity Analysis of *Average_Physical_Condition*

Factors	Base Value	***Average_Physical_Condition***				
		-20%	**-10%**	**0**	**+10%**	**+20%**
Threshold_of_Preventive_Maintenance	4	4.78	4.79	5.09	5.14	5.34
Relative_Importance_in_LHWBN	0.7	4.98	4.98	5.09	5.09	5.09
FHWA_CBPI	0.02	5.09	5.09	5.09	5.01	4.89
Load_Safety_Factor	1.3	5.59	5.28	5.09	4.71	4.52
ADTT_on_the_Bridge_of_Interest	Model	5.39	5.28	5.09	4.89	4.80
Ratio_of_Divisible_Load_to_Non-Divisible_Load	0.2	5.15	5.09	5.09	5.10	5.04
Enforcement_Level_of_TS&W_ Regulation	0.5	5.89	5.02	5.09	5.15	5.29

*Here, *HWB Replacement and Rehabilitation Program*=0

Table 6-2 gives the sensitivity analysis of the influencing factors on the *Average_Physical_Condition.* In Figure 6-17, a tornado diagram shows that *Load_Safety_ Factor*, *ADTT_on_the_Bridge_of_Interest* are the most sensitive parameters.

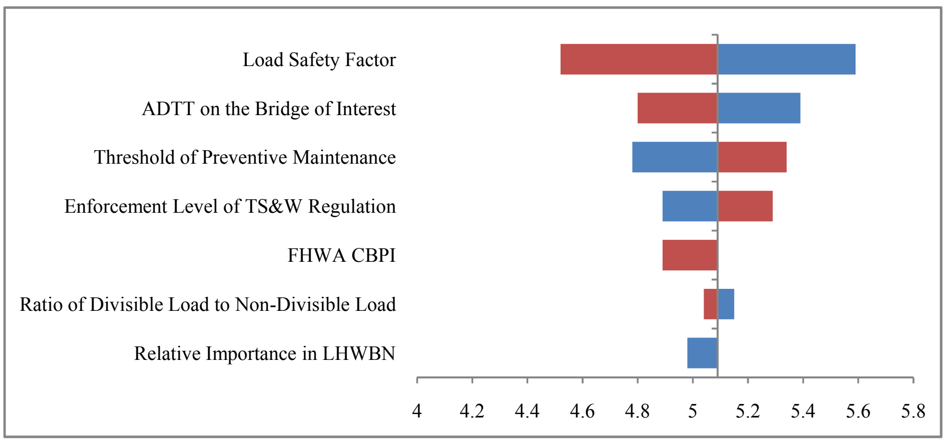


Figure 6-17, Tornado Diagram of Sensitivity Analysis on *Average_Physical_Condition*

6.6.2 Financial Factors and Bridge Condition

The second sensitivity analysis further tests how financial resources limit bridge performance. There are five sources designed in the Financing Module. For instance, this analysis examines how tolling factors influence bridge condition.

Table 6-3, Sensitivity Analysis of Tolls on *Average_Physical_Condition*

Factors	Base Value	*Average_Physical_Condition*				
		-20%	**-10%**	**0**	**+10%**	**+20%**
Toll_Collection_Period	80 Years	4.49	4.73	5.09	5.17	5.35
Initial_Truck_Tolls	$2.50	5.03	5.08	5.09	5.09	5.09
Initial_Auto_Tolls	$0.50	5.06	5.06	5.09	5.1	5.1
Increasing_Rate_of_Tolls (for tucks and autos)	0.05	4.97	5.04	5.09	5.1	5.1

If the local fund has a longer collection period than the period of loan payment, the additional maintenance expenses or upgrade potentiality reach a better *Average_ Physical_Condition.*

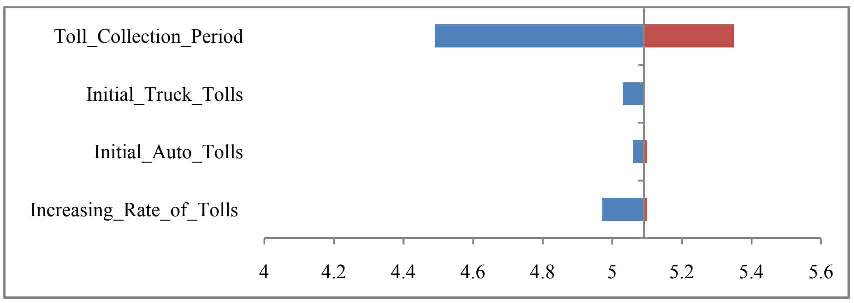


Figure 6-18, Tornado Diagram of Sensitivity Analysis of Financial Factors

Figure 6-18 illustrates that both toll has substantial influences on *Average_Physical Condition* by changing the financial factors. This indicates that a consecutive financial support along the whole life cycle is a necessity for a good overall performance.

6.7 Face Validity

This scenario-based environment allows a decision maker to explore a number of management and investment alternatives by varying levels and patterns of model parameters. In this research, face validity evaluates whether a model is reasonable. This section shows the face validity of each module by illustrating evolving curves over time. Meanwhile, important parameters for each module are listed to initialize a base scenario simulation as control bars within meaningful ranges. Shifting from the default values shows whether each module reacts in a reasonable manner.

Under different scenario, the face validity takes a test by checking the pattern matching between the simulation result and a rational model behavior. Major pattern components include trend, periods, and amplitudes. The fundamental pattern modes are exponential, balancing, and oscillation as illustrated in Appendix C. However, further knowledge on bridge engineering is necessary to identify what is an appropriate pattern for certain model performance. With limited exceptions, this section only tests the behaviors of the dependent variables to a base scenario and adjusted case values of parameters within the same module. In other words, “intra-module” testing is being done, not “inter-module” testing.

6.7.1 Test of the Financing Module

The following example illustrates the face validity of the Financing Modules. This test organizes project expenses and revenue in a parallel way to clearly identify project life cycle cost and profit. Financial management highlights the capital resources and the way they are expended on the bridge after its delivery. Bridge financial needs often exceed available funds (negative income), yet it is well known that commitment to a minimum level of funding is critical to managing future liabilities. The model has taken into account inflation by *FHWA_ CBPI*. It gives more flexibility in terms of project cash flow in which the amount of expenses depends on MR&R, upgrades, and available budget. That is, the amplitude of expenses and cash flows varies from period to period. Table 6-4 lists the parameter values for three scenarios that have different financing arrangements.

Table 6-4, Parameter Values in the Financing Module

Parameters	Base Scenario	Scenario *A*	Scenario *B*
Principal	$50 million dollars	$50 million dollars	$50 million dollars
Loan_Term	30 years	30 years	30 years
Interest_Rate	8%	8%	8%
Auto_Toll_Rate	$0.50	$0.50	$0.50

Truck_Toll_Rate	$2.00	$2.00	$2.00
Toll_Collection_Period	30 years	100 years	30 years
Tax_Rate_for_the_Bridge	0	0	0
Tax_Collection_Period	0	0	0
HWB_Replacement_and_Rehabilitation_Program	0 (No)	0 (No)	1 (Yes)
Relative_Importance_in_LHWBN	0.5	0.5	0.5

The base scenario assumes a 30 years of loan repayment by the toll revenues and state funds.

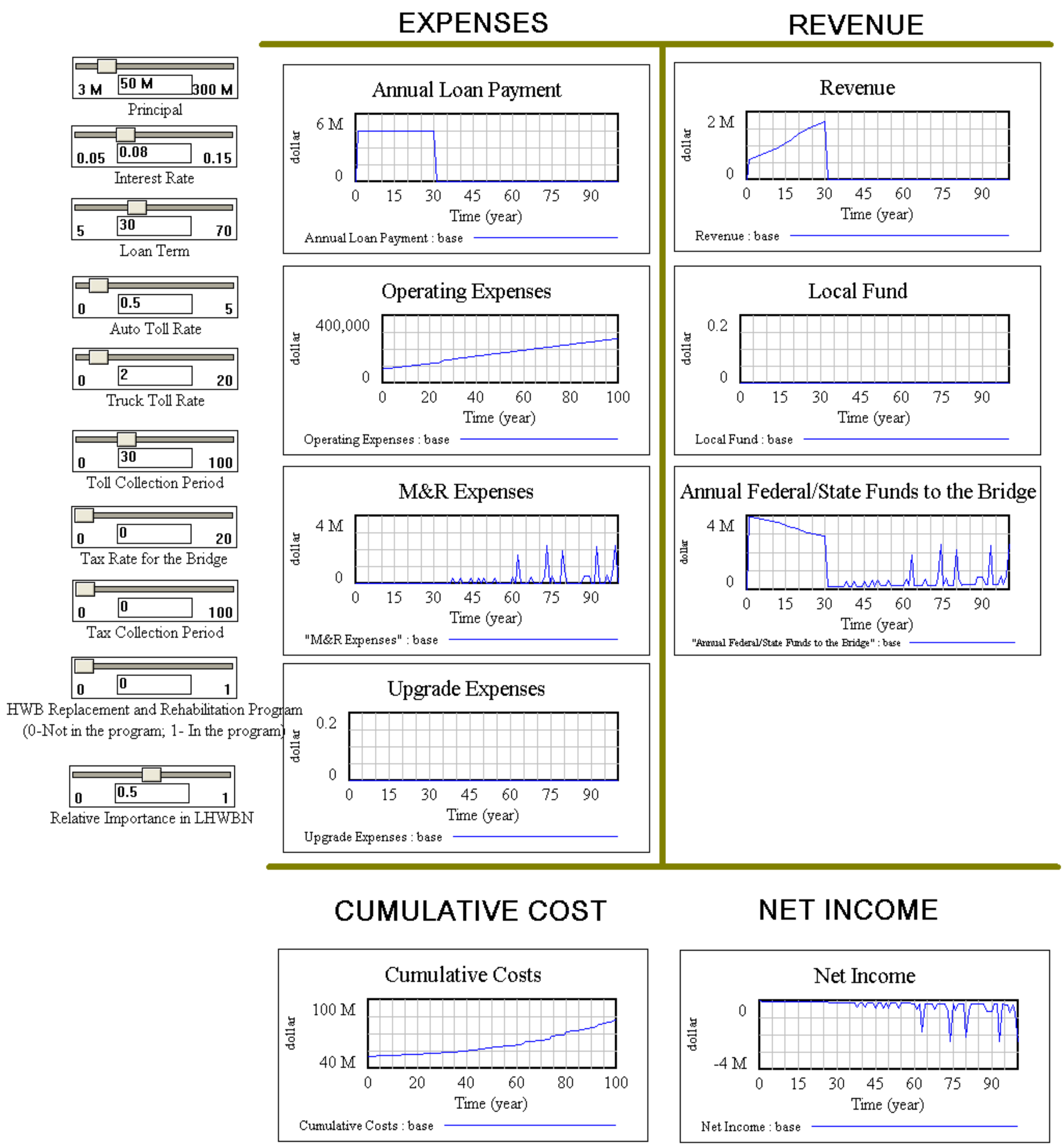


Figure 6-19, Financial Arrangement (Base Scenario)

As shown in Figure 6-19, *Annual_Federal/State_Funds_to_the_Bridge_of_Interest* from the government reimburses the shortage of toll revenue to annual loan payment in the first 30 years. *Net_Income* remains negative during the bridge life cycle. In the base scenario, the bridge relies more on the state fund for its maintenance and operation.

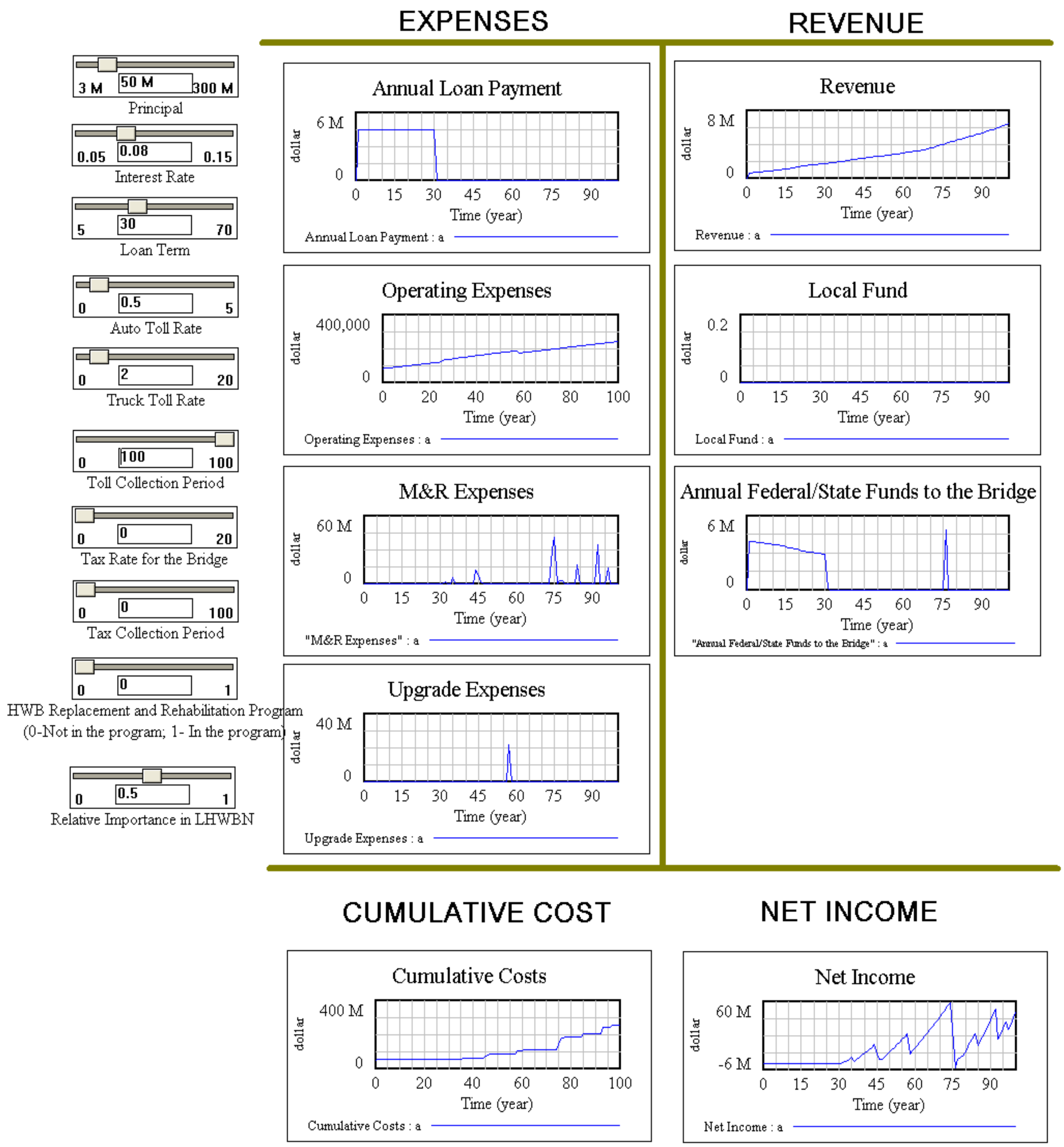


Figure 6-20, Extending Tolling Period to Full Bridge Life (Scenario *A*)

Scenario ***A*** imposes a toll over the bridge's lifecycle. Contrary to the base scenario, the model presents a scenario with discretionary funds for bridge management. In Figure 6-20, not only *Net_Income* becomes positive, but also *Cumulative_Cost* increases for more cost requirements being executed within the same timeframe. Consequently, these changes in the pace and magnitude of the bridge's physical condition curves result from releasing the budget constraints, which then results in a notably improved condition. Additionally, one upgrade is also possible around year 58 even without the support of *HWB_Replacement_and_ Rehabilitation_Program. Annual_Federal/State_Funds_to_the_Bridge_of_Interest* reduces over time.

In Scenario ***B*** (Figure 6-21), the bridge of interest is registered in *HWB_Replacement_ and_Rehabilitation_Program*. Compared to the base scenario, the bridge is updated twice around year 40 and 58. More cumulative costs occur in its life cycle.

Financial implications result from potential activities, for which information is collected from the Socioeconomics Module, the Maintenance Module, the Upgrade Module, and prioritization model section. With good face validity, this financial module illustrates the disparity between needs and funding, which accumulate over time and is reflected as a backlog. Thus, the impact of funding decisions can be effectively judged. The budget context provides a factual setting that is indicative of the capital constraints facing facilities decision-makers, and it serves as a basis for formulating investment scenarios.

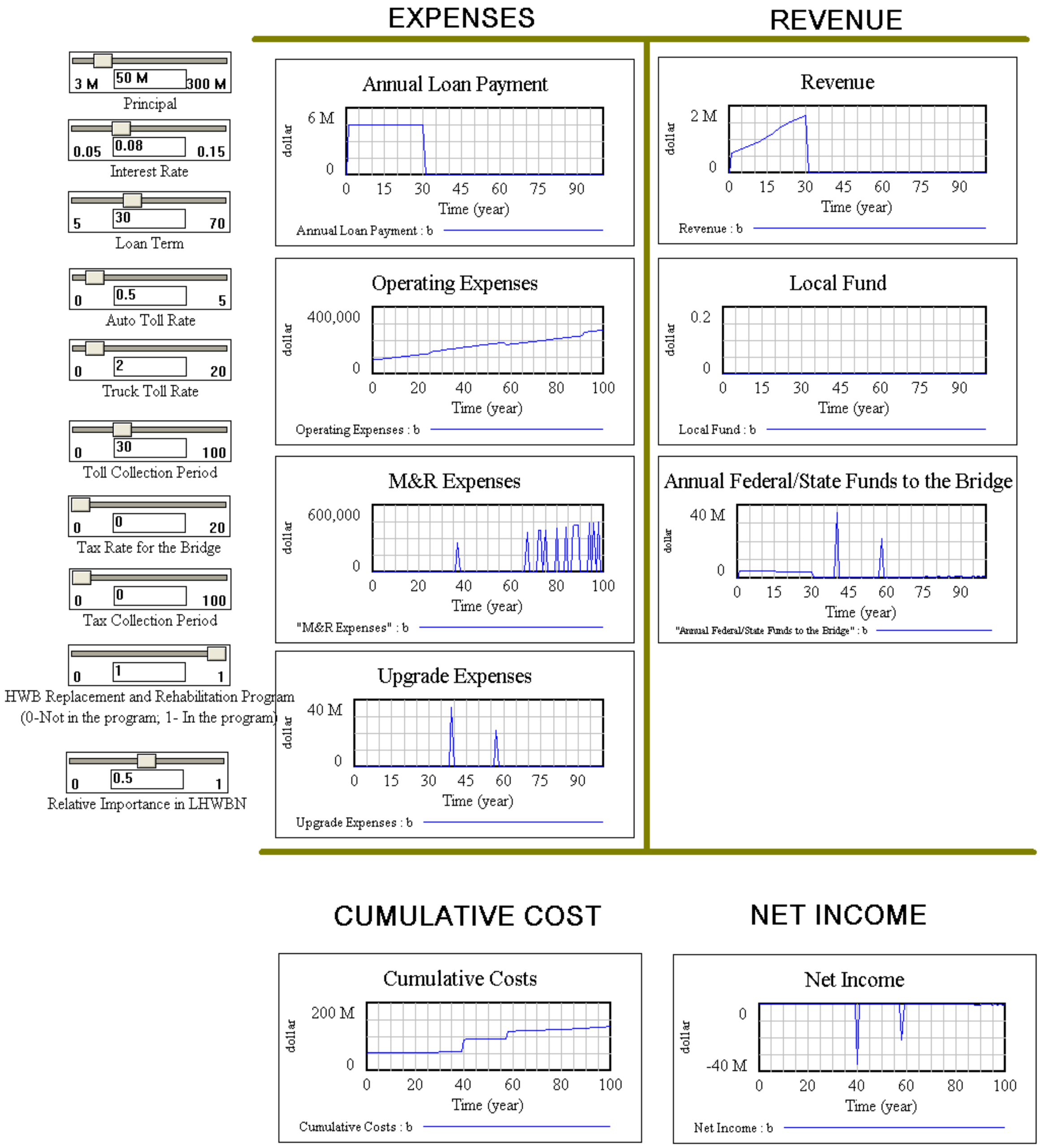


Figure 6-21, HWB Replacement and Rehabilitation Program (Scenario *B*)

6.7.2 Test of the Performance Evaluation Module

This section tests the face validity of the Performance Evaluation Module with three scenarios.

Table 6-5, Parameter Values in the Performance Evaluation Module

Parameters	Base Scenario	Scenario *A*	Scenario *B*
Approach_Width	12	12	12
Approach_Alignment	8	8	8
Main_Structure_Type	313 (steel suspension)	313 (steel suspension)	313 (steel suspension)
Detour_Length	18 miles	1 miles	1 miles
Bridge_Safety_Features	1011 (All features meet currently acceptable standards except transition)	1011 (All features meet currently acceptable standards except transition)	1011 (All features meet currently acceptable standards except transition)
STRAHNET	0 (Not a STRAHNET highway)	0 (Not a STRAHNET highway)	0 (Not a STRAHNET highway)
Lane_Width	3.5 m	4 m	4 m

The combination of 23 NBI items provides a fair representation of functional requirements and obtains a single index to indicate whether the sufficiency is scored as adequate (80-100), tolerable (70-79), inadequate (60-69), or critical (0-59). In Figure 6-22, we can find that the performance of a bridge becomes inadequate after 30 years of operation. Especially its *Essentiality_for_Public_Use* reaches 0 around the 40th year while its structural condition is still relatively acceptable. The renewal regulation and the steady growth of traffic flow exceed the capability of the existing bridge prior to a general bridge design service life.

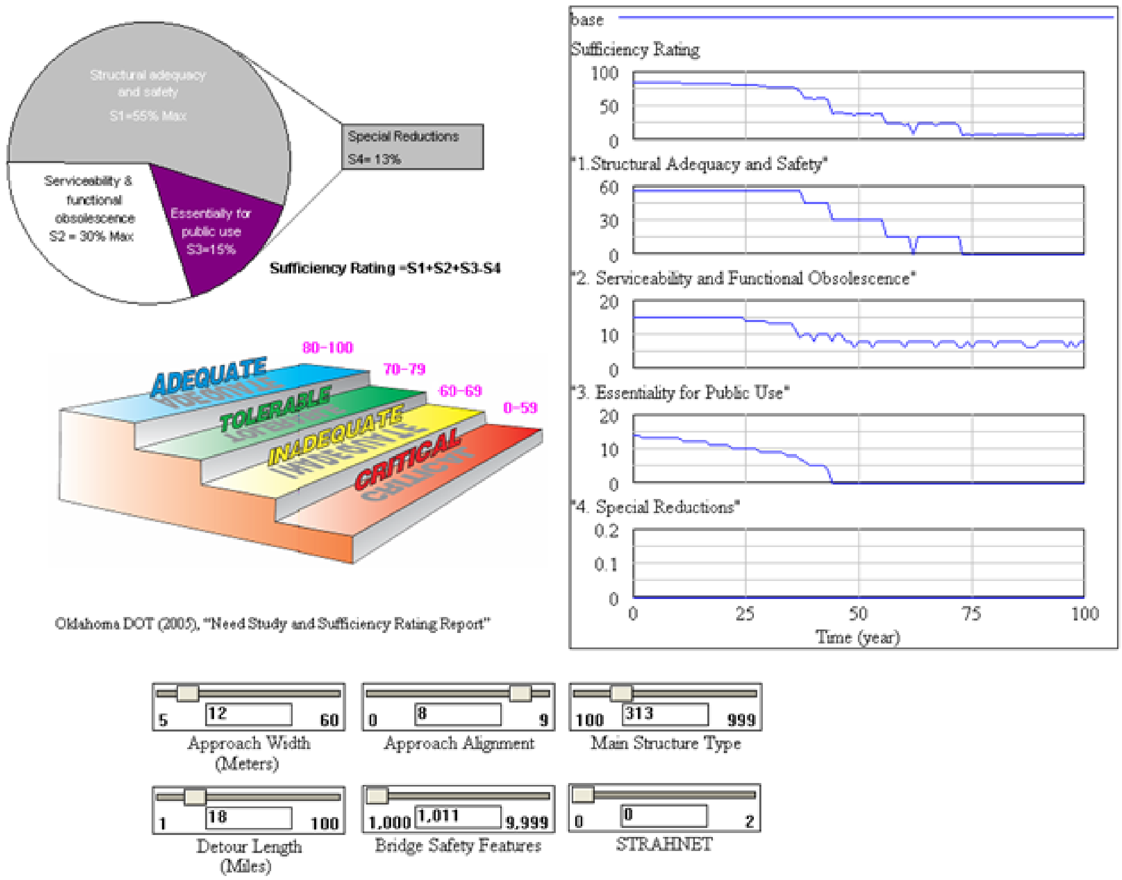


Figure 6-22, Bridge Sufficiency Rating (Base Scenario)

Bridge performance can be measured from different point of views. Figure 6-23 emphasizes the function deficiency, such as *Deck_Geometric_Rating* and *Load_Capacity_ Deficiency*. *Gap1-Expectation_Deficit* increases with increasing service expectation, while *Gap 3-Remaining_Service_Balance* decreases with deteriorating condition.

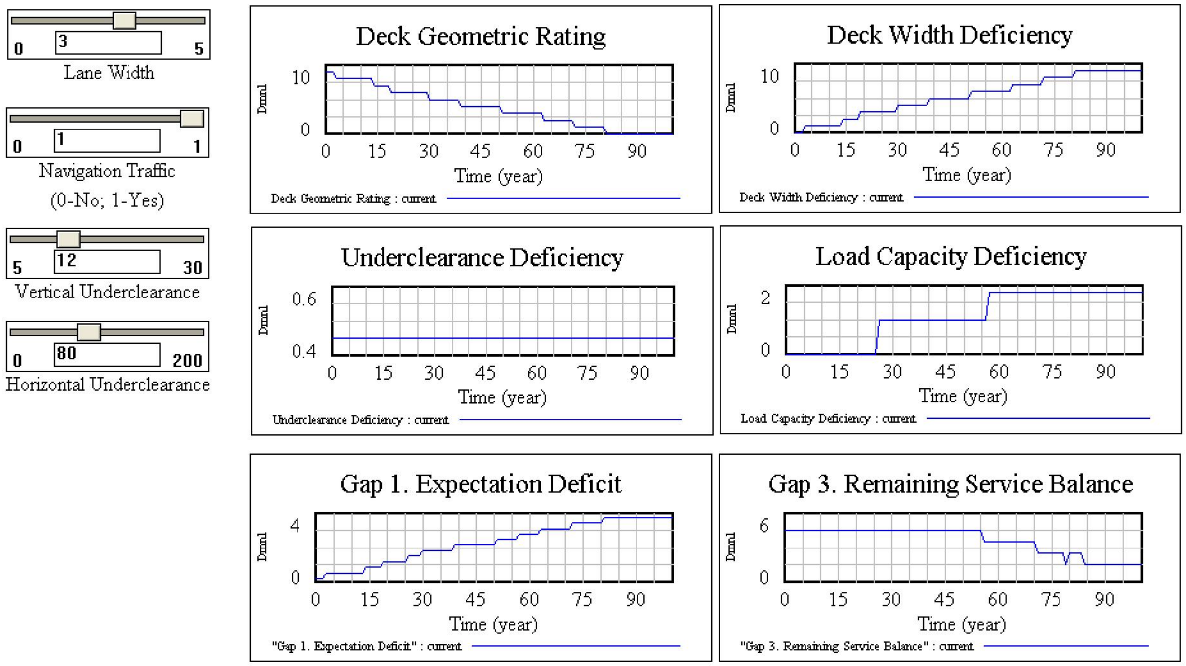


Figure 6-23, Highway Bridge Performance Evaluation (Base Scenario)

Figure 6-24 graphically illustrates bridge performance according to the Infrastructure Performance Theory.

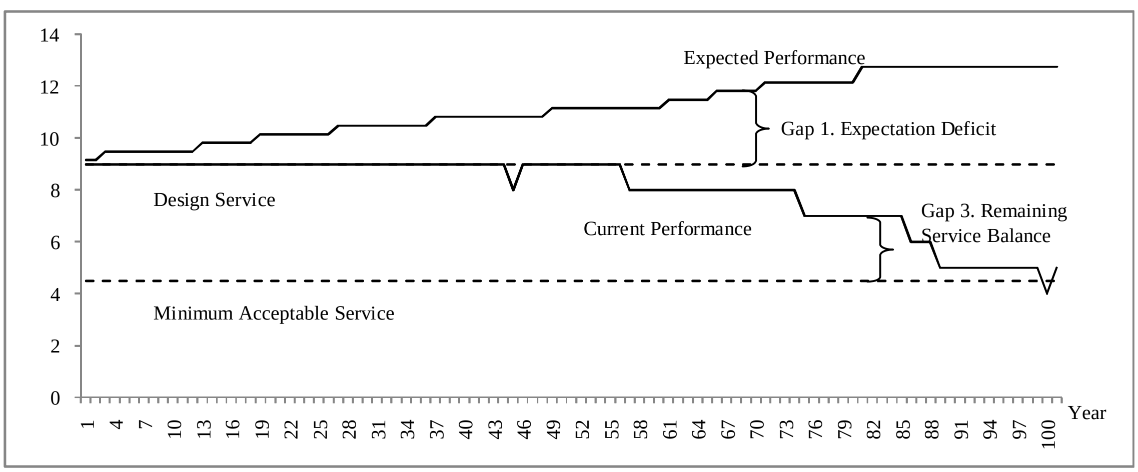


Figure 6-24, Highway Bridge Performance Curves (Base Scenario)

Bridge performance evaluation requires information from modules that reflect service supply and demand. Thus, its result mainly depends on outputs from other modules. Here, several new parameters are listed separately for the purpose of a complete calculation.

Adjusting these parameters will also change the module result. For example, Scenario ***A*** is a situation in which the bridge of interest has a shorter *Detour_Length* from 18 miles (base scenario) to 1 mile. In Figure 6-25, this makes a big difference for *Essentiality_for_Public,* since traffic has a smaller dependence on the bridge of interest. But *Detour_Length* has no relation with physical condition and function of the bridge of interest.

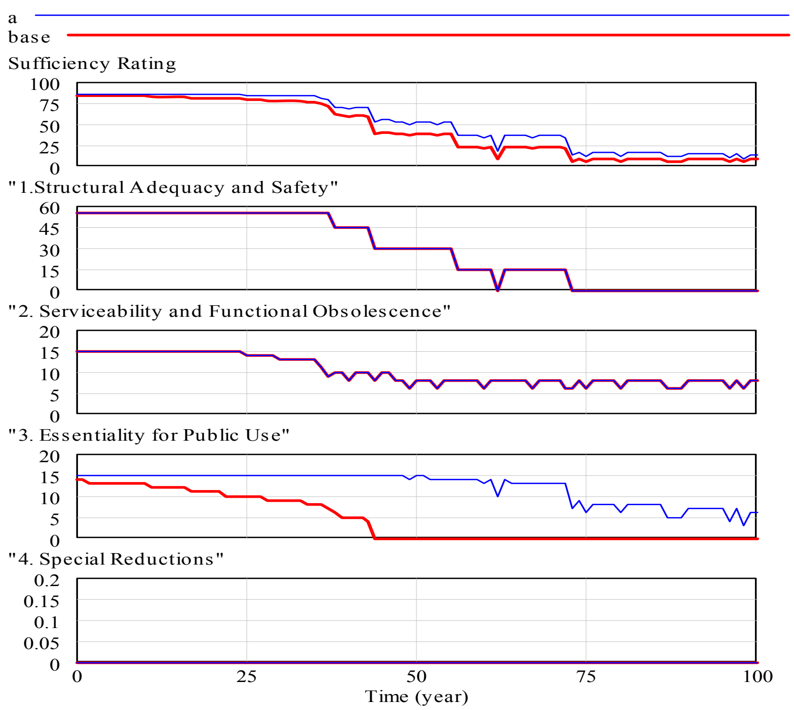


Figure 6-25, A Shorter *Detour_Length* (Scenario *A*)

To test the gap measures, Scenario ***B*** defines a wider *Lane_Width.* This reduces *Gap1-Expectation_Deficit.*

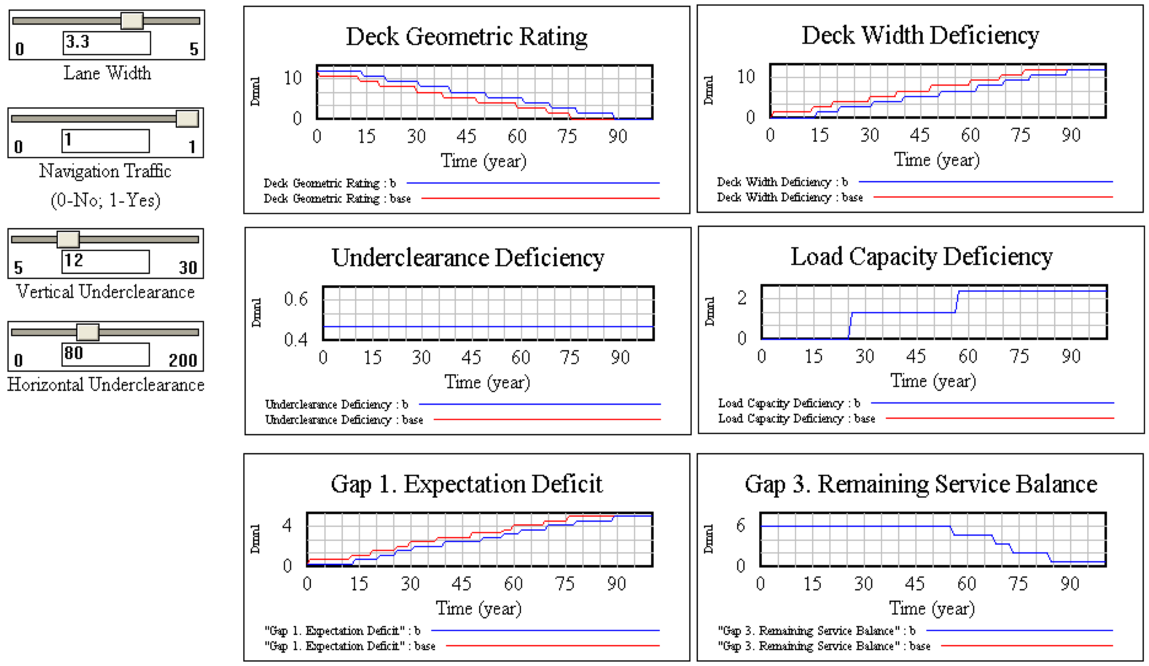


Figure 6-26, A Wider *Lane_Width* (Scenario *B*)

Appendix D gives face validity tests of all other modules.

6.8 Summary

Simulation is a powerful instrument to obtain result that is difficult for an analytical solution. The working model presented in this research captures the uncertainties in multiple systems and builds causal relations among engineering, socioeconomic, and political areas. This can challenge the reliability of the model is very challengeable. Therefore, a systematic validation and verification procedure was necessary for model credibility by checking assumptions, clarifying model structure, testing parameters, reducing variability, and calibrating if necessary. Through this process, the model prototype has achieved a well defined structure and credibility for case analyses.

7. CASE ANALYSES

A valuable system dynamics model requires suitable system assumptions, proper model structure and causal loops, and appropriate parameter values. The more complex and contextualized the objects of research, the more valuable the case analysis approach is regarded to be. As the last step of research design, case analyses not only test the model but also provide an opportunity to calibrate the model assumptions, structure, and parameters for greater credibility.

The system dynamics model is calibrated with background and historic data that are collected from a variety of sources: questionnaires to the bridge agency[8], archived documents, published literature, related research, and online information. Multiple sources are used simultaneously to reduce bias commonly introduced by a single source.

Three bridges are selected for their close connections with urban economics: the Williamsburg Bridge, the Woodrow Wilson Bridge, and the St. Anthony Falls Bridge. These critical links carry substantial traffic for commuters and long distance travels. With dramatic traffic increase, they have changed from convenient crossings to bottlenecks during local rush hours. Decisions regarding expansion, modernization or restoration efforts, however, can take many years since they are complicated by economic, financial, and sociopolitical issues. The Williamsburg Bridge had to accommodate faster and heavier motor vehicles than originally envisioned, so continuous upgrade of its loading capacity and other functions was necessary. After nearly one century of service, the NYCDOT decided to rehabilitate this vintage structure in lieu of building a new crossing. The Woodrow Wilson Bridge became problematic since its opening to public. Experienced an accelerating fatiguing rate, it was ultimately rebuilt after only four decades. Replacing the previous collapsed structure, the St. Anthony Falls Bridge was designed with a service life of 100 years.

Each case analysis is basically conducted in three steps. The first step is the synthesis of

[8] Appendix F is the questionnaire sent to the bridge management within which the content will be adjusted to refer the bridge in case.

background material regarding the bridges including operation and maintenance information. The second step tests the model's performance with the case history retrospectively. The last step conducts scenario analysis to observe the future of each bridge using various parameter values. A base scenario is run for each case, which extrapolates past conditions into the future. Additional scenarios are also run to assess the impact of changes in particular parameter values. This final step provides an indication of the value of the system dynamics model for decision-makers to conduct parametric or "what-if" analysis.

Three cases serve different purposes. In the first case, the Williamsburg Bridge, historic data is available on both service supply and demand sides. This allows more thorough calibration to simulate both sides well. In the second and third cases, the Woodrow Wilson Bridge and St. Anthony Falls Bridge, respectively only limited historic data is available. The model requires additional assumptions and results from other work to replicate missed information for simulation. The first case validates the model structure and functions, while the second and third cases demonstrate how to conduct parametric analyses for highway bridges with limited information.

7.1 Case Analysis 1 – The Williamsburg Bridge

7.1.1 Background of the Williamsburg Bridge

Connecting Manhattan with Brooklyn, the Williamsburg Bridge is one of the four East River crossings that carry traffic flow in the New York City metropolitan area. It was built over 7 years at a cost of $24.2 million dollars and was officially opened to traffic on December 19, 1903. With a total length of 2,227 meters (7,308 feet), it was been the world's longest suspension bridge for 17 years and doubled the load-carrying capacity of the Brooklyn Bridge. The bridge designer, Leffert L. Buck (1837-1909), had a philosophy that traffic should adapt itself to a bridge (Griggs, 2000). A traffic conflict to challenge his theory did not exist when the Williamsburg Bridge opened. Buck did not anticipate later traffic modal change along with increasing traffic flow. Now, the bridge is experiencing very high loads of 140,000 vehicles per day composed of automobiles and heavy trucks.

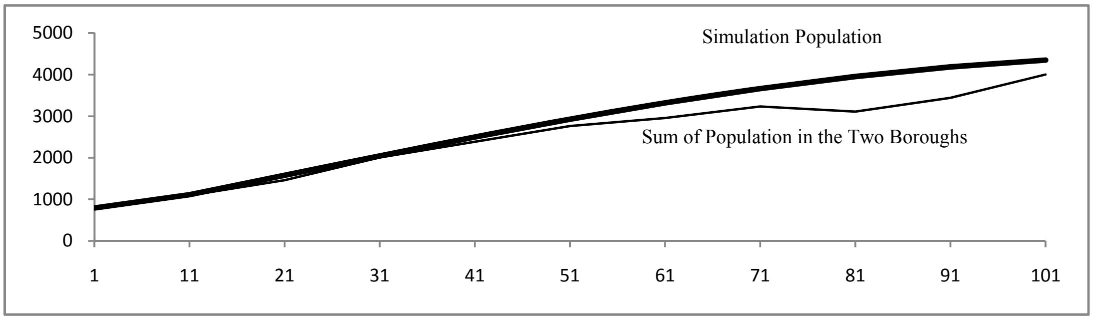
The first complete inspection of this bridge did not occur until the Federal government launched a comprehensive bridge inspection program about 80 years after its opening. During this inspection, localized corrosion was found in the steel members below the deck which led to the replacement of the cantilever floor beams, stringers, and deck in the outer roadways of the main span. Later inspection discovered extensive deterioration of the steel girders where structural conditions required immediate attention. The bridge was closed first for a period as emergency repairs were made. During this time, the city government decided to rehabilitate bridges of this type as opposed to replacing them in general, even if rehabilitation costs were to approach replacement costs.

7.1.2 Model Calibration for the Williamsburg Bridge

In each case analysis, the model prototype is initiated with available historic data to generate time series corresponding to these references. Necessary assumptions are made to estimate other parameters where accurate data is unavailable. The model was first run retrospectively to implement model V&V. Discrepancies were identified to calibrate assumptions, parameters, or even model structure to achieve acceptable simulation credibility with an iterative procedure as introduced in the research design. Calibration still follows basic principles to be consistent and universal for most types of bridges without sacrificing the model's applicability to the individual case analysis.

7.1.2.1 Socioeconomic Factors

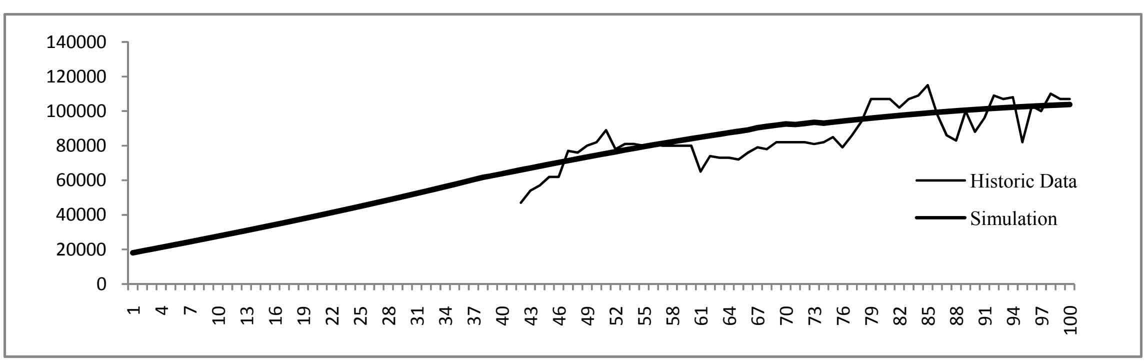
To predict service demand, the modeling process starts with the Socioeconomic Module. The Williamsburg Bridge is located on the East River between Manhattan and Brooklyn. Manhattan has the central business district with more commercial area and work opportunities that attract travel from Brooklyn which comprises primarily residential communities. With the construction of the Williamsburg Bridge, Brooklyn benefited from convenient traffic to the business area and more people moved there for lower living costs and reasonable travel distances. Figure 7-1 illustrates the simulation result of population over the past 100 years compared to historic data.



Correlation Coefficient = 0.986

Figure 7-1, Population in the City of Past 100 Years, Data from Gibson (1998) and U.S. Census Bureau

Along with population boom and economic development in the city, the traffic also dramatically increased. Due to land space limit, such increases did not behave as a linear curve. Traffic volume prediction in this research uses the four step method with model generating intermediate variables, such as *Gross_City_Product*, *Number_of_ Household*, *Household_Income, Motorization_Rate, Commercial_Area,* and utilities of main traffic modes for the prediction of *Passenger_AADT_on_the_Bridge_of_Interest* as well as *ADTT_on_the_Bridge_of_Interest* to sum up the *AADT_on_the_Bridge_of_Interest.*



Correlation Coefficient = 0.789 (for the most recent 60 years)

Figure 7-2, Simulated *AADT_on_the_Bridge_of_Interest* for the Past 100 Years

With calibration of both the Passenger Traffic Demand and the Freight Traffic Demand modules, the model generates reasonable traffic volumes on the bridge of interest as depicted in Figure 7-2. The model is not able to capture the fluctuation in historic data since the model is designed to estimate the general trend as opposed to periodic deviations. For the purpose of performance evaluation, the projected line follows the main trend of future traffic demand with a correlation coefficient at 0.789 for the most recent 60 years.

7.1.2.2 Deterioration and Obsolescence of the Williamsburg Bridge

The NYCDOT computes an overall bridge condition by combining the ratings of individual components using a weighted average formula. This formula assigns higher weights to the ratings of the bridge elements with the greatest structural importance and lesser weights for minor structural and non-structural elements. To standardize such a computation, the importance weights are assumed as their replacement cost percentages of each subsystem as the weight coefficient to calculate the overall condition rating. Historically, the same types of bridges in the city were analyzed. Figure 7-3 is a roughly defined deterioration curve adjusted from the steel bridge condition in the city (Yanev, 1998).

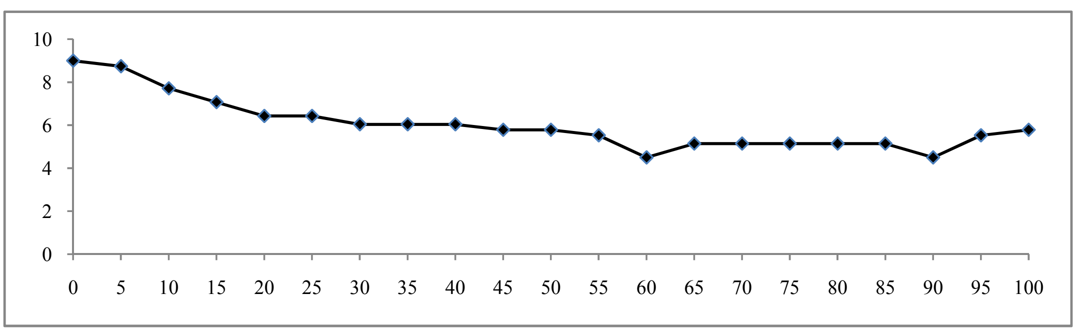


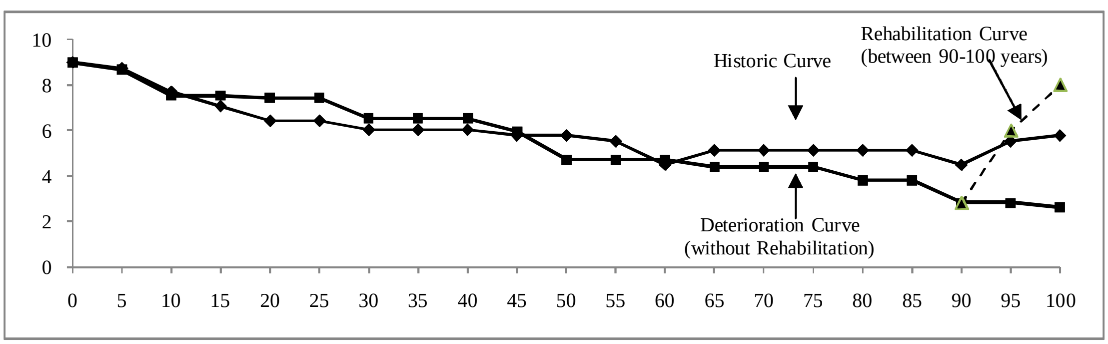
Figure 7-3, Condition Rating in the First 100 Years of Bridge Age in the City

Based on this condition rating curve and other historic records of the Williamsburg Bridge, the transition matrix can be estimated to apply Markov chain to simulate bridge physical deterioration. Table 7-1 lists the diagonal entries in the transition matrixes.

Table 7-1. Transition Matrix Entries of the Williamsburg Bridge's Subsystems.

General	Decking/ Roadway (10%)	Superstructure (57%)	Substructure (33%)
9	0.91	0.92	0.93
8	0.91	0.93	0.95
7	0.93	0.94	0.95
6	0.93	0.94	0.97
5	0.93	0.94	0.96
4	0.93	0.96	0.97
3	0.93	0.95	0.97
2	0.93	0.95	0.97
1	0.93	0.95	0.97
0	1.0	1.0	1.0

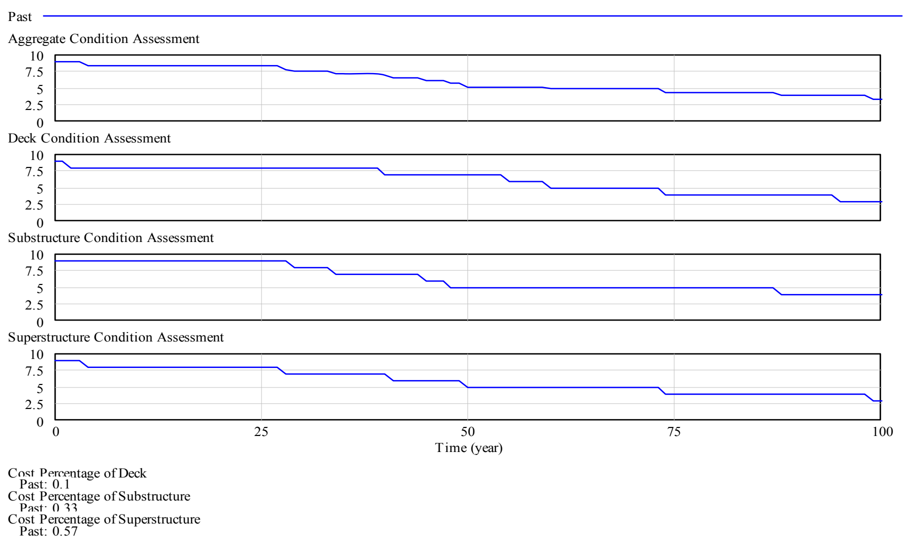
Before running the model, a step by step manual computation first tests the methodology. Figure 7-4 illustrates both the historic curve and manual calculation result of deterioration by employing the Markov chains. The correlation coefficient between them is 0.843, which indicates the transition matrices are well defined. Other than the algorithm of deterioration, rehabilitation of the bridge is a result of MR&R decision. The dash curve depicts the bridge back to a good condition after rehabilitation. Combined the Markov chains and MR&R decision, the method is a competent tool to simulate physical condition of a bridge of interest.



Correlation Coefficient = 0.843
(Between the Historic Curve and the Deterioration Curve without Rehabilitation)

Figure 7-4, *Aggregate_Condition_Rating* of the Williamsburg Bridge over the Past 100 Years

The system dynamics model uses the same transition matrixes in its Physical Condition Module to generate deterioration curves. Unlike tabulated calculation, MR&R activities in the Maintenance Module are intermediate model results instead of model inputs. Therefore, appropriate maintenance and repair activities generated by the model are critical factors in the simulation result of physical condition. By default, rehabilitation requires serious decision and particular parameter adjustment. Especially for this case, rehabilitation is not economic compared with a brand new bridge.



Correlation Coefficient = 0.825
(Between the Historic Curve and the Simulation Curve without Rehabilitation)

Figure 7-5, Simulated Physical Condition without Rehabilitation

Without the overall rehabilitation in the later stage, the three main subsystems, deck, superstructure, and substructure are separately calculated and combined together for the *Aggregate_Condition_Assessment* as depicted in Figure 7-5. The correlation coefficient between the historic data and simulation result is 0.825. The model can simulate the Williamsburg Bridge's deterioration reasonably.

The performance of the Williamsburg Bridge can be comprehensively measured by *Sufficiency_Rating* in terms of *Structural_Adequacy_and_Safety*, *Serviceability_and_ Functional_Obsolescence*, *Essentiality_for_Public_Use*, and *Special_Reductions*. Figure 7-6 illustrates *Sufficiency_Rating* of the bridge over the past 100 years. The parameters used in the calculation are based on the current NBI information and historical data.

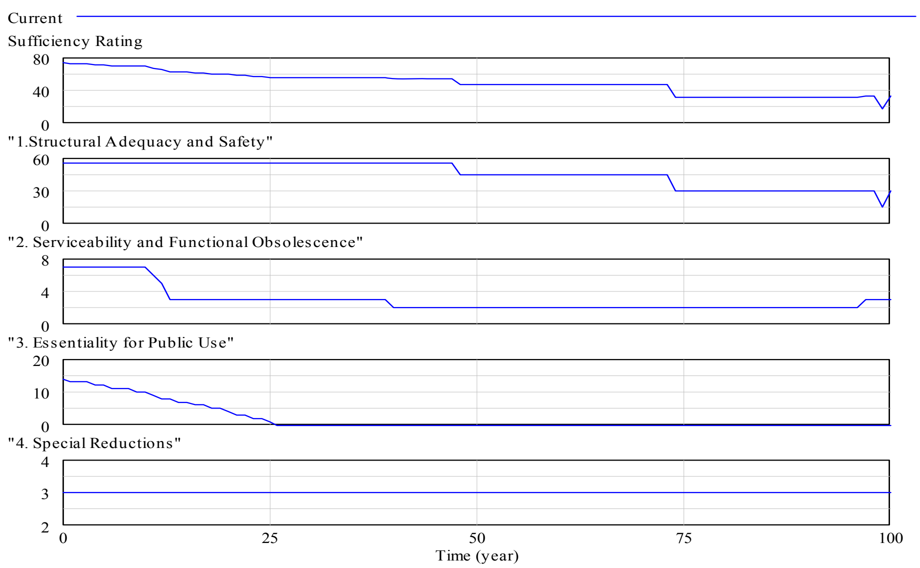


Figure 7-6, Sufficiency Rating of the Williamsburg Bridge in the Past 100 Years

According to modern standard, the Williamsburg Bridge became critical (when *Sufficiency_Rating* <60) quite early after 20 years as depicted in Figure 7-6. There are two reasons contributed to this result. First, the bridge's performance rating is defined with current standard based on modern vehicle speed, weight, safety, etc. These standards are not appropriate for earlier stages in this bridge's life when the traffic modes were quite different. Therefore, *Sufficiency_Rating* is an over rigorous measure for the Williamsburg Bridge in its early time of service. Second, the Williamsburg Bridge really experienced heavy traffic since its opening. This can be observed from its recent sufficiency rating which keeps at a very low level.

7.1.3 Scenario Analysis for the Williamsburg Bridge

By testing in a retrospective way, the model has been calibrated from a prototype to a specific one for this case analysis with specific demographic, geographic and engineering information. The next step aims to test how the bridge performs and apply the model as a prognostic decision support system.

Table 7-2, Upgrade of the Williamsburg Bridge around the 100th Year, Data from NBI by FHWA

NBI Items \ Year	2000	2201	2002	2003	2004	2005	2006	2007
Bridge Roadway Width Curb-To-Curb (xxx.x meters)	0221	0221	0221	0232	0232	0232	0232	0232
Deck Width, Out-To-Out (xxx.x meters)	0364	0364	0364	0356	0356	0356	0356	0356
Deck (4- Poor condition; 5- Fair condition; 9- Excellent condition)	4	5	5	9	9	9	9	9
Superstructure (3-Serious condition; 4- Poor condition; 5- Fair condition; 6- Satisfactory condition; 8- Very good condition)	3	4	4	8	8	5	5	6
Substructure (5- Fair condition; 7-Good condition; 8- Very good condition)	5	5	5	7	7	7	7	8
Operating Rating (xx.x metric tons)	48.9	48.9	48.9	48.9	49.9	49.9	49.9	51.2
Structural Evaluation (2- Basically intolerable requiring high priority of replacement; 3-Basically intolerable requiring high priority of corrective action; 5- Somewhat better than minimum adequacy to tolerate being left in place as is)	2	2	2	2	3	3	3	5
Deck Geometry (2- Basically intolerable requiring high priority of replacement)	2	2	2	2	2	2	2	2
Underclearance, Vertical & Horizontal (2- Basically intolerable requiring high priority of replacement; 3-Basically intolerable requiring high priority of corrective action)	2	2	2	2	3	3	3	3
Approach Roadway Alignment (3-Basically intolerable requiring high priority of corrective action; 8-Equal to present desirable criteria)	3	3	3	8	8	8	8	8
Deck Structure Type (1-Concrete Cast-in-Place; 4-Closed Grating)	1	1	1	4	4	4	4	4

Rehabilitation brought the Williamsburg Bridge back to generally good conditions for each subsystem after a decade-long rebuilding. Selected NBI records in Table 7-2 show the improvement of the bridge subsystems. The deck had an excellent condition. Both the superstructure and substructure had good conditions. The traffic safety features, such as bridge railings, transitions, approach guardrail, approach guardrail ends, were all upgraded to current standards. The bridge roadway width and deck width increased due to the elimination of the side walk, but it is not wide enough to improve the deck geometry evaluation. Subsystems of decking, superstructure, substructures all were enhanced. The approach roadway alignment requires no more speed reduction.

The bridge agency hoped this rehabilitation could extend the bridge for another 50 years of service. This section will examine this expectation by running various scenarios. The base scenario will extrapolate past conditions to determine whether or not the expected service life of 50 year following rehabilitation is feasible.

To predict the Williamsburg Bridge's performance in future 50 years, the model needs to set up parameters for future. This case analysis conducts three scenarios. The base scenario neutrally predicts what will happen by keeping all parameters same. Scenario ***A*** pessimistically predicts future performance by assuming certain severe change on demand side. After rehabilitation, the bridge may attract more local and long distance traffic. *External_Freight_Traffic_Ratio* illustrates the ratio between the long distance freight traffic and local freight traffic. In this scenario, the parameter assumes a higher value than the base case for heavier freight traffic on the bridge. Scenario ***B*** optimistically predicts future performance with a better maintenance policy. *Thershold_of_Preventive_Maintenance* increases from 2 to 4, which indicates a proactive maintenance on the bridge. Table 7-3 listed the critical demand variables and managerial variables in the scenario analysis for the bridge.

Table 7-3, Scenario Analysis for the Williamsburg Bridge

Parameters	Base Scenario	Scenario *A*	Scenario *B*
Population (in the starting year)	4 million	4 million	4 million
AADT (in the starting year)	100,000	100,000	100,000
External_Freight_Traffic_Ratio	0.5	1.0	0.5
Threshold_of_Preventive_Maintenance	2	2	4
Enforcement_Level_of_TS&W_Regulation	0.7	0.7	0.7
Load_Safety_Factor	1.3	1.3	1.3
Ratio_of_Divisible_Load_to_Non-Divisible Load	0.2	0.2	0.2

Figure 7-7 gives *Sufficiency_Rating* as the performance evaluation under the base conditions. Rehabilitation pushed the Williamsburg Bridge back to a good *Structural_ Adequacy_and_Safety,* which has about 40 years of acceptable conditions of its structure. Unfortunately, the bridge fails to meet the overall *Sufficiency_Rating* with such rehabilitation mainly because the *Serviceability_and_Functional_Obsolescence* does not benefit too much from rehabilitation.

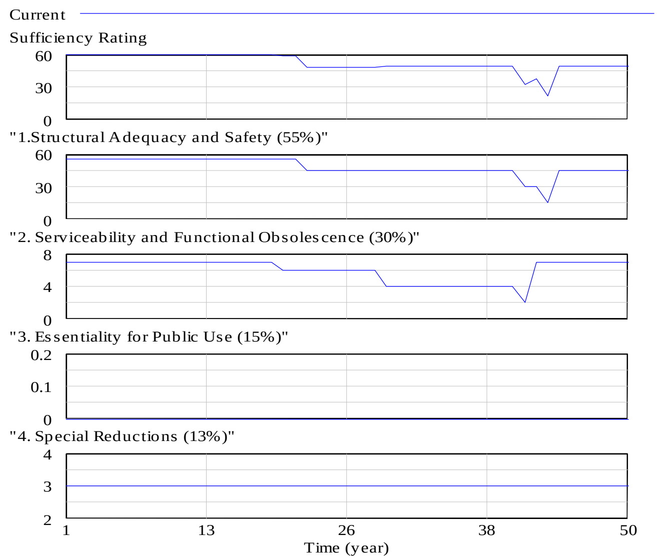
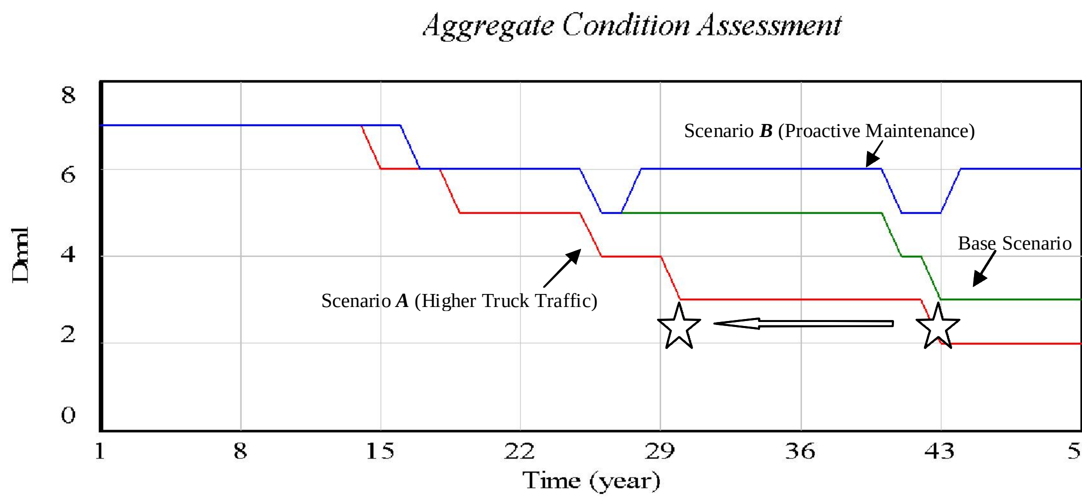


Figure 7-7, Sufficiency Rating of the Williamsburg Bridge in the Next 50 Years

A worse scenario could be the result of various circumstances. For instance, the legal truck load may increase due to NAFTA. Heavier freight traffic can increase fatiguing rate on the bridge structure and shorter its service life. In Scenario ***A***, The model assumes the *External_Freight_Traffic_Ratio* from 0.15 to 0.5 and compares the base scenario and worse scenario in Figure 7-8. The result shows that the overall bridge condition becomes 3, about 10 years earlier with increasing heavy truck weight.

As an old facility, bridge agency should pay more attention to keep it continuously in a good condition. Proactive maintenance is necessary for the Williamsburg Bridge in the next 50 years. In Scenario ***B***, proactive maintenance requires a higher *Threshold_of_Preventive_ Maintenance* along with a good budget for monitoring and repairing the bridge if necessary. By setting up the threshold as 4, the bridge will be repaired immediately back to at least a fair condition.



Results	Base Scenario	Scenario *A*	Scenario *B*
Physical_Life	43	31	>50
Service_Life	-	-	-
LCC	$168 Million	$200 Million	$258 Million
NPV_LCC	$25.4 Million	$25.5 Million	$25.9 Million

Figure 7-8, Three Scenarios in the Next 50 Years

Findings in simulation of the next 50 years: Rehabilitating the Williamsburg Bridge gave the bridge a better physical condition that all subsystems restored back closely to "Good". By assuming the same deterioration transit matrixes (decking has a better one), the bridge can stand for an acceptable structure integrity under normal traffic for about 40 years. AADT has reached a stable level due to the saturated urban density. However, the freight traffic presents a growing percentage among the total traffic. Additionally, the situation gets worse with a potential changed TS&W regulation. According to SR, the bridge remains a poor *Sufficiency_Rating* mainly due to the high traffic volume that very low *Serviceability_and_Functional_Obsolescence*, and *Essentiality_for_Public_Use*.

A potential conclusion from this case analysis is that the vintage value of the Williamsburg Bridge is significant so replacing it is not necessarily an option. The decision to rehabilitate is more about keeping an urban icon than achieving a better local transportation. And the bridge is not able to stand for another 50 years due to its poor *Sufficiency_Rating* and need for another massive rehabilitation after 40 years.

7.2 Case Analysis 2 – The Woodrow Wilson Bridge

7.2.1 Background of the Woodrow Wilson Bridge

The Woodrow Wilson Bridge (WWB) spans the Potomac River between the cities of Alexandria, Virginia and Oxon Hill in Prince George's County, Maryland. The bridge is one of only a handful of drawbridges in the U.S. Interstate Highway System, and contains the only portion of the Interstate system that is owned by the federal government. The WWB carries the Capital Beltway as one of the seven highway bridges crossing the Potomac River. The old WWB Bridge was built in 1961 with 6 lanes and 5,900 feet length. A bascule drawspan for water traffic could release the 50 feet vertical navigational clearance. As a critical link in the Washington, D.C. metropolitan area, it was notorious as one of the biggest bottlenecks on one of the most heavily used interstates in the nation, even worse when the drawspan opened. The lightweight WWB was not anticipated to become a major commuter route for local residents and I-95 was planned to travel through the District of Columbia. It was decided that constructing an interstate through the heart of Washington DC would be too disruptive to existing neighborhoods and this portion of the highway was never built that left the WWB to forever handle long distance traffic.

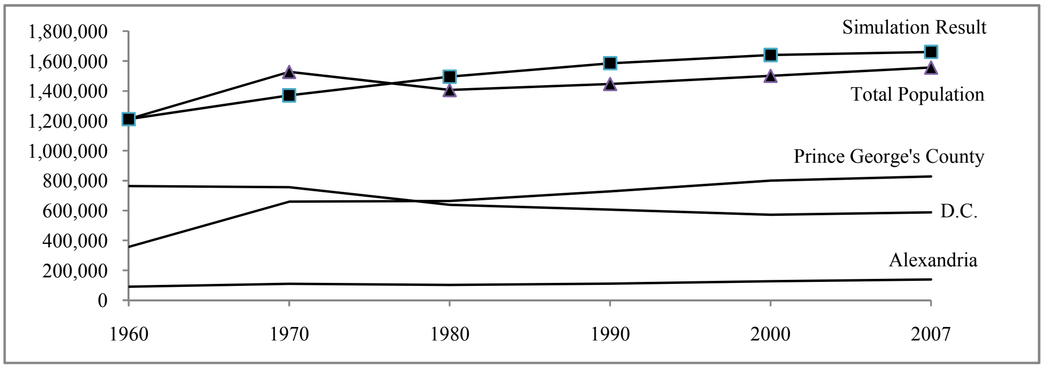
At its debut, the ADT on the bridge was about 47,900. Only after 8 years, the WWB began to carry more traffic than its design capacity of 75,000 vehicles per day. At the same time, Interstate 95 was widened from 6 to 8 lanes for higher traffic, which aggravated the WWB's insufficient performance. After 40 years of service, traffic on the roadway increased to around 203,000, nearly triple the bridge's design capacity. It also experienced nearly twice the accident rate of similar highways than average number in Maryland and Virginia (USDOT, 1999). Even worse, the maximum legal truck loads permitted on highways were significantly higher than its design load HS20. The bridge vibrated too hard and too often, which substantially accelerated its deterioration rate.

Narrow deck width, limited underclearance, and lower loading resistance are three main reasons that led to an unacceptable performance and substantially shortened its design service life. To alleviate the congestion, a new bridge was constructed to enhance mobility while addressing community and environmental concerns. The new crossing was designed with total 12 lanes and HS25 design load, 125% of the current standard highway design. It is expected to accommodate an ADT of 300,000. The underclearance has also increased from 50 feet to 70 feet that results in approximately 70% (from 260 times to 60 times per year) fewer openings and associated traffic delays.

7.2.2 Model Calibration for the Woodrow Wilson Bridge

7.2.2.1 Socioeconomic Factors

On the demand side, the demographic and business characteristics explain the local commuting traffic pattern. Located along the western bank of the Potomac River, Alexandria is approximately 6 miles (9.6 kilometers) south of downtown Washington, D.C. Like the rest of Northern Virginia, as well as central Maryland, modern Alexandria has been shaped by its proximity to the nation's capital. It is largely populated by professionals working in the federal civil service, the U.S. military, or for one of the many private companies which contract to provide services to the federal government. As of the 2000 census, the city had a total population of 128,283. A 2005 assessed-value study of homes and condominiums found that over 40 percent were in the highest bracket, worth $556,000 or more. The average family size was 2.87. The per capita income for the city was $37,645. Commuting travel between Alexandria and Washington DC contributes to the traffic during the rush hour. The Prince George’s County also attracts traffic from the eastern side of the bridge.



Correlation Coefficient = 0.736 (Between Historic Population and Simulation Result)

Figure 7-9, Total Population in the Three Urban Areas, Data from U.S. Census Bureau

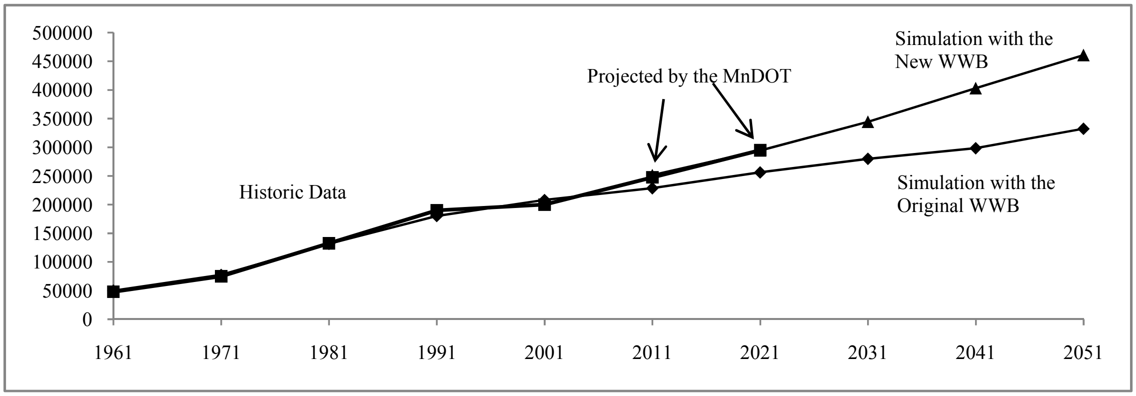
Figure 7-9 illustrates that total *Population* of the three urban areas has grown from 1.2 million to 1.5 million. The simulation result has a correlation coefficient 0.736 with the historic data.

In the past, *AADT_on_the_Bridge_of_Interest* exhibited a higher increasing rate than *Population* because *Household_Income, Motorization_Rate,* and larger commercial areas increased simultaneously. Additionally, statewide traffic also took a good portion of total traffic. The model is calibrated to incorporate these triggers to simulate the traffic volume on the WWB. As for this critical link for crossing the Potomac River, the improved facility capacity may incur more traffic in the long term. As a comparison, the model is run with both the original WWB and the new one for future traffic demand prediction.

Table 7-4, ADTT on the WWB (Simulated with the Original and New Structure)

Year	ADTT on the WWB	Simulation with the Original Structure	Simulation with the New Structure
1st	47900	49919	
11th	75000	77535	
21st	132500	131799	
31st	190000	180164	
41st	200000	208103	
51st	247500 (DOT Projection)	228663	251466
61st	295000 (DOT Projection)	256207	294558
71st		279994	344623
81st		298421	403343
91st		332395	461077

Table 7-4 lists the historic traffic and two projected traffic volumes on the 50th and 60th year by the bridge agency.



Correlation Coefficient = 0.995 (from 1961 to 2002)

Figure 7-10, Traffic on the WWB

With the congestion relieved by the new bridge, traffic volume continuously increases by attracting more vehicles. The system dynamics model reflects this change in its four step model by adjusting the LOOKUP, *Assigned_Traffic_Volume_to_the_Bridge_of_ Interest*. As illustrated in Figure 7-10, the future traffic volume with the new WWB keeps the past trend to future.

7.2.2.2 Bridge Deterioration and Obsolescence

In Table 7-5, the NBI data gives the basic information of the WWB before its rebuilding. With an allowable load at HS-20, the original the WWB was never posted. Although it required permits for heavy trucks, the bridge agency has not recorded the number of permits issued and the percentage of over load trucks. The old structure suffered a high fatiguing rate which resulted in poor conditions of all subsystems.

Table 7-5, Selected NBI Records of the Old WWB from 2000 to 2006

NBI Items \ Year	2000	2001	2002	2003	2004	2005	2006
Bypass/Detour Length (199-Structure on the dead end road)	199	199	199	199	199	199	199
Design Load (6-HS20)	6	6	6	6	6	6	6
Approach Roadway Width (xxx.x meters)	0338	0338	0338	0338	0338	0338	0338
Navigation Vertical Clearance (xxx.x meters)	0152	0152	0152	0152	0152	0152	0152
Navigation Horizontal Clearance (xxx.x meters)	0533	0533	0533	0533	0533	0533	0533
Bridge Roadway Width Curb-To-Curb (xxx.x meters)	0254	0254	0254	0254	0254	0254	0254
Deck Width, Out-To-Out (xxx.x meters)	0268	0268	0268	0268	0268	0268	0268
Deck (7-Good condition, 6-Satisfactory condition)	7	7	7	7	6	6	6
Superstructure (4-Poor condition)	4	4	4	4	4	4	4
Substructure (6-Satisfactory condition)	6	6	6	6	6	6	6
Operating Rating (xx.x metric tons)	324	324	324	324	324	324	324
Inventory Rating (xx.x metric tons)	324	324	324	324	324	324	324
Structural Evaluation (4-Meet minimum tolerable limits to be left in place as it)	4	4	4	4	4	4	4
Deck Geometry (4-Meet minimum tolerable limits to be left in place as it)	4	4	4	4	4	4	4
Bridge Posting (5-Equal to or above legal loads)	5	5	5	5	5	5	5
Waterway Adequacy (Bridge deck and roadway approaches above flood water elevations, chance of overtopping is remote)	9	9	9	9	9	9	9
Approach Roadway Alignment (No speed reduction required)	8	8	8	8	8	8	8
Average Daily Truck Traffic (percent)	11	11	11	11	11	11	11
Scour Critical Bridges (Bridge foundations determined to be stable)	5	5	5	5	5	5	5

Table 7-6, Diagonal Values of the Transition Matrixes for Each Subsystem of the WWB

State	Deck	Superstructure	Substructure
9	0.90	0.95	0.95
8	0.92	0.95	0.96
7	0.92	0.95	0.97
6	0.92	0.95	0.96
5	0.92	0.95	0.96
4	0.92	0.95	0.96
3	0.92	0.94	0.96
2	0.92	0.90	0.92
1	0.93	0.90	0.92
0	1.0	1.0	1.0

The model is calibrated to reflect the deterioration of the bridge structure based on the NBI data and MR&R history. Around the 20th year, the old WWB was redecked. From both literature and questionnaire data from the bridge management, there is not numerical data available for the physical conditions in early years. Therefore, model calibration assumes that the deck was replaced when it reached a serious condition which was rated as 3. Table 7-6 gives diagonal entries of transition matrices for the three subsystems.

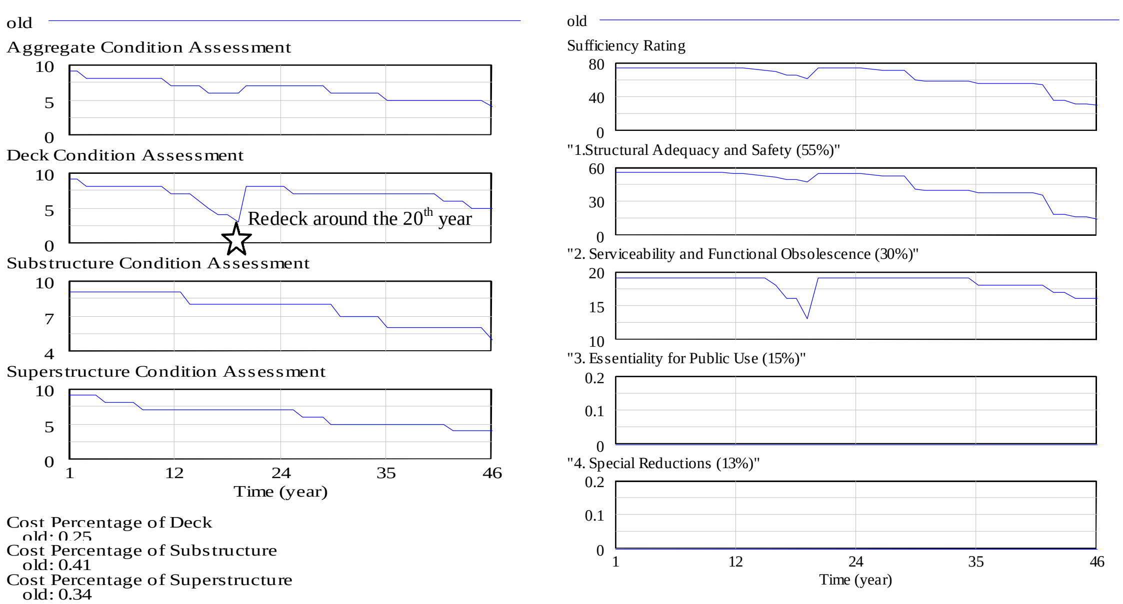


Figure 7-11, Condition and Sufficiency Rating of the Original WWB before Replacement

Figure 7-11 draws *Aggregate_Condition_Assessment* and *Sufficiency_Rating* of the original WWB before its replacement. *Sufficiency_Rating* reviews the performance and obsolescence since the bridge is opening. The original WWB becomes inadequate after 16 years of service. In the 20th year, the replacement of the deck system temporarily saved the bridge from a poor *Serviceability_and_Functional_Obsolescence*. With increasing traffic, the bridge performance still became critical about 10 years later.

7.2.3 Scenario Analysis for the New WWB

The original WWB itself has demonstrated one of the worst scenarios with its performance for about two decades. The new structure changed the situation by doubling the number of lanes with a design volume of 300,000 vehicles per day, increasing design load from HS 20 to HS 25, and expanding underclearance from 50 to 70 feet. Scenario analysis will test how the new WWB performs over its intended service life.

Table 7-7, Scenario *A* for the New WWB

Parameters	Base Scenario	Scenario *A*
Population (when new WWB opened)	1.55 million	1.55 million
AADT (when new WWB opened)	220,000	220,000
ADTT (*External_Freight_Traffic_Ratio*)	24,000 (0.5)	28,800 (0.8)
Threshold_of_Preventive_Maintenance	4	2
Enforcement_Level_of_TS&W_Regulation	0.3	0.3
Load_Safety_Factor	1.3	1.3
Ratio_of_Divisible_Load_to_Non-Divisible Load	0.2	0.2

In the base scenario, the parametric model extrapolates the past into future by incorporating the properties of the New WWB. Scenario ***A*** assumes a passive MR&R policy and higher truck traffic volume (*External_Truck_Traffic_Ratio* from 0.5 to 0.8) at the same time.

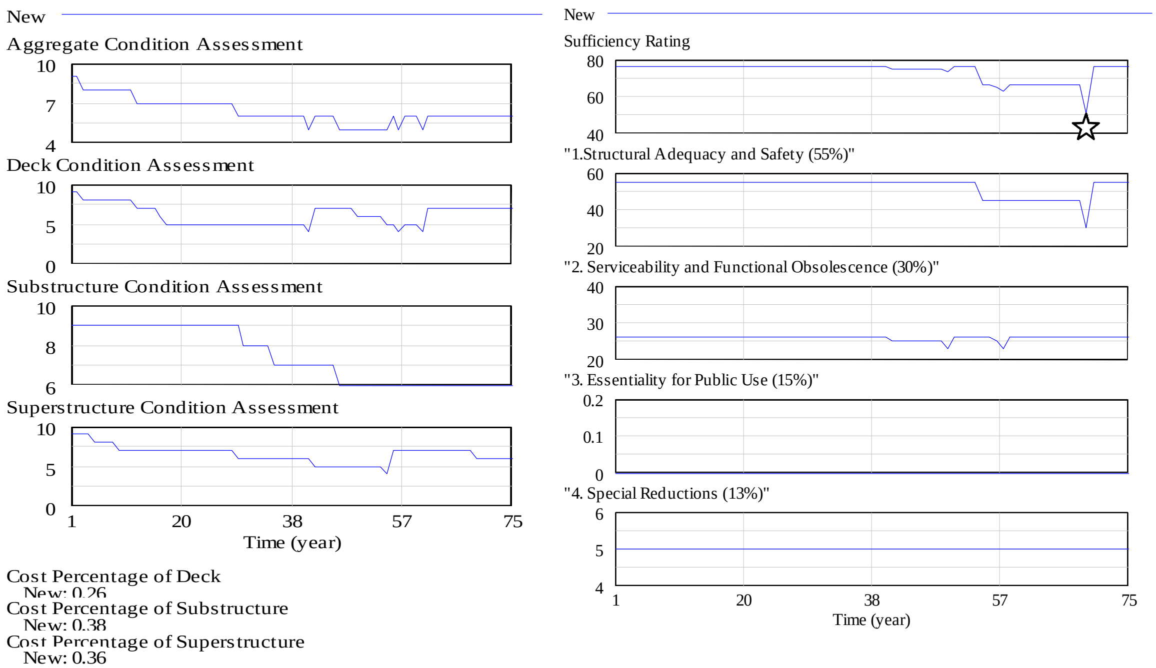


Figure 7-12, Base Scenario- Performance of the New WWB in the next 75 Years

Figure 7-12 illustrates both *Aggregate_Condition_Assessment* and *Sufficiency_Rating* of the new WWB for the next 75 years. Only until the year 69, the sufficiency rating becomes 51 that is lower than 60, a critical performance. However, it is mainly because *Structural_Adequacy_and_Safety* drops to a lower value. This requires the bridge management take extensive repair of the damaged structure to restore the lower condition to an acceptable level. *Serviceability_and_Functional_Obsolescence*, *Essentiality_for_Public_Use*, and *Special_Reductions* keep constant. Hence, the new WWB will only become critical by natural deterioration.

In the base scenario, the new WWB has already presented a good performance. However, it is valuable to test a worse scenario with combination of those critical factors.

Results	**Base Scenario**	**Scenario *A***
Physical_Life	>75	>75
Service_Life	69	54
LCC	$2.49 Billion	$3.62 Billion
NPV_LCC (Discount Rate=0.06)	$614 Million	$622 Million

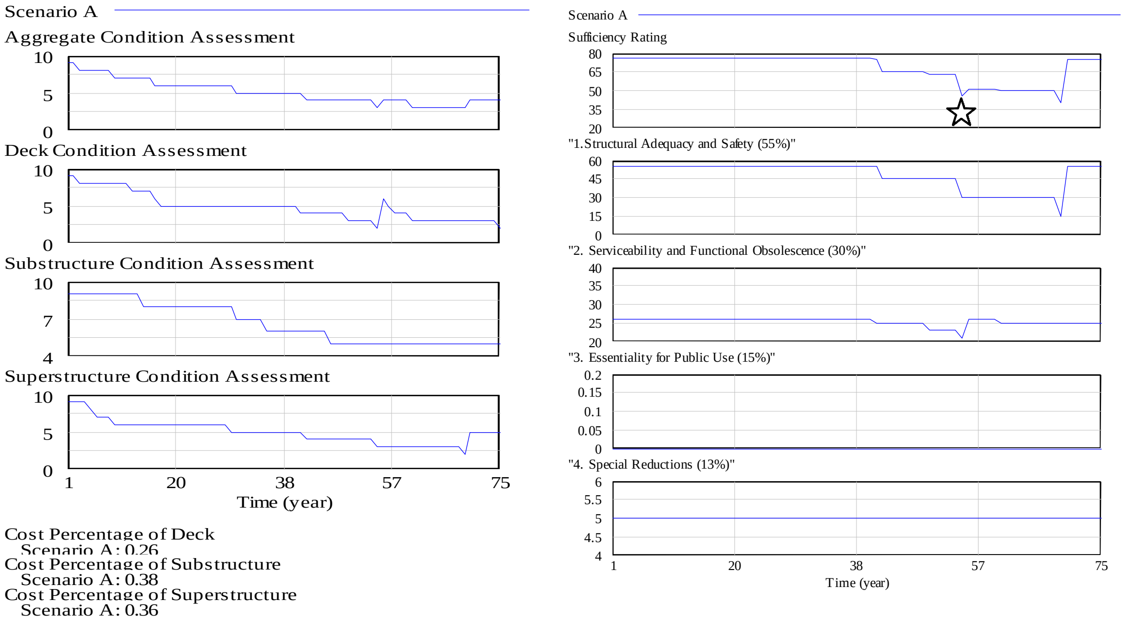


Figure 7-13, Scenario *A*- Performance of the New WWB in the Next 75 Years

As shown in Figure 7-13, the new WWB will require an extensive repair in the 54th year which is about 15 years earlier than the base scenario.

7.3 Case Analysis 3- the St. Anthony Falls Bridge

Responding to the tragic collapse of the I-35W Bridge in Minneapolis in August 2007, the new St. Anthony Falls Bridge reconnected I-35 over the Mississippi River within one year. It is a 1,216-foot-long, 10-lane precast concrete bridge supported by three land-based piers standing 70 feet tall. To predict performance of the new bridge, the model utilizes local socioeconomic information and historic traffic for the service demand and physical condition information from similar precast concrete bridges for the service supply.

7.3.1 Background of the I-35W Bridge

The I-35W Mississippi River Bridge (officially known simply as Bridge 9340) was an eight-lane steel truss arch bridge that carried I-35 across the Mississippi River in Minneapolis, Minnesota. The bridge was built in 1967 and maintained by the Minnesota Department of

Transportation (MnDOT). The bridge catastrophically failed during the evening rush hour on August 1, 2007, collapsing to the river and riverbanks beneath.

The bridge was designed and built during a time where the weight of trucks was less than what they are today. With four major revisions of the laws governing the weight limits on interstate highways, the chances are that the bridge was never properly updated structurally. To carry increasing traffic, the bridge has been expanded from original 4 lanes to 6, and eventually to 8 lanes by modifying its shoulders, while the substructure was kept same. The I-35W Bridge was rated safe for legal truckloads and permitted overweight truckloads of up to 136,000 lbs without an enforcement program. The National Transportation Safety Board (NTSB, 2008) suggested the failure of undersized, steel gusset plates was the probable reason I-35W Bridge buckled and then fell into the Mississippi River. The gussets used in the Minneapolis span were not structurally sound enough to meet safety margins even in the 1960s. Further repairs and renovations over the ensuing decades added even more weight and stress to the structure causing some of the gussets to snap finally.

7.3.2 Model Calibration for the St. Anthony Falls Bridge

7.3.2.1 Socioeconomic Factors

Minneapolis is the largest city in Minnesota and is the county seat of Hennepin County. The city lies on both banks of the Mississippi River, north of the river's confluence with the Minnesota River, and adjoins Saint Paul, the state's capital. The Twin Cities form the core of Minneapolis-St. Paul, the sixteenth-largest metropolitan area in the United States, with 3.5 million residents. The Minneapolis-St. Paul area ranks in the top 15th largest metropolitan economics in the U.S. According to the Bureau of Economic Analysis, it had \$128.06 Billion Gross Metropolitan Product (GMP) in 2001 which ranked 12th, and \$186.1 Billion GMP in 2007 which ranked 14th with \$53,708 per Capita GDP.

After the collapse of the I-35 bridge MnDOT responded by expanding Interstate 94 and converting Highway 280 into a limited access facility to cope with the traffic that would have normally used 1-35W. Tilahun and Levinson (2008) analyzed the travel impact after collapse of I-35 West Bridge and identified a wide range of influences from their survey. The impact resulted in additional congestion on the local and regional road system, with a daily road user cost of $400,000. Half of Minneapolis-Saint Paul residents work in the city where they live. Most residents drive cars but 60% of the 160,000 people working downtown commute by means other than a single person per auto. MnDOT's initial study concluded that road-user costs due to the unavailability of the river crossing would total $400,000 per day. In addition to the road user cost study, further analysis by MnDOT estimated the economic impact - or loss to Minnesota's economy – at about $17 million in 2007 and $43 million in 2008 (Tilahun and Levinson, 2008).

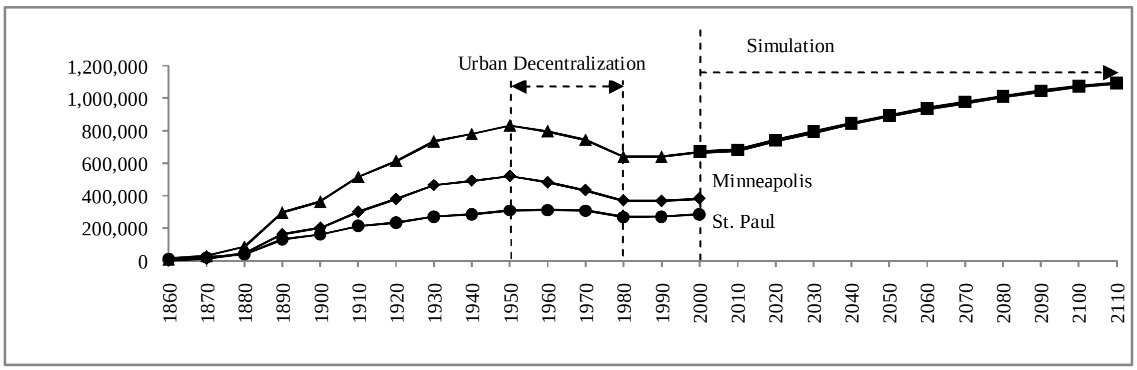


Figure 7-14, Population in Twin Cities

As shown in Figure 7-14, *Population* grew until 1950 when the census peaked at 521,718, and then declined as people moved to the suburbs until 1990's. U.S. Census Bureau estimates in 2006 show the population of Minneapolis to be 369,051, a 3.5% drop since the 2000 census. Overall, *Population* in the Twin Cities does not present a continuous increase in the past century. To be conservative, the model assumes a stable increasing trend for its *Population* in the following 100 years. The traffic volume is projected as per the prediction of *Population* and other socioeconomic factors.

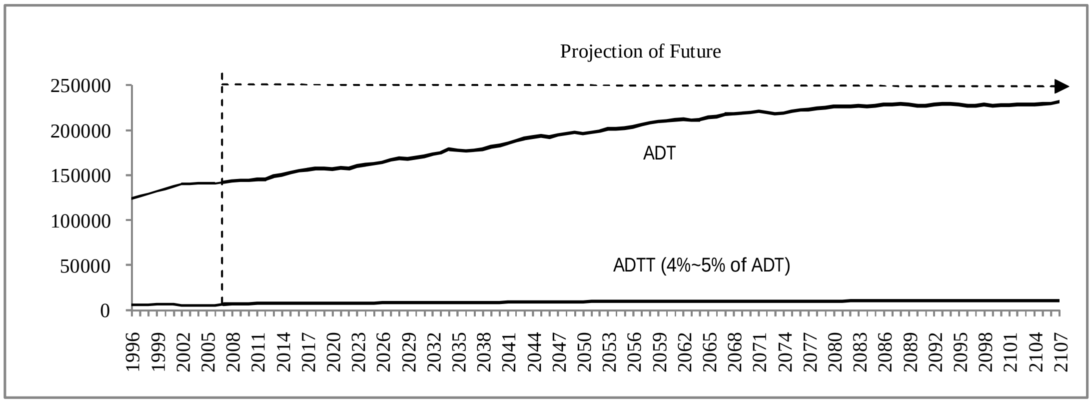


Figure 7-15, Traffic Demand Projection on the Bridge of Interest in the Next 100 Years

7.3.2.2 Deterioration of the St. Anthony Falls Bridge

The new St. Anthony Falls Bridge is a precast concrete girder bridge, 1,216 feet long bridge with two separate structures to carry totally 10 lanes. The 13 feet wide right shoulders and 14 feet wide left shoulders are convertible to additional lanes. Light Rail Transport-ready which may help accommodate future transportation needs. It is supported by three land based piers (four columns at each pier) standing 70 feet tall. The new bridge is built with redundant systems to keep the structure from collapsing. To achieve superior durability, the designer used high performance concrete embedded with more than 300 sensors that will generate a record of how it handles the stresses and strains of traffic, along with Minnesota's harsh climate. The sensors will also measure how the structure will handle loads and vibrations and how it will expand and contract between winter and summer seasons, as well as watch for any potential corrosion from rock salt and other road treatments.

Since this is a new bridge without historical data, physical deterioration projections can only use deterioration information from other bridges with similar structure and material. Cesare *et al.* (1992), Madanat *et al.* (1995) and Morcous (2006) gave both theoretic discussions and examples to apply Markov chains on physical deterioration of concrete bridge. For example, Table 7-8 lists general recommendations of the transition matrices for bridge components conducted by Cesare *et al.* (1992). Therefore, the model will apply the results concluded in this work to develop the transition matrices of the bridge of interest.

Table 7-8, Markov Transition Matrices for General Recommendation (Cesare *et al*., 1992)

Description	Count	T_{77}	T_{66}	T_{55}	T_{44}	T_{33}	T_{22}	Percentage (<3)	Percentage (<5)
Concrete									
Simple	214	0.950	0.977	0.987	0.998	0.999	0.999	0.50	26.14
Continuous	54	0.893	0.957	0.976	0.973	0.999	0.945	3.01	57.52
PS	36	0.827	0.997	0.971	0.895	0.915	0.945	1.04	7.01
Deck Arch	48	0.958	0.969	0.987	0.999	0.909	0.947	0.02	29.34
Culvert	36	0.893	0.967	0.968	0.997	0.829	0.904	0.39	48.65
Frame	86	0.000	0.000	0.000	0.970	0.949	0.938	56.06	100.00
Steel	456	0.886	0.961	0.974	0.982	0.989	0.977	2.36	57.78
All	830	0.862	0.966	0.981	0.982c	0.989	0.974	1.63	53.37

The new bridge has a design life of 100 years. Additional assumptions are necessary for the longest time span among all these case analyses. First, current vehicles are equipped with internal combustion engines with petroleum. What can been seen in the near future are electric, fuel battery, and bio-diesel. This case analysis assumes these new technologies will not fundamentally change vehicle speed, weight and user costs in order to run the model. Additionally, the residents will keep the same travel patterns of working, shopping, and recreation.

7.3.3 Scenario Analysis for the St. Anthony Falls Bridge

The base scenario illustrates the deterioration process of each subsystem and Sufficiency Rating of the St. Anthony Falls Bridge over the next 100 years under a stable population increase and traffic demand.

Table 7-9, Base Scenario of the St. Anthony Falls Bridge

Parameter	Base Scenario Value in 2008
Threshold_of_Preventive_Maintenance	3
External_Freight_Traffic_Ratio	0.5
Truck_Weight_Regulations	No change
Enforcement_Level_of_TS&W_Regulation	0.3
Load_Safety_Factor	1.3
Ratio_of_Divisible_Load_to_Non-Divisible Load	0.2

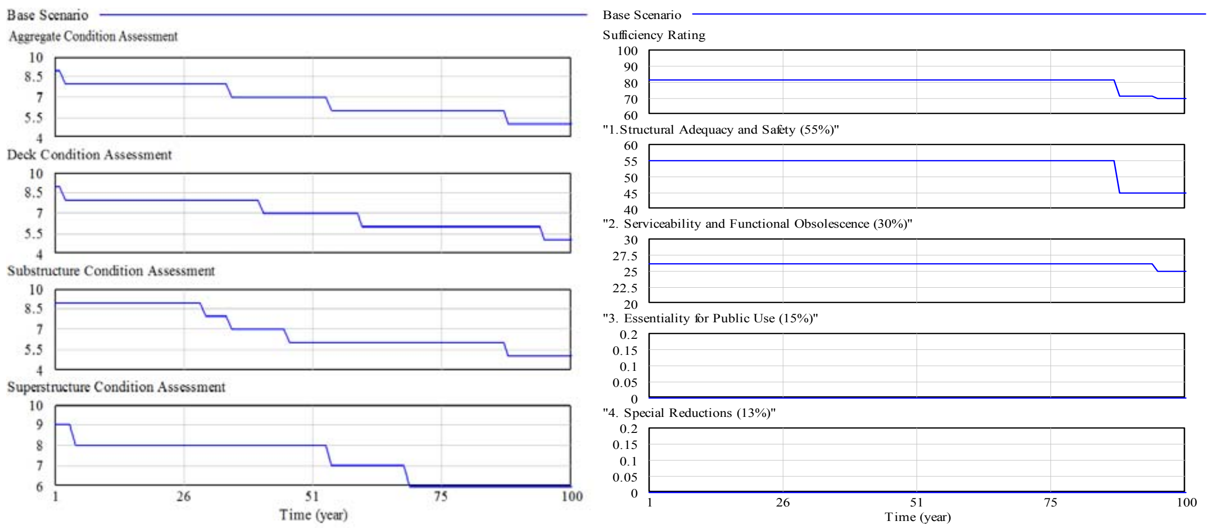


Figure 7-16, Base Scenario - Performance of the St. Anthony Falls Bridge

In Figure 7-16, the St. Anthony Falls Bridge can stand for the next 100 with acceptable physical condition. *Sufficiency_Rating* indicates that this new bridge will be deficient after 84 years. The life cycle cost of the bridge is $894 million, about 4 times of the initial construction cost.

Table 7-10, Results of Base Scenario

Parameter	Base Scenario Value in 2008
Physical_Life (without rehabilitation)	100 years
Service_Life(without rehabilitation)	85 years
LCC	$894 million
NPV of LCC (DC=0.06)	$262 million

Comparing with the base case under a benign condition, the scenario analysis assesses the performance of the St. Anthony Falls Bridge under severe usage and regulatory change that challenge the bridge agency.

In the base scenario, ADTT is about the 4% to 5% of total ADT which is based on the historic information. This proportion can increase due to a variety of potential triggers, such as expanding the commercial area, more external freight traffic, reallocation of more traffic on the new bridge due to its higher capacity. The higher transportation capacity of the new structure may introduce more local and long distance traffic, which results in higher fatigue damage. Scenario ***A*** doubles the parameter, *External_Freight_Traffic_Ratio,* to a higher volume of truck traffic and tests the physical condition and performance of the St. Anthony Falls Bridge in the future 100 years.

Table 7-11, Scenario *A* of the St. Anthony Falls Bridge

Parameter	Base Scenario Value in 2008	Scenario *A* Value in 2008
Threshold_of_Preventive_Maintenance	3	3
External_Freight_Traffic_Ratio	0.5	1.0
Truck_Weight_Regulations	No change	No change
Enforcement_Level_of_TS&W_Regulation	0.3	0.3
Load_Safety_Factor	1.3	1.3
Ratio_of_Divisible_Load_to_Non-Divisible Load	0.2	0.2

In Figure 7-17, both *Aggregate_Condition_Assessment* and *Sufficiency_Rating* presents obvious discrepancies against the base scenario.

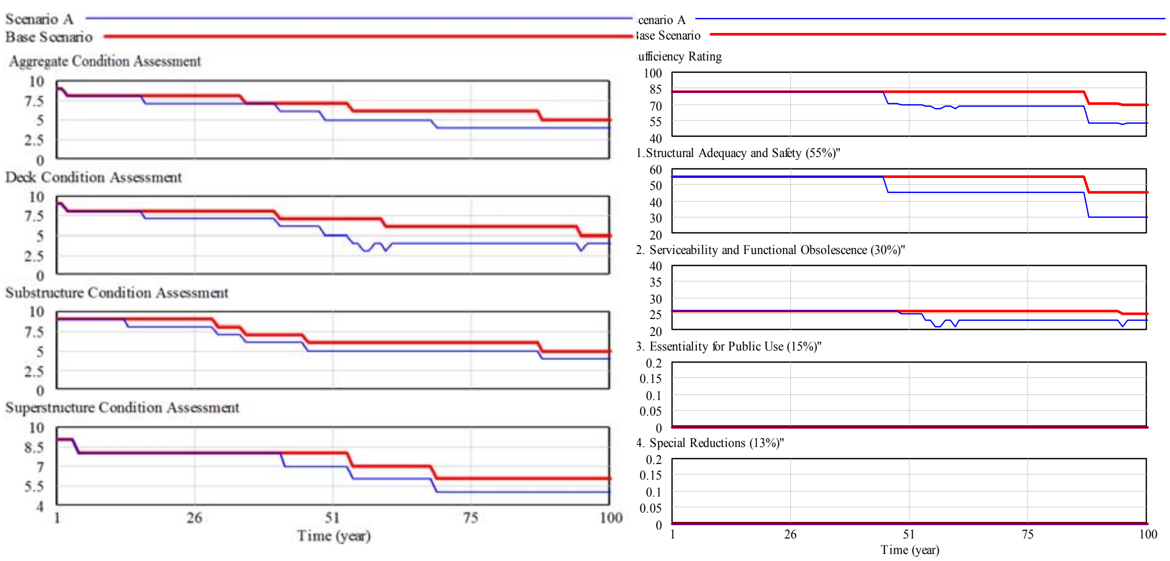


Figure 7-17, Scenario *A* – Higher *External_Freight_Traffic_Ratio*

The MnDOT can collect site-specific information with the embedded monitoring system for a proactive maintenance policy. The model assumes the highest the priority of the bridge by setting the *Relative_Importance_in_LHWBN* as 1. As shown in Table 7-12, the additional fatigue damage does not shorten the *Physical_Life*. However, the *Service_Life* reduces to 87 years and the LCC increases to $1.291 billion to counteract deterioration.

Table 7-12, Simulation Result of Scenario *A*

Parameter	Base Scenario Value in 2008	Scenario *A* Value in 2008
Physical_Life (without rehabilitation)	100 years	100 years
Service_Life(without rehabilitation)	100 years	87 years
LCC	$ 894 million	$1.291 billion
NPV of LCC (DC=0.06)	$262 million	$266 million

The St. Anthony Falls Bridge was designed as HS25, adequate to the current standard on the interstate. However, there is a big possibility that the legal truck weight exceeds this in the next 100 years.

Table 7-13, Scenario *B* of the St. Anthony Falls Bridge

Parameter	Base Scenario Value in 2008	Scenario *A* Value in 2008	Scenario *B* Value in 2008
Threshold_of_Preventive_Maintenance	3	3	3
External_Freight_Traffic_Ratio	0.5	1.0	1.0
Truck_Weight_Regulations	No change	No change	Change from 120kips to 140 kips in the 51th year
Enforcement_Level_of_TS&W_Regulation	0.3	0.3	0.3
Load_Safety_Factor	1.3	1.3	1.3
Ratio_of_Divisible_Load_to_Non-Divisible Load	0.2	0.2	0.2

Scenario ***B*** runs the model at even worse usage level, 140 kips from 120kips after 50 years that combines the change in Scenario ***A*.**

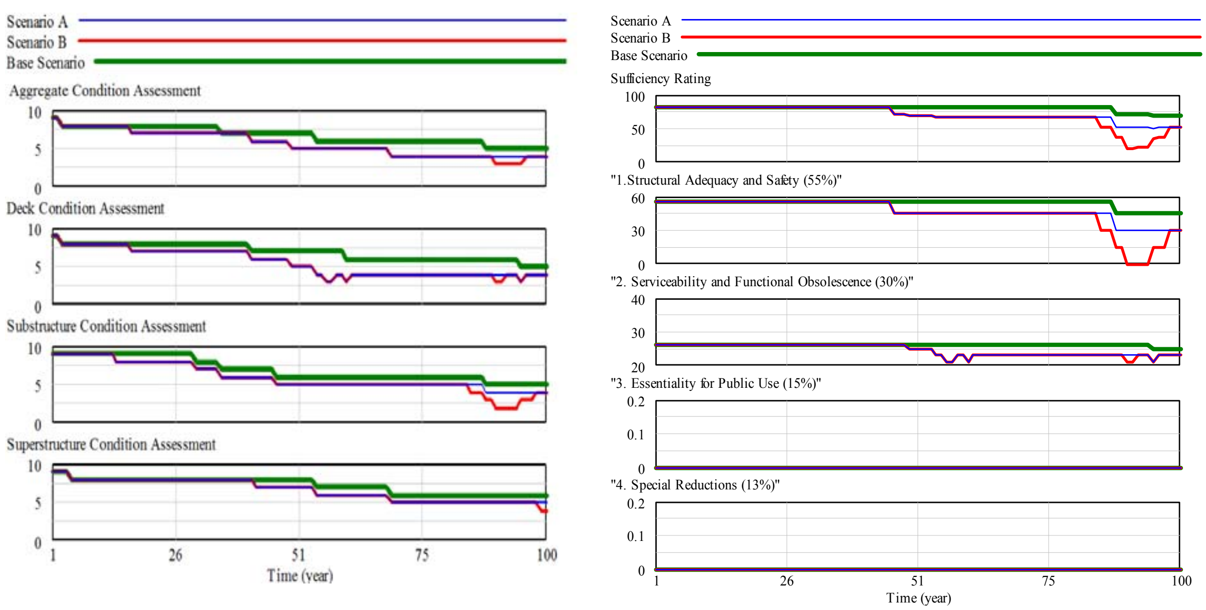


Figure 7-18, Scenario *B* – Higher Legal Truck Weight

In Figure 7-18, Scenario ***B*** illustrates a worse physical condition after the new *Truck_Weight_Regulations*. The *Physical_Life* reduces to 89 years and the *Service_Life* drops to 84 years. Hence, rehabilitation is necessary for continuous usage of the bridge. The life cycle cost correspondingly jumps to $1.874 billion.

Table 7-14, Simulation Result of Scenario *B*

Parameter	**Base Scenario**	**Scenario *A***	**Scenario *B***
Physical_Life (without rehabilitation)	100 years	100 years	89 years
Service_Life (without rehabilitation)	100 years	87 years	84 years
LCC	$ 894 million	$1.291 billion	$1.874 billion
NPV of LCC (DC=0.06)	$262 million	$266 million	$269 million

The new I-35W bridge presents a satisfied performance according to its design level. It is able to meet the design service life in the base scenario. However, potential heavier freight traffic and regulation change of the truck industry challenge this and may result in rehabilitation at its late stage.

8. CONCLUSION

8.1 Summary of Research

Obsolescence is as much a consideration as deterioration for infrastructure management. Research on the serviceability of infrastructure facilities allows government agencies to improve the sustainability and accountability of their public services. The continuously prolonged backlog of deficient facilities requires decision support systems to intelligently allocate budgets to fix this problem. Managers must consider the predominant issues that influence the performance of their portfolios. Performance is certainly a function of service supply, service demand, and managerial policy. This research proposed an approach to analyze highway bridge performance by exploring the relationship between these functional areas within a flexible modeling and analysis framework.

As a research product, the parametric model is a proof-of-concept of the Infrastructure Performance Theory adopted from Lemer in this research. Through a research approach of theory proposition, exploration and confirmation, this research defined the impacts of both engineering and socioeconomic factors that influence highway bridge performance and built a modeling structure to include these dimensions in the infrastructure decision-making process. It provides a numerical environment to analyze how related parameters influence performance of a highway bridge and its remaining service life. Although the application of this research focused on highway bridges, its framework is applicable to other types of facilities.

The main challenge to build and operate the model is data collection. Most of the national bridges were built before 1960's, so complete historic data is hard to retrieve. Even current bridge management practice doe not collect information relevant for all the factors considered in this research. The modeling process employed necessary assumptions in cases where historic data was unavailable.

8.2 Contributions

Until now, the problem of quantifying both service supply and demand factors has not been sufficiently addressed to allow a comprehensive analysis of factors that influence bridge performance. This research established a quantitative approach to operationalize a conceptual observation of the relationship between service supply and demand forwarded by Lemer (1996). The model brought together financing, engineering, and socioeconomic factors for bridge managers to conduct parametric analyses in a user-friendly environment. The scenarios that bridge managers can analyze to assess bridge lifecycle performance is only limited by pragmatic considerations.

Before building the model, essential parameters are identified by CDA with NBI data to objectively reflect the performance of highway bridges. CDA is still new to the infrastructure industry. However, it is an efficient statistical method for data analysis, especially after the FHWA and local DOTs have collected extensive data on infrastructure facilities. In the modeling process, the flexibility of system dynamics required constraints for the model to generate rational results, such as setting input limits of the parameters. This research proposed a systematic V&V procedure in the model design stage, which continued through the case analyses. Finally, the model's credibility was illustrated by retrospectively simulating past bridge performance before running future scenario analysis.

The connection between the physical and nonphysical aspects is essential for supply and demand analysis of infrastructure. The diverse measures prevent an easy approach to build equations under the causal relations. For example, fatigue damage plays a critical role in analysis of effects of truck weight regulation, freight traffic on bridge deterioration and its performance. However, most research concentrates on one aspect, such as evaluation criteria on truck load spectra by Chang (2007), annual fatigue damage with stress histogram by Zhou (2006), fatigue damage with truck weight histogram by Chotickai and Bowman (2006), application of Markov chain in fatigue damage analysis by Rowatt and Spanos (1998), nonstationary Markov chain for fatigue damage analysis by Pappas *et al.*(2001). To build the relation between the traffic demand and facility performance, this research proposed an approach to combine several nonphysical factors in calculating load spectra and fatigue damage by nonstationary Markov chains.

The case analyses demonstrated that nonphysical factors could significantly change a highway bridge's performance and remaining service life. This should prompt decision makers to at least consider these factors and motivate them to collect historical data regarding regulatory, economic, and user demand as important factors for infrastructure management. In addition, the bridge agencies are normally interested in the effectiveness of its maintenance policy along with the expenditure. The parametric model allows a decision maker to simultaneously observe the effects of various policies along with life cycle cost and incomes of the bridge of interest. The model is also expandable to include other user costs or savings for a benefit cost analysis.

8.3 Limitations

1. Symbiosis of Project Level and Network Level

This research built a system dynamics model at the project level. However, information at the network level was necessary to run the model, such as budget prioritization. The model included a simplified structure for the local bridge network, which might not accurately reflect the local traffic pattern.

2. More Consistent Evaluation Criteria

The bridge of interest is measured by its *Aggregate_Condition_Assessment* and *Sufficiency_Rating*, which both strictly follow the current standards. However, these criteria may be inappropriate to evaluate performance in the future, since standards will likely change with time. The model does, however, provide some flexibility to account for future circumstances, such as the ability to use alternative criteria for condition evaluation.

3. Applicability

Calibration of case analysis is time consuming because many factors mutually work on each other. Most times, it is not possible to calibrate one section or module solely. And revisiting each model section is necessary to check model consistency. This requires a broader point of view to run a system dynamics model.

8.4 Recommendations for Future Work

Based on above limitations, there are several recommendations for future work.

1. Embed the System Dynamics Model into a Network Level Model

Commonly, bridge agencies require decision tools at a network level to leverage their budget and plan MR&R activities. Therefore, prevalent BMSs are mostly designed at the network level. In this research, the model platform has initiated a systematic platform to investigate highway bridge performance concentrating primarily at a project level. This arrangement is necessary to introduce more details when modeling the relationship of service supply and demand and managerial issues.

It is challenging to embed this work into existing BMSs. Such challenges come from concept, algorithm, and down to coding. As for concept, current BMSs still concentrate on the supply side and allocate budgets by prioritizing all bridges according to conditions of the components. As for algorithm, this research introduced many influencing factors and model V&V techniques which make it even more challenging to combine with an existing BMS. As for coding, system dynamics is built on causal relationships among all variables either directly or indirectly. It is challenging to program system dynamics with a database language that is generally employed by prevalent BMSs.

2. Design Evaluation Criteria Other than Sufficiency Rating

Sufficiency_Rating is a comprehensive indicator to measure serviceability of highway bridges and assists state and federal programs with budget allocation. It includes information from the demand side in terms of ADT. However, it does not directly count TS&W and its influence on bridge performance. In the case analyses, both bridges fell into a worse situation when there was heavier truck traffic in the future. Such a scenario is very likely since the freight industry will continue to rely on trucks for the foreseeable future and potential changes of TS&W regulation are very plausible. Based on the Infrastructure Performance Theory, further measures can be expanded from the gaps between the optimum performance, the real performance, and the minimum acceptable performance.

Secondly, *Sufficiency_Rating* is an "absolute value" evaluation tool designed based on the current traffic standard. Therefore, new performance evaluation criteria that measures "relative value" may be more appropriate for a long term performance assessment by eliminating the hidden bias introduced by the criteria themselves.

3. A Standard Procedure to Operate the System Dynamics Model

The system dynamics model has been calibrated in each case analysis to attain higher credibility. This process not only requires adjustment of model parameters but also slight modification of model structure if necessary. The last working model is in a better shape for further application. However, it requires being familiar with both model structure and parameters to operate the model. For further application, the total number of parameters may be cut down to reduce the data collection effort without losing much confidence of the conclusion.

4. Bring the Findings in This Research Back to the Industry

The model was mainly built based on available literature and data. Direct contact with bridge managers indicated that some of the concepts are still not widely used in their management, such as enforcement programs for heavy truck management. With this modeling platform, bridge managers can easily understand the necessity and influences of certain factors and decide whether such factors are useful to improve their management.

5. Application for Other Types of Infrastructure Facilities

In this research, highway bridges were chosen as the research subject to define the service supply and demand vectors as well as the evaluation criteria. However, the

Infrastructure Theory and the approach proposed here are applicable for other types of infrastructure facilities, such as tunnels, pavement, pipelines, etc. In such an effort, the vectors and evaluation criteria need be redefined as per the properties of the entity. But the core algorithms employed in the research are universal. For example, Markov chains have been widely used for pavement (Guillaumot et al., 2003), tunnel (Touran, 1997), pipeline (Jeong et al., 2005) to simulate their deterioration. The four step method is widely used in DOTs to predict both passenger and freight traffic demands as the primary parameters for service evaluation of highways, bridges, and tunnels. The financial module incorporates five typical sources that cover common financial arrangement of infrastructure. This design allows further application of the theory and model for other types of infrastructure facilities.

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Appendix A, Canonical Discriminant Analysis of the NBI data

App A.1 SAS Code

```
*csv is saved by excel with smaller size and reliable data structure. ;
*import data from csv;
PROC IMPORT OUT= WORK.bridges;
        DATAFILE= "D:\nbi data\2006va.csv";
        DBMS=CSV REPLACE;
   GETNAMES=YES;
   DATAROW=2;
RUN;
*find all type of service_on are highway and generate hwb;
data hwb;
  set bridges;
    if type_of_service_on_bridge =1;
run;
*histogram of main structure type;
proc univariate data=hwb;
histogram type_of_design_construction /cfill=red;
run;
* structure type;
data slab;
  set hwb;
    if type_of_design_main =1;
run;
data stringer;
  set hwb;
    if type_of_design_main =2;
run;
data girder;
  set hwb;
    if type_of_design_main =3;
run;
data teebeam;
  set hwb;
    if type_of_design_main =4;
run;
data boxbeam_multiple;
  set hwb;
    if type_of_design_main =5;
run;
data boxbeam_single;
```

```
    set hwb;
        if type_of_design_main =6;
run;
data frame;
    set hwb;
        if type_of_design_main =7;
run;
data orthotropic;
    set hwb;
        if type_of_design_main =8;
run;
data truss_deck;
    set hwb;
        if type_of_design_main =9;
run;
data truss_thru;
    set hwb;
        if type_of_design_main =10;
run;
data arch_deck;
    set hwb;
        if type_of_design_main =11;
run;
data arch_thru;
    set hwb;
        if type_of_design_main =12;
run;
data suspension;
    set hwb;
        if type_of_design_main =13;
run;
data stayed_girder;
    set hwb;
        if type_of_design_main =14;
run;
data movable_lift;
    set hwb;
        if type_of_design_main =15;
run;
data movable_bascule;
    set hwb;
        if type_of_design_main =16;
run;
data movable_swing;
```

```
   set hwb;
      if type_of_design_main =17;
run;
data tunnel;
   set hwb;
      if type_of_design_main =18;
run;
data culvert;
   set hwb;
      if type_of_design_main =19;
run;
data mixed_types;
   set hwb;
      if type_of_design_main =20;
run;
data segmental_box_girder;
   set hwb;
      if type_of_design_main =21;
run;
data channel_beam;
   set hwb;
      if type_of_design_main =22;
run;
data other_type;
   set hwb;
      if type_of_design_main =0;
run;
*Stepdisc procedure of CDA;
proc stepdisc data=hwb;
     class type_of_design_main;
run;
*Candisc procedure of CDA;
proc candisc data=hwb ncan=3;
     class ServType_on;
 var Inventory_Rte__Min_Vert_Clearan Bypass_Detour_Length  Functional_Class_Of_Inventory_Rt
Year_Built   Lanes_On_Structure Lanes_Under_Structure  Average_Daily_Traffic  Design_Load
Approach_Roadway_Width Navigation_Vertical_Clearance Navigation_Horizontal_Clearance
Kind_of_Material_Main Kind_of_Material_App  Type_of_Design_App
Number_Of_Spans_In_Main_Unit  Number_Of_Approach_Spans Inventory_Rte_Total_Horz_Clearan
Structure_Length Bridge_Roadway_Width_Curb_To_Cur Deck_Width__Out_To_Out
Min_Vert_Clear_Over_Bridge_Roadw  Minimum_Vertical_Underclearance
Minimum_Lateral_Underclearance Min_Lateral_Underclear_On_Left Deck Superstructure Substructure
Method_Used_To_Determine_Operati Operating_Rating Method_Used_To_Determine_Invento
Inventory_Rating Structural_Evaluation Deck_Geometry  Underclear__Vertical___Horizont
```

```
Bridge_Posting Waterway_Adequacy Approach_Roadway_Alignment Deck_Structure_Type
Type_of_Wearing_Surface Type_of_Membrane Deck_Protection
AVERAGE_DAILY_TRUCK_TRAFFIC  SCOUR_CRITICAL_BRIDGES Skew  Culverts
Length_Of_Maximum_Span SUFFICIENCY_RATING;
run;
```

App A.2 Category of Highway Bridges

The first question before applying CDA is the division of classes of all research elements. The classification of primal target is based on the service type as listed in Table A-1. The first screening is bridge type of service on. For the interest of this research, bridges with type of service on the bridge as highway are selected.

Table A-1, Type of Service (2 digits)

42A-Type of Service on	**42B-Type of Service Under**
First Code Description	**Second Code Description**
1 Highway	1 Highway, with or without pedestrian
2 Railroad	2 Railroad
3 Pedestrian-bicycle	3 Pedestrian-bicycle
4 Highway- railroad	4 Highway- railroad
5 Highway- pedestrian	5 Waterway
6 Overpass structure at an interchange or second level of a multilevel interchange	6 Highway- waterway
7 Third level (Interchange)	7 Railroad- waterway
8 Fourth level (Interchange)	8 Highway- waterway- railroad
9 Building or plaza	9 Relief for waterway
0 Other	0 Other

Then these bridges are categorized according to their main structure type. Bridges in Virginia are used in this analysis.

Table A-2, Category of Highway Bridges in Virginia

Type of Design and Construction	Number of Bridges
01 Slab	1491
02 Stringer/Multi- beam or Girder	6010
03 Girder and Floor beam System	89
04 Tee Beam	909
05 Box Beam or Girders - Multiple	264
06 Box Beam or Girders - Single or Spread	11
07 Frame (except frame culverts)	135
08 Orthotropic	0
09 Truss – Deck	6
10 Truss – Thru	154
11 Arch – Deck	121
12 Arch – Thru	10
13 Suspension	0
14 Stayed Girder	1
15 Movable – Lift	3
16 Movable – Bascule	4
17 Movable – Swing	8
18 Tunnel	0
19 Culvert (includes frame culverts)	3645
20 Mixed types	0
21 Segmental Box Girder	4
22 Channel Beam	1
00 Other	9

App A.3 STEPDISC Procedure

The candidate variables are those introduced in the Chapter 4 from both supply and demand sides that recorded in the NBI. The STEPWISE procedure is called according to the type of design/construction.

PROC STEPDISC begins by displaying summary information about the analysis. This information includes the number of observations with non-missing values, the number of classes in the classification variable, the number of quantitative variables under consideration, the significance criteria for variables to enter and to stay in the model, and the method of variable selection being used. The frequency of each class is also displayed.

The STEPDISC Procedure

The Method for Selecting Variables is STEPWISE

Observations	12875	Variable(s) in the Analysis	47
Class Levels	19	Variable(s) will be Included	0
		Significance Level to Enter	0.15
		Significance Level to Stay	0.15

Class Level Information

Type_of_Design_Main	Variable Name	Frequency	Weight	Proportion
0	_0	9	9.0000	0.000699
1	_1	1491	1491	0.115806
2	_2	6010	6010	0.466796
3	_3	89	89.0000	0.006913
4	_4	909	909.0000	0.070602
5	_5	264	264.0000	0.020505
6	_6	11	11.0000	0.000854
7	_7	135	135.0000	0.010485
9	_9	6	6.0000	0.000466
10	_10	154	154.0000	0.011961
11	_11	121	121.0000	0.009398
12	_12	10	10.0000	0.000777
14	_14	1	1.0000	0.000078
15	_15	3	3.0000	0.000233
16	_16	4	4.0000	0.000311
17	_17	8	8.0000	0.000621
19	_19	3645	3645	0.283107
21	_21	4	4.0000	0.000311
22	_22	1	1.0000	0.000078

For each entry step, the statistics for entry are displayed for all variables not currently selected. The variable selected to enter at this step (if any) is displayed, as well as all the variables currently selected. Next are multivariate statistics that take into account all previously selected variables and the newly entered variable.

The STEPDISC Procedure
Stepwise Selection: Step 1
Statistics for Entry, DF = 18, 12856

Variable	R-Square	F Value	Pr > F	Tolerance
Inventory_Rte__Min_Vert_Clearan	0.0762	58.91	<.0001	1.0000
Bypass_Detour_Length	0.0124	8.93	<.0001	1.0000
Functional_Class_Of_Inventory_Rt	0.0174	12.67	<.0001	1.0000
Year_Built	0.0531	40.01	<.0001	1.0000
Lanes_On_Structure	0.0735	56.66	<.0001	1.0000
Lanes_Under_Structure	0.1000	79.36	<.0001	1.0000
Average_Daily_Traffic	0.0408	30.37	<.0001	1.0000
Design_Load	0.0588	44.65	<.0001	1.0000
Approach_Roadway_Width	0.0307	22.60	<.0001	1.0000
Navigation_Vertical_Clearance	0.3590	400.01	<.0001	1.0000
Navigation_Horizontal_Clearance	0.4104	497.05	<.0001	1.0000
Kind_of_Material_Main	0.4478	579.29	<.0001	1.0000
Kind_of_Material_App	0.1030	81.98	<.0001	1.0000
Type_of_Design_App	0.1227	99.91	<.0001	1.0000
Number_Of_Spans_In_Main_Unit	0.0053	3.78	<.0001	1.0000
Number_Of_Approach_Spans	0.4406	562.64	<.0001	1.0000
Inventory_Rte_Total_Horz_Clearan	0.0237	17.31	<.0001	1.0000
Structure_Length	0.0977	77.35	<.0001	1.0000
Bridge_Roadway_Width_Curb_To_Cur	0.4262	530.49	<.0001	1.0000
Deck_Width__Out_To_Out	0.4216	520.63	<.0001	1.0000
Min_Vert_Clear_Over_Bridge_Roadw	0.0829	64.60	<.0001	1.0000
Minimum_Vertical_Underclearance	0.0432	32.27	<.0001	1.0000
Minimum_Lateral_Underclearance	0.0546	41.22	<.0001	1.0000
Min_Lateral_Underclear_On_Left	0.0444	33.19	<.0001	1.0000
Deck	0.8982	6302.80	<.0001	1.0000
Superstructure	0.8879	5657.18	<.0001	1.0000
Substructure	0.9127	7466.54	<.0001	1.0000
Method_Used_To_Determine_Operati	0.0948	74.80	<.0001	1.0000
Operating_Rating	0.0695	53.34	<.0001	1.0000
Method_Used_To_Determine_Invento	0.0944	74.42	<.0001	1.0000
Inventory_Rating	0.1261	103.03	<.0001	1.0000
Structural_Evaluation	0.1061	84.75	<.0001	1.0000
Deck_Geometry	0.5754	967.76	<.0001	1.0000
Underclear__Vertical___Horizont	0.1435	119.62	<.0001	1.0000
Bridge_Posting	0.0970	76.71	<.0001	1.0000
Waterway_Adequacy	0.1365	112.86	<.0001	1.0000
Approach_Roadway_Alignment	0.0419	31.21	<.0001	1.0000
Deck_Structure_Type	0.2754	271.39	<.0001	1.0000
Type_of_Wearing_Surface	0.2775	274.30	<.0001	1.0000
Type_of_Membrane	0.1083	86.76	<.0001	1.0000
Deck_Protection	0.0301	22.19	<.0001	1.0000
AVERAGE_DAILY_TRUCK_TRAFFIC	0.0203	14.77	<.0001	1.0000
SCOUR_CRITICAL_BRIDGES	0.2236	205.71	<.0001	1.0000
Skew	0.0269	19.76	<.0001	1.0000
Culverts	0.9689	22285.9	<.0001	1.0000
Length_Of_Maximum_Span	0.4764	649.85	<.0001	1.0000

The STEPDISC Procedure
Stepwise Selection: Step 1
Variable Culverts will be entered.
Variable(s) that have been Entered
Culverts
Multivariate Statistics

Statistic	Value	F Value	Num DF	Den DF	Pr > F
Wilks' Lambda	0.031053	22285.9	18	12856	<.0001
Pillai's Trace	0.968947	22285.9	18	12856	<.0001

Average Squared Canonical Correlation 0.053830

For each removal step, the statistics for removal are displayed for all variables currently entered. The variable to be removed at this step (if any) is displayed. If no variable meets the criterion to be removed and the maximum number of steps as specified by the MAXSTEP= option has not been attained, then the procedure continues with another entry step.

The stepwise procedure terminates either when no variable can be removed or no variable can be entered or when the maximum number of steps as specified by the MAXSTEP= option has been attained. In this example at Step 38 no variables can be either removed or entered.

The STEPDISC Procedure
Stepwise Selection: Step 41
Statistics for Removal, DF = 18, 12818

Variable	Partial R-Square	F Value	Pr > F
Bypass_Detour_Length	0.0176	12.74	<.0001
Functional_Class_Of_Inventory_Rt	0.0119	8.56	<.0001
Year_Built	0.0101	7.28	<.0001
Lanes_On_Structure	0.0263	19.21	<.0001
Lanes_Under_Structure	0.0066	4.74	<.0001
Average_Daily_Traffic	0.0103	7.38	<.0001
Design_Load	0.0086	6.15	<.0001
Approach_Roadway_Width	0.0027	1.95	0.0092
Navigation_Vertical_Clearance	0.1941	171.56	<.0001
Navigation_Horizontal_Clearance	0.2551	243.88	<.0001
Kind_of_Material_Design	0.2461	232.43	<.0001
Bridge_Roadway_Width_Curb_To_Cur	0.0559	42.20	<.0001
Minimum_Vertical_Underclearance	0.0119	8.56	<.0001
Minimum_Lateral_Underclearance	0.0479	35.83	<.0001
Deck	0.1091	87.18	<.0001
Superstructure	0.1920	169.17	<.0001
Substructure	0.2957	299.01	<.0001
Method_Used_To_Determine_Operati	0.0159	11.47	<.0001
Operating_Rating	0.0228	16.59	<.0001
Method_Used_To_Determine_Invento	0.0148	10.72	<.0001
Inventory_Rating	0.0219	15.93	<.0001
Structural_Evaluation	0.1646	140.33	<.0001
Deck_Geometry	0.0287	21.02	<.0001
Bridge_Posting	0.0434	32.30	<.0001
Waterway_Adequacy	0.0134	9.71	<.0001
Approach_Roadway_Alignment	0.0071	5.10	<.0001
Average_Daily_Truck_Traffic	0.0126	9.07	<.0001

No variables can be removed.
No further steps are possible.

At last, 27 variables are selected.

Appendix B, Model Assumptions

Assumptions are checked by the face validity test, literature review, sensitivity analysis, and other methods. If one assumption is rejected, the corresponding model structure will be calibrated and tested again. This appendix lists all assumptions in each module.

Table B-1, Assumptions in the Socioeconomics Module

No.	Assumption	Test	Result and Calibration
1	The performance of individual bridge can be overlooked to the local economics for the sake of model simplification.	For critical links, their performance should correlate with the local economics	Refused. Adjust the model to consider the contribution of critical links to the local economics.
2	The daily aggregate traffic demand depends on two factors, local *Population* and the *Local Industrial Output.*	Refer to existing model in other's work (Kim, 1998).	Accepted
3	There is a direct relation between the local *Traffic Density* and the local *Economic Development.*	This assumption is related with the first assumption in this module.	Refused. It is adjusted with the introduction of *Highway_ Comprehensive_ LOS*

Table B-2, Assumptions in the Regulation Module

No.	Assumption	Test	Result and Calibration
1	The infrastructure regulation intent to limit the traffic in order to protect the infrastructure facility and balance the urban development.	Recently, regulation makers have switched from increasing infrastructure supply to balance supply and demand	Accepted
2	All regulations are assigned a uniform distribution with a given initial year and frequency (All these parameters are adjustable for a proper simulation, controlled by the user).	There is not a reference to quantify regulatory changes. Decision makers can give their best estimation.	Accepted
3	The magnitude of each regulation is fixed with a predefined value to reduce a potential turbulent influence on bridge performance.	Decision makers define the frequency as per assumption 2 in this module. Limited magnitude of each regulatory change helps to converge model variance.	Accepted

Table B-3, Assumptions in the Financing Module

No.	Assumption	Test	Result and Calibration
1	A bridge of interest will be prioritized in the local bridge network, based upon its component condition and replacement cost, to share the state budget for its MR&R.	Although this model works at a bridge level, it still need follow the industrial practice of bridge management at the network-level.	Accepted
2	Before the maturity of the loan, revenue collected by tolling vehicles that pass the bridge and the dedicated tax will be used for the annual return of the loan payment. The insufficient part of such annual payment will then be	This special arrangement does not conflict with assumption 1 in this module. A tolled bridge may use local funds to update its performance.	Accepted

	reimbursed by the state funds. Otherwise, the remaining amount will be used for upgrade, MR&R of the bridge of interest only.		
3	To simplify model structure, loan payment of the capital cost assumes an equal annual value with a fixed interest rate.	Model can be adjusted to other methods of loan payment if it is necessary.	Accepted
4	The state investment on the local highway network is calculated as a percentage of the local industrial output.	Other work calculated the state transportation income with the registered vehicles, fuel assumption (Chasey, 1995). Accepted as a simplification of the noncritical part of the model.	Accepted

Table B-4, Assumptions in the Budgeting Module

No.	Assumption	Test	Result and Calibration
1	Within its life cycle, each bridge subsystem keeps a constant percentage of the total replacement cost.	Capital investment on subsystem will change its cost percentage to the whole facility.	Rejected. Model is adjusted to record such improvement costs.
2	Budget is allocated mainly based on the physical condition of the bridge subsystem. The lower the condition rating, the higher priority it acquires and more budget is allocated to the subsystem.	This arrangement is in accord with typical bridge management systems. Alternatively, *Sufficiency_Rating* can be sued as an index for prioritization.	Accepted
3	The relative importance of the bridge in the local highway network depends on the route it carries for prioritization.	This design gives a higher priority to the critical links in budget allocation.	Accepted
4	The budget allocation keeps within the domain of bridge subsystems, i.e. deck, superstructure, substructure. To simplify the calculation, subsystem of the bridge of interest is compared with the bridge portfolio directly.	This simplification does not change the last result proved by equation simplification.	Accepted

Table B-5, Assumptions in the Passenger/Freight TDP Modules

No.	Assumption	Test	Result and Calibration
1	To simplify the four step method in prediction of traffic, the researched area is divided into two zones connected by the bridge of interest and other bridges if there are.	System dynamics is not a modeling tool to deal with geographic information. This assumption is necessary for application of the four step method in a system dynamics model.	Accepted
2	There are not bounds of the development of commercial areas in the zones.	This is questionable in a developed urban area.	Refused. The model adds an upper bound for each commercial area
3	If there is not clear geographic boundaries, the zones are set based on the percentage of the external traffic controlled by 15% and this limit the scope of socioeconomics module.	This follows common rules in transportation planning.	Accepted
4	There is not a step of trip distribution due to the simplification of two zones.	In the four step method, trips are distributed among one zone to all others. Since model is simplified into two zones (as Assumption 1 in this module), there is no need to distribute traffic.	Accepted
5	Mode choice is proportional to one mode's utility which is a function of average travel cost and time by the mode.	Average travel time and cost are most significant factors in choosing a traffic	Accepted

		mode (Hobeika, 2006).	
6	This model only predicts the internal traffic, while the external traffic will be assigned a user defined ratio as of the internal traffic.	Trips between two zones are composed of trips generated within the two zones and the external traffic. The model is not designed to predict external traffic. Therefore, it requires decision makers to give a best estimation.	Accepted
7	In the last step, trip assignment is proportional to the bridge capacity to other bridges connecting the two zones.	This assumption indeed uses the bridge capacity as link capacity.	Accepted

Table B-6, Assumptions in the Management and Maintenance Module

No.	Assumption	Test	Result and Calibration
1	The deck system will only be replaced when the bridge is registered in the Highway Bridge Replacement and Rehabilitation Program.	Generally, improvement of a bridge requires federal funds, but a tolled bridge can replace its deck if the local funds are enough.	Rejected. The module also allows replacement of deck system if local funds allows.
2	The annual repair activities on the bridge subsystem are limited by the budget allocated on the individual subsystem	The model first proposes potential MR&R activities and implements if the budget allows.	Accepted
3	*Threshold_of_ Preventive_Maintenance* sets up the starting point of MR&R.	A lower threshold equals passive maintenance; A higher threshold equals proactive maintenance	Accepted
4	The restoration rate of repair is proportional to the ratio of the repair cost to the replacement cost of the subsystem.	Both onetime repair cost and replacement cost is adjusted with the FHWA CBPI. Then the repair effect is proportional to its investment.	Accepted
5	*Enforcement_Level_of_TS&W_Regulation* controls the overload trucks at an acceptable ratio.	Chang (2007) tested and identify a relation between *Enforcement_ Level_of_TW&S_Regulation* and overload truck traffic.	Accepted
6	The bridge agency posts the bridge to limit heavy trucks when the load resistance is lower than current truck weight regulation.	There may be a delay to take this action due to the interval of bridge condition assessment. But it is closer to the model time step, 1 year.	Accepted

Table B-7, Assumptions in the Upgrade Module

No.	Assumption	Test	Result and Calibration
1	A bridge will only be upgraded if it is registered in the Highway Bridge Replacement and Rehabilitation Program.	Deck replacement has been designed in the MR&R module. Upgrading load resistance or geometry follows this rule.	Accepted

Table B-8, Assumptions in the Bridge Condition Module

No.	Assumption	Test	Result and Calibration
1	State independence assumption: The Markovian process that the “future” only depends on “today”, without relation with “yesterday”(Ross, 2000)	Simple frequency analysis; Chi-square statistical test. References include Madanat et al.(1995), DeStefano	Accepted

		and Grivas (1998), Abraham and Iseley (2001), Morcous (2006),	
2	The transition probabilities do not depend on bridge age, i.e., that the transition probabilities are age-homogeneous.	No special test designed for this assumption (Guignier and Madanat, 1999)	Accepted
3	If the step of deterioration rate is longer than 1 year, then the Markov transition matrix assumes a semi-diagonal format. Model is able to substitute the transition matrix with a vector, Lookup function in Vensim.	A vector can record same information for a semi-diagonal matrix if the sum of two entries in the same row always equals to one (except of the last row). Similar work includes Cesare and Santamarina (1992)	Accepted
4	In the calculation of the overall condition of the bridge, weights of the subsystems are proportional to the replacement costs.	The weighted average formula assigns weights to the ratings of the bridge elements as per its structural importance. Since the model divides the bridge into three subsystems which are all of major structure, the replacement costs of these subsystems indicates importance and the relationship between the budget and potential condition restoration.	Accepted

Appendix C, Dynamic Complexity

Introduced by Forrester (1961) in 1960s, system dynamics has been widely applied in the disciplines of management, politics, economic behavior, medicine, and engineering. After 35 years of development and application, Forrester concluded "*System dynamics provides a common foundation that can be applied wherever we want to understand and influence how things change through time*" (Forrester, 1991). Compared with Discrete Event Simulation adopted in the construction industry, system dynamics is relatively flexible for the modeling structure and variable definition. However, this research will touch some "soft" science, such as technology development, management attitude. System dynamics allows causal relation between the variables belongs to different systems, such as one of demography and another of engineering. It is necessary to introduce several relevant works about the application of system dynamics in the area of infrastructure.

Dynamic complexity can arise even in simple systems with low combinatorial complexity (Sterman, 2000). Dynamic complexity results from the combination of interactions among system elements over time. Complex behavior is observed in systems that are dynamic, tightly coupled, governed by feedback, non-linear, adaptive, counterintuitive, and policy resistant. After face validity test, we try to think what type of behavior is logic.

There are three basic types of model behavior in system dynamics, exponential behavior, equilibrium behavior and oscillation behavior.

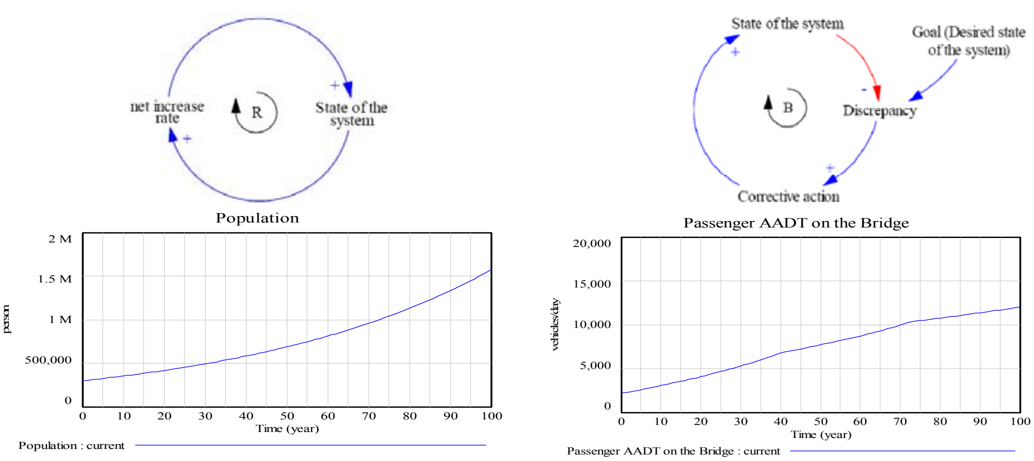

Figure C-1 , Exponential and Balancing Types of Cardinal Model Structures

If the cardinal causal loop presents a negative relation (accumulates all positive and negative signs along the cardinal loop), then the model is an equilibrium structure. Otherwise, it is an exponential structure. For the equilibrium structure, the model result always converges at certain point. For an exponential structure, the model result will increase or decrease with greater amplitude proportional to its current size.

Comparing with the model results in the face validity test, *Population, Local_Industrial_Output* evolve following an exponential growth shape within the setting time span. Conversely, *Passenger_AADT_on_the_Bridge_of_Interest, AADT_on_the_Bridge_ of_Interest,* and *Sufficiency_Rating* have balancing growth curves.

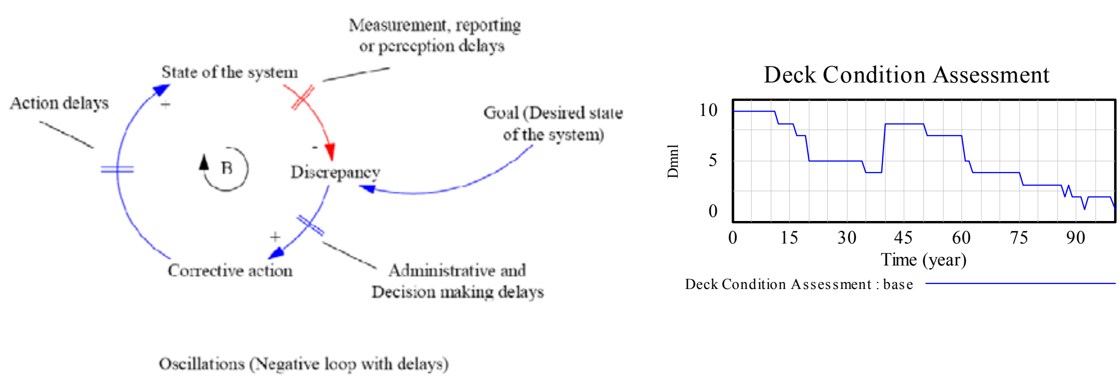

Figure C-2, Oscillation Behavior

However, most variables present unstable changes. For example, *Physical Condition of Deck* and *M&R Expenses* oscillate over time. Figure conceptually explains that delays of action and correction are the resources of oscillation in this type of structure.

Appendix D. Module Face Validity Test

App D.1, Face Validity of the Socioeconomics Module

A face validity test for the Socioeconomics Module is relatively simple. Figure D-1 illustrates changes in population, local industrial output and economic development in the base scenario. On the left hand side, parameters are set at base values.

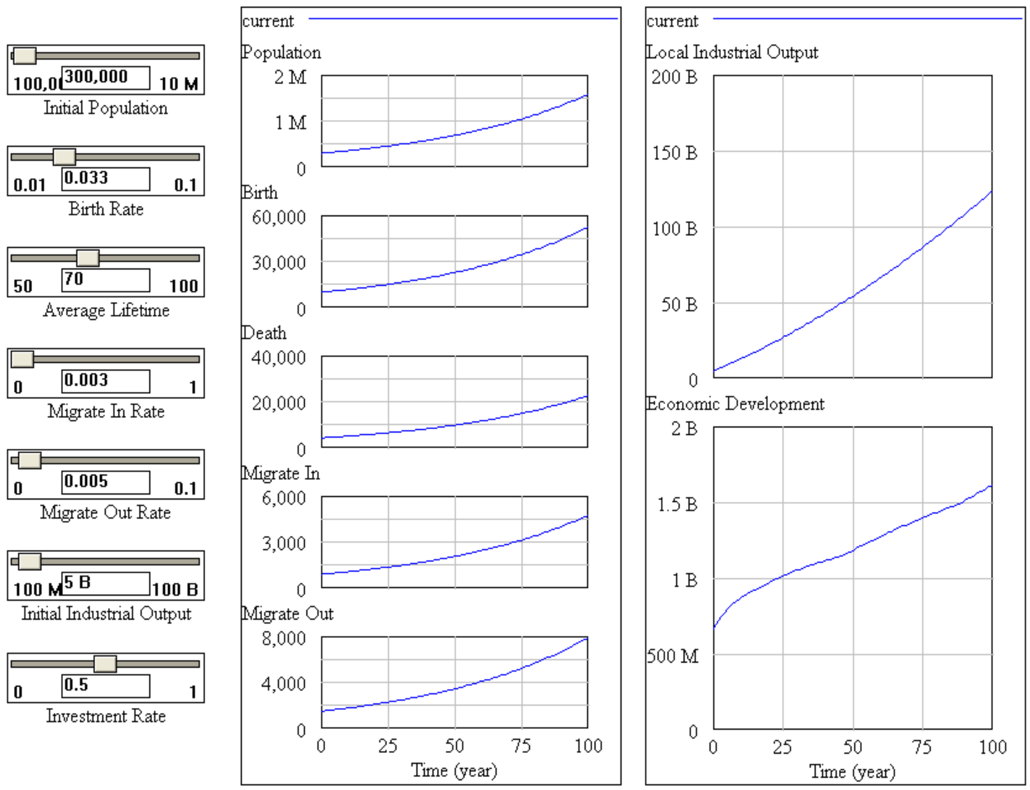

Figure D-1, Demography and Industrial Output (Base Scenario)

Basically, this module expresses both population and industrial output as exponential curves under the base scenario. This follows a normal situation for a local area before it becomes overpopulated. To test a scenario of high population density, we can adjust the birth rate to a higher level by keeping all other parameters constant.

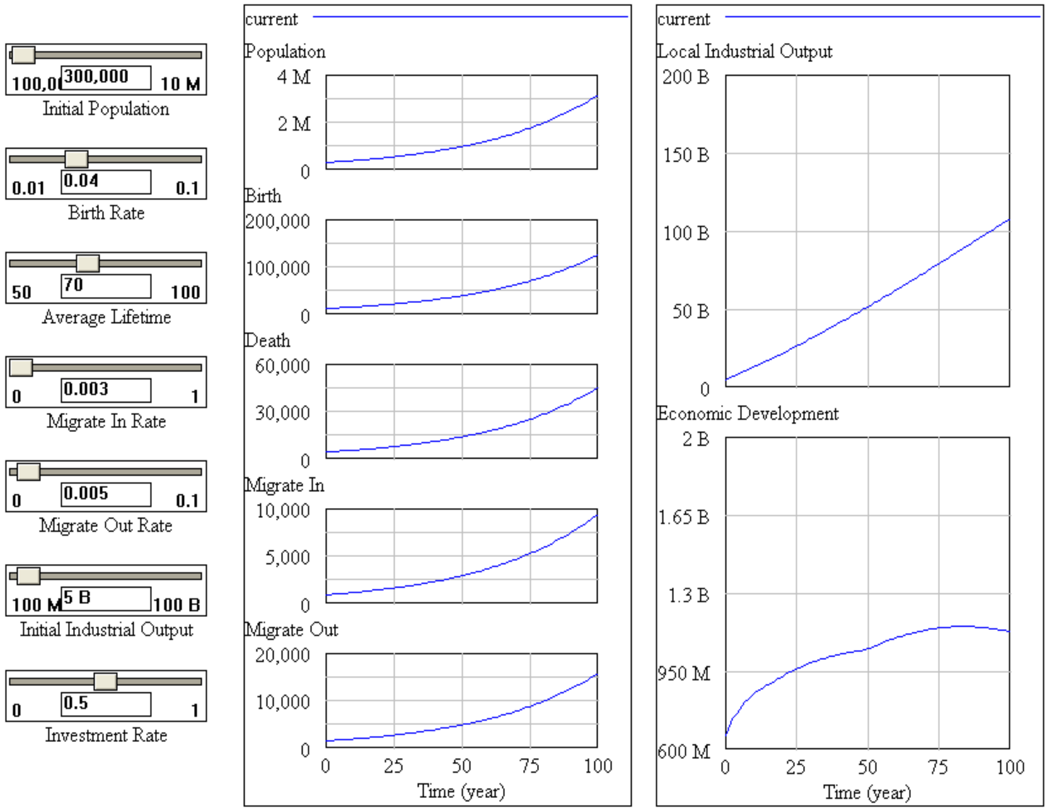

Figure D-2, Increasing Birth Rate and its Influence on Local Economics (Scenario *A*)

In Scenario ***A***, a change of birth rate from 3.3% to 4% nearly doubles the population one hundred years later. Different from the base scenario, economic development suffers due to high population density in part because more traffic is introduced in the local area.

App D.2 Face Validity of the Government Regulation Module

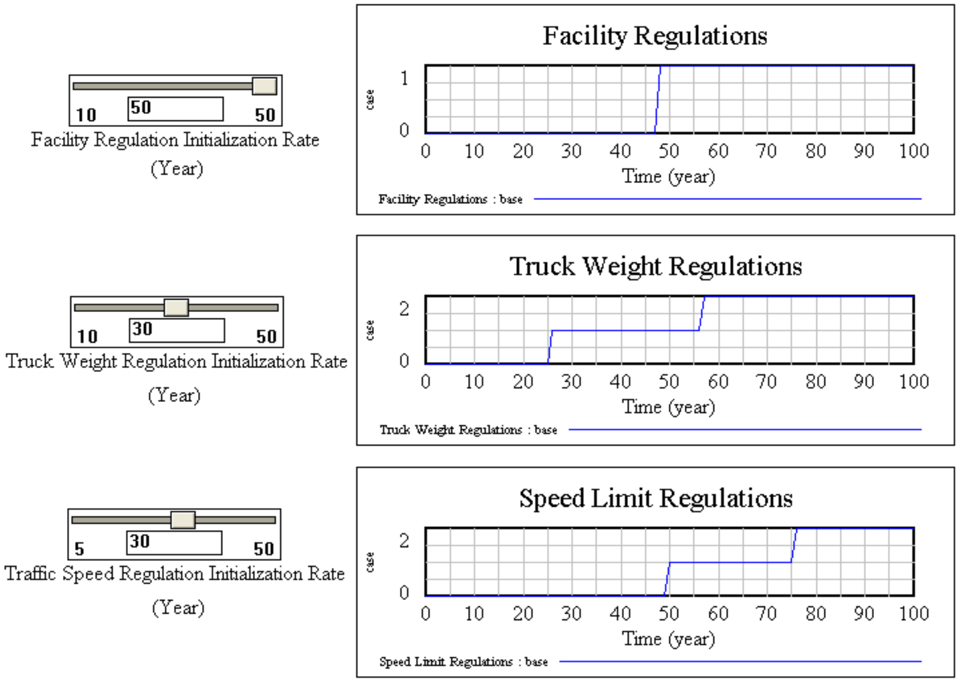

Figure D-3, Regulatory Change (Base Scenario)

Currently, this module includes potential regulations for mandatory upgrades on a bridge, truck weight increases, and speed limits. For simplicity, the module only requires an estimate of the interval for initiation of a new regulation. Then, this module generates a series of random cases for each type of regulation. Figure D-3 generates one case of a mandatory upgrade on the bridge around year 47, two cases of loading increases, and two cases of speed limits changes.

Without a special definition, *Regulation_Pool_on_Truck_Weight* change does not directly indicate whether there is an increase or decrease in freight weight limits. If the base time is set back to early 1950's, truck regulations are issued to limit the booming of heavy trucks. Consequent regulations afterward may either set stricter ones, or deregulate and release the limit to meet the demand of the trucking industry. To avoid confusion, the new regulation refers to the increase of truck weight allowance related to NAFTA only. Currently, the module basically eliminates deregulation by setting a very low possibility in the module.

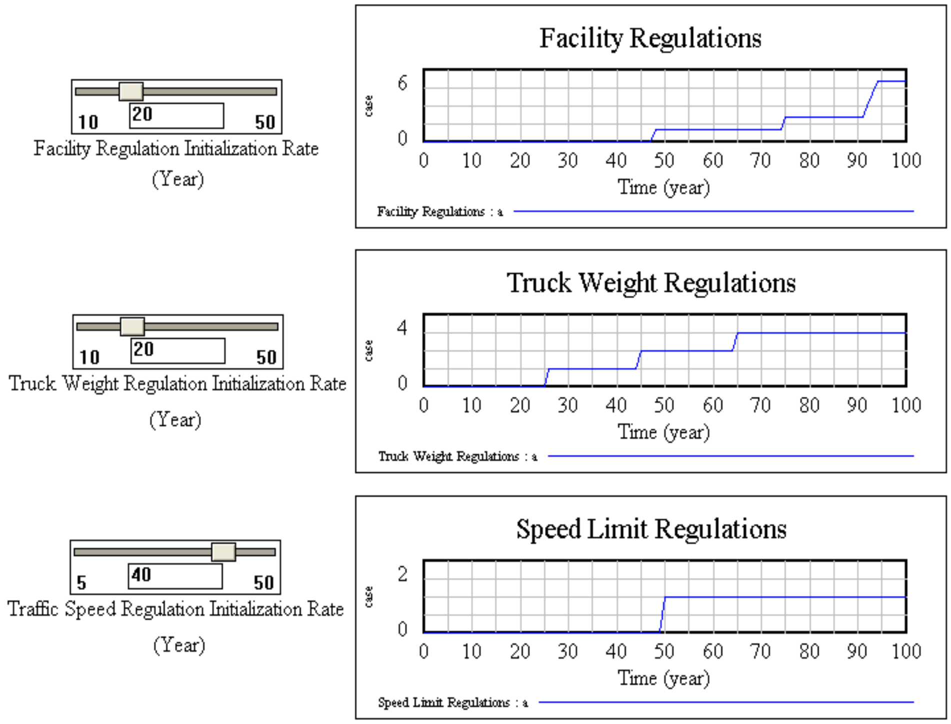

Figure D-4, Adjustment of Regulation Initialization Rates (Scenario *A*)

Figure D-4 presents a different scenario. Since these three sections are independent from each other, we change their initialization rates together. Shortening *Bridge_Regulation_ Initialization Rate* and *Truck_Weight_Regulation_Initialization_Rate* increases the frequency of these two regulations' change rate. Lengthening *Traffic_Speed_Regulation_Initialization_ Rate* decreases the change frequency of *Speed_limits_Regulations.*

App D.3 Face Validity of the Passenger TDP Module

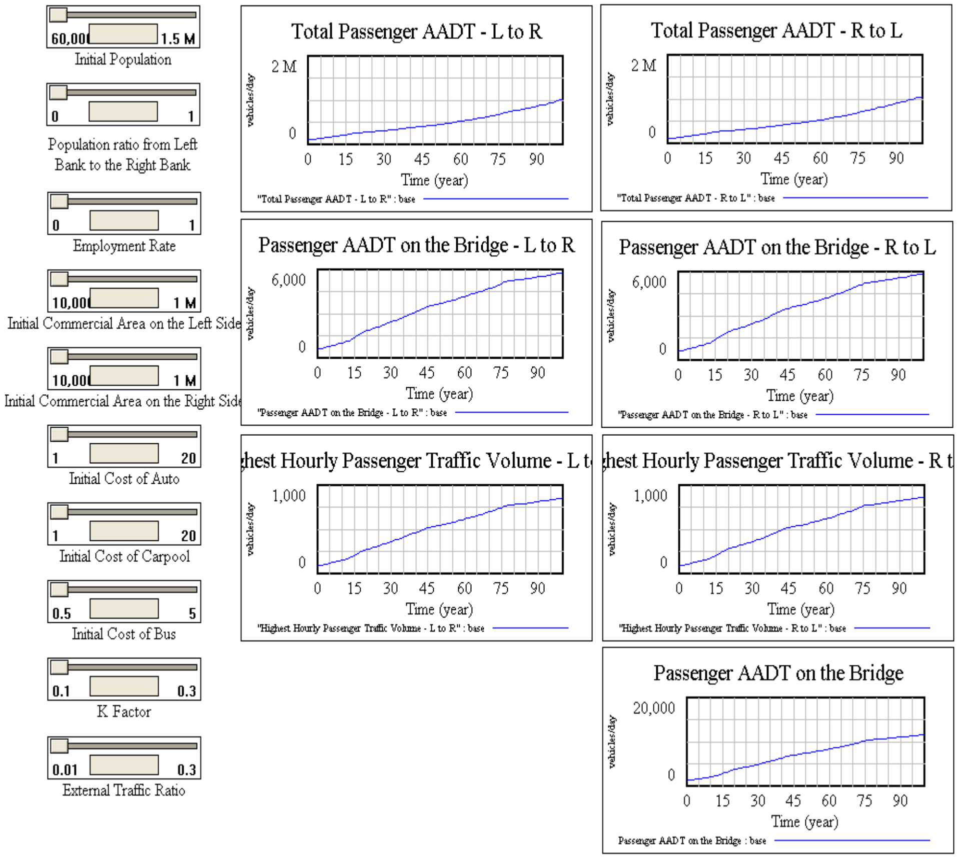

Figure D-5, Passenger TDP by Four Step Method (Base Scenario)

Traffic demand prediction provides the basic argument for performance needs in bridge service life prediction. AADT on the critical crossing depends on several factors identified from prior work. Figure D-5 illustrates the base scenario parameters and output. By adjusting the values of population, commercial area, or mode costs, the module will produce different traffic demands on the bridge. For example, simply doubling the initial population in Scenario ***A*** nearly doubles the initial traffic demand on the bridge. However, this ratio decreases step by step since more traffic is allocated to other facilities when the bridge of interest reaches its capacity (Figure D-6).

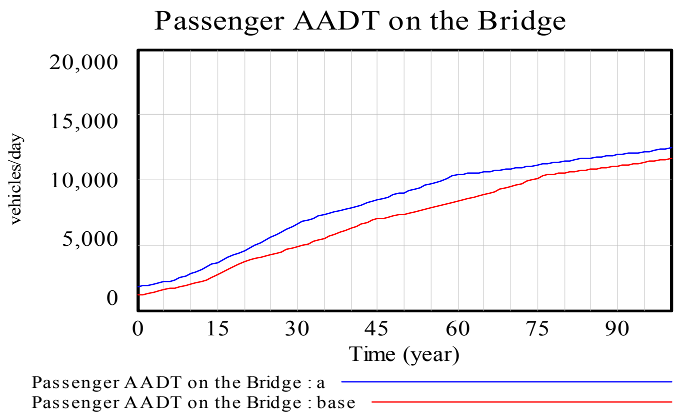

Figure D-6, Double Initial Population (Scenario *A*)

In Scenario ***B*** (Figure D-7), doubling costs of all modes will decrease AADT correspondingly.

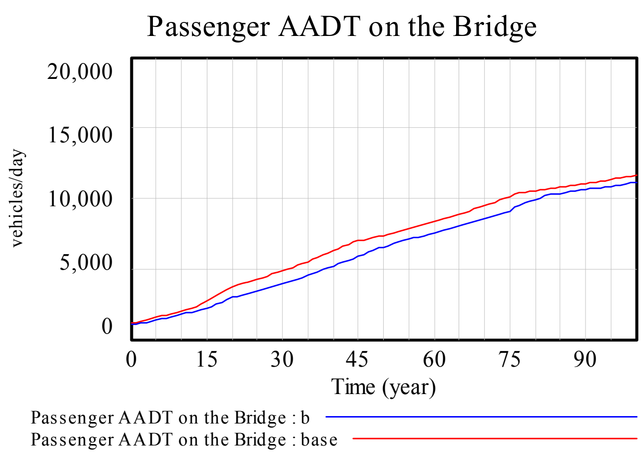

Figure D-7, Double Costs of all Passenger Traffic Modes (Scenario *B*)

App D.4 Face Validity of the Freight TDP Module

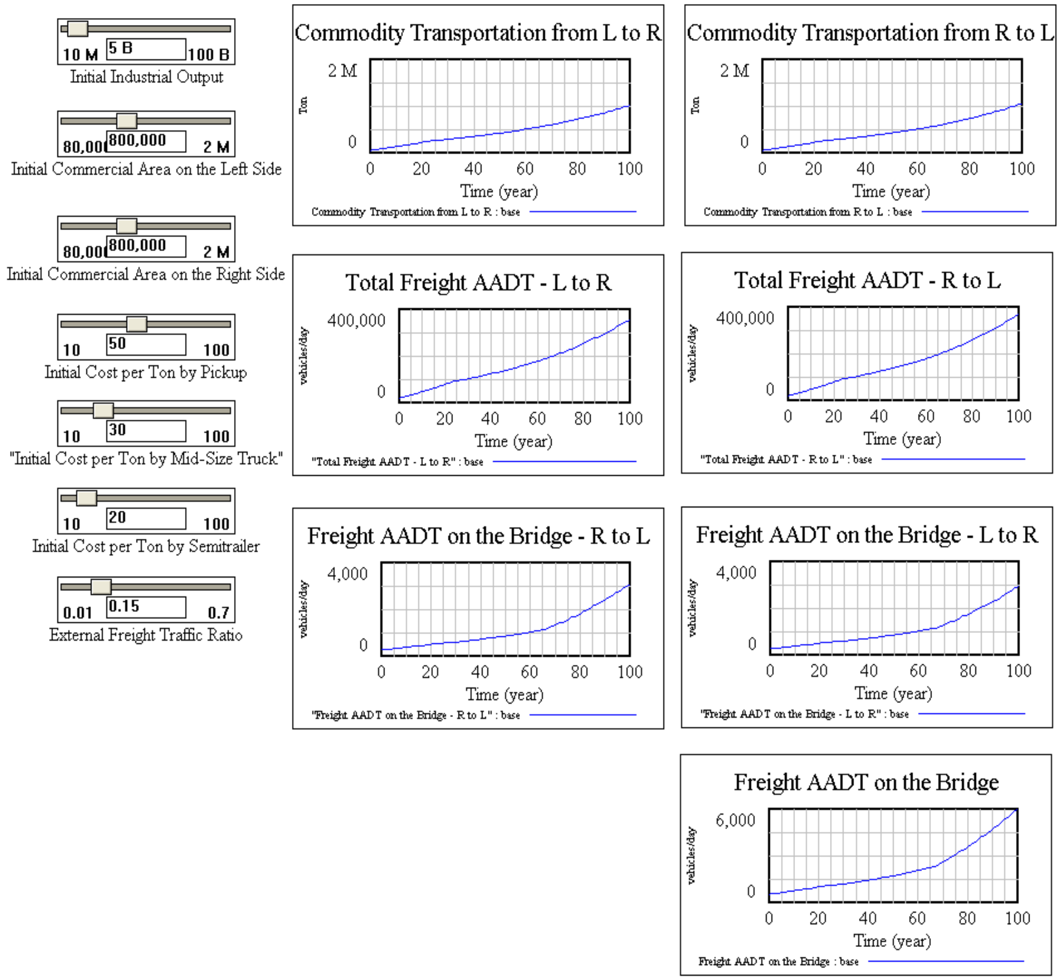

Figure D-8, Freight TDP by Four Step Method (Base Scenario)

The Freight TDP Module has a similar structure and projected results as the Passenger TDP Module in terms of traffic volume generation. Figure D-8 shows the base scenario.

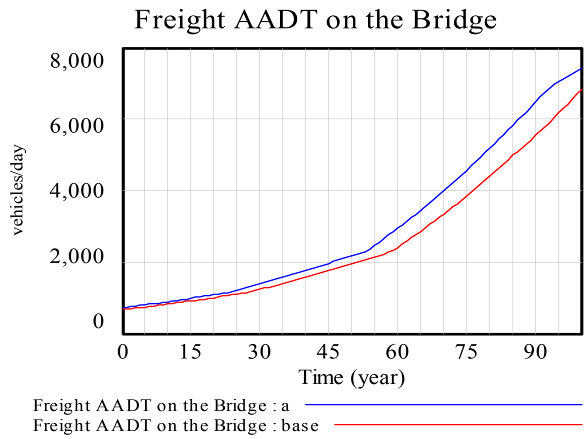

Figure D-9, Double Commercial Area (Scenario *A*)

Figure D-9 presents Scenario ***A*** when commercial building square footage doubles. This will generate more freight traffic demand and the amount of space allocated on the bridge also increases.

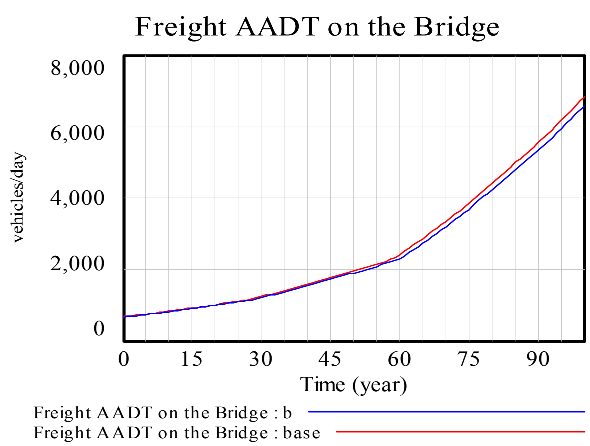

Figure D-10, Double Costs of All Freight Traffic Modes (Scenario *B*)

In Scenario ***B*** (Figure D-10), traffic volume drops slightly when doubling the costs for all freight traffic modes. Freight transportation is not as sensitive to traffic cost as passenger transportation, determined by the utility functions defined in the modules.

App D.5 Face Validity of the Maintenance Module

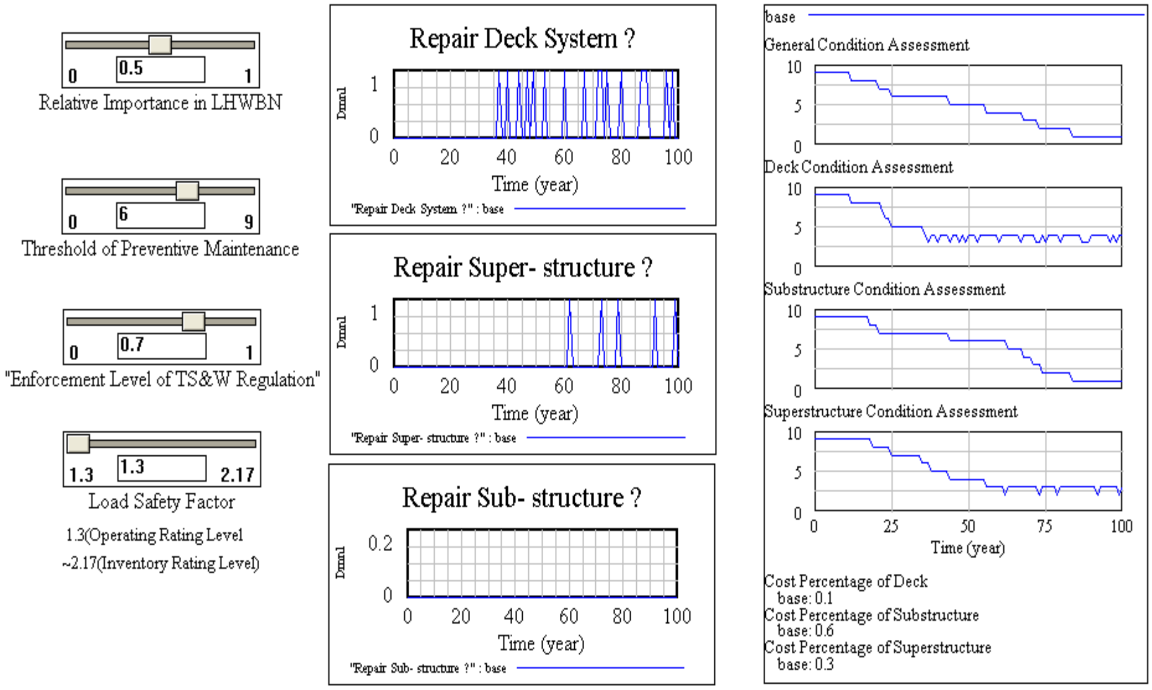

Figure D-11, Maintenance Activities (Base Scenario)

Figure D-11 illustrates the base scenario for the Maintenance Module. In Scenario ***A***, *Relative_Importance_in_LHWBN* is changed from 0.5 to 1.0 which generates different maintenance rate and life condition curves (Figure D-12). In the other words, a bridge on a secondary highway (0.5) receives less financial funds than a bridge on the interstate (1.0).

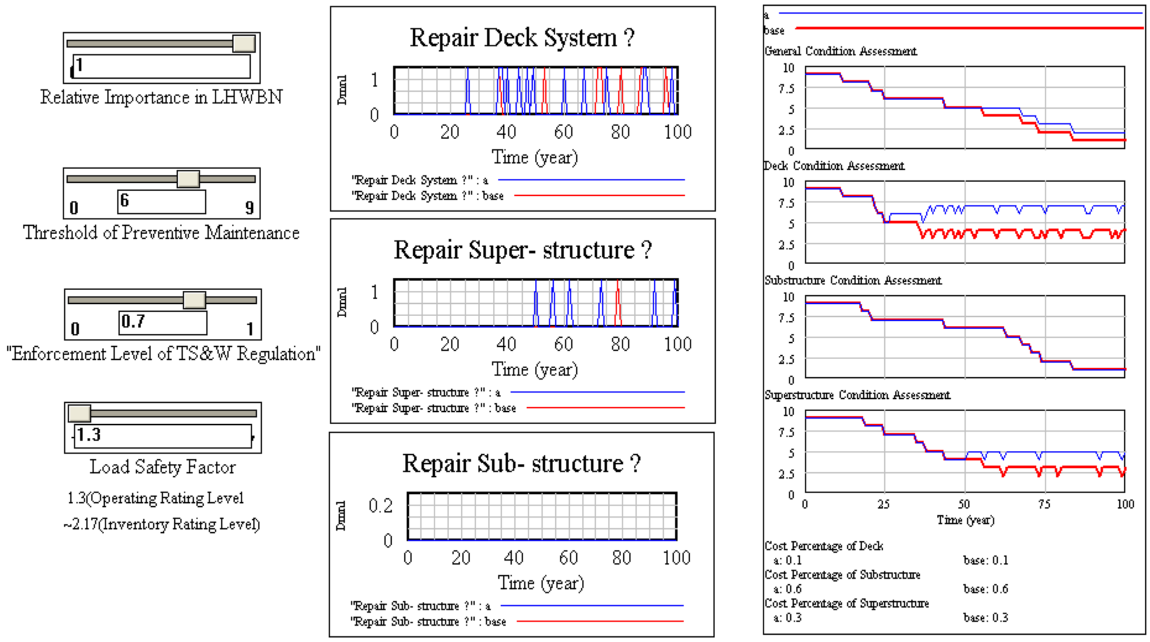

Figure D-12, A Higher *Relative Importance in LHWBN* (Scenario *A*)

In Scenario ***B***, *Threshold_of_Preventive_Maintenance* is set to 2 which generates different maintenance rates and life condition curves (Figure D-13). However, *Threshold_of_ Preventive_Maintenance* does not generate as much difference as *Relative_Importance_ in_LHWBN*, so it appears that a budget-related parameter plays an important role.

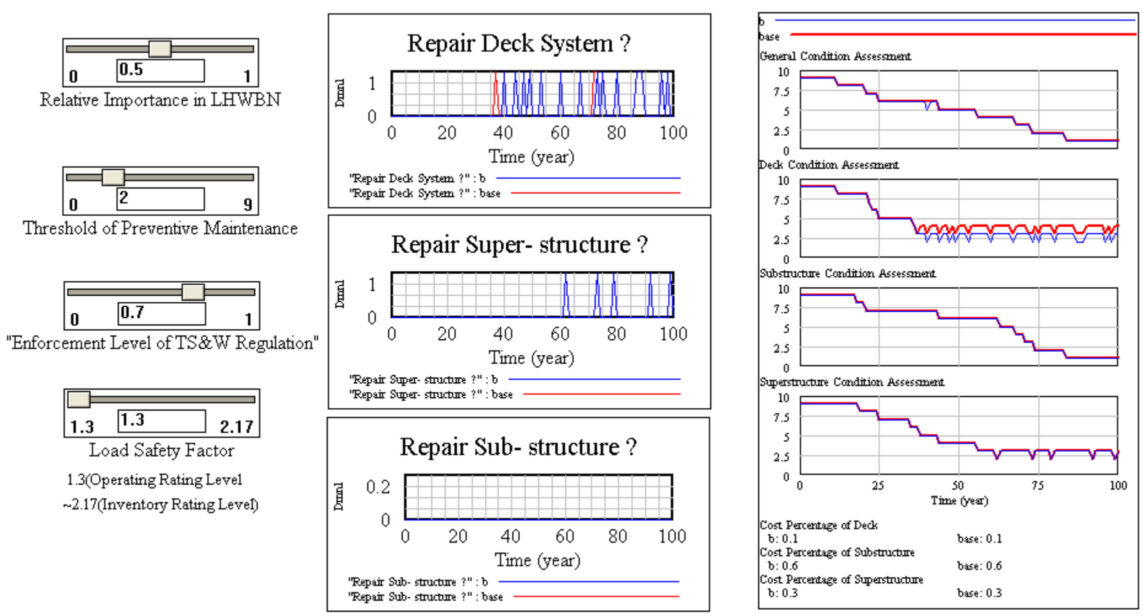

Figure D-13, A Lower *Threshold of Preventive Maintenance* (Scenario *B*)

Clearly, availability of financial resources impacts M&R activities. The Financing Module includes some of the parameters that influence these resources. If user fees are collected on the bridge (a condition set in the Financing Module) then more funds are potentially available for M&R. Figure D-14 illustrates Scenario ***C*** where such a change was made in the Financing Module. Overall, the condition of the bridge is better compared to the base scenario.

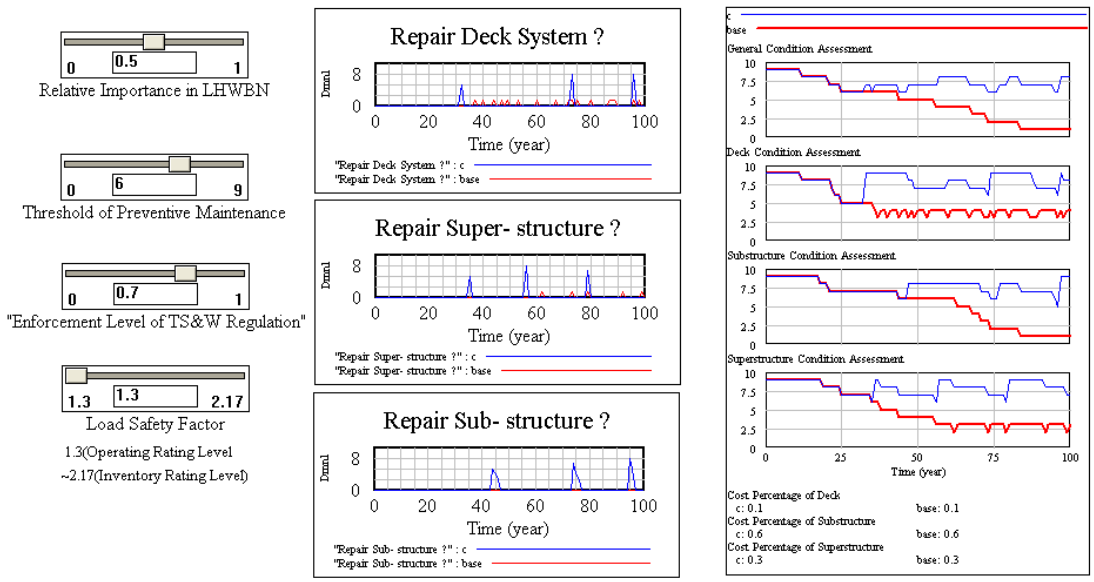

Figure D-14, Maintenance Activities with Sufficient Funding (Scenario *C*)

App D.6 Face Validity of the Bridge Condition Module

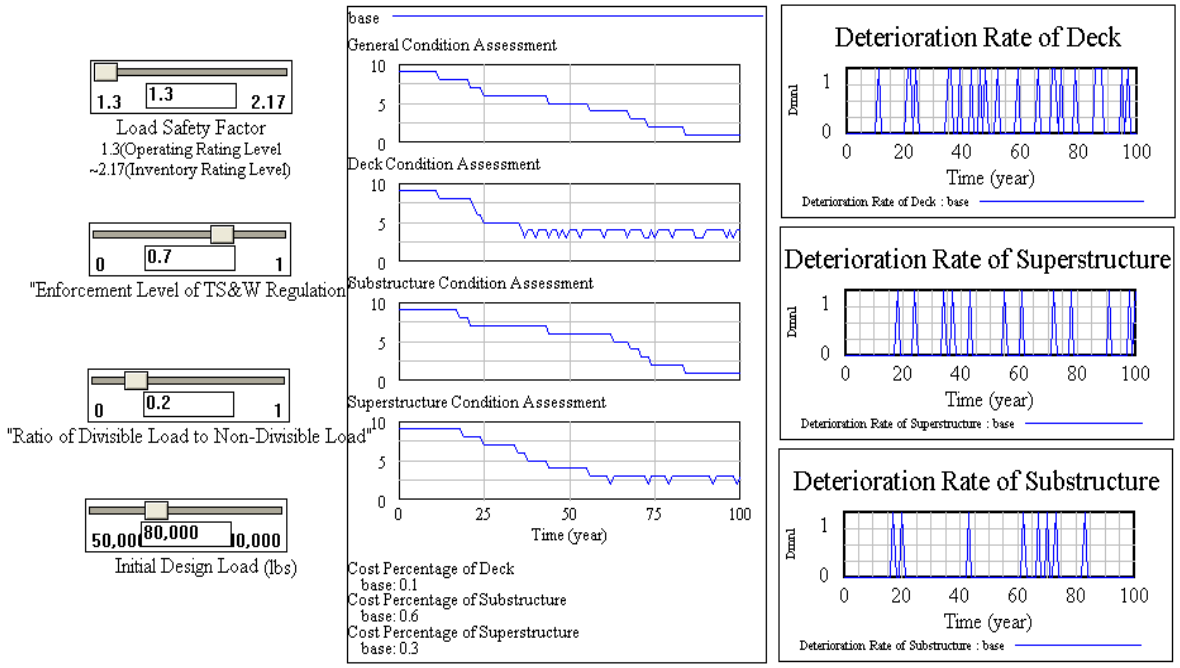

Figure D-15, Bridge Physical Condition (Base Scenario)

This module mainly observes the deterioration of subsystems and how their physical condition changes. *Aggregate_Condition_Assessment* is a sum of all subsystem conditions multiplied by weights of their replacement costs. From the simulation curves (Figure D-15), *Deck_Condition_Assessment* shows a quicker and more severe descent than the superstructure and substructure under normal maintenance. This conforms to the reality that increasing traffic load results into a higher deterioration rate of the decking system. Without replacement, decks are in poor condition for a relatively longer period. Then, the bridge agency needs to rehabilitate the deck system to prevent further accelerating deterioration.

There are several parameters influencing the assessed condition. The first one is *Load_ Safety_Factor*. By assigning a different value, the evaluator can reach a higher or lower level of assessment result as the input for decision making. *Load_Safety_Factor* can assume a value of 1.3 at the Operating Rating Level, or 2.17 at the Inventory Rating Level, or an intermediate one. A higher factor returns a lower evaluating result as Scenario ***A*** (Figure D-16).

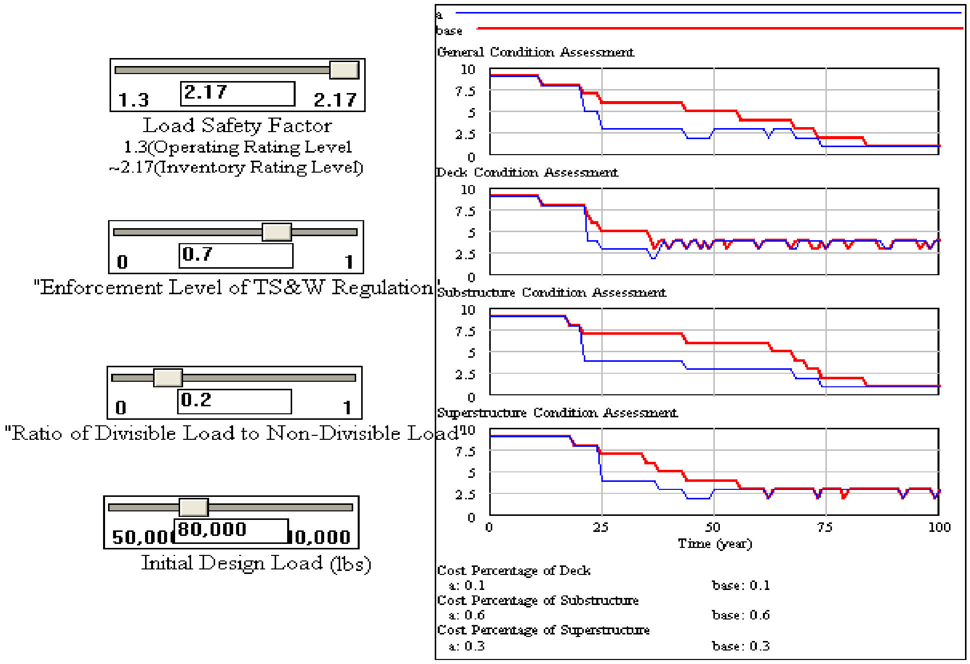

Figure D-16, Condition with Different Load Safety Factor (Scenario *A*)

Enforcement_Level_of_TS&W_Regulation and *Ratio_of_Divisible_Load_to_Non-Divisible_Load* are two related freight controlling variables. A higher enforcement level curtails the overload ratio. Ideally, 100% enforcement level can avoid all over load trucks with higher expenses. Comparing the base scenario (enforcement level = 0.7, divisible load ratio = 0.2) and Scenario ***B*** (enforcement level =0, load ratio =0.3), the model generates a slight difference where Scenario ***B*** has a worse condition.

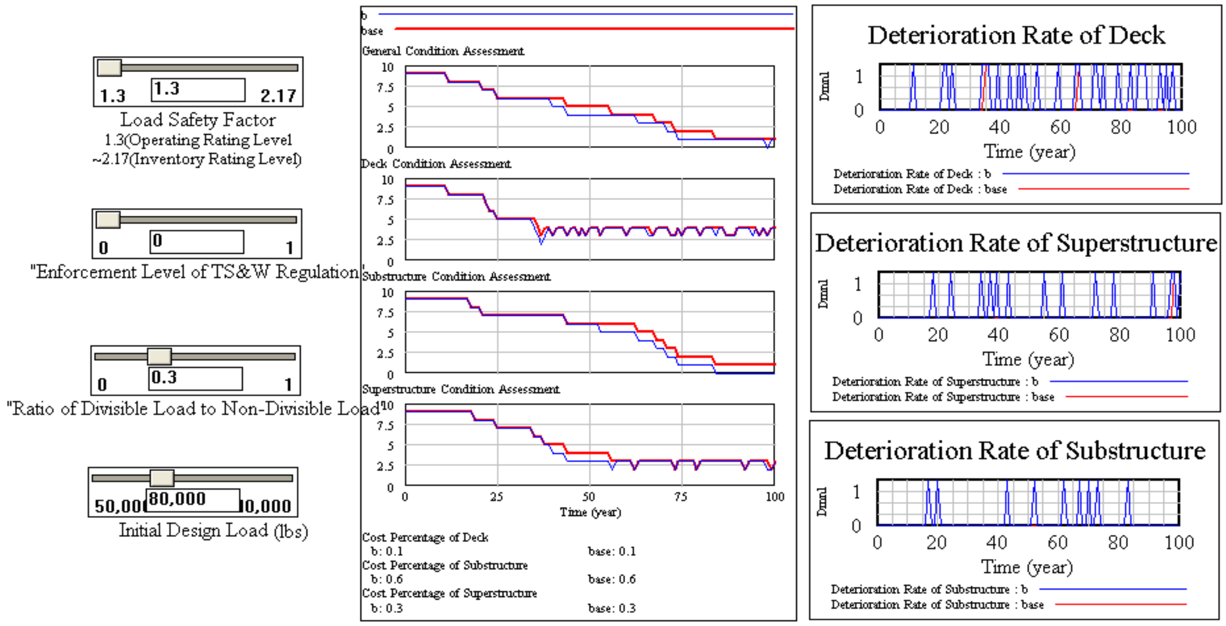

Figure D-17, Condition under Different Enforcement Level and Divisible Ratio (Scenario *B*)

App D.7 Face Validity of the Upgrade and Bridge Function Modules

Since the Bridge Function Module is simple and purely depends on the Upgrade Module, this report combines them together to test the face validity.

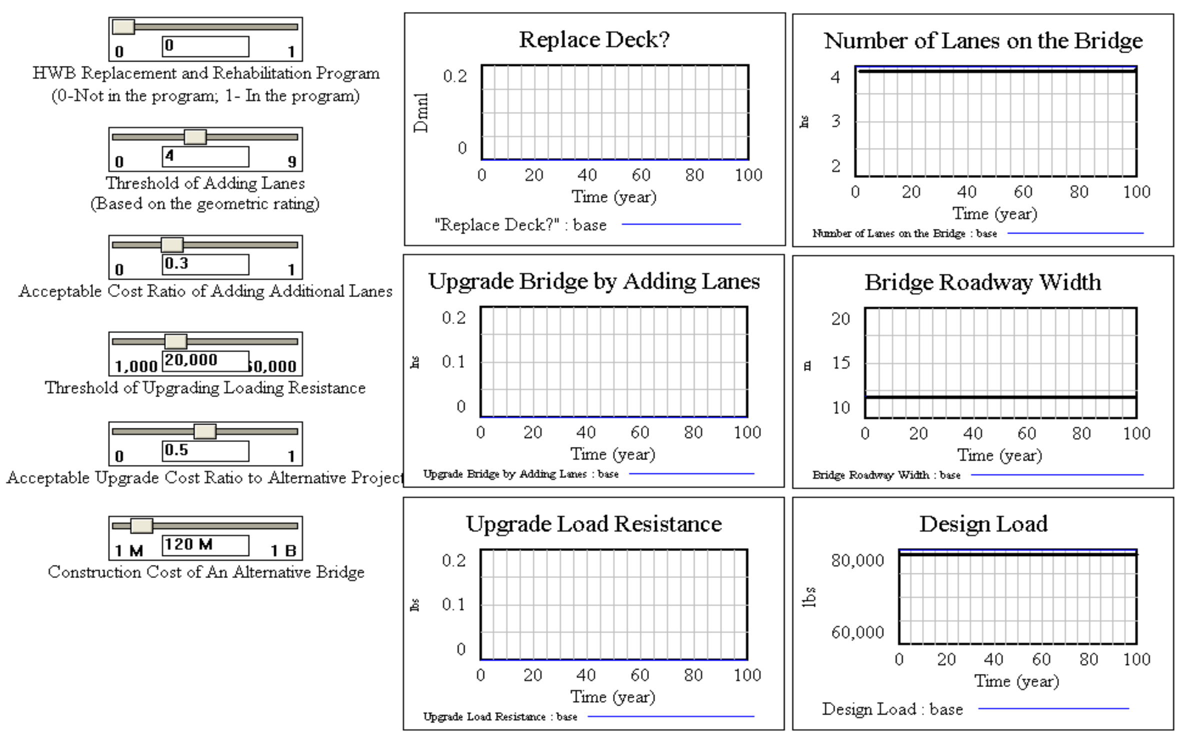

Figure D-18, Upgrade and Function (Base Scenario)

There are two types of bridge upgrade activities in this module, adding lanes and upgrade *Loading_Resistance*. Deck replacement belongs to bridge rehabilitation. It is grouped into this GUI since replacing existing decks also increases *Loading_Resistance* or widens bridge roadway. Not all bridges are designed to accommodate an upgrade. Most of time, it is not economical to improve an existing bridge compared to build a new one. The model requires the decision maker to set the threshold for each type of upgrade as well as provides construction costs of an alternative bridge.

The bridge agency may consider upgrading a bridge when the bridge is registered into *HWB_Replacement_and_Rehabilitation_Program*. If this variable is 0 as a default, a bridge is seldom upgraded during its service life. Otherwise, the model allows certain upgrade activities based on the economic feasibility analysis. The only exception is a mandatory upgrade, such as environmental protection, which is not limited by the economic analysis. By setting a bridge in the replacement and rehabilitation program first, the model will add lanes when the construction cost of a new bridge is $120Million at year 11 with a threshold of geometric evaluation at year 7. Similarly, the model will upgrade its loading resistance by 20000 lbs at year 43 by setting *Acceptable_Upgrade_Cost_Ratio_to_Alternative_Project* equals 0.4, *Threshold_to_Upgrade_Loading_Resistance* equals 20000 lbs.

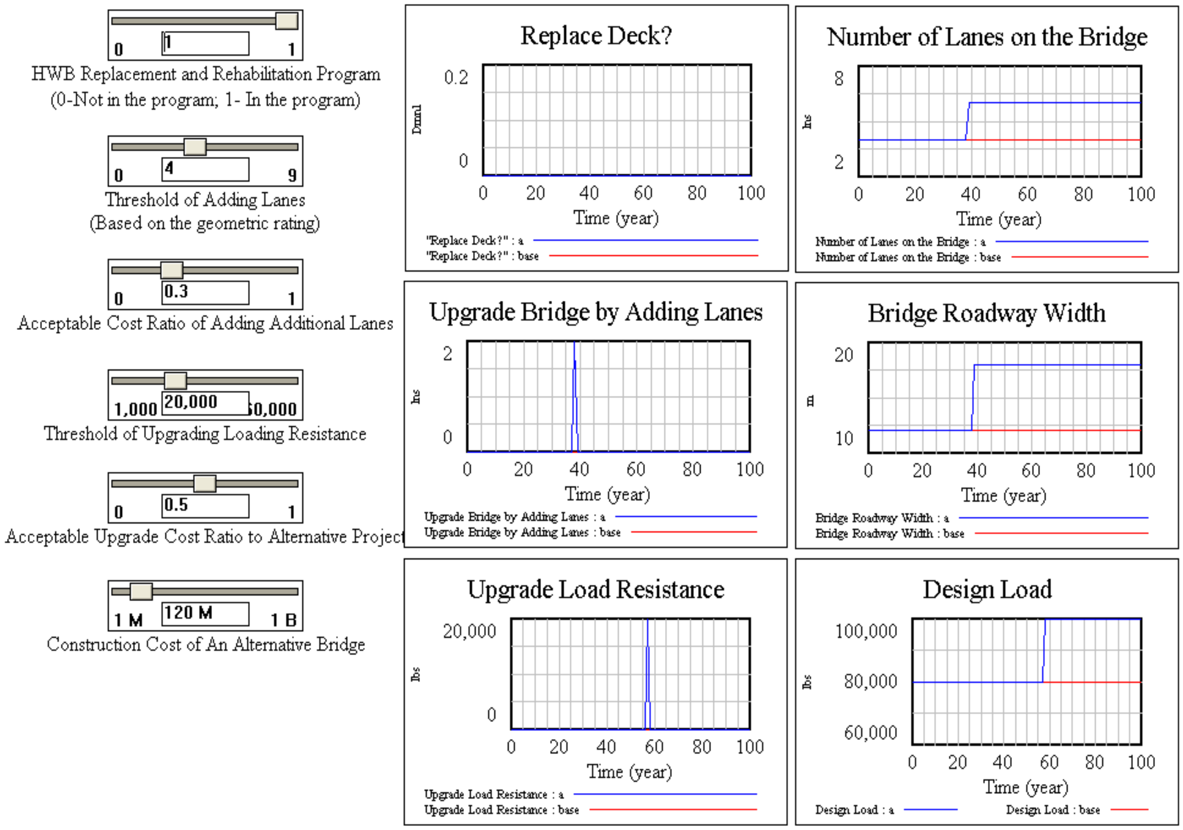

Figure D-19, Upgrade Roadway Width and Loading Resistance (Scenario *A*)

In Scenario ***B***, the module assumes a cheaper alternative bridge with *Construction_ Cost_of_An_Alternative_Bridge* equaling $40 million. Then, no upgrade action happens even if this bridge is still registered in the rehabilitation program (Figure D-20).

This module assumes a lower *Threshold_of_Upgrading_Loading_Resistance* in Scenario ***C.*** This means the bridge of interest should be upgraded for its loading resistance with a smaller deficient loading capacity. Figure D-21 shows there are twice as many upgrades of loading resistance for the bridge that is registered in the *HWB_Replacement_ and_Rehabilitation_Program.*

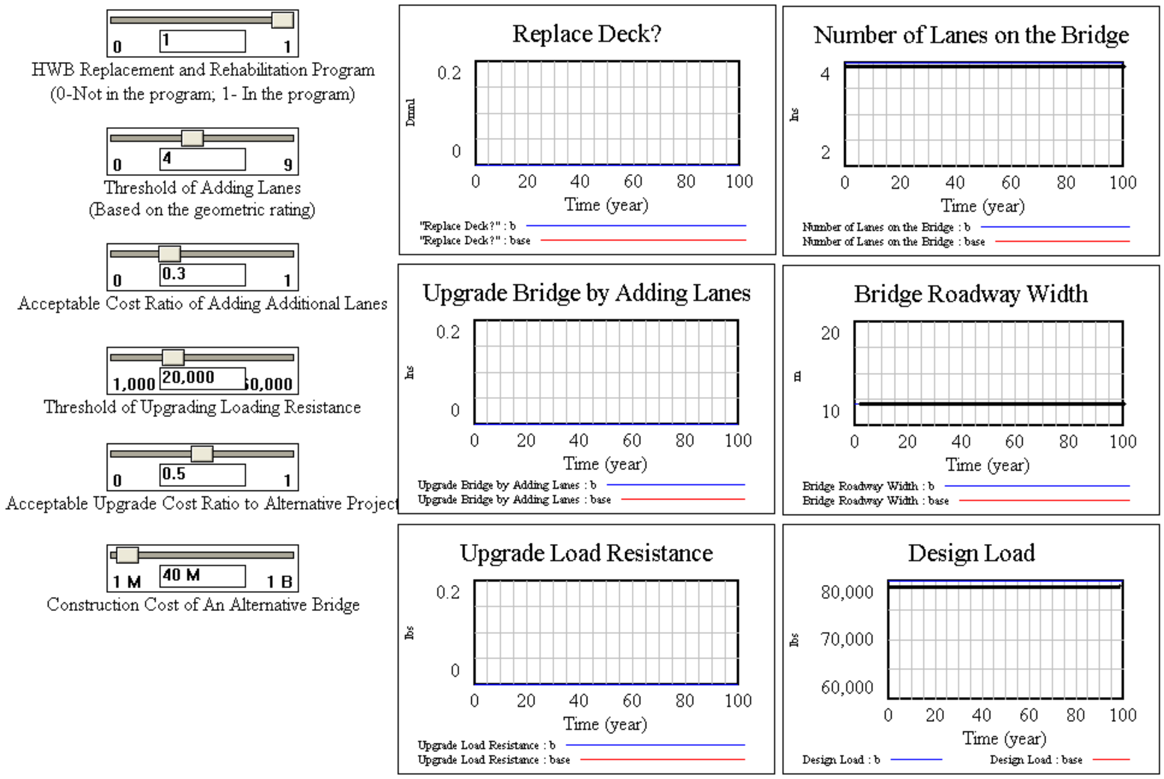

Figure D-20, A Cheaper Alternative Bridge (Scenario *B*)

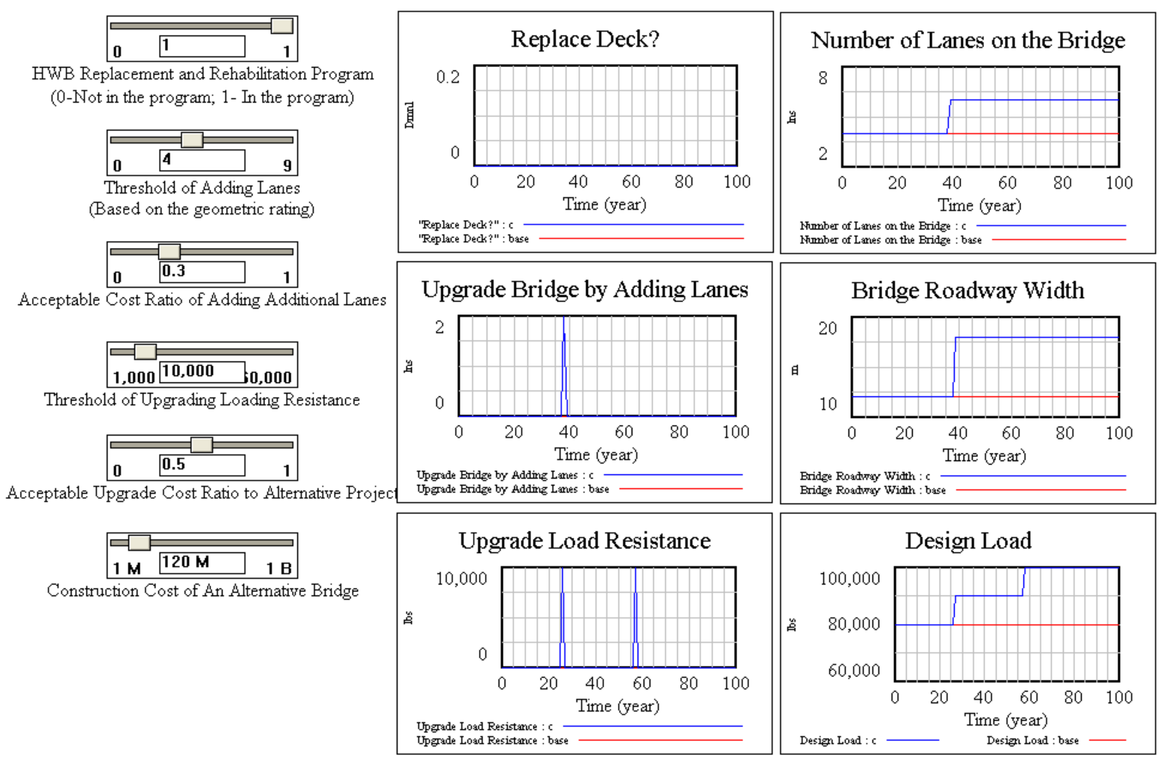

Figure D-21, A Lower *Threshold of Upgrading Loading Resistance* (Scenario *C*)

Appendix E, Model Variables

Table E-1, Socioeconomic Factors

NAME	TYPE	TDP	UNIT	VALUE
Aggregate Daily Transportation Demand	Model	Yes	Vehicles/Day	-
Average Lifetime	User	No	Year	70
Average Traffic Density	Model	Yes	Pc/mi/ln	-
Birth Rate	Model	Yes	Person/Year	-
Birth Factor	User	No	Percent	0.033
Death Rate	Model	Yes	Person/Year	-
Economic Development	Model	Yes	Dollar	-
Employment Rate	User	No	Percent	0.9
Highway Comprehensive LOS	Model	Yes	Dmnl	-
Initial Industrial Output	User	No	Dollar	5.00E+09
Initial Population	User	No	Person	300000
Investment Ratio	User	No	Percent	0.5
Local Industrial Output	Model	Yes	Dollar	-
Migrate In Factor	User	No	Percent	0.008
Migrate In Rate	Model	Yes	Person/Year	-
Migrate Out Factor	User	No	Percent	0.003
Migrate Out Rate	Model	Yes	Person/Year	-
Population	Model	Yes	Person	-

Table E-2, Regulatory Factors

NAME	TYPE	TDP	UNIT	VALUE
Adjustment of Speed Limit	Model	Yes	Mph	-
Bridge Deregulation Rate	Model	Yes	Case	-
Bridge Regulation Initialization Rate	User	No	Year	20
Bridge Regulation Initiation	Model	Yes	Case	-
Bridge Regulation	Model	Yes	Case	-
Mandatory Improvement of Bridges	Model	Yes	Case	-
Speed Limit Deregulation Rate	Model	Yes	Case	-
Speed Limit Initiation	Model	Yes	Case	-
Speed Limit Regulation	Model	Yes	Case	-
Speed Limit	Model	Yes	Mph	-
The Starting Year of Bridge Regulation	Model	Yes	Year	-

The Starting Year of Speed Limit Initiation	Model	Yes	Year	-
The Starting Year of Truck Weight Regulation Change	Model	Yes	Year	-
Traffic Speed Regulation Initialization Rate	User	No	Year	30
Truck Weight Deregulation Rate	Model	Yes	Case	-
Truck Weight Regulation Initialization Rate	Model	Yes	Case	-
Truck Weight Regulation	Model	Yes	Case	-

Table E-3, Financial Factors

NAME	TYPE	TDP	UNIT	VALUE
Annual Federal/State Funds to the Bridge	Model	Yes	Dollar	-
Annual Loan Payment	Model	Yes	Dollar	-
Annual Expenses on Other HWBs	Model	Yes	Dollar	-
Auto Toll Rate	User	No	Dollar	0.5
Balance of the Loans	Model	Yes	Dollar	-
Cumulative Expenses on Other HWBs in the LHWBN	Model	Yes	Dollar	-
Cumulative M&R Expenses	Model	Yes	Dollar	-
Cumulative Operation Expenses	Model	Yes	Dollar	-
Cumulative Upgrade Expenses	Model	Yes	Dollar	-
Dedicated Tax Rate for the Bridge of Interest	User	No	Dollar	0
Federal Funds Collection Rate	Model	Yes	Dollar	-
Interest	Model	Yes	Dollar	-
Interest Rate	User	No	Percent	0.08
Investment Percent in LHWBN	User	No	Percent	0.01
Loan Payment	Model	Yes	Dollar	-
Loan Payment by Federal/State Funds	Model	Yes	Dollar	-
Loan Payment by Local Funds	Model	Yes	Dollar	-
Loan Payment by User Fees	Model	Yes	Dollar	-
Loan Term	User	No	Dollar	30
Local Fund	Model	Yes	Dollar	-
Local Fund to the Bridge of Interest	Model	Yes	Dollar	-
LHWBN Budget	Model	Yes	Dollar	-
M&R Expenses	Model	Yes	Dollar	-
Net Income	Model	Yes	Dollar	-
Operation Expenses	Model	Yes	Dollar	-
Principal	User	No	Dollar	2.42E+07
Revenue	Model	Yes	Dollar	-
State Infrastructure Investment in LHWBN	Model	Yes	Dollar	-

Tax Collection Period	User	No	Year	0
Tax Collection Rate	Model	Yes	Dollar	-
Toll Collection Period	User	No	Year	30
Tolling?	User	No	Dmnl	1
Truck Toll Rate	User	No	Dollar	2
User Fee/Toll	Model	Yes	Dollar	-
User Fee to the Bridge of Interest	Model	Yes	Dollar	-

Table E-4, Budgeting Factors

NAME	TYPE	TDP	UNIT	VALUE
Annual Budget of the Bridge of Interest	Model	Yes	Dollar	-
Annual Budget of Deck	Model	Yes	Dollar	-
Annual Budget of Substructure	Model	Yes	Dollar	-
Annual Budget of Superstructure	Model	Yes	Dollar	-
Bridge Replacement Cost	Model	Yes	Dollar	-
Cost Percentage of Deck	User	No	Percent	0.1
Cost Percentage of Substructure	User	No	Percent	0.6
Cost Percentage of Superstructure	User	No	Percent	0.3
FHWA CBPI	Model	Yea	Dmnl	-
Original Construction Cost	User	No	Dollar	2.42E+07
Prioritize Deck System in LHWBN	Model	Yes	Dmnl	-
Prioritize Substructure System in LHWBN	Model	Yes	Dmnl	-
Prioritize Superstructure System in LHWBN	Model	Yes	Dmnl	-
Relative Importance in LHWBN	User	No	Dmnl	0.5
Replacement Cost of Deck	Model	Yes	Dollar	-
Replacement Cost of Substructure	Model	Yes	Dollar	-
Replacement Cost of Superstructure	Model	Yes	Dollar	-

Table E-5, Maintenance Factors

NAME	TYPE	TDP	UNIT	VALUE
Annual M&R Cost	Model	Yes	Dollar	-
M&R Restoration Vector of Deck	User	No	Dmnl	(0,0),(0.02999,0),(0.03,1),(0.06,2),(0.1,3),(0.15,4),(0.25, 5),(0.8,6)
M&R Restoration Vector of Substructure	User	No	Dmnl	(0,0),(0.02999,0),(0.03,1),(0.08,2),(0.13,3),(0.2,4),(0.4,5),(0.8,6)
M&R Restoration Vector of Superstructure	User	No	Dmnl	(0,0),(0.04999,0),(0.05,1),(0.08,2),(0.12,3),(0.2,4),(0.3,5),(0.8,6)

Maintenance Cost of Deck	Model	Yes	Dollar	-
Maintenance Cost of Substructure	Model	Yes	Dollar	-
Maintenance Cost of Superstructure	Model	Yes	Dollar	-
Possible Deck Restoration Rate	Model	Yes	Dmnl	-
Possible Substructure Restoration Rate	Model	Yes	Dmnl	-
Possible Superstructure Restoration Rate	Model	Yes	Dmnl	-
Repair Cost Vector of Deck	User	No	Dmnl	0,0),(1,0.03),(2,0.06),(3,0.1),(4,0.15),(5,0.25),(6,0.9)
Repair Cost Vector of Substructure	User	No	Dmnl	(0,0),(1,0.03),(2,0.08),(3,0.13),(4,0.2),(5,0.4),(6,0.8)
Repair Cost Vector of Superstructure	User	No	Dmnl	(0,0),(1,0.05),(2,0.8),(3,0.12),(4,0.2),(5,0.3),(6,0.8)
Repair Deck?	Model	Yes	Dmnl	-
Repair Substructure?	Model	Yes	Dmnl	-
Repair Superstructure?	Model	Yes	Dmnl	-
Replace Deck?	Model	Yes	Dmnl	-
Threshold of Preventive Maintenance	User	No	Dmnl	6

Table E-6, Upgrade Factors

NAME	TYPE	TDP	UNIT	VALUE
Acceptable Cost Ratio of Adding Additional Lanes	User	No	Percent	0.3
Acceptable Cost Ratio to an Alternative Bridge	User	No	Percent	0.3
Add Lanes on the Bridge of Interest	Model	Yes	Lns	-
Annual Upgrade Cost	Model	Yes	Dollar	-
Construction Cost of an Alternative Bridge	User	No	Dollar	1.20E+08
Cost of Adding Lanes	Model	Yes	Dollar	-
Cost of Upgrading Load Resistance	Model	Yes	Dollar	-
Cost Vector of Upgrade Load Resistance	User	No	Percent	(0,0),(10000,0.1),(20000,0.2),(30000,0.3),(40000,0.4), (50000,0.5),(60000,0.6)
Decision to Add Additional Lanes	Model	Yes	Lns	-
Decision to Upgrade Bridge	Model	Yes	Dmnl	-
Decision to Upgrade Loading Resistance	Model	Yes	Lbs	-
HWB Replacement and Rehabilitation Program	User	No	Dmnl	-
Increase Loading Resistance	Model	Yes	Lbs	-
Initial Design Load	User	No	Lbs	80000
Initial Number of Lanes on the Bridge	User	No	Lns	4

Loading Capacity Difference	Model	Yes	Lbs	-
Maximum Possible Lanes on the Bridge of Interest	User	No	Lns	8
Number of Lanes on the Bridge of Interest	Model	Yes	Lns	-
Threshold of Adding Lanes	User	No	Lns	4
Threshold of Upgrading Loading Resistance	User	No	Lbs	20000

Table E-7, Passenger TDP Factors

NAME	TYPE	TDP	UNIT	VALUE
Assigned Traffic Volume to the Bridge of Interest - L to R	User	No	Vehicles/Day	(10000,200),(100000,500),(200000,1000),(300000,2000),(400000,3000),(500000,3500),(600000,4000),(700000,4500),(1e+006,5000),(2e+006 ,6500)
Assigned Traffic Volume to the Bridge of Interest - R to L	User	No	Vehicles/Day	(10000,200),(100000,500),(200000,1000),(300000,2000),(400000,3000),(500000,3500),(600000,4000),(700000,4500),(1e+006,5000),(2e+006 ,6500)
Auto Volume from L to R	Model	Yes	Vehicles/Day	-
Auto Volume from R to L	Model	Yes	Vehicles/Day	-
Average Income	Model	Yes	Dollar	-
Balanced Trips from L to R	Model	Yes	Passenger /Day	-
Balanced Trips from R to L	Model	Yes	Passenger /Day	-
Bus Volume from L to R	Model	Yes	Vehicles/Day	-
Bus Volume from R to L	Model	Yes	Vehicles/Day	-
Carpool Volume from L to R	Model	Yes	Vehicles/Day	-
Carpool Volume from R to L	Model	Yes	Vehicles/Day	-
Commercial Area in Zone - L	Model	Yes	M^2	-
Commercial Area in Zone - R	Model	Yes	M^2	-
Commercial Area Increase Rate - L	Model	Yes	M^2	-
Commercial Area Increase Rate - R	Model	Yes	M^2	-
Cost of Auto	Model	Yes	Dollar	-
Cost of Bus	Model	Yes	Dollar	-
Cost of Carpool	Model	Yes	Dollar	-
Employed People - L	Model	Yes	Person	-
Employed People - R	Model	Yes	Person	-
Employment Rate	User	No	Percent	0.9
External Traffic Rate	User	No	Percent	0.15
Highest Hourly Passenger Traffic Volume - L to R	Model	Yes	Vehicles/Day	-
Highest Hourly Passenger Traffic Volume - R to L	Model	Yes	Vehicles/Day	-
Household Income	Model	Yes	Thousand Dollar	-

Household Size	Model	Yes	Person	-
Household Size Change Rate	Model	Yes	Person	-
Increase Rate of Auto Cost	Model	Yes	Dollar	-
Increase Rate of Bus Cost	Model	Yes	Dollar	-
Increase Rate of Carpool Cost	Model	Yes	Dollar	-
Initial Commercial Area - L	User	No	M^2	800000
Initial Commercial Area - R	User	No	M^2	800000
Initial Cost of Auto	User	No	Dollar	4
Initial Cost of Bus	User	No	Dollar	1
Initial Cost of Carpool	User	No	Dollar	2
Initial Household Size	User	No	Person	3
Initial Motorization Rate	User	No	Vehicles /Person	0.1
K Factor	User	No	Dmnl	0.148
Motorization Rate	Model	Yes	Vehicles /Person	-
Number of Household - L	Model	Yes	Household	-
Number of Household - R	Model	Yes	Household	-
Passenger AADT on the Bridge - L to R	Model	Yes	Vehicles/Day	-
Passenger AADT on the Bridge - R to L	Model	Yes	Vehicles/Day	-
Passenger per Bus	User	No	Person	10
Passenger per Carpool	User	No	Person	2.5
Population Ratio L	User	No	Percent	0.5
Population - L	Model	Yes	Person	-
Population - R	Model	Yes	Person	-
Registered Auto - L	Model	Yes	Vehicle	-
Registered Auto - R	Model	Yes	Vehicle	-
Sum of Passenger Vehicle Utility	Model	Yes	Dmnl	-
Total Passenger AADT - L to R	Model	Yes	Vehicles/Day	-
Total Passenger AADT - R to L	Model	Yes	Vehicles/Day	-
Travel Time of Auto	Model	Yes	Minute	-
Travel Time of Bus	Model	Yes	Minute	-
Travel Time of Carpool	Model	Yes	Minute	-
Trip Attraction - L	Model	Yes	Person	-
Trip Attraction - R	Model	Yes	Person	-
Trip Production - L	Model	Yes	Person	-
Trip Production - R	Model	Yes	Person	-
Utility of Auto	Model	Yes	Dmnl	-
Utility of Bus	Model	Yes	Dmnl	-

Utility of Carpool	Model	Yes	Dmnl	-

Table E-8, Freight TDP Factors

NAME	TYPE	TDP	UNIT	VALUE
ADTT on the Bridge - L to R	Model	Yes	Vehicles/Day	-
ADTT on the Bridge - R to L	Model	Yes	Vehicles/Day	-
Commodity Transportation From L to R	Model	Yes	Ton	-
Commodity Transportation From R to L	Model	Yes	Ton	-
Commodity Trip Generation - L	Model	Yes	Ton	-
Commodity Trip Generation - R	Model	Yes	Ton	-
Highest Hourly Freight Traffic Volume - L to R	Model	Yes	Vehicles/Day	-
Highest Hourly Freight Traffic Volume - R to L	Model	Yes	Vehicles/Day	-
Increase Rate of Pickup Cost	Model	Yes	Dollar	-
Increase Rate of Truck Cost	Model	Yes	Dollar	-
Increase Rate of Semitrailer Cost	Model	Yes	Dollar	-
Initial Cost per Ton by Mid-Size Truck	User	No	Dollar	30
Initial Cost per Ton by Pickup	User	No	Dollar	50
Initial Cost per Ton by Semitrailer	User	No	Dollar	20
Pickup Capacity	User	No	Ton	2.5
Pickup Volume from L to R	Model	Yes	Vehicles/Day	-
Pickup Volume from R to L	Model	Yes	Vehicles/Day	-
Semitrailer Capacity	User	No	Ton	30
Semitrailer Volume from L to R	Model	Yes	Vehicles/Day	-
Semitrailer Volume from R to L	Model	Yes	Vehicles/Day	-
Sum of Freight Utility	Model	Yes	Dmnl	-
Truck Capacity	User	No	Ton	15
Total Employment	Model	Yes	Person	-
Total Freight ADTT - L to R	Model	Yes	Vehicles/Day	-
Total Freight ADTT - R to L	Model	Yes	Vehicles/Day	-
Travel Time of Pickup	Model	Yes	Minute	-
Travel Time of Semitrailer	Model	Yes	Minute	-
Travel Time of Truck	Model	Yes	Minute	-
Truck Volume from L to R	Model	Yes	Vehicles/Day	-
Truck Volume from R to L	Model	Yes	Vehicles/Day	-
Unit Cost per Ton by Pickup	Model	Yes	Dollar	-
Unit Cost per Ton by Semitrailer	Model	Yes	Dollar	-
Unit Cost per Ton by Truck	Model	Yes	Dollar	-

Utility of Pickup	Model	Yes	Dmnl	-
Utility of Semitrailer	Model	Yes	Dmnl	-
Utility of Truck	Model	Yes	Dmnl	-

Table E-9, Physical Condition Factors

NAME	TYPE	TDP	UNIT	VALUE
Annual Bridge Fatigue Damage	Model	Yes	Dmnl	-
Deck Condition Assessment	Model	Yes	Dmnl	-
Deterioration Rate of Deck	Model	Yes	Dmnl	-
Deterioration Rate of Substructure	Model	Yes	Dmnl	-
Deterioration Rate of Superstructure	Model	Yes	Dmnl	-
Enforcement Level of TS& W regulation	User	No	Dmnl	0.7
Evaluation Criteria	Model	Yes	Dmnl	-
Aggregate Condition Assessment	Model	Yes	Dmnl	-
Load Safety Factor	User	No	Dmnl	1.3
Loading Resistance	Model	Yes	Lbs	-
Loading Spectra	Model	yes	Psi	-
Markov Transition Matrix of Deck	User	No	Dmnl	(0,0),(1,0.15),(2,0.15),(3,0.15),(4,0.18),(5,0.2),(6,0.13),(7,0.12),(8,0.1),(9,0.05)
Markov Transition Matrix of Substructure	User	No	Dmnl	(0,0),(1,0.05),(2,0.05),(3,0.05),(4,0.05),(5,0.06),(6,0.07),(7,0.06),(8,0.04),(9,0.04)
Markov Transition Matrix of Superstructure	User	No	Dmnl	(0,0),(1,0.08),(2,0.07),(3,0.07),(4,0.08),(5,0.09),(6,0.08),(7,0.05),(8,0.06),(9,0.03)
Physical Condition of Deck	Model	Yes	Dmnl	-
Physical Condition of Substructure	Model	Yes	Dmnl	-
Physical Condition of Superstructure	Model	Yes	Dmnl	-
Posting	Model	Yes	Dmnl	-
Ratio of Divisible Load to Non-Divisible Load	User	No	Dmnl	0.2
Restoration Rate of Deck	Model	Yes	Dmnl	-
Restoration Rate of Substructure	Model	Yes	Dmnl	-
Restoration Rate of Superstructure	Model	Yes	Dmnl	-
Substructure Condition Assessment	Model	Yes	Dmnl	-
Superstructure Condition Assessment	Model	Yes	Dmnl	-

Table E-10, Performance Factors

NAME	TYPE	TDP	UNIT	VALUE
AADT on the Bridge of Interest	Model	Yes	Vehicles/Day	-

Approach Alignment	User	No	Dmnl	8
Approach Roadway Width	User	No	M	20
Bridge Roadway Width	Model	Yes	M	-
Deck Geometric Rating	Model	Yes	Dmnl	-
Deck Width Deficiency	Model	Yes	Dmnl	-
Detour Length	User	No	Km	1
Functional Class	User	No	Dmnl	2
Gap 1 Expectation Deficit	Model	Yes	Dmnl	-
Gap 3 Remaining Service Balance	Model	Yes	Dmnl	-
Horizontal Underclearance	User	No	M	500
Lane Width	User	No	M	41
Load Capacity Deficiency	Model	Yes	Dmnl	-
Navigation Traffic	User	No	Dmnl	1
Navigational Underclearance	Model	Yes	Dmnl	-
Number of Lanes on the Bridge of Interest	Model	Yes	Dmnl	-
Underclearance Deficiency	Model	Yes	Dmnl	-
Underclearance Rating	Model	Yes	Dmnl	-
Vertical Underclearance	User	No	M	12

Appendix F, Questionnaire for Case Analyses

Questionnaire

Q1. Since its opening to public, what department has been managing the bridge?

Q2. What was the design service life of the bridge? What was its design load?

Q3. Has the bridge ever been closed or partly closed? If yes, what were the reasons for these closures?

Q4. What are the state code and the structure number of the bridge in the National Bridge Inventory (NBI)?

Q5. Is the bridge carrying live loads which are above the original design load?

Q6. What is the evaluation method used for the bridge (LRFD or LRFR)?

Q7. Has a Bridge Management System been used for the bridge? What is the system and when did its use begin?

Q8. Has the heavy truck traffic ever been limited on the bridge?

Q9. How has the managing agency enforced the Truck Size and Weight regulations? What percent are overloaded trucks in the whole freight traffic? What percent of overloaded trucks have been captured by your enforcement program?

Q10. Does the agency keep track of trucks that have divisible vs. non-divisible loads? If yes, how?

Q11. Has the speed limit changed on the bridge or along its route?

Q12. Do you have historical cost data for the bridge including original construction cost data? M&R data? If yes, can this data be segregated by sub-system such as costs of the deck, superstructure, and substructure?

Q13. How was the original development/construction cost financed?

Q14. What factors influence the decision to perform a major upgrade or repair?

Q15. What is the average frequency and magnitude of repair activities on the bridge subsystems?

Q16. What is the average annual maintenance cost of the bridge, and what funding sources are available for these maintenance costs?

Q17. What priority for funding does this bridge receive relative to other bridges that your agency manages?

Q18. What would be the rough cost to improve the deck system's condition from poor or near failure to good? Similarly, what are the amounts for superstructure and substructure to restore them from poor condition to good?

Q19. Has the bridge been upgraded or repaired because of any government regulatory change? (for example, removal of lead paint and repaint the bridge)

Q20. Has the bridge been upgraded because of other reasons?

Q21. If the bridge has been upgraded, what are the conditional or functional improvements after its upgrade? What are the financial sources, and the amounts?

Q22. When did the traffic on the bridge meet its design capacity?

Q23. Was there substantial traffic delay caused by the old facility's limited capacity before its replacement?

Q24. Did the original design sufficiently meet the traffic demand in terms of load resistance, and safety?

Q25. Does the under clearance of the bridge meet the needs of under traffic?

Q26. Is the bridge registered in Highway Bridge Replacement and Rehabilitation Program?

Q27. Would this bridge ever be replaced? If so, what criteria would be used in a decision to replace the bridge?

Time Series (annual data):

Variables	**Unit**
Average Daily Traffic	Vehicles/day
Truck ADT (%)	%
Physical Condition of Deck	Dmnl
Physical Condition of Superstructure	Dmnl
Physical Condition of Substructure	Dmnl
Sufficiency Rating	Dmnl

The following are fundamental information of case analysis:

Variables	Unit	Value
Design Load	Lbs	
Number of Lanes on the Bridge	Lns	
Principal of Loans	Dollar	
FHWA CBPI	Dmnl	
Construction Cost	Dollar	
Annual Maintenance Cost	Dollar	
Total Upgrade Cost	Dollar	
Load Resistance	Lbs	
Posting	Lbs	
Detour Length	Km	
Bridge Roadway Width	M	
Approach Roadway Width	M	
Vertical Underclearance	M	
Horizontal Underclearance	M	
Inventory Rating	Ton	

Additional materials:

Can you provide any report about traffic demand analysis of the bridge?