A TRANSPORTATION PLANNING MODEL FOR STATE HIGHWAY MANAGEMENT: A DECISION SUPPORT SYSTEM METHODOLOGY TO ACHIEVE SUSTAINABLE DEVELOPMENT

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(ABSTRACT)

The realization that the U.S. infrastructure is deteriorating and that there is a need to establish a strategy to prevent an infrastructure catastrophe have propelled the development of various infrastructure management systems. Often, the expansion of transportation facilities is regarded as a means to the improvement of the condition of transportation infrastructure. However, building more infrastructure than can be properly maintained causes serious deterioration of the existing infrastructure. Sustainable development from a highway management perspective can be equated with qualitative development, which improves the current condition of the highway system, rather than expanding its physical resources.

The objective of this research is to develop a highway management strategy to help achieve sustainable development for the Commonwealth of Virginia. This research is performed by developing a transportation planning model for state highway management (TPMSHM) within the framework of a decision support system (DSS). The planning model consists of ten subsystems, including pavement and bridge management subsystems. These subsystems encompass various socioeconomic parameters that influence the physical status of highways. In the dynamic simulation model, these parameters are expressed in causal relationships using a system dynamics methodology.

The types of trajectories for highway conditions that lead to sustainable development are provided.

This research proposes a state-dependent prioritization strategy for calculating efficient budget shares by hierarchical levels of highway conditions. In this strategy, the proportions of the highway budget allocated to each level of management activity are determined by the physical conditions of the highways. Highways in the worst condition are given the first priority to receive the budget allocations. The model also addresses the policy of raising fuels tax to increase the state's transportation revenue. The adverse impact of a fuels tax increase is discussed in terms of revenue, the physical sufficiency of highways, and user benefits.

The TPMSHM constitutes a leading component of the DSS and governs the building processes of other two components, which include a Data Base and a Display Base. A Data Base is constructed by listing all the parameters needed by the TPMSHM within a frame designed in terms of the records and fields of the parameters. A Display Base is demonstrated in a possible form using system dynamics' Powersim software. The graphical capability of representing the simulation results and the interactive user interface inherent in the software are examined.

The emphasis of this research is placed on the development of the TPMSHM, which strives to manage the physical condition of the state highway system at an acceptable level through a state-dependent prioritization strategy to achieve sustainable development.

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CHAPTER 1

INTRODUCTION

1.1 Overview

The nation's infrastructure is the integrated network of private and public works that provides the basic services essential to maintain a modern society and to meet the challenges of an increasingly competitive global economy [Drew et al. 1998]. Infrastructure systems are established for the purpose of transporting people, conveying goods and services, supplying water, and providing for energy generation and distribution. In the United States, these systems represented an investment estimated at $20 trillion in late 1980's [NCPWI 1988].

In January 1992, the U.S. National Science Foundation (NSF) established the Civil Infrastructure Systems (CIS) Task Group, which sponsored a workshop three months later to secure inputs from nationally recognized experts. The Task Group's Report, "*Civil Infrastructure Systems Research: Strategic Issues*" was published in January 1993 [NSF 1993]. This report concludes that population growth, demographic changes, and increased expectations for service from deteriorating systems are increasingly complex and difficult to manage intelligently.

Transportation infrastructure constitutes an enormous component of the CIS in terms of its scale and its contribution to the various socioeconomic sectors in the nation. The U.S. transportation infrastructure comprises an extensive network of highways, railroads, transit systems, pipelines, waterways, ports, and airports. It serves 260 million people, 6 million business establishments, and 87,000 governmental units scattered over the 3.7 million square miles of the United States [BTS 1996]. In 1994, the transportation system carried more than 4.2 trillion passenger miles and 3.7 trillion ton miles of freight [BTS

1995]. From the point of view of economy, the value of transportation-related goods and services amounted to 725 billion dollars, or 10.8 percent of the Gross Domestic Product (GDP), in 1994 [BEA 1994].

Managing the nation's transportation infrastructure in dependable and efficient condition must be an essential process for the nation's health. The Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991 states that "*It is the policy of the United States to develop a National Intermodal Transportation System that is economically efficient and environmentally sound, provides the foundation for the Nation to compete in the global economy, and will move people and goods in an energy efficient manner*."

Since the early 1980's, however, there have been warnings about the decline in the U.S. infrastructure, and a series of reports throughout the country have tried to assess the infrastructure's condition. An assessment drawn from one report, "*Fragile Foundations*," stressed that "*the quality of America's infrastructure is barely adequate to fulfill current requirements and insufficient to meet the demands of future economic growth and development* [NCPWI 1988]." The deterioration of the transportation infrastructure in terms of highways can be seen in the following statistics.

Pavement conditions of rural highways that were judged fair or worse increased from 49 percent in 1990 to 54 percent in 1995 [BTS 1997]. 9.8 percent of urban interstate highways were judged poor in pavement condition in 1995, which was an increase from 9.4 percent in 1993 [Hartgen and Bowman 1997]. The overall pavement condition of the nation's highways shows that 58 percent of total mileage was rated fair or worse in 1994, as summarized in Table 1.1.

The dilapidation of bridges is also evident. The number of deficient bridges in the nation's interstate system was reported to be as many as 13,262 bridges in 1994, and another 81,529 deficient bridges on arterial and collector streets [BTS 1995, 1996]. An Associated Press computer analysis of Federal Highway Administration data found that

182,730 bridges of the nation's 581,942 bridges, or 31.4 percent, were rated deficient as of June 1996, as shown in Table 1.2 [Salant 1997].

Table 1.1 Nation's Pavement Condition (1994)

Highway System	Poor	Mediocre	Fair	Good	V. Good	Unpaved
Interstate (%)	8	27	24	31	11	0
Other arterials (%)	12	26	27	23	12	0
Collectors (%)	7	12	35	16	21	9
Total (%)	9	18	31	20	17	5

Source: FHWA 1995

Table 1.2 Bridge Condition in Selected States and the D.C. (As of June 30, 1996)

State	Total Bridges	Percent Deficient
California	23,205	27 %
Illinois	25,090	24 %
Massachusetts	5,008	57 %
New York	17,361	61 %
Texas	47,196	24 %
Virginia	12,613	31 %
West Virginia	6,578	45 %
Washington D.C.	247	61 %
Nation	581,942	31 %

Source: Federal Highway Administration

The status of the transportation infrastructure in Virginia is not any better than the nation's condition. As indicated in Table 1.2, 31 percent of state 12,613 bridges were reported as deficient, which is a similar percentage to the nation's average of deficient bridges. According to a preliminary report presented to legislators on August 11, 1997, "*Virginia's highways, port and air traffic will become nightmarishly congested in the coming years as the state's transportation needs overwhelm its resources* [Roanoke Times 1997a]."

The deterioration in transportation infrastructure is originally caused by an unbalanced development in the supply and demand of transportation. In other words, transportation infrastructure has not grown significantly to meet a dramatically increasing travel demand. Over the period from 1985 through 1995, urban vehicle miles increased 45 percent, whereas lane miles of urban highways increased only 19 percent. The difference was even greater for rural roads where vehicle miles increased 29 percent over the 10 years, and lane miles actually experienced a slight decrease [BTS 1997]. Nationally, annual vehicle miles per capita have increased from 4,800 in 1965, to 8,700 in 1995 [BTS 1996].

Another important cause of deterioration can be found in the fact that the U.S. transportation systems are seriously underfunded. The transportation inefficiencies resulting from this underfunding cost the United States far more in waste than the U.S. government is saving in withheld funds [ITE 1996-1997]. It is reported that 57 billion dollars should be invested annually in roads, bridges, and transit capital to maintain systems at the current level of service, but only 41 billion dollars are being spent [ITE 1996-1997]. Also, whereas for federal transportation programs, 3.5 percent of the total federal spending was on ground transportation in 1965, this share dropped to 1.6 percent in 1995 [Larwin 1997]. The funding shortage for transportation systems in Virginia is also evident. It is reported that Virginia faces a 2.1 billion to 4.1 billion dollar annual shortfall in the next 20 years for building and maintaining its roads, ports, rail lines and airports [Roanoke Times 1997b]. Uncertain federal funding impedes solutions to the increased traffic brought about by Virginia's population and employment growth. Most “growth states” are facing a similar situation. In Southern California, the problems have become so severe that the state has begun to rely on private road-building companies that charge user fees.

The transportation infrastructure deterioration process can be described as an evolving process with a cause and effect relationship, as follows: An inappropriate infrastructure cannot fulfill the needs of the national economy. Consequently, industrial activities will be influenced detrimentally, and productivity will be reduced. If the same infrastructure investment rate is maintained, the actual amount of the investment will be decreased. The decreased investment will reduce the quality of the infrastructure system. The deterioration of the infrastructure will negatively affect the economy again, and this process will continue with further deterioration of the infrastructure, unless improved policy is applied.

A lack of financial resources for infrastructure maintenance draws attention to developing a spending priority for performing necessary rebuilding, maintaining, or required new construction. A highway investment and management process has a dynamic, cause and effect structure. Investment in facility maintenance will upgrade the physical condition of highways, but physical deterioration will take place simultaneously. If the investment is sizable enough, the physical condition of facilities will be maintained in good condition. However, improper allocation of money or lack of investment may lead to further deterioration of facilities. This system of processes includes the improvement process, the deterioration process, the evaluation process, and other related cause and effect relationships. The systems approach is useful in supporting decision making about highway infrastructure management.

Another aspect of the vision for transportation infrastructure is to move toward a sustainable development decision support system for the planning, design, construction, operation, maintenance and management of infrastructure, and the determination of socioeconomic impacts throughout the life-cycle of the infrastructure, through mathematical modeling. Sustainable development is defined as the process in which a given generation solves its problems without making it doubtful that future generations will be able to solve their problems. A decision support system (DSS) is an instrumentality, usually computer-based, that helps decision makers utilize model-based, data-based, and display-based components in the analysis of development-environmental tradeoffs [Drew et al. 1997].

This research presents a paradigm and a framework for highway system management developed for the Commonwealth of Virginia. It uses a systems approach based on a decision support system methodology to achieve sustainable development.

1.2 Objectives of the Research

The planning, policy, and investment decisions for highway management should be implemented using a scientifically or logically reasonable methodology that is applicable to an existing and a future highway system. The construction of the methodology initially requires a broad understanding of the whole structure of the system and the interrelationships among the system's components. Based on this understanding, then, the selection or creation of an appropriate highway management plan is possible. In addition, from a practical point of view, the developed methodology should be utilized easily and flexibly in the decision making processes. This practicality can be facilitated by adopting a decision support system architecture for the use of highway management decision makers.

The objective of this research is to demonstrate a decision support system methodology developed for state highway management to help them achieve sustainable development for the Commonwealth of Virginia. The accomplishment of this objective involves extensive and detailed analyses of the state transportation system and related socioeconomic sectors. The following paragraphs summarize the analytical methods that are performed in this research.

- Identify various components and subsystems that constitute the highway management system in Virginia. This task is then further extended to include investigations of interrelationships among the transportation and socioeconomic subsystems that affect the physical and functional condition of state highways.

- Develop a Transportation Planning Model for State Highway Management (TPMSHM) as a model base for the decision support system. This task is performed through the improvement and extension of the existing highway management system model to state-wide perspectives. The TPMSHM is composed of demography, pavement management, bridge management, transportation, travel demand, functional, regional economy, finance, and appraisal subsystems.
- Validate the developed TPMSHM to improve the reliability and credibility of the model. This task necessarily involves a process of parameter estimation based on observed socioeconomic data.
- Predict basic transportation, socioeconomic, and demographic variables. As they are interconnected and thus their values change with other variables, identification of their interrelationships is a key task.
- Forecast changes in the future condition of state highways. The measurement of pavement and bridge conditions is facilitated by adopting a physical and functional sufficiency index. Also, the impact of variations in future highway condition is quantified.
- Analyze some policies affecting the management activities of state highways. Subtle issues, such as raising fuels tax, are investigated with regard to their impact on the transportation budget and highway conditions.
- Evaluate these policies in terms of their benefits and costs. The benefits are calculated from savings in highway user costs, and the costs are obtained from annual maintenance costs and capital investment costs.
- Construct a Data Base to be utilized in the TPMSHM. This task involving the identification and collection of data is steered by the data needs of the TPMSHM.
- Demonstrate a Display Base to show a “man-machine” interface. This task is implemented by using system dynamics software.

1.3 Background of the Research

This research is based on the recent evolution of increasing concerns about the Virginia highway management system, summarized as follows.

In response to warnings about the deteriorating conditions of the highway system in Virginia, the Virginia Department of Transportation (VDOT) planned to fund a research project to develop a model of a Highway Management System (HMS) for the Commonwealth to serve as an instrumentality for guiding policy making, planning, budgeting and programming. In May 1995, VDOT invited a team from Virginia Tech to submit a proposal to address the problem of maintenance management. The key issue was to determine what level of maintenance is required for the transportation network in Virginia.

In a letter dated May 15, 1995, Drs. J. M. de la Garza, A. D. Chasey, and D. R. Drew of Virginia Tech's Department of Civil Engineering submitted a proposal entitled, "*The Impact of Deferred Maintenance on the Interstate System* [de la Garza et al. 1995]." This research proposal was based on a framework that relates the effect of maintenance and construction on a highway system through the concept of a Comprehensive Level of Service, which is a framework, developed at Virginia Tech, for determining the impact of deferred maintenance and/or obsolescence of a highway system. This framework was to be customized for use by VDOT policy-making personnel by modeling the Salem District maintenance process, collecting specific data on the highway subsystem, calibrating the data to a simulation model, and developing a visual decision aid. The framework would be used as a foundation in the development of a specific model and simulation tool for VDOT to answer questions that could be posed by either VDOT personnel or the State Transportation Board.

A contract was entered into between VDOT and Virginia Tech for one year, to begin on August 1, 1995, and terminate on July 31, 1996. A simulation model for determining the impact of deferred maintenance of the interstate system calibrated for the Salem District was developed as a portion of the contract [Kim 1996]. The model was developed to answer the following types of questions:

- What is the impact of reducing ordinary maintenance expenditures?
- What would be the minimum level of highway maintenance expenditures and/or highway construction expenditures necessary to keep a desired level of service of the highway system?
- What is the impact of deferring a rehabilitation or maintenance project to future years?
- How does that impact translate into user and non-user benefits?

In July 1996, the final report of the contract was submitted to VDOT [de la Garza et al. 1996]. The report includes useful suggestions for network-level highway management decisions according to policy, planning, and budgeting scenarios.

The HMS model as a crucial component of the final report, however, needs to be further refined and extended in terms of the following aspects.

- The HMS model is limited in its modeling scope. In other words, its analysis concentrates only on the interstate highway system within a specific geographical area.
- The model does not provide a clear linkage between highway management activities and the highway budget that supports those activities.
- The allocation fraction of the budget to each highway condition is not state-dependent. The use of fixed portions of the budget often results in negative values of highway lane miles, which is not acceptable in practice.
- The processes of transportation revenue generation and allocation are not clearly modeled and simulated, even though they are expressed in the form of a causal diagram.
- A part of the revenue generation processes based on user tax collection, is misleading.

- The reliability and credibility of the outputs of the model are questionable, because they are not properly validated by the observed socioeconomic data.
- The model simplifies inputs from the surrounding socioeconomic systems. In this context, the surrounding systems only play an exogenous role in simulation of the model. The dynamics between highway management and the consequences of management activities to the surroundings should be taken into account.
- Travel demand generation and the calculation of highway user costs are not fully expressed. In particular, vehicle operating costs and accident costs, as major costs produced by highway users, need to be estimated, in addition to travel time costs.

The TPMSHM strives to overcome these shortcomings found in the existing HMS model. The TPMSHM visualizes the state-wide highway management system in a more comprehensive and detailed manner, within the framework of a decision support system.

1.4 Scope of the Research

The scope of this research can be defined in terms of functional, geographical, and time contexts. In the functional context, four functional hierarchies of state highways, which are also referred to as an administration system, are under consideration. They are the interstate, primary, secondary, and urban highways. Geographically, the TPMSHM covers the whole administrative area of Virginia, which consists of nine construction districts: Salem, Bristol, Lynchburg, Richmond, Suffolk, Staunton, Culpeper, Northern Virginia, and Fredericksburg. The prediction of future highway conditions and management activities is performed for the 20-year period from the year 2000 as a base year through the year 2020.

The establishment of a complete version of a decision support system requires extensive research tasks, each of which should be specialized for the construction of a model base, a data base, and a display base. Building a DSS for highway management must be a collaborative work among experts from various fields: transportation planning, highway engineering, pavement and bridge management, computer science, and administration. The model base constitutes the backbone of the construction of a DSS, and model building governs and leads the construction procedures of the other components of a DSS. This research focuses on the development of a model base by presenting the TPMSHM. The possible forms of the Data Base and the Display Base are demonstrated for future development by providing a complete list of data required for the TPMSHM and by showing a graphical user interface.

1.5 Organization of the Research

This dissertation is composed of nine chapters, which are described as follows:

- Chapter 1 presents the observed problems as to the deteriorating condition of the transportation infrastructure, and the background, necessity, objectives, and scope of this research.
- Chapter 2 reviews literature regarding transportation infrastructure management and the concept of decision support systems. Research regarding civil infrastructure, highway, pavement, and bridge management are reviewed in detail. The application of the DSS to infrastructure planning and management is also outlined.
- Chapter 3 reviews the concept of sustainable development and the current movements toward sustainable development. Various perspectives for viewing sustainability are examined, and the importance of adopting systems modeling to achieve sustainability in planning and management is discussed. A simple mathematical model is provided to help understand the implementation of the concept of sustainable development as presented in this research.
- Chapter 4 outlines the research requirements and the corresponding methodology to be adopted in this research. A comprehensive view of the systems approach presented in this research and system dynamics is provided.

- Chapter 5 is devoted to the explanation of the structure of the transportation planning model for state highway management. The model is conceptualized in a three-dimensional form, which consists of various subsystems of the TPMSHM, highway functional hierarchies, and geographic classifications. A detailed description of the TPMSHM is provided for each of the following subsystems: demography, pavement management, bridge management, transportation, travel demand part A, travel demand part B, functional, regional economy, finance, and appraisal subsystem. Identification of causal links among those subsystems and development of the whole framework of the model are focused upon in this chapter. The explanation of the model is facilitated by providing causal diagrams and components of the DYNAMO source code for each subsystem. As the overall performance and credibility of the research depend on model building, this chapter should be regarded as the core of this dissertation.
- In Chapter 6, the TPMSHM is validated by observed conditions so as to measure the reliability of the model. The model parameters are estimated, based on observed transportation and socioeconomic data. The model's performance is examined by comparing estimates generated through the model to observed values of key variables: population, vehicle registrations, vehicle miles of travel, gross state product, employment, and transportation revenue. The model verification process described in this chapter and the model development process explained in Chapter 6 are iterative. In other words, the TPMSHM is repeatedly redefined, updated, or rebuilt until the outcomes of the model fall within an acceptable range of deviations from the real data.
- Future simulation and policy analysis are implemented in Chapter 7 by running the constructed and validated TPMSHM. First, future estimates of key variables such as population, vehicle registrations, vehicle miles of travel, gross state product, employment, and transportation revenue are presented for the period from the year 2000 through 2020. Future estimation of highway conditions and the corresponding maintenance magnitudes originates from reasonable predictions of these key variables. The highway user benefits and management costs are quantified to show the impacts of the amount of the budget allocated and the respective maintenance works. Apart from

the base scenario, a recent issue arising concerning fuel tax increases is analyzed as a policy analysis.

- Chapter 8 illustrates two other components of the DSS: a Data Base and a Display Base. The data structure used in accordance with the TPMSHM is provided. A demonstration for the future development of the Display Base is provided. A user interface bridging the Data Base and the Display Base is provided using a graphical software of system dynamics.
- Finally, Chapter 9 summarizes the findings of this research. Based on the outputs of this research, recommendations concerning the management of state highways and the construction of a decision support system are made in the context of sustainability. The limitations of this research and implications for the future research are also discussed.

CHAPTER 2
INFRASTRUCTURE MANAGEMENT SYSTEMS

2.1 Infrastructure Management

Infrastructure is a fundamental installation on which the life and growth of a nation depend. Infrastructure includes the following [NRC 1987]:

" … *both specific functional modes – highways, streets, roads, and bridges; mass transit; airports and airways; water supply and water resources; wastewater management; solid-waste treatment and disposal; electric power generation and transmission; telecommunications; and hazardous waste management* - *and the combined system these modal elements comprise*."

As seen in the above description, it is obvious that infrastructure is an integrated system. Hence, there is a need for a broad scope of research in order to address and solve the current infrastructure problems. However, research efforts to improve public infrastructure have most frequently concentrated on immediate and local problems. The basic premise that infrastructure is an integrated system requires that any research concerning infrastructure development be implemented in accordance with a systems perspective, rather than a narrow and isolated view.

As noted in the previous chapter, the significant unbalance between supply and demand growth patterns becomes a major cause of the deterioration of infrastructure, including transportation facilities. A shortage of funds exacerbates the problem, and results in further deterioration of the facilities. Since World War II, the U.S. government has become the primary sponsor of all research and development (R&D) for infrastructure by providing about 43 percent of R&D spending in the United States [NSF 1992]. The federal government is estimated to be the major source of infrastructure research spending, but only a small portion of the total government R&D funding is devoted to infrastructure. A survey conducted by the Civil Engineering Research Foundation (CERF) found this spending to be between $1.026 and $1.386 billion in the fiscal year 1992, approximately 1.6 percent of total federal R&D expenditures [CERF 1993]. This shortage of funds leads to a need to conceptualize and adopt a systematic research framework to guide efficient management activities, given limited finances.

Addressing the complexity of infrastructure needs in the United States, a CIS Task Group recommended a Research and Knowledge Transfer Program "*to enhance system performance and the longevity of existing and future infrastructure systems* [NSF 1993]." Table 2.1 summarizes the broad areas of Research and Knowledge Transfer in the CIS Program.

Table 2.1 CIS Program Elements

Research	• Deterioration science • Assessment technologies • Renewal engineering
Knowledge Transfer	• Proof-of-concept projects • Education, workshops, seminars • Expert systems, information systems, publications • International cooperation

Source: NSF 1993

Responding to current and anticipated infrastructure needs, the National Research Foundation (NSF) established seven research niche areas within the broad context of the U.S. infrastructure research establishment, as follows [NRC 1994]:

- *Systems life-cycle management,* including maintenance practices, system performance assessment, management, renewal decisions, quality of environmental management,

- *Analysis and decision tools*, for planning and design, needs assessment, dealing with capacity issues,
- *Information management*, including data collection, storage, assessment, and retrieval in forms that support decision making,
- *Condition assessment and monitoring technology*, for facilities and service performance,
- The *science of materials performance and deterioration*, including mechanical and chemical behavior and changes with time and use,
- *Construction equipment and procedures*, including construction management method, and
- *Technology management*, such as selection of treatment process or transport mode, bases for decision making, and environmental or social consequences.

Even though each of these seven research niches represents a unique research area, the boundaries among these broad areas are vague and difficult to define. Some specific topics presented in different niche areas can be overlapped or duplicated. Such overlaps are caused by an infrastructure that is complex and integrated.

This research is also not restricted to or focused only on one of these areas. It concerns several important tasks among these areas, such as systems life-cycle management, analysis and decision tools, information management, and deterioration processes.

Management of infrastructure is an essential activity so that infrastructure will be able to provide and support a wide range of services over an extended period of time. That activity should encompass various management needs arising from the changes in infrastructure conditions over time. Therefore, management activity needs to be time-dependent and state-dependent. However, primarily because of infrastructure's complex nature, there is no generally accepted methodology that is applicable to all management tasks. To be effective, infrastructure management efforts must achieve an appropriate balance between need and capability. There are few methods for exploring the relationships between service demands and service supply. Infrastructure management needs to address these causal relationships, as noted by NRC [NRC 1994] stating:

"… *research to enhance knowledge of the sources of infrastructure demand and how demand interacts with the system to influence service life to enable development of more effective infrastructure management tools and procedures*."

Demand responsive management is incorporated in the recommendations about maintenance management as proposed by Markow, with special reference to highways [Markow 1993]. He proposes new analysis methods in highway management, as follows:

- Tradeoffs between routine maintenance and capital activities such as resurfacing and rehabilitation,
- Tradeoffs between in the levels of service to be provided in one or more activities,
- Consideration of both agency and user costs within a life-cycle cost framework,
- Optimal resource allocation, and
- Reduction of data and summarization for management purposes.

These types of analyses are assumed to be performed within a framework referred to as a demand responsive approach to maintenance management. In other words, Markow views management activities as a response to the demand for maintenance work such as the deterioration of the highway system, or changes in its condition.

In summary, infrastructure management would be enhanced by the adoption of an appropriate research framework to fill the gap between needed funding and available funding. A methodology for infrastructure management should take into consideration supply and demand interactions.

2.2 Transportation and Economic Development

Transportation systems are designed to overcome the friction imposed by geography. As such, they shape the distribution of activities and influence the share that each region contributes to the national product. A major impetus for growth comes from the ability of a region to produce goods and services demanded by the national economy and to market these at a competitive advantage with respect to other regions [Kraft et al. 1971]. Transportation improvements can be seen as resulting from the following [Huang 1990]:

- Promotion of the productivity of labor by improving the welfare of commuters,
- Promotion of the productivity of capital by encouraging the spatial concentration of factors of production, and
- Reduction of the cost of transportation for both firms and commuters.

Transportation benefits accruing to road users, in terms of the following three benefits, are the primary effects of transportation improvements.

- *Travel time savings*: change in user’s travel time cost due to improvements,
- *Vehicle operating savings*: change in road users’ vehicle operating costs due to improvements, and
- *Accident savings*: change in accident costs due to improvements. These are divided into three types: fatal, personal injury, and property damage accidents.

These transportation user benefits are the main components of benefit cost analysis, which provides a quantitative assessment of the relative benefits of different alternatives in terms of a common monetary measure.

In addition to user benefits, economic impacts measure the secondary effects of transportation capital expenditures on the regional economy. They affect income, employment, production, resource consumption, pollution generation and tax revenues.

These impacts may be classified broadly into three types: direct, indirect and induced impacts. Direct impacts are the consequences of economic activities carried out on the site in construction and operation. Indirect impacts derive primarily from the off-site economic activities associated with the production of intermediate goods and services required for the construction and operation of the improvement. Induced impacts are the multiplied effects of the direct and indirect impacts [Perera 1990].

The impact of transportation on national and regional economic development is evident in the following scenario. By connecting regions, transportation develops regional resources on the basis of interregional comparative advantage. Good interregional connections facilitate the convergence of the factors of production, including labor, toward the centers of production. This concentration of activities provides advantages to large-scale production.

The significance of the impact of transportation on national and regional economic development is examined and quantified in many studies. An investigation into the relationships between the Gross National Product (GNP) and roadway infrastructure was performed by Queiroz et al. [Queiroz et al. 1994]. Three regression models and a cross-sectional model were built with data sets from different countries. For the U.S. and Canada, time series regression models were built with gradients of the links defining the marginal productivity of roadway infrastructure. It was found in this research that roads cannot develop countries or regions, but are necessary elements in the development process. In other words, a lack of roads can be a significant constraint to development.

Seskin expands the typical technique of user benefit assessment by adding an assessment of regional economic benefits [Seskin 1990]. These benefits are measured in terms of changes in business costs, both in absolute terms and in relation to costs experienced by areas not affected by the proposed improvement. Regional economic benefits include opportunities for business expansion, business attraction, and tourism development. Business expansion benefits include the indirect and induced effects of user benefits. Business attraction benefits include the effects of highway investment on the types and quantity of new economic activity that may occur in the affected region as a result of a highway. Tourism benefits include changes in expenditures resulting from new tourist travel patterns. Through case studies performed in Wisconsin, Massachusetts, and Indiana, it is estimated that the values of regional benefits are equal to 50 to 150 percent of user benefits. It should be noted, however, that these regional benefits are sensitive to the level of improvement of the affected links and to the implementation of related public policies.

As exemplified by these studies, it can be seen that efforts are being made to evaluate the economic impact of an improved transportation infrastructure. However, some of the studies are limited in scope in that they usually evaluate the effects of local transportation infrastructure in a small geographic area. These efforts are not successful in evaluating complete regional transportation systems. It is necessary to apply a comprehensive methodology to measure regional economic impacts of transportation systems for all regions. This research corresponds to this need in terms of statewide perspectives.

In addition to assessment issues about the impacts of transportation, the current realization of the deteriorating transportation infrastructure leads to discussions about how infrastructure should be financed. A recent critique of fund allocations for transportation infrastructure in Virginia is worthy of note. In the proceedings of the colloquium, "*Financing Tomorrow's Infrastructure: Challenges and Issues*," Williams criticized current allocation portions of transportation funds to management in Virginia, i.e. 45 percent to construction and 40 percent to maintenance [Williams 1996]. Instead of this budget allocation, he proposed a different allocation scheme to prevent infrastructure deterioration: 5 percent to operations, 20 percent to maintenance, and 75 percent to construction. Although he does not specify the methodology that justifies this allocation, Williams claims that its adoption will improve Virginia's transportation infrastructure. However, the accuracy of his claims can be questioned. First, instead of using time-variable percentages among construction and maintenance, is the use of fixed percentages an assured method to improve the infrastructure? Second, is there any acceptable methodology for justifying those allocation fractions? These questions should be answered in scientific ways with reasonable methodologies, as is attempted in this research.

2.3 Pavement Management System

State governments in America are commonly faced with the problem of deteriorating roads and the shortage of funds to maintain their highway systems. Public funds that have been designated for highway management programs must therefore be used as effectively as possible. One proven method to mitigate the effects of depleted finances is the use of a pavement management system (PMS) [Monismith et al. 1988]. A PMS is a set of tools or methods that assist decision makers in finding optimum strategies for providing and maintaining pavements in a serviceable condition over a given period of time [NCHRP 1987, Haas 1978]. Without such a routine pavement maintenance program, roads require more frequent reconstruction, thereby costing state governments millions of dollars.

A PMS has the following legal basis for its development. In 1989, the Federal Highway Administration (FHWA) issued a policy requiring all states to have a PMS that would cover principal arterials under state jurisdiction. The scope of federal and state involvement in pavement management expanded when Congress passed the ISTEA of 1991 and required all states to have a PMS that covers all Federal-aid highways.

Many studies have defined concept and system elements, and have developed models for PMS since the early 70’s. These models were defined in different ways, according to their purposes, methodologies, and maintenance activities. Maintenance activities for highway pavement have been classified in several ways. Currently, the following definitions are being proposed for standardization [Smith and Nazarian 1992].

- *Routine Maintenance*: This is localized maintenance activity such as pothole patching, spot sealing, and other repairs not funded for specific planned treatments for identified pavement segments.
- *Preventive Maintenance*: Treatments are applied to preserve the existing pavement integrity and reduce the rate of deterioration.
- *Corrective Maintenance*: Treatments are applied to an existing pavement to maintain surface characteristics and structural integrity for continued serviceability.
- *Restoration*: New surface layers and repairs are intended to restore the pavement structure to a level approximately equivalent to that which was originally present.
- *Major Rehabilitation*: Lane-width, full-length layers are added to the existing surface to increase the structural strength to handle future traffic loads.
- *Reconstruction*: This is lane-width, full-length removal and replacement of pavement, mostly on existing alignment including rehabilitation of associated structures generally to improved standards.

Although all of these activities imply an equal significance in a PMS, the special importance of preventive maintenance is stressed by FHWA in that preventive maintenance has the potential to both improve quality and reduce expenditures for pavement networks [FHWA 1996]. This potential was recognized in the ISTEA, and was strengthened under the National Highway System bill (*Public Law 104-59-Nov.28, 1995*) which states in Section 309:

"*A preventive maintenance activity shall be eligible for Federal assistance under this title if the State demonstrates to the satisfaction of the Secretary that the activity is a cost-effective means of extending the useful life of a Federal-aid highway*."

The in-depth descriptions of preventive maintenance are well documented in a report, *FHWA-SA-96-027*, published by the Federal Highway Administration [FHWA 1996]. This document describes the need for and benefits of preventive maintenance, discusses the engineering applications of these treatments, reviews the materials used for preventive maintenance, and describes the application process for these treatments.

The types of maintenance activities explained above are determined by the types of pavement distress. Regardless of what maintenance activities are applied to deficient highways, the common objective of these treatments is to return the pavement to an acceptable level of service. Depending on the level of service desired, different levels of maintenance costs for each of maintenance activities will also be required.

An early understanding of deteriorating pavement condition and lack of maintenance schemes can be found in an Advisory Circular dated December 3, 1982 [FAA 1982]. This AC points to a variety of causes of poor maintenance of airport pavements and discusses specific types of distress, inspection guidelines, and recommended methods of repair. It is noteworthy in this AC that a basis condition rating procedure by surveying or sampling techniques is outlined. Even though this report is intended primarily for use at airports, it manifests different maintenance tasks, use of materials and equipment, and determination methods of a pavement condition index (PCI), which can be commonly applied to highways. The discussion presented in this AC is further extended in an updated version, an Advisory Circular published in 1988, through the provision of the concept and the purpose of a PMS [FAA 1988]. According to this AC, the PMS is implemented by pursuing the following objectives:

- to provide consistent objectives and systematic procedures for setting priorities and schedules, allocating resources, and budgeting for pavement maintenance and rehabilitation, and
- to quantify information and provide specific recommendations for actions required to maintain a pavement network at an acceptable level of service while minimizing the cost of maintenance and rehabilitation.

As implied in these objectives, a PMS strives to develop a prioritization method to allocate the available budget. Also, this prioritization should be based on an efficient and reasonable allocation method and should improve the pavement condition of a network. The PMS used to achieve these objectives needs to be established by specific and systematic procedures. The AC in 1988 specifies these procedures as follows:

- A systematic means for collecting and storing information,
- An objective and repeatable system for evaluating pavement condition,
- Procedures for identifying alternative strategies,
- Procedures for predicting the performance and costs of alternative strategies, and
- Procedures for identifying the optimum alternative.

This report emphasizes a data base as an essential component of a PMS, and outlines how it can be used in making cost effective decisions. A representative application of the concept provided by this report is Micro-PAVER, which is a PMS that has been used on airport pavement networks at the state and local levels. This system was developed by the U.S. Army Construction Engineering Research Laboratory under contract to the Federal Aviation Administration. The data base of this program is capable of storing various data items such as pavement condition history, pavement testing data, construction and maintenance history, and cost data. Based on this data base, Micro-Paver provides many capabilities, including the evaluation of current conditions, the prediction of future conditions, the identification of maintenance and rehabilitation needs, inspection scheduling, economic analysis, and budget planning.

Micro-Paver is often used as a PMS tool that has many applications for maintaining highway systems. One of these applications can be found in a road maintenance project for the area of Rhode Island [Bowen and Lee 1991]. The primary purpose of this project was to select the most appropriate microcomputer-based PMS software and to implement the selected system in Rhode Island. Micro-Paver was selected for this project primarily because it is one of the simplest menu-driven programs. The simplicity of the use of this program enables users to perform practical decision making for cost effective maintenance alternatives for highways. This project also discusses the integration of geographic information system (GIS) technology with a PMS, which was identified as one of the most promising and logical applications for enhancing the capabilities of a municipal-level PMS.

One of the adaptations of GIS in highway pavement management can be found in the experiment performed for the Aichi Region in central Japan [Osman and Hayashi 1994]. This trial utilizes the following advantages provided by GIS in managing highway pavement: the realistic representation of real-world entities, an organized data structure, and powerful analysis and presentation capabilities. In this experiment, the PMS coupled with a GIS is comprised of a spatial data base, an attribute data base, a general and a specific analysis module, and an output generation module. It is concluded that the quality of relevant data is improved and that the interaction between the system and users is facilitated.

Each state provides different management levels or perspectives of PMS. However, in its common features and objectives, a PMS evaluates the current pavement condition, predicts its future condition, and provides cost-effective solutions for various management levels [Weeks 1994, Bosch 1994, Cumberledge and McCullough 1994]. A PMS also includes a data inventory or a data base management system, as historic data on the pavement is crucial for prediction of pavement condition.

The PMS developed for Minnesota incorporates a number of programs for data management functions, user interface, analysis, and reporting [Hill et al. 1991]. It operates on a personal workstation which is linked to the Transportation Information System on the Mn/DOT’s mainframe computer. The PMS consists of two major subsystems: a Status and Needs Subsystem and a Rehabilitation Optimization Subsystem. The former facilitates displaying the current status of each segment of the network, or the network as a whole, with regard to its present serviceability rating, structural adequacy rating, surface rating, and a composite pavement quality index. The latter is capable of calculating capital, maintenance, and user delay costs for each alternative and possible implementation year. It is worth noting that Minnesota's PMS suggests a sound technical basis for decision-supporting architecture by providing a data base, models, programs, and reporting functions.

The PMS developed for the Ohio Department of Transportation (ODOT) provides deterministic degradation models that are based on detailed statistical analyses of historical data [Majidzadeh et al. 1990]. The ODOT PMS predicts a pavement condition rating (PCR) and deducts values for a given pavement segment strategy considered in its network optimization. It defines fourteen categories of maintenance and rehabilitation actions for different pavement types. On the basis of the available budget and desired performance levels, the optimization of the PMS selects one of the feasible plans for each individual segment. Optimization is implemented either by maximizing PCR subject to budgetary limitations, or by minimizing cost subject to performance constraints.

A highway maintenance management system developed for Saudi Arabia integrates a PMS, a bridges and structures management system, and a non-pavement management system [Harper et al. 1989]. The PMS applies a stochastic optimization technique based on minimal historical data. It predicts the probability of a pavement segment transitioning from condition state i to condition state j for feasible maintenance and rehabilitation actions. Two network-level LP models are used in the PMS: The first is a steady-state goal-setting model that determines the optimal condition states of the network so that cost is minimized. The second model is the multiyear model that determines the optimal policy to move from the current network condition to the optimal steady state levels.

The PMS model developed by Howard and Teague concentrates mainly on the realization of low cost data collection systems to facilitate automated processing [Howard and Teague 1995]. This PMS generates life cycle cost analyses of pavement using the World Bank's Highways Design and Maintenance Standard, HDM-3, and optimizes maintenance investment decision making. The HDM-3 prediction model is directly interfaced to the data base which primarily comprises reference data for each road section, traffic data, structural data, roughness, visual condition data, historical construction and maintenance data, and cost data for pavement maintenance and rehabilitation treatments. Noticeable in this model is that it provides cost-effective flows from automatic data processing to the PMS data base.

Csicsely-Tarpay et al. investigate the PMS's use for allocating resources to various road maintenance actions and distributing them to different road management regions [Csicsely-Tarpay et al. 1996]. They use Hungary's PMS, and their investigation suggests important effects of various budget scenarios in terms of user costs. The simulation shows that as the budget increases, highway user costs decrease. This result is an expected one because the pavement condition improves according the increase in budget or maintenance investment. However, the marginal benefits arising from savings in user costs decrease with the increase in budget size. Moreover, once administration costs are also considered in addition to user costs, the gaps in the marginal benefits are narrowed.

2.4 Bridge Management System

The highway system in the U.S. is highly dependent upon its approximately 582,000 bridges. Many of these bridges were designed in another era and are now being forced to withstand current traffic volumes and vehicle designs. Forty percent of the 582,000 bridges are built of concrete, and of this number 40 percent require some repair or rehabilitation. This reflects about 93,000 concrete bridges in need of support efforts. This support can be realized through sufficient investment in bridge maintenance, repair, and rehabilitation. However, as 100 percent maintenance funding is never achieved, there is a need for applying a methodology by which the optimum level of service can be achieved within a limited budget. Recently, this methodology has been provided within the framework of a bridge management system (BMS).

A BMS can be broadly defined as a systematic framework that formalizes a decision-making process for bridge improvements [Farid et al. 1994]. In other words, a BMS is an integrated system by which appropriate management actions are identified to improve bridge conditions in a systematic and cost-effective manner. Thus, a BMS can be used as a tool to assist highway and bridge agencies in their choice of optimal improvements to the bridge network. Those necessary actions could be stated as inventorying bridges, evaluating priorities, selecting projects, and improving bridges [U.S. DOT 1987]. These general actions concerning bridge management need to be implemented in more specific and comprehensive ways. A BMS should be capable of the following functions [U.S. DOT 1987]:

- A suitable data base,
- Incorporation of analytical tools for objectively assessing bridge needs,
- Integration of all decisions and activities relating to bridges, including design, programming, maintenance, rehabilitation, and replacement, and
- Provision of a system-wide perspective to complement the project perspective.

A comprehensive BMS should be designed to coordinate all bridge-related activities and to cover a broad array of functions involving input from many organizational units. Central coordination will be essential to setting up or significantly improving a BMS. The concept of a comprehensive BMS is explicitly described in Figure 2.1, which identifies various management activities, management inputs, engineering inputs, and outputs [RTR 1992]. In this figure, a data base is established by inputs from various field activities, and then it predicts costs, bridge conditions, and deterioration of bridges. A central element described as an analytical process plays a coordinating role in order to generate outputs. This diagram provides a general structure for a prototype of a BMS.

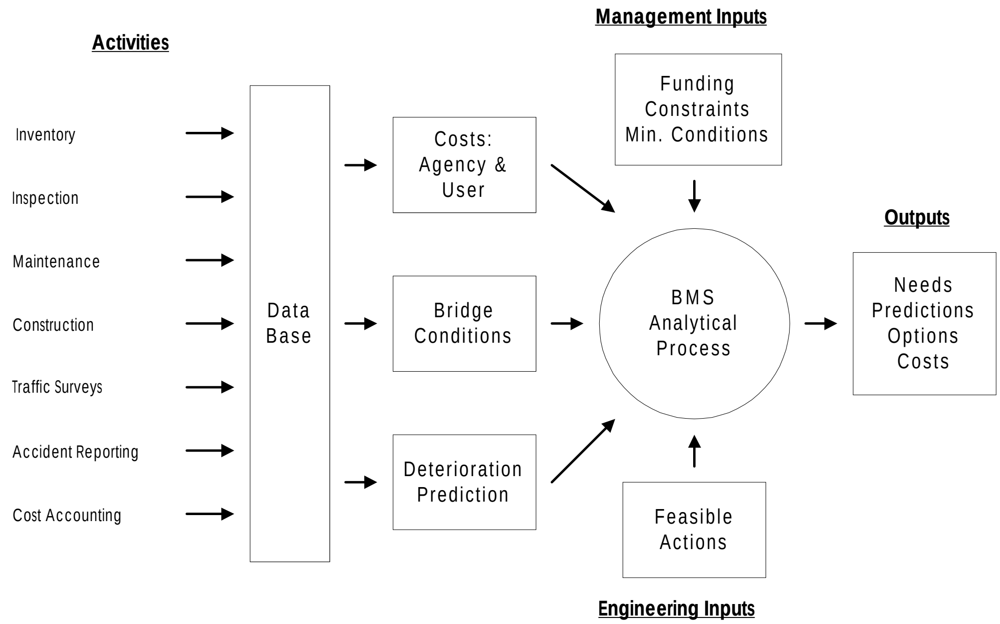

Figure 2.1 Comprehensive Structure of a BMS
Source: RTR 1992

Similar to the building processes of other infrastructure management systems, the construction of a BMS begins with the recognition of problems and the identification of their causes. Major causes of the deterioration in bridges can be summarized as follows: poor design details, construction deficiencies, lack of maintenance, corrosion, overstress, temperature, chemical attack, traffic impact, fire, reactive materials, and foundation movements [Minor et al. 1988]. Most causes listed are the result of either natural or traffic-related deterioration processes, which are difficult to prevent. On the other hand, causes such as deficiencies in design, construction, and maintenance can be regarded as human factors or errors which can be remedied through the adoption of appropriate management systems. In particular, the lack of maintenance should be a target aim to be mitigated through a BMS.

The judgement as to the condition of a bridge and the need for maintenance, rehabilitation, or replacement is made based on the rating scheme of a BMS. The National Cooperative Highway Research Program (NCHRP) sets decision guidelines to assist the inspector in coding the condition ratings for the concrete components of a bridge [Minor et al. 1988]. Four sets of guidelines are proposed by NCHRP: deck, reinforced concrete superstructure, prestressed concrete superstructure, and substructure. These guidelines are able to assist the inspector in making uniform condition ratings for the structural inventory and appraisal report. Although these condition ratings are classified according to the components of bridges, most codes and descriptions are commonly shared. Table 2.2 provides the condition rating scheme of bridges for the deck component.

Maintenance of bridges involves four distinct levels of activity which are usually scheduled separately [Klaiber et al. 1987].

- *Routine maintenance*: The technical aspect of the upkeep of the bridges. It is preventive in nature. Maintenance is the work required to keep a bridge in its present condition and to control potential future deterioration.
- *Rehabilitation*: The process of restoring bridges to their original service level.
- *Strengthening*: The increase of the load-carrying capacity of an existing structure by providing the structure with a service level higher than the structure originally had.
- *Repair*: The technical aspect of rehabilitation. Action taken to correct damage or deterioration on a structure or element to restore it to its original condition.

Table 2.2 Condition Rating of Bridge

Code	Condition	Description
9	As Built Condition	No noteworthy deficiencies.
8	Very Good Condition	No problems noted.
7	Good Condition	Some minor problems. Sealable deck cracks, light scaling, less than 10 percent of deck area is deteriorated.
6	Satisfactory Condition	Some minor deterioration. Open cracks at intervals of 5 ft or less. Need corrective action.
5	Fair Condition	Excessive cracking resulting in 2 percent to 5 percent of the deck spalled. Need corrective action.
4	Poor Condition	Advanced section loss, deterioration, or spalling. Need corrective action.
3	Serious Condition	More than 60 percent of the deck is water-saturated and/or deteriorated or contaminated. Need corrective action.
2	Critical Condition	Full deck failures over much of deck.
1	Failure Condition	Bridge closed. Corrective action may put back into light service.
0	Failure Condition	Bridge closed. Replacement necessary.

Source: Minor et al. 1988

Any actions taken to improve deteriorated bridges have the primary purpose of extending the service life of bridges. The service life is the period of time between the opening of the bridge to traffic, and its closure. Two principal reasons for bridge closure are structural inadequacy and functional inadequacy [RTR 1992]. The former can be alternately referred to as insufficient structural stability. The major causes of structural inadequacy are natural aging, environmental actions, catastrophic failure, traffic on the bridge, and maintenance faults. The latter occur when the bridge does not meet actual traffic requirements or loads. The reasons for functional inadequacy are new standards, road widening, heavier traffic, bottlenecks, and roads out of service. The measures for delaying structural and functional inadequacies include the adoption of the four levels of maintenance activities, avoidance of traffic disruptions, and changes in loads and clearance regulations.

Regardless of what measures are taken, however, those activities are inevitably confronted with budget constraints. In order to utilize a limited budget in an efficient manner for improving bridge conditions, a new prioritization system is needed that will ensure bridge safety and cost benefits for the allocation of maintenance, repair, and rehabilitation funding. Usually a prioritization method translates physical conditions and level of service deficiencies into a priority index for each bridge. A prioritization procedure, investigated by Kesselring [Kesselring 1995], addresses service life assessment and extension procedures. The service life assessment phase utilizes engineering analysis, historical data, physical inspection, and structural sampling testing. Parameters such as current traffic volumes, vehicle sizes, and vehicle loadings, are analyzed to determine the delta between design and actual service life. After the service life has been assessed, life extension efforts are examined. First, life extension efforts are categorized into preventative maintenance, minor and major repairs, rehabilitation, and replacement activities. An individual concrete bridge may require any or all combinations of the above categories. An overview of maintenance, repair and rehabilitation activities and their service life improvement potential are calculated. Next, costs are associated with each of the various maintenance, repair, and rehabilitation efforts.

The determination of Equivalent Uniform Annual Costs (EUACs) developed for evaluating the cost-effectiveness of strengthening bridges is identified as a useful prioritization method [Klaiber et al. 1987]. Once bridges have been identified as needing repair, strengthening, rehabilitation, or replacement, they need to be evaluated for priority of maintenance. The EUAC method can be applied to select the most cost-effective alternative. The alternative with the lowest EUAC is determined as the most desirable choice. The model to determine EUACs includes life-cycle costs and user benefits. The major cost items that affect the values of EUACs are replacement structure first costs, initial strengthening costs, annual maintenance costs, and future expenditures.

The prioritization scheme for bridge maintenance can provide rankings for bridges, by which bridges with the worst-ranked conditions are maintained first until the available funds are exhausted or the desirable levels of service are achieved. However, this prioritization does not necessarily provide optimal solutions in terms of the utilization of resources. One attempt to achieve the optimization of resources involves employing the neural network concept [Mohamed et al. 1995]. The objective of this method is to show how artificial neural networks can be used to optimize the system's resources to generate the group of bridge improvements that maximizes network benefits. Two objective functions, i.e. the minimization of the total loss of system benefits and the benefit loss for any year, are formulated to construct the neural network. The architecture of the developed network provides the efficient operational merit of reducing memory storage space and improving the speed of operation. These functions and the neural network provide the potential of being used in the optimal allocation of budget to bridge projects in a specific year.

The BMS developed by Harper and Majidzadeh uses an optimization methodology, which includes three network level models based on Markovian decision models using linear programming techniques [Harper and Majidzadeh 1991]. The three models are as follows:

- A steady-state model to establish steady state minimum cost goals,
- A multiyear model to optimize expenditures within a desired time horizon leading to a steady state, and
- A financial exigency model to force the total network to meet a specified budget.

These models provide results in terms of decision variables, i.e. the proportions of each category of bridges that should receive various maintenance activities for different condition states within the budget constraints. The solution of the LP formulations is facilitated in a straightforward manner by adopting Lagrange methods.

The Markov chain process is utilized as a useful representation of bridge deterioration [Hawk 1995]. The BRIDGIT BNS software developed by Hawk uses condition state quantities to model the transition of bridge elements through their various condition states. By the Markov chain process, transitional rates are calculated to project the quantities of a bridge element that will move to lower condition states in a defined time interval. BRIDGIT uses derivatives of Markov chain processes to model aging patterns of unprotected elements, protection systems, and protected elements of bridges.

In summary, the purpose of a bridge management system is to improve the overall condition of bridges by setting priorities for management investment. A key issue in constructing the system is what priority methodologies should be applied in an efficient manner given limited resources.

2.5 Decision Support System

The implementation of any kind of project or research concerning infrastructure planning and management involves different types and levels of decisions. There have been many attempts to classify those decisions. One of the classifications that shows hierarchical descriptions of information and decision flows among each type of decision is the following [Anthony 1965]:

- *Strategic planning decisions*: decisions related to choosing the highest-level policies and objectives,
- *Management control decisions*: decisions made for the purpose of assuring effectiveness in the acquisition and use of resources,
- *Operational control decisions*: decisions made for the purpose of assuring effectiveness in the performance of operations, and
- *Operational performance decisions*: day-to-day decisions made while performing operations.

Strategic decisions are associated with the most important and least frequently used decision levels. Operational performance decisions are related to daily decisions that are concerned with specific tasks. A key point in this classification is that high-consequence decisions are made less frequently than low-consequence decisions.

Highway management is a process that accompanies several highway-related activities involving planning, design, construction, operation, maintenance, and research developments. Each of these activities requires frequent decision making in order to approach various problems that are ambiguous in terms of their scientific aspects. Moreover, because of the uncertainty of these problems and their subjective, sociopolitical elements, there is no wholly objective way of finding the best solution [Gendreau and Duclos 1989]. Hence, in order to carry out the management process effectively, some type of decision support system is essential [Fedra and Reitsma 1990, Clarke 1990].

In general, a Decision Support System (DSS) can be defined as a system that supports technological and managerial decision making by assisting in the organization of knowledge about ill-structured, semi-structured or unstructured issues [Sage 1991]. A DSS is an interactive, computer-based system that helps decision makers utilize data and models to solve unstructured and ambiguous problems. A DSS caters to the needs of all levels of management decisions. However, it is oriented toward the needs of strategic and tactical level management [Mittra 1986]. The decision levels of particular interest for this research also involve strategic planning and management control decisions.

The functions of a DSS range from information collection and display, extrapolation, inference, and logical comparison to complicated modeling. Whereas information systems are based on a sequential structure of analysis and decision support resulting in unique answers, a DSS emphasizes the significance of interactive activity and the direct involvement of the end user. This implies feedback between the different elements of the system. Based on this feedback mechanism inherent in a DSS, the use of a DSS can improve the decision-making quality and can move management toward achieving better use of limited highway resources.

The role of the DSS is to help answer “what is, what would, and what if” questions. No DSS, no matter how inspired, can automatically solve a decision maker’s problems. A problem is a subjective presentation conceived by the decision maker confronted with a reality that is perceived to be unsatisfactory in terms of observations and facts. Because of this subjective dimension, decision making or decision finding is more of a process based on knowledge than it is a problem-solving event obtained from some “black-box.”

The major components of a DSS include a model-base management system (MBMS), a data-base management system (DBMS), and a display generation and management system (DGMS). The architectural aspects of the DSS for this research are shown in Figure 2.2. The key word is “knowledge.” One approach to knowledge is model driven; the other is data driven. In the view of the former, knowledge is understanding; in the case of the latter, knowledge is information. Understanding is a strategic approach to knowledge; information is a tactical approach gained piece by piece from data. Referring to Figure 2.2, the knowledge base should be obtained from both information and understanding; both a Data Base and a Model Base are needed. As indicated in Figure 2.2, a DSS requires wisdom, which is knowledge applied within a Value Base or value system so as to be able to trade off highway mobility and highway safety, for example. Lastly, a Display Base is needed to interpret studies. The following sections describe the major features and roles of each management system.

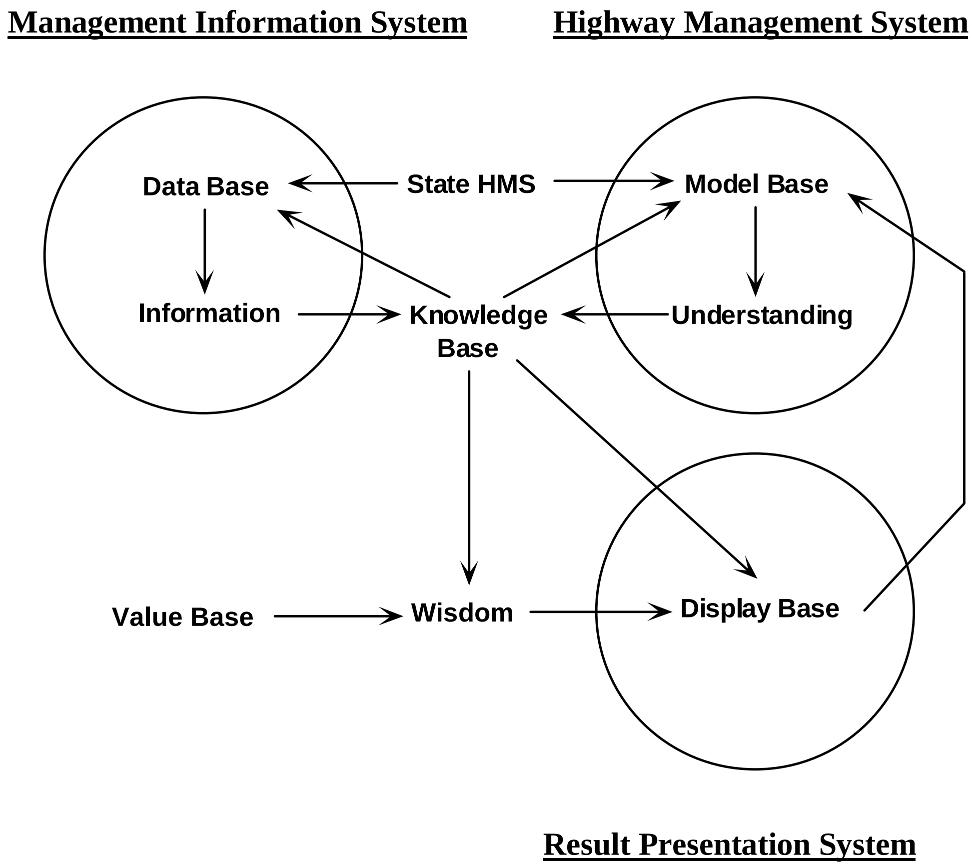

Figure 2.2 Decision Support System Architecture

2.5.1 Model-base Management System

A model is an abstraction of reality that duplicates the functional essence of the system in sufficient detail to be used instead of the system for investigation and experimentation with less time, less money, and less risk. To the extent that a particular model is an appropriate representation of the system, it can be a valuable aid to policy analysis, decision-making, and problem solving.

The most important characteristic of an MBMS is that it enables the decision maker to make decisions through use of the data base with a model base of algorithmic procedures. The model formulation process is time consuming and plays a major role in the result of the decision-making process. Broadly, the purpose of an MBMS is to generate information that is useful for decision making by utilizing data from a DBMS. The major objectives of a MBMS are to provide efficient models for use in specific applications, to centralize model-base management in the DSS framework, and to provide for model access and integration [Sage 1991].

The model is the backbone of the DSS. If a model can be expressed entirely as a set of equations, three benefits occur. First the model can be preserved over time without a loss of precision, making it a potentially permanent contribution to recorded knowledge. Second, it can be executed on a computer where policy variables and measures of effectiveness can be outputted over future time in a form of scenario analysis. Third, the model is a base for its own improvement using ensuing data or information. It is important to stress that model building comes before data collection – indeed the model determines and prioritizes the data requirements.

In performing highway management using a DSS, a model should satisfy the following requirements for its successful use [Markow 1993]:

- Major maintenance activities should be addressed,
- Inventories of physical assets to be maintained should be accompanied by data on their conditions, and
- Distinct measures of levels of service should be defined and incorporated within the HMS planning and budgeting routines.

The highway management model as a part of the DSS provides a specialized analysis of maintaining highway conditions at an acceptable level of service in the form of a simulation and optimization model. The DSS proposed by Osman and Hayashi addresses a highway management model as a part of the MBMS [Osman and Hayashi 1994]. The DSS constructed in their research is linked with the GIS so as to facilitate the acquisition and preparation of highway-related data, and the graphical representation of basic data and analysis results. A pavement management model as an analysis module in the MBMS is used to analyze pavement condition, to predict future deterioration of highway pavements, and to select and simulate repair alternatives under different budgets and scenarios. The model also provides performance evaluation regarding the surface and service conditions of the highway system and changes in vehicle operating costs.

2.5.2 Data-base Management System

A DBMS is one of the three fundamental components of a DSS. Throughout the decision-making process, there exists a consistent need for personal, local, and system-wide databases to utilize and run a model of particular interest for decision making. A DBMS is established to pursue three major objectives: data independence, data redundancy reduction, and data resource control. Some of the desirable characteristics of a DBMS include the following [Sprague 1980]:

- Ability to combine a variety of data sources through a data capture and extraction process,
- Ability to add and delete data sources quickly and easily,
- Ability to portray logical data structures in user terms, and
- Ability to handle personal and unofficial data at the user's request.

The crucial function of a DBMS rests on its interpretation of a real world that is outside of the data base in terms of real-world objects and activities. Thus, a DBMS should perform some sort of transformation from perceived real objects and activities to those representations that will be used in the physical data base. In order to meet this requirement and construct a DBMS, a data model should first be identified. A data model is a collection of data structures and operations. It defines the types of data objects that may be manipulated within a DBMS and referenced from an MBMS. There are at least four models that may be used to represent data: the individual record model, the relational model, the hierarchical model, and the network model [Sage 1991].

Both the individual record model and the relational model are the types of record-base models that use computer implementations of spreadsheet-shaped forms. The individual record model is the oldest data model representation. The data structure of this model is simply a set of records, with each record consisting of a set of fields. This is little more than an electronic file drawer in which records are stored. The relational model is a modification of the individual record model, i.e. it may be the result of "cut and paste" operations from a variety of files or individual record data. Whereas the individual model imposes some deficiencies in relating each field and building a data structure, the relational model combines field sets that are related. In this model, therefore, every relation may be described by a table form in which each row and column represents a record and a field, respectively. The overall structure of the hierarchical model can be viewed as a tree structure, i.e. there are a number of nodes that are connected and directed by links. The basic operation in this model is that of searching a tree to find items of value. When a query is posed with a hierarchical data base, all branches of the hierarchy are searched and those nodes that meet the query conditions are noted and returned to the DBMS and MBMS. However, this model is not as well suited as the relational model for use in DSS because it is not as easily analyzed as a relation model due to its complicated structures. Also, in a hierarchy, data has to be arranged such that "one child has only one parent," which is unrealistic in many instances. The network model overcomes these shortcomings by relating each record. That is, some fields in the hierarchical model become relational in a network model. Further, the relationships in a network model are explicit and may be bi-directional. However, this model also causes navigation or searching problems because of the complexity of its structures.

Having compared all the assets of the major four models for data representation and operation, the relational model emerges as the preferable data model among them. The individual record model formulates data structures in a scattered manner, causing inefficient access to values. The hierarchical and network models, which both utilize a basic tree data structure, have difficult problems such as strictly nested features and complexity in searching. The relational model provides an explicit formulation of a variety of data and operates efficient data access. Furthermore, generation of data reports is comparatively simple when the data base uses a relational model [Mittra 1986].

The primary motivation for the development of a DBMS is the need to support highway management activities through effective storage, retrieval, and analysis of data. The need for information and techniques used in highway management to be coordinated and integrated with the aid of data base systems has been pointed out in many studies [Haas and Hudson 1987, Byrd and Sinha 1987, Grivas 1988]. The original development of a data base was limited to passive repositories of data, but it has been greatly enhanced by the availability of relational data base management systems. This availability has made it possible to develop integrated data base systems that incorporate all features of the decision process and utility programs within the boundaries of highway management [NRC 1986, Eastman 1981].

Grivas et al. specify the functional aspects of an integrated data base system with special reference to pavement management [Grivas et al. 1991]. In their research, the pavement integrated data base system (PIDBS) that supports the pavement management activities at the New York State Thruway Authority (NYSTA) is developed. The structure of the PIDBS follows a top-down design that encompasses all functions within the pavement management process. The design of the data base uses the entity-relationship data modeling technique, in which data elements are viewed in the form of entities having defined keys and attributes and relationships among these entities. This integrated data base is implemented using the ORACLE relational data base management system (RDBMS) [Oracle Corp. 1988]. Through the development of the PIDBS, it is stressed that the functional design of a data base requires a complete analysis of the structure of the management system.

A commonly adopted technology that is particularly promising for infrastructure management DSS is GIS. Highway networks are inherently geographic because they extend over wide areas, and network components and events are also locational in nature. Thus spatial considerations in the analysis of different highway management activities are essential and can vastly improve the quality of the decision-making process [Paredes et al. 1990]. Several studies discuss effective and efficient assets of GIS for the application of their DBMSs [Schwartz et al. 1991, Simkowitz 1989, Petzold and Freund 1990, Abkowitz et al. 1990]. The typical form of a DBMS consists of a spatial data base and an attribute data base. The spatial data base includes data describing the spatial distributions of geographic features in an area. The basic features primarily include a highway network and a region's boundaries. The attribute data base includes the representative non-graphic information associated with each area and road section. This information includes, for example, pavement type, traffic volume, road capacity, etc.

2.5.3 Display Generation and Management System

The Result Presentation System based on Display Base can be broadly categorized into a DGMS. The primary purpose of the DGMS is to enhance the propensity and ability of the system user to utilize and benefit from the DSS. The DGMS is designed to satisfy knowledge representation, and control and interface requirements of the DSS. The DGMS is responsible for presentation of the information outputs of the DBMS and MBMS to the decision makers and for acquiring and transmitting their inputs to the DBMS and the MBMS. It should accommodate the languages or control mechanisms which enable the user to manage the DSS outputs and inputs in the form of dialogues or processes. The types of languages or modes of communications can be broadly categorized into three types; words, mathematics, and graphics [Sage 1991]. The words and mathematics types of languages are utilized in a conversational manner in which the user interacts with the system by describing what it is that the user wishes to happen through the use of a command language.

Schneiderman [Schneiderman 1987] identifies five primary interaction styles for human-computer interaction:

- *Menu selection*: in which the user reads a list of items and selects the one most appropriate for a particular task. It provides a very distinctive structure for decision making.
- *Command language*: in which the user utilizes a high-level language, such as C, to perform complex and detailed interactions with the system. It requires the users to entirely understand the DSS, and training is necessary.
- *Forms*: in which the data entry is required to fill in blanks in a question-answer-type format. Users should understand the logical structure of a DBMS to use this approach.
- *Natural language*: in which users are able to input ordinary conversational dialogue and the system is able to understand such dialogue.
- *Direct manipulation*: in which the user is able to use graphical representations.

The question concerning which interaction style is appropriate or best for the system can be answered by relying entirely on the development features of an MBMS and a DBMS. The one that provides an easy and efficient handling of a data base and a model base and that displays an explicit result representation can be considered as an interaction language or interface. No matter what type of DGMS is adopted, the user interface should provide the following capabilities [Sprague 1980]:

- Ability to handle a variety of dialogue styles,
- Ability to shift among them according to the user's choice,
- Ability to accommodate user actions in a variety of media,
- Ability to present data in a variety of formats and media, and
- Ability to provide flexible support for the user's knowledge base.

The main function of the DGMS is to produce a screen display of data and information generated by the MBMS. These outputs could be in a thematic map or in tabular formats or data files. These representations are usually facilitated by utilizing GIS in many studies [Simkowitz 1989, 1990]. A recent federally supported program solicitation states [U.S. DOT 1995]:

"*There is definitely a place for [geographic information systems, or GISs] in transportation planning. Applications have tended to be cumbersome and complex … innovative approaches are needed to address use of GIS in the Statewide and metropolitan transportation process.*"

Most full GIS implementations consist of a data base and a display base [Schwartz et al. 1991]. The display base using GIS presents the results of data queries and analyses in a geographic context. As a common feature, GIS enables users to query data for individual transportation features, e.g., a pavement section, by pointing to a geographic display of the transportation network. Moreover, the visualization of the results by color-coded geographic displays of the highway network enables more powerful interpretations and syntheses than are possible from text-based reports.

The adoption of GIS technology, however, comes with a high price tag in terms of hardware, software, data communications, and training. Without using GIS, a display module developed by the Florida DOT provides interactive color graphics to communicate pavement information in a cost-effective manner [Dietrich 1991]. The display module, a pavement management graphic reporting system (PMGRS), uses existing IBM hardware and SAS software. The system is accessible from any of several hundred terminals and personal computers around the state that are networked into the department's IBM 3090 mainframe computer. The system allows users to interactively create color-coded geographic maps of various pavement features on the state highway system. It is driven by menus and does not require extensive computer experience to operate. The PMGRS provides the basic function needed to display various graphic maps of pavement condition, although it does not rely on the commercially available GIS technology.

In summary, this chapter has reviewed features and research concerning transportation infrastructure systems and decision support systems, with emphasis on the necessary objectives and elements that should be considered. According to the literature review, the necessity for an appropriate prioritization methodology to manage transportation infrastructure has been addressed. This methodology can best be implemented within the framework of a decision support system, which assists the decision maker in arriving at various management policies.

CHAPTER 3
SUSTAINABLE DEVELOPMENT

3.1 Concept

Since the advent of a global, market-based economy, it has become clear that vast amounts of commodities are being produced, distributed, and consumed. However, economic growth and development have at times been at the expense of the environment and the quality of life of groups and individuals. Over the past three decades, there has been increasing concern for the well being of the environment and the conservation of natural resources. As the *Global 2000* report noted,

"*If present trends continue … serious stresses involving population, resources, and environment are clearly visible ahead. Despite the greater material output, the world's people will be poorer in many ways than they are today* [Barney 1980]."

Clearly, the recognition that the global market system is putting a major strain on the socioeconomic and ecological systems of the planet has resulted in a demand for sustainable forms of development [Clark and Munn 1986].

Since the 1980s, sustainable development has been regarded as the appropriate mechanism by which two opposing ideologies, economic development and environmental conservation, are brought together to create a more holistic approach to the advancement of society. In 1980, the term "sustainable utilization of resources" was noted in the World Conservation Strategy. The World Conservation Strategy had three principal aims, which were to maintain essential processes and life support systems, to preserve genetic diversity, and to ensure sustainable utilization of species and ecosystems [IUCN 1980]. In 1987, the concept of sustainable development gained further attention in the *Brundtland Report*, entitled "*Our Common Future*," where sustainable development was defined as,

" … *meeting the needs of, and aspiration of, the present generation without compromising the ability of future generations to meet their needs* [WCED 1987]."

Another commonly used definition of sustainable development, which has been adopted by the International Union for the Conservation of Nature (IUCN), is the type of development which improves the quality of life within the carrying capacity of the earth's life support system [IUCN, WWF, and UNEP 1991]. These three publications have led to detailed discussions about the implications of sustainable development as an important paradigm for the twenty-first century, from both academic and policy-making perspectives. Unfortunately, the details of this new paradigm are still unclear in terms of developing measures to examine sustainability and models to achieve sustainable development. Also, there are many different approaches to understanding and implementing sustainable development, as described in the following paragraphs.

Sustainable development has evolved from philosophical concerns about mankind's responsibility for nature [Passmore 1974], to locally and nationally based environmental groups demanding that more attention be paid to the environment [Lowe and Goyder 1983]. From this environmental point of view, sustainable development can be seen as the bridge between economic growth and environmental protection. Identification of specific issues on various aspects of the environment is explicitly shown in Table 3.1 [DASETT 1991]. Noticeable in this identification is that it illustrates in detail social and environmental consequences caused by transportation in general, and highways in particular.

Table 3.1 Sustainable Development Issues and Transportation Development

Aspect of environment	Summary of Issues
Atmosphere	• Photochemical smog • Motor vehicle emissions • Health aspects of deteriorating air quality
Marine	• Port development and impact of engineering works
Biodiversity	• Habitat destruction for native species of wildlife
Urban	• Urban sprawl and infrastructure requirements • Maintain access to open space • Air pollution from electric and diesel vehicles • Noise pollution from vehicles
Transportation Developments	• Greenhouse gas and other pollutant emissions • Automobile dependence and lack of viability for public transport in low density urban sprawl • Road surface pollutants • Spills from storage, handling, and transport of fuels • Noise and vibration from railways, airports, and vehicles • Marine oil spills and ballast discharges in ports

Source: derived from DASETT 1991

In the United States, the environmental concerns of transportation within a framework of sustainable development was addressed in June 1993, when President Clinton created the President's Council on Sustainable Development, with the primary goal of developing policy recommendations that encourage job growth and effective use and protection of our natural and cultural resources [PCSD 1996]. The council has created six primary task forces to address various sustainability issues, with transportation being addressed primarily by the Energy and Transportation Task Force. After implementing various energy and transportation scenarios, the Task Force concluded the following [PCSD 1995]:

- Despite measurable progress in improving environmental quality, some current trends are unsustainable.
- A desire to achieve greater social equity could change the nature of environmental protection and possibly constrain some options.
- Rapid technological advances may help achieve economic aspirations and ecological goals, but may not by themselves adequately address equity concerns.

The recommendations in the transportation area made by the Task Force show a significant concern for the environment [PCSD 1995].

- Increase national and economic security through reduced dependence on oil imports and the use of alternatives to single-occupancy vehicle use.
- Reduce greenhouse gas emissions from the transportation sector and traffic congestion in urban areas.
- Decrease per capita vehicle miles traveled.

Another sustainable development perspective is to relate sustainable development to the systems planning process. Table 3.2 contains some of the recommendations on transportation policy and planning made by the *Transport Working Group on Ecologically Sustainable Development* in Australia [Commonwealth of Australia 1991]. These recommendations are related to six steps of the planning process, with particular reference to urban areas. It should be noted that these recommendations place particular emphasis on goals and objectives and prescribing solutions, but are somewhat less emphatic about analytical methods, i.e. systems modeling.

The multiplicity of perspectives in addressing sustainable development demonstrates the need for the development of a comprehensive system. This need can be facilitated by adopting the concept of systems modeling, which employs a system dynamics methodology. The following section describes sustainable development from a systems modeling perspective.

Table 3.2 Sustainable Development Recommendations in Systems Engineering

Phase of the Process	Summary of recommendations
Establishing Goals, objectives, And values	• Comprehensive information and consultation programs • Traffic calming prominence and funding • Include cycling in transport planning and decision making • Technical advice on demand management • Coordination between government and planning agencies • Review existing planning arrangements to achieve better integration
Data, research	• Study how to incorporate full economic social and environmental costs into energy prices • Research into transport system in line with sustainable development • Air quality studies and monitoring
Modeling	• No specific suggestions. Implicit in several recommendations
Solutions	• Urban consolidation with range of housing types and densities • Suburban employment at public transport nodes • Locations for reduced travel demand • Road pricing mechanisms • Route advisory systems • Transit and HOV lane priority • Urban public transport investment
Evaluation	• Sustainable development consideration in decision making • Apply environmental impact assessment to policies, programs, and projects
Implementation	• Develop appropriate mechanisms to monitor implementation of recommendations and provide information

Source: Commonwealth of Australia 1991

3.2 Systems Modeling of Sustainable Development

A systems model is an abstracted representation of a system, by which the basic causal processes can be made clear and where the simulated output replicates the observed behavior of the system. Once a reasonable, empirically verified model is produced, then it can be used to explore scenarios of different policies which, if implemented, could illustrate whether or not one scenario is more or less sustainable than the current unsustainable pattern of development. Consider the following statement by Drew et al. [Drew et al. 1998], which illustrates the need for sustainable development:

"*The concept that the term sustainable development embodies is simple. It is the reconciliation of economic development in which protection of the environment, or the knowledge that infrastructure, the economy, and the environment, instead of being discrete and separate entities, are interconnected in fundamental and crucial ways*."

Systems modeling is a useful approach when incorporated into various management decision making problems with the goal of achieving sustainable development. James [James 1996] stresses that, in order to address ecosystem management problems adequately, the following requirements should be satisfied:

- Management procedures must be holistic and comprehensive.
- Sustainable development includes people and their activities in the ecosystem.
- Sustainable development describes system dynamics through such concepts as stability and feedback.
- Planners must look at different levels or scales of system structure, process, and function.

Slocombe [1993] believes that a systems approach is required for sustainability. He proposes guidelines for planners and scientists to ensure that sustainable development is achieved.

- Recognize goals and take an active management orientation.
- Incorporate stakeholder and institutional factors in the analysis.
- Use an anticipatory, flexible research, and planning process.
- Exercise the ethics of quality, well-being, and integrity in the management of resources.
- Recognize systemic limits to action – define and seek sustainability.

These requirements and guidelines illustrate some important aspects of sustainable development from a system management perspective. First, management should concentrate on qualitative development by improving current conditions, rather than by the expansion of physical resources [Meadows 1974]. This qualitative development can be achieved by maintaining or improving resources at an acceptable level, without deterioration over time. However, the management of a system is inevitably confronted by a shortage of financial resources. To overcome these limitations, system management should be cost effective and continuously responsive to changing resource inputs.

In order for a system to be sustainable, it should be analyzed in terms of its feedback and stability structures, as noted by James [James 1996]. This leads to the necessity for adopting a system dynamics methodology. This methodology helps to conceptualize a system into numerous components which are interactive and causally related. The conceptualization of causal relationships in a system facilitates the prediction of the future behavior of the system, and as its consequence, prevention of the positive feedback loops that cause exponential growth. This methodology requires a comprehensive insight into system behavior.

3.3 Modeling Approach

The approach to sustainable development utilized in this research is based on a realization of the systems management issues described in the previous section. The model developed in this research expresses a comprehensive mechanism of highway infrastructure management from a systems perspective. The importance of adapting the concept of sustainable development by infrastructure management can be seen in claims such as " … *engineers must become innovative thinkers, ensuring that technological applications incorporate sustainable development concepts (in infrastructure planning*) [Wright 1996]" and " … *in infrastructure planning and management decision making, infrastructure obsolescence and replacement strategies should be considered from the viewpoint of sustainable development* [Hendrickson and Horvath 1997]."

The modeling approach of this research is demonstrated by providing an infrastructure life-cycle planning for sustainable development (LCPSD) model. This simple model provides a basic concept of the transportation planning model for state highway management, which translates general infrastructure management problems into more specific transportation problems. The problems found in transportation are indicative of a more pervasive infrastructure problem – that of simply building more infrastructure than can be properly maintained. This mathematical model can illustrate how new construction, preventive maintenance and replacement maintenance can be coordinated to determine the long time physical and functional adequacy of a nation's or a region's infrastructure. A diagrammatic expression of the model is presented in Figure 3.1. Then, a list of equations generated by the model using DYNAMO code, which is a representative language of system dynamics, is provided in Figure 3.2. Fundamental to this model is the division of infrastructure into three hierarchical levels of condition and the investigation of the dynamics of the levels over time. The interrelated variables and constants generate the dynamic behaviors of the levels, as shown in Figure 3.3, which is a result of simulation. Figure 3.4 shows variations in the physical condition of the highway over time, which is represented by the physical sufficiency index.

The sustainability of this model can be checked in Figure 3.4. In this Figure, the value of the physical sufficiency index decreases during construction because of a shortage in the maintenance budget. However, the index begins increasing at the construction termination time, and begins stabilizing as time passes. This improvement and stabilization are due to an increase in maintenance activities during the non-construction period. Detailed descriptions of the various forms of the system dynamics model demonstrated in this section are provided in the next Chapter.

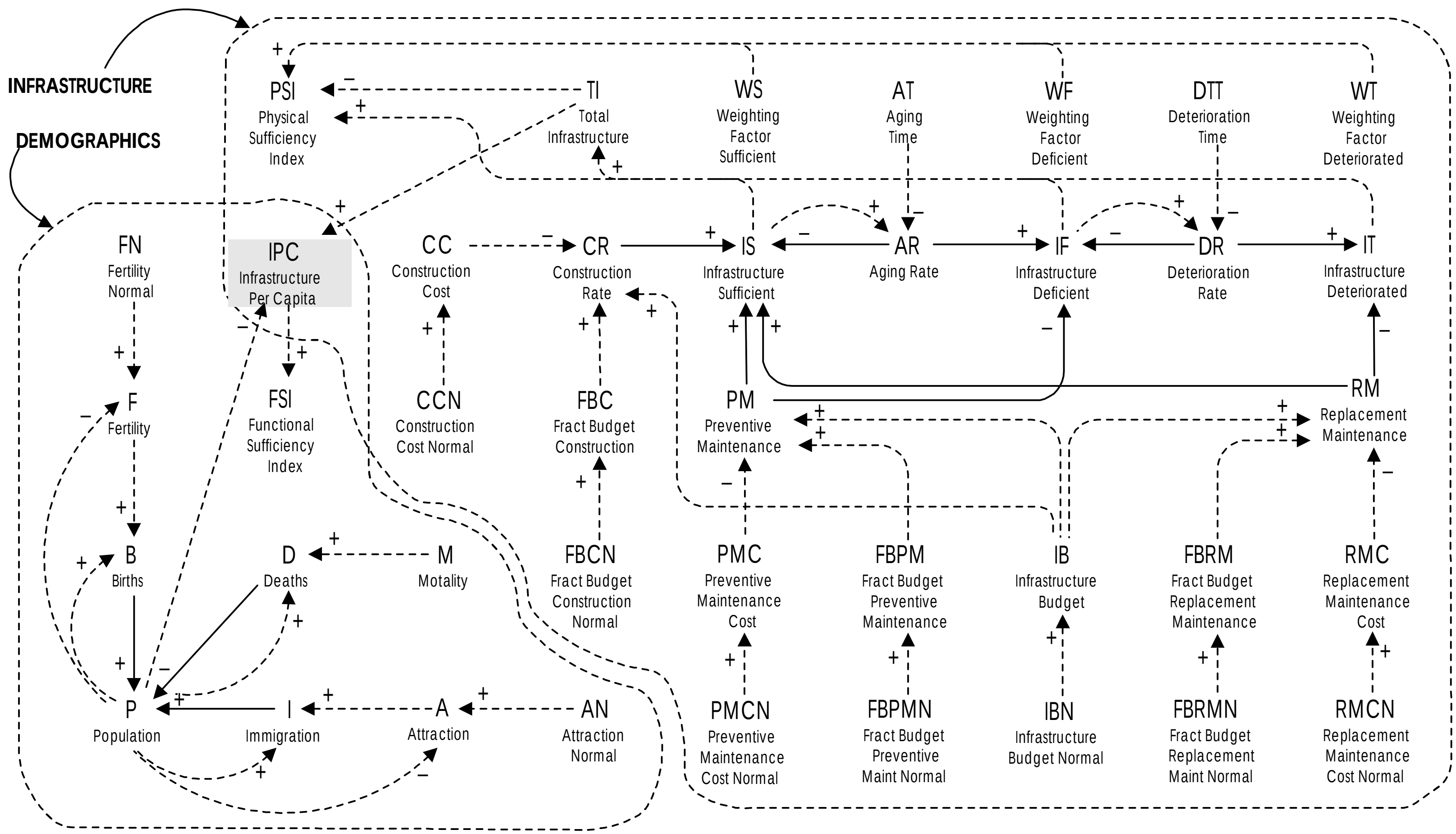

Figure 3.1 Causal diagram of infrastructure LCPSD model

```
* LIFE-CYCLE PLANNING FOR SUSTAINABLE DEVELOPMENT *

L IS.K=IS.J+(DT)(CR.JK+PM.JK+RM.JK-AR.JK)
N IS=ISN
C ISN=100E6
NOTE IS-INFRASTRUCTURE SUFFICIENT
L IF.K=IF.J+(DT)(AR.JK-PM.JK-DR.JK)
N IF=IFN
C IFN=0
NOTE IF-INFRASTRUCTURE DEFICIENT
L IT.K=IT.J+(DT)(DR.JK-RM.JK)
N IT=ITN
C ITN=0
NOTE IT-INFRASTRUCTURE DETERIORATED
A TI.K=IS.K+IF.K+IT.K
NOTE TI-TOTAL INFRASTRUCTURE
N TIN=ISN+IFN+ITN
NOTE TIN-TOTAL INFRASTRUCTURE INITIAL
R AR.KL=IS.K/AT
NOTE AR-AGING RATE
C AT=5
NOTE AT-AGING TIME
R DR.KL=IF.K/DTT
NOTE DR-DETERIORATION RATE
C DTT=20
NOTE DTT-DETERIORATION TIME
R PM.KL=IB.K*FBPM.K/PMC.K
NOTE PM-PREVENTIVE MAINTENANCE
R RM.KL=IB.K*FBRM.K/RMC.K
NOTE RM-REPLACEMENT MAINTENANCE
R CR.KL=IB.K*FBC.K/CC.K
NOTE CR-CONSTRUCTION RATE
A FBC.K=CLIP(0,FBCN,TIME.K,CTT)
NOTE FBC-FRACT BUDGET TO CONSTRUCTION
C CTT=100
NOTE CTT-CONSTRUCTION TERMINATION TIME
C FBCN=0.8
NOTE FBCN-FRACT BUDGET TO CONSTRUCTION NORMAL
A FBPM.K=CLIP(FBPME,FBPMN,TIME.K,CTT)
NOTE FBPM-FRACT BUDGET TO PREVENTIVE MAINTENANCE
C FBPMN=0.1
NOTE FBPMN-FRACT BUDGET TO PREVENTIVE MAINT NORMAL
C FBPME=0.6
NOTE FBPME-FRACT BUDGET TO PREVENTIVE MAINT EQUILIBRIUM
A FBRM.K=CLIP(FBRME,FBRMN,TIME.K,CTT)
NOTE FBRM-FRACT BUDGET TO REPLACEMENT MAINTENANCE
N FBRMN=1.0-FBPMN-FBCN
NOTE FBRMN-FRACT BUDGET TO REPLACEMENT MAINT NORMAL
N FBRME=1.0-FBPME
NOTE FBRME-FRACT BUDGET TO REPLACEMENT MAINT EQUILIBRIUM
A IB.K=IBN*(1.0+INFL*DT)**TIME.K
NOTE IB-INFRASTRUCTURE BUDGET
A PMC.K=PMCN*(1.0+INFL*DT)**TIME.K
NOTE PMC-PREVENTIVE MAINTENANCE COST
A RMC.K=RMCN*(1.0+INFL*DT)**TIME.K
NOTE RMC-REPLACEMENT MAINTENANCE COST
A CC.K=CCN*(1.0+INFL*DT)**TIME.K
NOTE CC-CONSTRUCTION COST
C INFL=0.04
NOTE INFL-ANNUAL RATE OF INFLATION
C IBN=200E9
NOTE IBN-INFRASTRUCTURE BUDGET NORMAL
C PMCN=0.01E6
NOTE PMCN-PREVENTIVE MAINTENANCE COST NORMAL
C RMCN=0.02E6
NOTE RMCN-REPLACEMENT MAINTENANCE COST NORMAL
C CCN=0.1E6
NOTE CCN-CONSTRUCTION COST NORMAL
L P.K=P.J+(DT)(B.JK+I.JK-D.JK)
N P=PN
C PN=100E6
NOTE P-POPULATION
R D.KL=P.K*M
NOTE D-DEATHS
C M=0.015
NOTE M-MOTALITY
R B.KL=P.K*F.K
NOTE B-BIRTHS
A F.K=FN*PN/P.K
NOTE F-FERTILITY
C FN=0.050
NOTE FN-FERTILITY NORMAL
R I.KL=P.K*A.K
NOTE I-IMMIGRATION
A A.K=AN*PN/P.K
NOTE A-ATTRACTION
C AN=0.010
NOTE AN-ATTRACTION NORMAL
A IPC.K=TI.K/P.K
NOTE IPC-INFRASTRUCTURE PER CAPITA
N IPCN=TIN/PN
NOTE IPCN-INFRASTRUCTURE PER CAPITA NORMAL
A PSI.K=(IS.K*1.0+IF.K*0.7+IT.K*0.5)/TI.K
NOTE PSI-PHYSICAL SUFFICIENCY INDEX
A FSI.K=IPC.K/IPCN
NOTE FSI-FUNCTIONAL SUFFICIENCY INDEX
```

Figure 3.2 DYNAMO program of infrastructure LCPSD

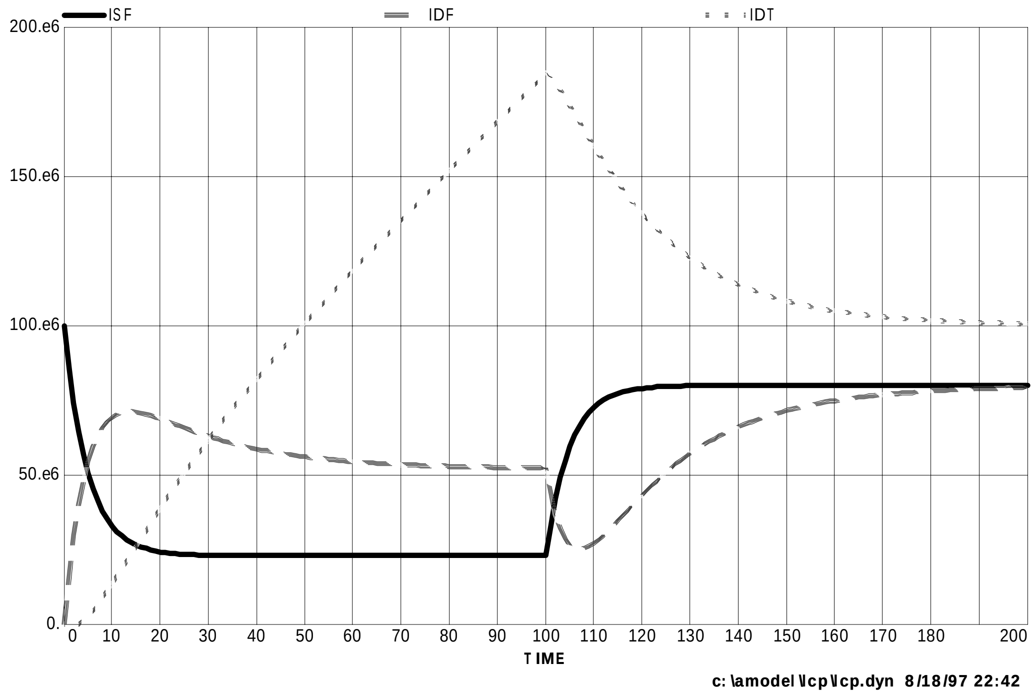

Figure 3.3 Result plot of system behavior of LCPSD using DYNAMO

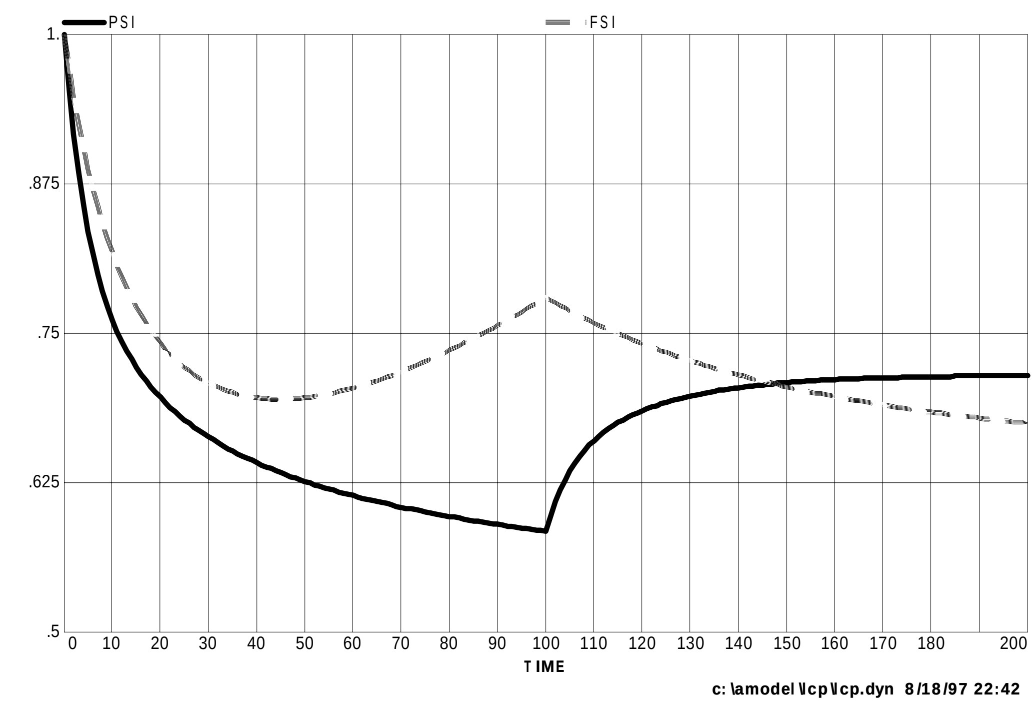

Figure 3.4 Result plot of performance indices of LCPSD using DYNAMO

CHAPTER 4
SYSTEMS APPROACH AND METHODOLOGY

4.1 Overview

In the beginning of this chapter, the characteristics and scope of this research are described, and the necessity for adopting the systems concept is raised. The system dynamic methodology is selected to address the objectives of this research. Overall descriptions of system dynamics are provided, with an emphasis on causal relationships and feedback structure. Finally, the use of DYNAMO equations for this research is indicated, including an elaboration on the DYNAMO language and its advantages.

4.2 Research Requirements

The essence of this research can be explained by examining two aspects of the transportation system: supply-demand interaction, and the linkage with the regional economy. This examination helps configure the research requirements, and based on those requirements, a research methodology is presented.

Transportation infrastructure management can be viewed as one part of the transportation system planning process. Broadly speaking, one can apply two terms used in economics, “supply and demand,” to the formulation of transportation systems. The supply-side approach to transportation concentrates on the issues of the construction and management of transportation facilities. On the other hand, the demand-side approach attempts to address issues related to the volume of traffic using the facilities. From the viewpoint of transportation management, these two components of transportation are not separable. In other words, any decisions as to transportation supply can not be reached without considering travel demand. Travel demand affects the form, the size, the number and the location of the facilities. Transportation infrastructure also determines the behavior of travel and the size of the traffic demand. Therefore, transportation infrastructure management should not be an isolated issue confined only to the supply aspect of transportation. One should be both necessary and sufficient condition to the other.

The establishment of a transportation system in a region can be realized in relation to the regional economy. The quality of the civil infrastructure, as well as the transportation infrastructure, is often regarded as a reflection of a regional economy. This recognition originates in the fact that the amount of investment in the infrastructure is a function of the economic condition of a region. Economic well-being itself never guarantees an improvement in the condition of the infrastructure without appropriate and systematic actions by management. However, the economic factor plays a major role in infrastructure improvement as a crucial contributor to the overall transportation system. This contribution is apparent as the growth in the regional economy affects the formation of transportation revenue. The scale of transportation fund allocation to various management programs depends on the amount of the transportation revenue.

In summary, the linkage between the supply and demand aspects of transportation, and the relationship between transportation and the regional economy should be conceptualized and revealed in management planning. In the construction of a transportation infrastructure management plan, each aspect affecting the transportation system is not supposed to be analyzed in isolation. Therefore, this research requires a wide and comprehensive view to understand the complex structures of the transportation system and to investigate possible relationships concerning the system. The analysis dealing with these complex structures can be facilitated not by a simple representation of single mathematical model, but through a systems approach. The systems approach can help establish an extensive view in a well-organized, scientific manner. The following section explains the concept of the systems approach and specifies the modeling methodology adopted in this research.

4.3 Systems Approach and Methodology

The word “system” is used so often and so generally to describe various objects or concepts that it is hard to derive an exact meaning that is inclusive of all the situations to which the term “system” is applied. However, a working definition of the term can be; “*a system is a set of objects together with relationships between the objects* [Hall and Fagen 1956].” This definition can be interpreted in such a way that one or more elements constitute an organized entity, and that the existence of one element is based on its relationship with another. This interpretation can be further extended by assuming that a system is an entity that is separable from the rest of the world by means of a physical or a conceptual boundary [Karnopp and Rosenberg 1975]. In other words, the world encompasses a number of systems, and each system stands as one unit that interacts with the surrounding environment.

These definition and extensions of meaning concerning systems can be recognized in real-world situations, including specific scientific and engineering applications. These applications, using a systems viewpoint, are concerned with the operation of an overall system rather than with the operation of a separated system component. In order to apply a systems analysis to a real problem, the systems approach should be utilized within a suitable framework. A simple framework suggested by Black [1981] provides seven steps, as shown in Figure 4.1.

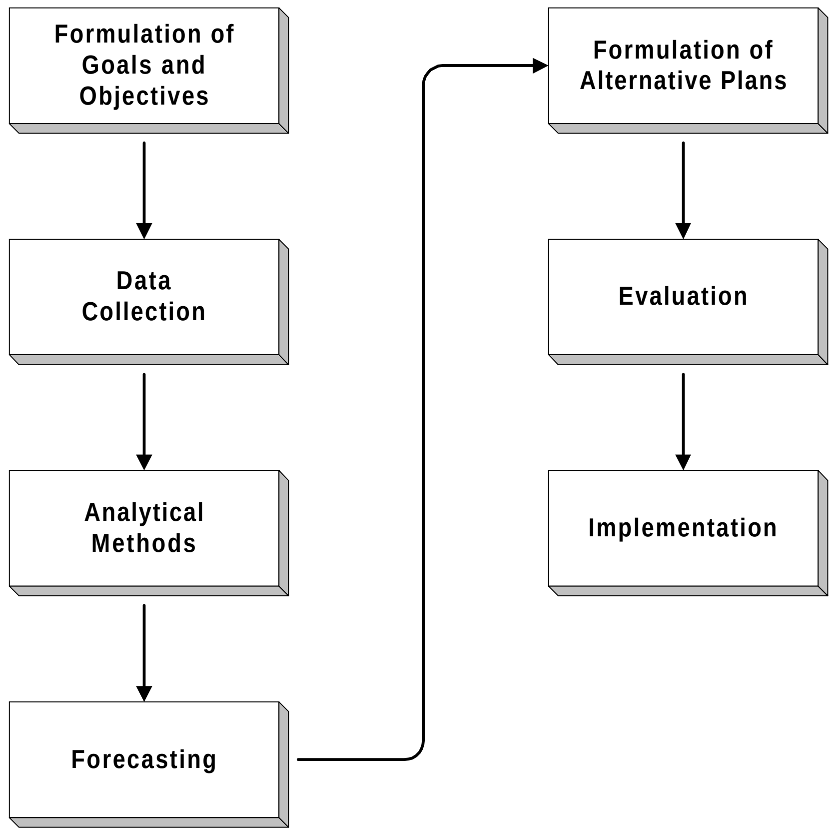

Figure 4.1 Framework for a Systems Approach
Source: Black 1981

The framework provided in Figure 4.1, however, can be criticized in two regards. First, data collection as a second step in the process should not precede the analytical methods used. If the term “analytical methods” means “model formulation,” data should be collected according to the model requirements. The problem arising from the sequence in Figure 4.1 is twofold: data redundancy, and data shortage. Data redundancy can be found in the fact that not all data gathered before the model formulation are used in the planning process. The data shortage refers to the case in which, after building the model, necessary data to be inputted in the model are often missing. This problem causes unnecessary and time-consuming effort in the modeling process. The second criticism is a lack of feedback loops in the systems approach. Regarding the systems engineering process, Blanchard and

Fabrycky state that "*the systems engineering process … employs a sequential and iterative methodology to reach cost-effective solutions to design alternatives* [Blanchard and Fabrycky 1981]." The modeling process should be iterative to achieve the basic requirements of a model. These requirements include the replication of a real system and the prediction of the possible behavior of the system, and can be satisfied by estimating the parameters in an iterative manner.

The concept of a system and the systems approach discussed above are utilized in this research. The TPMSHM is developed by adopting system dynamics methodology, which is a representative method used for systems modeling. The highway management system of Virginia functions as one system, and major parts of this system are categorized as subsystems. These subsystems take the demographic, administrative, and economic aspects of major sectors into consideration. Each subsystem is modeled separately in the initial stage of modeling, and then is combined with other subsystems by means of interrelated exogenous variables. The variables constituting subsystems are assumed to have a same meaning as a "system component." The systems approach shown in Figure 4.1 is modified and redefined. The modeling process used to conceptualize and analyze the highway management system is established on the basis of the redefined systems approach. The following sections describe the overall characteristics of the system dynamics methodology.

4.4 System Dynamics Methodology

4.4.1 Overview of the Methodology

The term "dynamics" in system dynamics refers to a system situation that is changing with time. Dynamics can be also interpreted as changes in the state of a system responding to changes in input variables. This understanding of dynamics, along with the definition of a system described in the previous section, leads to the definition of system dynamics as:

“*the mathematical modeling of a combination of system components so as to solve a set of equations which represent the dynamic behavior of the system and which can be solved to determine the response to various types of stimuli* [Doebelin 1972].”

System dynamics was developed at Massachusetts Institute of Technology during the 1950s by Jay W. Forrester. He developed a philosophy leading to a systems viewpoint and a set of mathematical techniques for simulating complex, nonlinear, multiloop feedback systems. The first system dynamics model applied to general management problems addresses the problems of inventory fluctuations, the instability of the labor force, and falling market shares [Forrester 1961]. The primary assumption of the system dynamics paradigm is that the dynamic tendencies of a complex system arise from its causal and feedback structure. That is, a system is structured based on the causal relationships and feedback loops formed by the components in a system.

The element in the system structure that represents the system is referred to as the state variable. The overall system dynamics model can be simply generalized using the state variable, input variables, output variables, and the measures of the effectiveness of the system, as shown in Figure 4.2. In the figure, the dynamic system responds to inputs that generate various performance measures of the system. The feedback structure and causal relationships exist in the dynamic system, which is represented by state variables, and determines the type of reaction to the input variables.

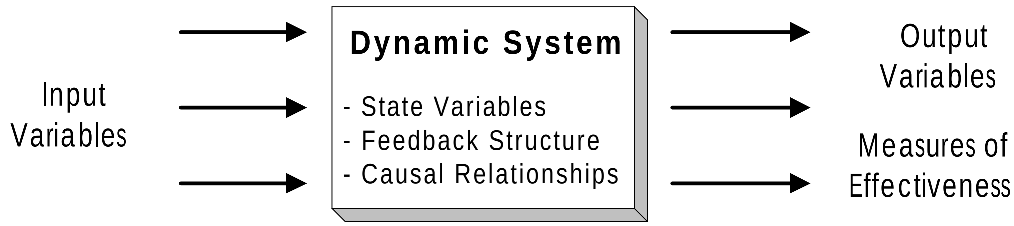

Figure 4.2 General System Dynamics Model

The following sections explain the structure of the system dynamic model and explain its structure, taking into account the various system variables used in the model.

4.4.2 Building Blocks of System Dynamics

The modeling process in system dynamics begins with the perception and understanding of the real system under consideration. Then, these perceptions and understandings are translated into various types of languages in a systematic structure. The structure that facilitates this translation consists of several substructures or building blocks. Using a system dynamics point of view, these building blocks can be represented by three alternative forms: a verbal model, a visual model, and a mathematical model. These forms of the model are usually utilized in a sequential manner in which, for example, the construction of a visual model is dependent upon the definitions of the verbal model.

In the verbal model, a system is described in words, including the definition of existing or possible problems, the identification of the system components, and the relationships among the system components. The mental description entailed in this type of model encompasses a keen insight into a complex real system.

The visual model graphically represents a working mechanism of the system with simplified and abstracted notations. This representation is best accomplished by incorporating a causal diagram. The verbal expression in the forth step in the verbal model is explicitly diagrammed by depicting a causal relationship between system components. In order to explain notations, a simple example of a causal diagram is provided in Figure 4.3. This diagram, which is actually used in this research as a part of the TPMSHM, demonstrates almost all the types of variables and symbols in a concise manner.

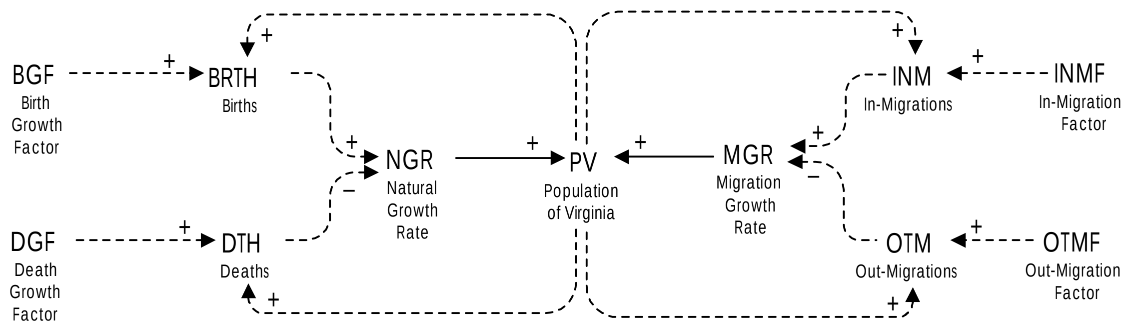

Figure 4.3 Simple Example of Causal Diagram

In Figure 4.3, solid arrows and dashed arrows denote physical flows and information flows. Three types of variables are observed in this diagram: a "level variable," a "rate variable," and an "auxiliary variable." The level variable can be found at head of the solid arrow, and the rate variable at the tail of the solid arrow. In this example, the PV, population of Virginia, represents the level variable, and both the NGR, natural growth rate, and the MGR, migration rate, constitute the rate variables. The auxiliary variable represents all other variables at the head and tail of the dashed arrow, except for rate variables connected to the level variables and constants. In the diagram, BRTH, births, DTH, deaths, INM, in-migrations, and OTM, out-migrations, are auxiliary variables. The constant contains the parameter value that feeds other variables at the end of the dashed arrow. A polarity sign on the arrow denotes the relationship between the dependent variable at the head of the arrow and the independent variable at the tail of the arrow. The "+" sign is placed where the dependent variable changes in the same direction as the independent variable. The "–" sign is for the opposite direction.

Due to its abstracted and implicit symbols, the causal diagram is self-explanatory. It should be stressed that the construction of a causal diagram should be based on a full understanding of the system under consideration, and the identification of correct relationships among its components. The difference in the positive and the negative sign is significant. The wrong choice of the sign will mislead the user of the model to make deviated decisions, rather than "real" decisions.

The visual model itself cannot provide the exact behavior of the system with regard to time-dependent variations. Also, the relationship expressed by the polarity between two variables is too general to suggest the magnitude and structure of their linkage. In the mathematical model, the graphical representations in the causal diagram are postulated into mathematical equations. The basic mathematical aspect utilized in the equations is the accumulation of the discrete case or the integration of the continuous case. For accumulation, level variables can be represented by the following discrete form of equations [Drew 1996].

$$L(t+1) = L(t) + (dt)\sum_{i=1}^{n} R_i(t) \qquad (4.1)$$

where, $L(t+1)$ = level variable at time t+1,
$L(t)$ = level variable at time t, and
$R_i(t)$ = rate variable i at time t.

The continuous form of the equation can be expressed by:

$$L(t+1) = L(t) + \int_{t}^{t+1} R(t)dt \qquad (4.2)$$

The Equation (4.1) represents that the value of level variable at present time is calculated by adding a sum of rate variables at a previous time to the value of the level variable at a previous time. The time interval is expressed as dt, and the rate variables are assumed to be constant over this interval. Here, the rate variables are functions of level variables, auxiliary variables, and constants. For example, the causal diagram shown in Figure 4.3 can be translated into the following mathematical form.

$$dPV_t = (NGR_t + MGR_t)dt \qquad (4.3)$$

In Figure 4.3, rate variables NGR_t and MGR_t are functions of auxiliary variables. The equation (4.3) is integrated in terms of time so as to obtain the equation for the level variable, PV. The final form of this equation is expressed as a combination of constants and time. The simulated values for level variables are the results of calculating this equation at various times.

By constructing mathematical equations for various types of variables, the quantification of system components, which were described in the verbal model, is finally realized. The simulation using mathematical equations facilitates analyzing system behaviors over the specified time period. The major advantage gained from mathematical formulation and simulation is that analysts gain structural knowledge about the future system in a scientific manner.

4.4.3 Feedback Structure of the System

Modeling in system dynamics should be based on an understanding of the feedback structure that is inherent in the complex system. The causal relationship between two variables is not necessarily confined to their link. A combination of the links often results in the formation of feedback loops. Feedback loops can be observed in a causal diagram in which causally related variables are interconnected and form closed loops. In these loops, a change in the value of one variable generates a “domino” effect on the values of other variables in the chain.

It should be noted, however, that the feedback structure does not only imply the feedback loop, but also provides a broader concept that encompasses several feedback components. Four hierarchical components can be defined in the feedback structure [Roberts 1978]: variable linkages, feedback loops, and the feedback system.

The variable is a quantity whose value changes over time. Three types of variables described in the previous section, i.e. the level variable, the rate variable, and the auxiliary variable, constitute this basic element of the structure.

A linkage is referred to as a cause and effect relationship between two variables. This linkage could represent either a positive relationship or a negative relationship between variables, as mentioned in the previous section. The accuracy and reliability of the system dynamics model depends on the correct and reasonable establishment of this linkage.

A feedback loop consists of two or more linkages connected each other. The loop starts from one variable from which information or physical flows emanate. These flows are transmitted to a series of variables in the chain through the appropriate transformation process, and finally return to the starting variable. The feedback loops have two polarities, positive or negative, depending on the number of negative signs at the linkages. If the signs are counted as odd numbers, the polarity of the loop is negative, or vice versa. In Figure 4.3, the positive loops can be found in a series of variables connected as PV→BRTH→NGR→PV and PV→INM→MGR→PV. The loops of PV→DTH→NGR →PV and PV→OTM →MGR→PV constitute negative loops. The positive loop results in the steady growth or the decline of variables in the loop. On the other hand, the negative loop affects the variables in the loop that fluctuate or reach equilibrium over time.

The feedback system comprises one or more feedback loops connected to each other. The feedback system is categorized based on the characteristics of the feedback loops and the total number of level variables in the system. Depending on the category of the system, analytical methods used to derive system equations vary, and thus the system's behavior as a result of the analysis shows a significant difference in each categorized system.

The interpretation of a real system cannot be completed without the investigation and understanding of the feedback structures described so far. The analysis of the system should not be isolated in a cause-and-effect relationship, but should be implemented in a nest of circular and interconnected structures [Forrester 1980]. In these structures, an action can induce not only a correction, but also an oscillation or counterpressure to the system. These various impacts inherent in the feedback structure are to be anticipated and addressed in the course of a system dynamics analysis.

4.4.4 Mathematical Analysis of System Dynamics

The system equations formulated as the result of a step-by-step establishment of verbal, visual, and mathematical models need to be solved in order to quantify the system variables. The solution of the system equations can be facilitated in two ways: through an analytical solution method, and through computer simulation. This section takes the analytical solution method into consideration. The subsequent section is devoted to an explanation of the computer implementation of system dynamics.

The analytical solution is the basis of computer simulation, as the simulator generates each estimate using a mathematical formulation in either a discrete or a continuous way. Assuming a system that reaches equilibrium at some time, the variations in the system over time can be thought of in two phases – the phases before and after the equilibrium point – in which the values of system variables do not change. Analysis concerning the former phase is called a "transient analysis." In transient analysis, time-dependent equations for variables are derived to configure the system's behavior until reaching the equilibrium point. This derivation is implemented by solving a set of differential equations. On the other hand, the analysis considering the latter phase is called a steady-state analysis. The solution of steady-state analysis is easily obtained by setting the values of rate variables to zero. This method is based on the fact that, beyond the equilibrium point, rate variables do not affect the level variables, and as a result, the values of the level variables remain constant. The steady-state solution is often incorporated into the transient solution, and causes the transient solution to be a function of time, constants, and variables at equilibrium. The form of the transient solution varies in accordance with feedback polarity, the order of the feedback system, and the type of system.

Whether or not a system reaches equilibrium depends on the model structure, not on the adjustment of parameter values. A change in parameter values only affects the magnitude of the behavior, but does not impact the pattern of behavior. In a case where a model shows a different time-dependent pattern from the real system, it should be remedied not by data manipulation, but by changing or reconstructing the model's structure.

4.4.5 Computer Implementation of System Dynamics

Numerous factors affect the formation and function of a real system, resulting in making a whole system more complex. The complexity of a system causes the analyst inevitably to adopt a large number of system components or variables so as to account for the working mechanisms of the system. However, the derivation of a mathematical formulation for each of the system variables is accompanied by a vast amount of calculation work, which usually causes time-consuming and repeated effort. This obstruction can be resolved efficiently by utilizing simulation languages. A simulation language is a set of computer codes that implement a large amount of computations by following predefined simulation rules. User-friendly software that uses simulation languages enable an analyst to build a system dynamics model in an efficient and specific manner. A representative simulation language of system dynamics is the DYNAMO language. The construction of the TPMSHM in this research is performed by utilizing DYNAMO.

DYNAMO is a program that implements continuous simulation so as to solve system dynamics' mathematical models. It facilitates quantifying time-dependent behaviors of any type of complex feedback structure in a system dynamics model. Modeling using DYNAMO utilizes the following steps. The primary skeleton of a program written in DYNAMO is constructed by equations for level, rate, and auxiliary variables, and constants. Having completed the construction of a model in text form, the program is then compiled in order to change text-type equations into computer codes. In the course of the compilation, any syntax errors counter to the grammar specified in DYNAMO are examined. As a final step in system dynamics modeling, the simulation of a model is implemented after the compilation. In simulating the model, any logical errors are given to the programmer. The results of the simulation can be presented in the form of table or plot. DYNAMO is a useful tool for calculating a large number of system equations and various types of system structures and feedback loops. The following paragraphs describe the rules of programming in DYNAMO, and examples are provided.

In order to express system variables as a function of time, DYNAMO employs specific time subscripts. The subscript .K stands for the present time. Compared to the notation for the present, the subscripts .J and .L stand for the past time and the future time, respectively. Referring to Equations (4.1) and (4.2), t in the equations corresponds to the notation .K, and t+1 to the notation .L. The subscript .J can be expressed as t–1 in the mathematical formulation.

The term dt in the equations is represented by DT in DYNAMO, which is called a step size. The determination of the step size depends on the analyst. Because DYNAMO applies an integration method based on the step size, the smaller the step size, the more accurate the results. However, the simulation time increases as one chooses a small step size. Regarding this tradeoff, two integration methods, the Euler's method and the Runge-

Kutta method, are compared by Pugh [Pugh 1980]. In this comparison, a model is first simulated by using the Euler's method with a fixed step size, and then is simulated by using the Runge-Kutta method, which is based on the variable step size described by Forsythe [Forsythe 1977]. The comparison shows that the use of the Runge-Kutta method produces more accurate results with fewer errors, but requires more cycles of calculations at the cost of computation time. This trade off between accuracy and simulation time needs to be considered in the course of simulation.

The rate variable is expressed as a combination of the subscripts, either .JK or .KL. If a rate variable is placed on the right side of the equation of the level variable, the subscript .JK is used. On the other hand, in the equation of the rate variable, the subscript .KL should be used. As implied by both subscripts, the rate variables expressed by .JK or .KL mean that changes occurred in the time segment between the past and the present, or between the present and the future. Based on the notations described so far, Equation (4.3) can be coded in DYNAMO as follows.

$$\text{L} \qquad PV.K = PV.J + (DT)(NGR.JK + MGR.JK) \tag{4.4}$$

Here, the letter L denotes that the equation written next is for the level variable, i.e. PV in this example. Fourteen equation types are used in DYNAMO including R for rate variable, A for auxiliary variable, and C for constant [Pugh-Roberts Associates 1994]. The rate variable NGR in Figure 4.3 can be coded in a DYNAMO equation as follows.

$$\text{R} \qquad NGR.KL = BRTH.K + DTH.K \tag{4.5}$$

The systems model can be also solved by using computer software made for the analysis of system dynamics models. The software, which usually provides a user-friendly interface, includes STELLA®, POWERSIM®, and VENSIM®. The major advantage of using this software is twofold: they can reduce the modeling effort in such a way that the construction of a causal diagram and the corresponding system equations can be performed simultaneously, and they can represent the simulation results in graphical forms in an interactive manner. The disadvantage arising from using this software is that their representation via causal diagrams does not provide full knowledge about the relationship between variables, due to a lack of polarities in the diagram.

The next chapter provides detailed information about modeling procedures, conceptualization, and the structure of the TPMSHM. The structure of each subsystem in the TPMSHM is explained by presenting a partial list of DYNAMO codes.

CHAPTER 5
TRANSPORTATION PLANNING MODEL FOR STATE HIGHWAY MANAGEMENT

5.1 Model Development

A model can be defined as a representation of a part of reality. A model is designed for a specific purpose, and depending on the modeling purpose, the model may be classified as physical model expressed as a type of scale model, or a mathematical model, i.e. a model that utilizes quantitative equations. All models, however, provide one common characteristic, regardless of the modeling intention: the transformation of a portion of the real world into a model [Black 1981]. This transformation is usually performed on a basis of the following processes:

- Perception of the real world,
- Interpretation of the real world,
- Generalization of specific conditions or environments,
- Simplification of the system,
- Abstraction of the given objectives, and
- Translation of the system into a type of model, following the given objectives.

If a complex system is being addressed, in which the application of a simple scale or descriptive model is insufficient in terms of a deeper explanation of the real system, a quantitative approach is often adopted, using a type of mathematical model. A mathematical model employs the language of mathematics to interpret and represent a system and its behavior. The mathematical language used to express the complex, real world must be highly abstract.

“*Mathematical notation is a more precise language than English. Because it is less ambiguous, a mathematical model is a description which has greater clarity than most verbal models* [Lee 1973].”

Once a mathematical model based on a quantitative approach is applied in a systems context, the approach is termed “systems modeling.” Systems modeling can be implemented by a single representative model, or by a combination of interrelated submodels. However, in any case, either using a single model or using a group of models, the identification of interrelationships among the system components should be a prerequisite for the modeling. In the course of this research, a transportation planning model, termed the Transportation Planning Model for State Highway Management, is developed by establishing and completing each step of the systems modeling process, as follows:

1. Definition of the problems,
2. Identification of the objectives,
3. Determination of the systems associated with the problems and the objectives,
4. Conceptualization of the model,
5. Determination of the model components,
6. Definition of interrelationships among the components,
7. Collection of data required for the model established,
8. Estimation of parameters in the systems,
9. Simulation of the systems,
10. Validation of the systems model,
11. Prediction of future behavior of the systems, and
12. Evaluation of policies.

In this process, steps from 5 to 11 should be necessarily iterative until reliable outputs are generated. The flowchart showing the modeling process in this research is provided in Figure 5.1.

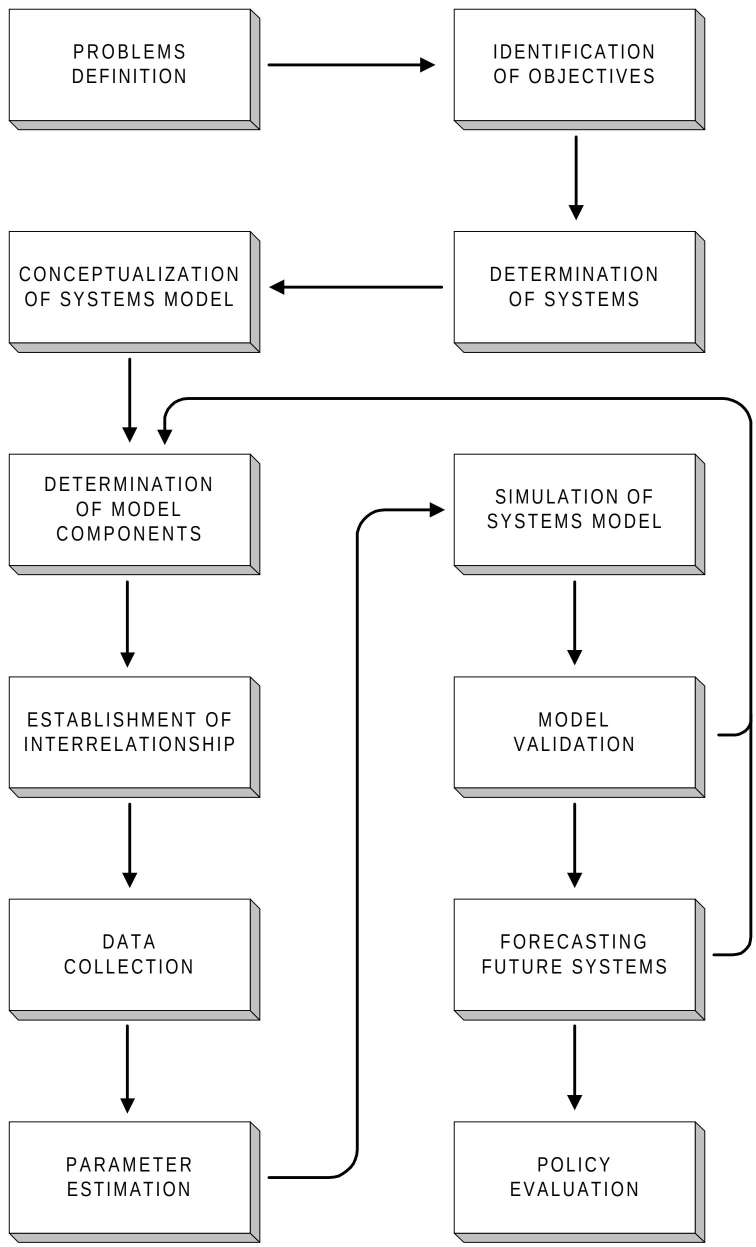

Figure 5.1 Systems Modeling Process

5.2 Model Conceptualization

The TPMSHM is conceptualized as a three-dimensional entity consisting of ten subsystems, as shown in Figure 5.2.

One dimension contains the chronological tasks inherent in highway management which are identified in this research as the Demography Subsystem, the Transportation Subsystem, the Travel Demand Subsystems, the Pavement Management Subsystem, the Bridge Management Subsystem, the Functional Subsystem, the Regional Economy Subsystem, the Finance Subsystem and the Appraisal Subsystem. The Demography Subsystem estimates the basic socioeconomic and transportation parameters to be utilized in the other subsystems. The Transportation Subsystem calculates the demand capacity ratio and the travel time of traffic on highways. The Travel Demand Subsystems are further divided into two sectors in terms of the modeling purpose: the Travel Demand Subsystem A and the Travel Demand Subsystem B. The former Subsystem generates vehicular demand for general-purpose trips, and the latter Subsystem estimates commuter and truck demand on highways. The Pavement Management Subsystem and the Bridge Management Subsystem depict the dynamics of the physical condition of highway pavements and bridges. The Functional Subsystem includes routines for unit cost items for highway management. The Regional Economy Subsystem models the regional level of industrial activities in order to estimate the Gross State Product (GSP) of Virginia, and employment in Virginia. The Finance Subsystem includes the budget allocation and revenue generation processes which support the entire system. The Appraisal Subsystem contains the routines for user costs, economic benefits, and other measures of effectiveness.

The second dimension is devoted to the administration subsystem, which consists of the four highway categories: Interstate, Primary, Secondary, and Urban Highways. Each of these categories can be defined as follows:

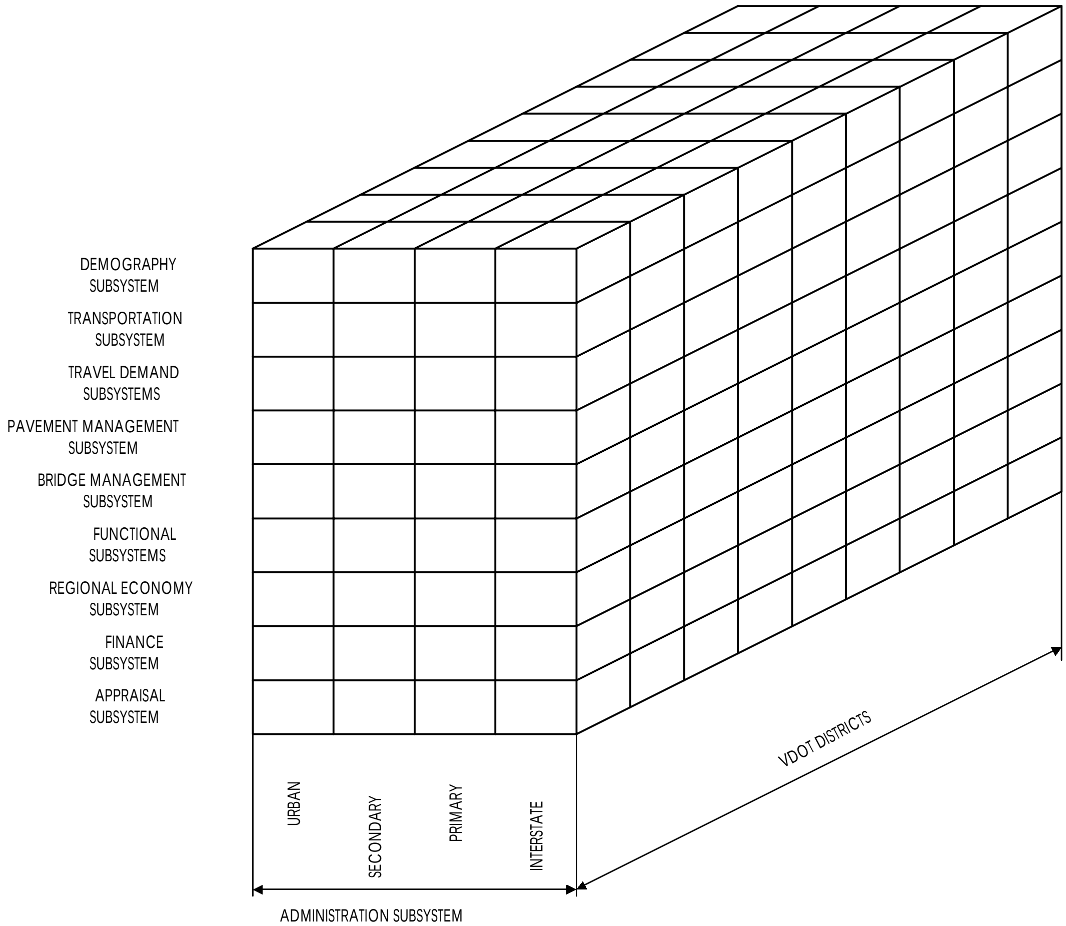

Figure 5.2 Model Conceptualization

- *Interstate system*: four-lane divided highways with controlled access,
- *Primary system*: arterial network which complements the interstate system and connects major cities and towns,
- *Urban system*: primary highways which pass through cities and towns over 3000 in population, and
- *Secondary system*: all public roads in the counties and all public roads and community roads leading to and from public schools, streets, bridges, and wharves in incorporated towns with 3500 or fewer residents.

The third dimension is the geographical classification of the Virginia Department of Transportation into nine Districts, which include the Salem, Bristol, Lynchburg, Richmond, Suffolk, Staunton, Culpeper, Northern Virginia, and Fredericksburg Districts, as shown in Figure 5.3.

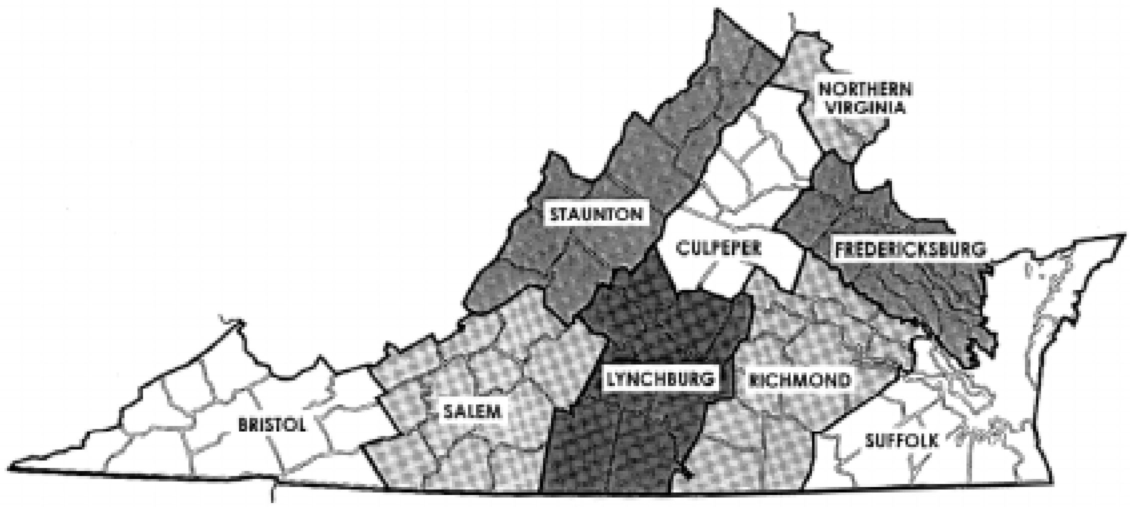

Figure 5.3 VDOT Construction Districts

The model conceptualization establishes the scope of the overall problem as a 9×4×9 surface, organized into 324 elements as shown in Figure 5.2.

Figure 5.4 shows salient relationships among the subsystems. In each subsystem, key variables representing their system are identified. The arrow signs indicate a cause-and-effect relationship between a Subsystem at the tail of arrow and another at the head of arrow. On the whole, this model can be observed as two-sided, with a demand side and a supply side. Demand-side transportation refers to Travel Demand Subsystems A and B, which address the generation process of travel demand on highways. On the other hand, supply-side transportation indicates the Physical Subsystem, which addresses the pavement and bridge conditions of highways. Both Subsystems converge into the Transportation Subsystem to assess the overall traffic condition of highways by calculating a demand capacity ratio. In the Appraisal Subsystem, the demand capacity ratio provides a basis for the evaluation of benefits arising from management activities concerning deteriorated highways. The Demography Subsystem supplies most of the demographics for Travel Demand Subsystems, and the Regional Economy Subsystem through the Finance Subsystem provides an impetus to the Physical Subsystem. The eight Subsystems formulate numerous feedback loops and causal relationships. Details on each Subsystem are explained in the subsequent sections.

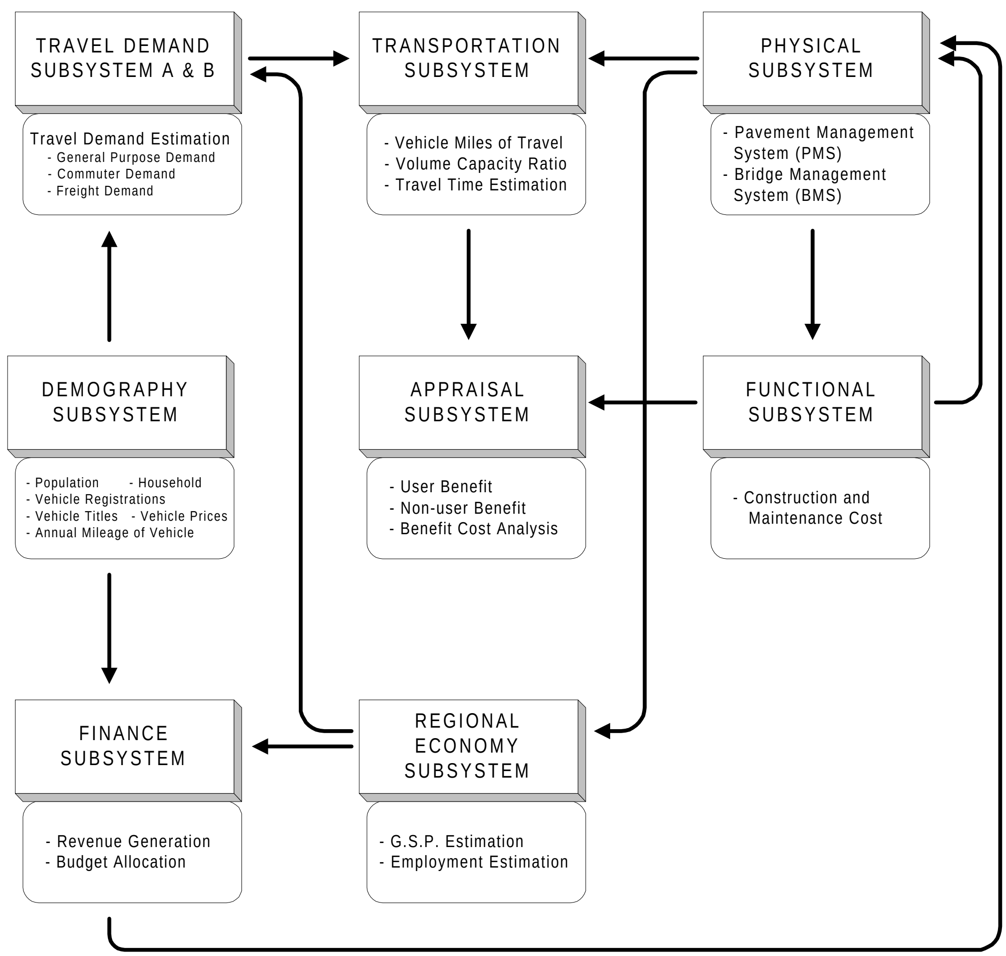

Figure 5.4 Causal Relationships among the Subsystems.

5.3 Model Description

In this section, the Subsystems of the TPMSHM are described by providing key DYNAMO equations. The development of the equations is based on the diagrammatic formulation of the model through causal diagrams, which are provided in the Appendix. It is helpful to refer the causal diagrams to understand the structure of the TPMSHM.

5.3.1 Demography Subsystem

The demography subsystem estimates the socioeconomic parameters that are fundamental to the other subsystems. This subsystem verifies and forecasts the following parameters for the State of Virginia:

- Population,
- Number of households,
- Number of vehicles registered,
- Number of vehicles titled,
- Average vehicle price,
- Average miles traveled per vehicle, and
- Average distance traveled per gallon.

The subsequent sections describe each of the parameters in detail, with the presentation of mathematical formulations.

- **Population**

The population of Virginia provides an essential input for the Travel Demand Subsystem A and the Finance Subsystem. Two major factors affect the size of the population in the model: natural growth, and migration growth rates. The pattern of natural growth is determined by the number of births and deaths. That is, the natural growth rate increases with an increase in the number of births and decreases with an increase in the number of deaths. The birth and death factors are used to estimate the number of births and deaths in a year. These factors can be obtained by observing the proportions of births and deaths over the whole population over past years. This part of the program can be expressed in a DYNAMO language, as follows:

```
L PV.K=PV.J+(DT)(NGR.JK+MGR.JK)
NOTE PV-POPULATION OF VIRGINIA (PERSONS)
R NGR.KL=BRTH.K-DTH.K
NOTE NGR-NATURAL GROWTH RATE (PERSONS/YR)
A BRTH.K=PV.K*BGF
NOTE BRTH-BIRTHS (PERSONS/YR)
NOTE BGF-BIRTH GROWTH FACTOR (DIM)
A DTH.K=PV.K*DGF
NOTE DTH-DEATHS (PERSONS/YR)
NOTE DGF-DEATH GROWTH FACTOR (DIM)
```

As another factor affecting population growth, the migration growth rate is expressed as in-migration minus out-migration. Besides the difference in the values of an in-migration factor and an out-migration factor, the same forms of equations used to calculate the natural growth rate are applied to obtain the migration growth rate. The value of the migration rate reflects the attractiveness of an area. If the rate shows a positive sign, the area can be regarded as attractive compared to other areas. Many factors contribute to the determination of attractiveness: job opportunities, living environment, or the number of universities, etc. The equations estimating the migration growth rate are shown as follows:

```
R MGR.KL=INM.K-OTM.K
NOTE MGR-MIGRATION GROWTH RATE (PERSONS/YR)
A INM.K=PV.K*INMF
NOTE INM-IN-MIGRATIONS (PERSONS/YR)
NOTE INMF-IN-MIGRATION FACTOR (DIM)
A OTM.K=PV.K*OTMF
```

NOTE OTM-OUT-MIGRATIONS (PERSONS/YR)
NOTE OTMF-OUT-MIGRATION FACTOR (DIM)

- **Number of Households**

The number of households is calculated by dividing the population size by the average household size. In Virginia, the average household size has been decreasing over the years at an annual rate of –0.75 percent and the total number of households is increasing at the rate of 2.24 percent, as shown in Table 5.1. This trend is often observed as a social phenomenon common to industrializing and developing areas. The equations representing this trend are provided as follows.

Table 5.1 Number of Households and Average Household Size in Virginia

Year	Number of Households (households)	Average Household Size (persons/household)
1980	1,863,000	2.87
1981	1,904,726	2.85
1982	1,950,000	2.81
1983	1,991,004	2.79
1984	2,029,000	2.78
1985	2,067,000	2.76
1986	2,122,000	2.73
1987	2,171,000	2.72
1988	2,228,000	2.70
1989	2,274,000	2.68
Annual Growth Rate	2.24%	-0.75%

Source: CPS annual

A HV.K=PV.K/AHS.K
NOTE HV-HOUSEHOLDS IN VIRGINIA (HOUSEHOLDS)
A AHS.K=AHSN*(1+AHSGR)**TIME.K
NOTE AHS-AVERAGE HOUSEHOLD SIZE (PERSONS/HH)
NOTE AHSN-AVG. H.H. SIZE NORMAL (PERSONS/HH)
NOTE AHSGR-AVG. H.H. SIZE GROWTH RATE (DIM)

- **Number of Vehicles Registered**

The number of vehicles registered in Virginia is estimated as a product of population and vehicle ownership. Vehicle ownership is expressed in the unit of vehicles per person. Vehicle ownership can represent the economic condition of a region or a nation. The development of the regional economy propelled by industrialization improves the living conditions of people, and results in an increase in vehicle ownership over time. However, past annual data concerning vehicle registrations and ownership in Virginia show fluctuations in the pattern of increase, without providing steady growth. This trend prevents the use of a fixed annual rate because it causes a high random error in the estimation. A reliable way to reduce the error would be an application of regression analysis. The linear regression analysis applied here fits the estimated values to the observed values so as to minimize random error. The formulation of the regression model is shown in the following DYNAMO equations.

A VR.K=PV.K*VOS.K
NOTE VR-VEHICLE REGISTRATIONS IN VIRGINIA (VEHICLES)
A VOS.K=RCVOS*TIME.K+RIVOS
NOTE VOS-VEHICLE OWNERSHIP IN VIRGINIA (VEH/PERSON)
NOTE RCVOS-REGRESSION COEFFICIENT (DIM)
NOTE RIVOS-REGRESSION INTERCEPT VALUE (DIM)

- **Number of Vehicles Titled**

Another important factor for the Finance Subsystem is the number of vehicles titled or the number of vehicles newly registered. The revenues from motor vehicle sales and use tax derives from vehicles. Both new and used vehicles whose ownership has been transferred to another owner are subject to new registration by the State. Thus, an estimation of the number of vehicles titled should be performed both for new vehicles and for used vehicles. The number of new and used vehicles newly registered over past years is summarized in Table 5.2.

As indicated in Table 5.2, the annual growth rate of new vehicles titled was – 0.79 percent, and that of used vehicles was 1.49 percent. It should be pointed out that the number of new vehicles titled has diminished over the years. This trend can be interpreted as being attributed to the following conditions. The period between 1985 and 1986 was a peak in new vehicle sales in the nation, as well as in the state. New vehicle sales decreased annually until about the year 1991, when they began to rise again. Economic conditions play a role in the number of vehicles consumers are willing to buy. If the economy is not strong, people are less willing to make large expenditures to buy new cars. In addition, the price of vehicles had been rising much faster than the increase in inflation. From the viewpoint of technology, since the quality and durability of vehicles have improved over time because of the development of manufacturing technology, the life of vehicles is extended. Therefore, consumers can delay the purchase of new vehicles. The following equation contains the estimation of new vehicles titled, using an annual growth rate.

```
A NVT.K=NVTN*(1+NVTG)**TIME.K
NOTE NVT-NEW VEHICLES TITLED (VEHICLES)
NOTE NVTN-NEW VEHICLES TITLED NORMAL (VEHICLES)
NOTE NVTG-NEW VEHICLES TITLED GROWTH FACTOR (DIM)
```

Table 5.2 Number of Vehicles Titled

Year	New Vehicles Titled (vehicles)	Used Vehicles Titled (vehicles)
1985	388,551	929,371
1986	432,968	1,007,765
1987	399,063	958,372
1988	385,343	970,329
1989	354,479	958,630
1990	307,528	959,504
1991	254,237	918,616
1992	274,951	976,388
1993	318,220	988,306
1994	361,687	1,061,273
Annual Growth Rate	-0.79 %	1.49 %

Source: VDMV, 1997

- **Average Vehicle Price**

An estimation of average vehicle prices for new vehicles and used vehicles is performed by using the annual price growth rates. As summarized in Table 5.3, the average new vehicle price had been increasing with an annual growth rate of 4.48 percent over the 1985 to 1994 period. A higher annual growth rate is observed for used vehicles. The equation for the average new vehicle price is provided in the following.

```
A ANVP.K=ANVPN*(1+NVPG)**TIME.K
NOTE ANVP-AVERAGE NEW VEHICLE PRICE ($)
NOTE ANVPN-AVG. NEW VEHICLE PRICE NORMAL ($)
NOTE NVPG-NEW VEH PRICE GROWTH FACTOR (DIM)
```

Table 5.3 Average Vehicle Price (Current Price)

Year	Average New Vehicle Price ($/vehicle)	Average Used Vehicle Price ($/vehicle)
1985	12,324.67	2,708.68
1986	13,202.67	2,910.46
1987	13,722.67	3,136.34
1988	14,270.83	3,292.66
1989	14,870.83	3,354.46
1990	15,328.00	3,367.03
1991	15,816.83	3,518.11
1992	16,737.00	3,736.51
1993	17,222.67	4,023.38
1994	18,281.39	4,508.76
Annual Growth Rate	4.48 %	5.83 %

Source: VDMV, 1997

- **Average Miles Traveled per Vehicle**

Along with vehicle registrations, the parameter of average miles traveled per vehicle is used to compute the revenue from motor vehicle fuels tax in the Finance Subsystem. Table 5.4 contains the annual travel mileage per vehicle for the selected years.

Table 5.4 Average Miles Traveled per Vehicle per Year (AMTV)

Year	1980	1985	1990	1992	1993	1994	1995	Annual Growth Rate
AMTV	9,458	10,018	11,107	11,558	11,597	11,683	11,801	1.49 %

Source: BTS 1997

The following equation calculates the average miles using an annual growth rate. The average daily travel mileage is obtained by dividing the annual mileage by 360. The daily mileage is utilized in the travel time estimation in the Transportation Subsystem.

```
A AMTV.K=AMTVN*(1+AMTVGR)**TIME.K
NOTE AMTV-AVG MILES TRAVELED/VEH (MI/VEH-YR)
NOTE AMTVN-AMTV NORMAL (MI/VEH-YR)
NOTE AMTVGR-AMTV GROWTH RATE (DIM)
A ADMTV.K=AMTV.K/360
NOTE ADMTV-AVERAGE DAILY MILES TRAVELED PER VEHICLE (MI/VEH-DAY)
```

- **Average Distance Traveled per Gallon**

The average distance traveled per gallon provides an essential factor in estimating the revenue from the motor vehicle fuels tax in the Finance Subsystem. The average distance traveled has been increasing at an annual rate of 1.62 percent, as shown in Table 5.5. This trend reflects the improvement in the fuel efficiency of vehicles, caused by the development of the manufacturing technology of vehicles. The following equation uses the annual growth rate to estimate the average distance traveled per gallon.

Table 5.5 Average Miles Traveled per Gallon (AMTG)

Year	1980	1985	1990	1992	1993	1994	1995	Annual Growth Rate
AMTG	13.29	14.62	16.40	16.90	16.74	16.74	16.91	1.62 %

Source: BTS 1997

```
A ADTG.K=ADTGN*(1+ADTGGR)**TIME.K
NOTE ADTG-AVERAGE DISTANCE TRAVELED PER GALLON (MI/GAL)
NOTE ADTGN-ADTG NORMAL (MI/GAL)
NOTE ADTGGR-ADTG GROWTH RATE (DIM)
```

5.3.2 Pavement Management Subsystem (PMS)

The PMS consists of three level variables, five rate variables, and other auxiliary variables and constants. A budget from the Finance Subsystem, a demand capacity ratio from the Transportation Subsystem, and unit costs for both construction and maintenance from the Functional Subsystem are the major inputs to the PMS. The relationships among various variables and constants are explicitly expressed in a causal diagram provided in Appendix.

Highways in Virginia can be divided into three categories in terms of their pavement condition: Highways in Sufficient Condition (HSF), Highways in Deficient Condition (HDF), and Highways in Deteriorated Condition (HDT). New construction of highways and appropriate and timely maintenance ensure that lane mileage of the HSF will be increased. Two maintenance intensities, the Maintenance Rate of Deficient Highway (MRDFH) and the Maintenance Rate of Deteriorated Highway (MRDTH), are applied to reduce the HDF and the HDT, respectively. On the other hand, the HDF and the HDT increase over time due to their aging. This part of the program can be expressed in a DYNAMO language, as follows.

```
L  HSF.K(H)=HSF.J(H)+(DT)(CRH.JK(H)+MRDFH.JK(H)+MRDTH.JK(H)-ARH.JK(H))
NOTE  HSF-HIGHWAY IN SUFFICIENT CONDITION (LANE-MI)
L  HDF.K(H)=HDF.J(H)+(DT)(ARH.JK(H)-MRDFH.JK(H)-DRH.JK(H))
NOTE  HDF-HIGHWAY IN DEFICIENT CONDITION (LANE-MI)
L  HDT.K(H)=HDT.J(H)+(DT)(DRH.JK(H)-MRDTH.JK(H))
NOTE  HDT-HIGHWAY IN DETERIORATED CONDITION (LANE-MI)
* CRH-CONSTRUCTION RATE OF HIGHWAY (LANE-MI/YR)
* MRDFH-MAINTENANCE RATE FOR DEFICIENT HIGHWAY (LANE-MI/YR)
* MRDTH-MAINTENANCE RATE FOR DETERIORATED HIGHWAY (LANE-MI/YR)
* ARH-AGING RATE OF HIGHWAY (LANE-MI/YR)
* DRH-DETERIORATING RATE OF HIGHWAY (LANE-MI/YR)
```

The aging rate of highways is negatively affected by the aging time of highways. Also, aging time is accelerated with higher traffic volume, and thus results in an increase in aging rates. In the model, two types of aging rates are applied: the Aging Rate of Highways (ARH) and Deteriorating Rate of Highways (DRH). The following program shows the estimation of the ARH and the aging time, along with the negative relationship between traffic demand and aging time.

```
R  ARH.KL(H)=HSF.K(H)/ATH.K(H)
A  ATH.K(H)=ATHN*ATHM.K(H)
NOTE  ATH-AGING TIME OF HIGHWAY (YR)
NOTE  ATHN-AGING TIME OF HIGHWAY NORMAL (YR)
A  ATHM.K(H)=TABLE(ATHMT,DCRH.K(H),0.0,1.0,0.1)
T  ATHMT=1.0/0.98/0.96/0.94/0.92/0.90/0.88/0.86/0.84/0.82/0.80
NOTE  ATHM-AGING TIME OF HIGHWAY MULTIPLIER (YR)
* DCRH-DEMAND CAPACITY RATIO OF HIGHWAY (DIM)
```

Construction and maintenance rates increase proportionally with expenditures on both activities. Also, the costs required for construction and maintenance activities negatively affect both management rates. Hence, the larger the costs, the smaller the rates. The amount of expenditures on various management activities is determined by the PMS budget, with an appropriate proportion of the budget allocation for each activity. The following equations calculate the maintenance rate for deficient highways.

```
R  MRDFH.KL(H)=MIN(MEDFH.K(H)/MCDFH.K(H),HDF.K(H))
A  MEDFH.K(H)=HME.K(H)*FHMEDFH.K(H)/MAX(FHMEDFH.K(H)+FHMEDTH.K(H),1E-6)
NOTE  MEDFH-MAINTENANCE EXPENDITURE FOR DEFICIENT HIGHWAY ($/YR)
A  HME.K(H)=PMSB.K(H)*FPMSBM.K(H)
NOTE  HME-HIGHWAY MAINTENANCE EXPENDITURE ($/YR)
* MCDFH-MAINTENANCE COST OF DEFICIENT HIGHWAY ($/LN-MI)
* PMSB-PMS BUDGET ($)
* FPMSBM-FRACTION OF PMS BUDGET TO MAINTENANCE (DIM)
* FHMEDFH-FRACTION OF HME TO DEFICIENT HIGHWAY (DIM)
* FHMEDTH-FRACTION OF HME TO DETERIORATED HIGHWAY (DIM)
```

The essence of this PMS is the adoption of a state-dependent prioritization strategy. In this strategy, the proportions of the highway budget allocated to each level of management activity are determined by the physical conditions of the highways. Highways in the worst condition are given the first priority to receive the budget allocations in the following way. First, a fraction of the budget for construction (FPMSBC) is obtained as a proportion of highways in sufficient condition (HSF) over the whole highway network. Then, the remaining fractions of the budget are devoted to the two maintenance activities. The fraction of the budget for deficient highways (FHMEDFH) increases with an increase in the lane mileage of highways in deficient condition, and similarly, the fraction of the budget for deteriorated highways is a function of the lane mileage of highways in deteriorated condition. This allocation scheme realizes the following interactions between highway condition and highway management: as the highway system deteriorates over time, highways in sufficient condition diminish, and thus the fraction for construction investment is reduced. Instead of a reduced fraction of expenditures on construction, larger fractions of the budget are placed into the two maintenance activities, causing higher maintenance rates. As a result of the increased maintenance rates, the overall pavement condition of highways is improved. The following programs reflect this allocation mechanism.

```
A  FPMSBC.K(H)=CLIP(0,HSF.K(H)/TLMH.K(H),TIME.K,CTMT)
NOTE  FPMSBC-FRACTION OF PMS BUDGET TO CONSTRUCTION (DIM)
NOTE  CTMT-CONSTRUCTION TERMINATION TIME (YR)
A  FPMSBM.K(H)=1-FPMSBC.K(H)
A  FHMEDFH.K(H)=CLIP(FPMSBM.K(H)*HDF.K(H)/(HDF.K(H)+HDT.K(H)),0,HDF.K(H),0)
A  FHMEDTH.K(H)=FPMSBM.K(H)-FHMEDFH.K(H)
* TLMH-TOTAL LANE MILEAGE OF HIGHWAY (LANE-MI)
```

Measures of effectiveness for the PMS can be divided into two categories: physical sufficiency, and functional adequacy. The former indicates a level of surface condition of highways, and the latter represents whether the highways meet the traffic demand on their facilities. A Physical Sufficiency Index (PSIH) measures the physical condition of highways. It ranges from 0.5, the worst, to 1.0, the best. A Functional Adequacy Index (FAI) is expressed in terms of the lane mileage of highways per capita, and a higher value of this index is desirable. The following program shows the two indices as measures of effectiveness for the PMS.

```
A  PSIH.K(H)=(HSF.K(H)*WFHSF+HDF.K(H)*WFHDF+HDT.K(H)*WFHDT)/TLMH.K(H)
NOTE  PSIH-PHYSICAL SUFFICIENCY INDEX OF HIGHWAY (DIM)
NOTE  WFHSF-WEIGHTING FACTOR FOR HSF (DIM)
NOTE  WFHDF-WEIGHTING FACTOR FOR HDF (DIM)
NOTE  WFHDT-WEIGHTING FACTOR FOR HDT (DIM)
A  FAI.K(H)=(TLMH.K(H)/PV.K)/(TLMHN(H)/PVN)
NOTE  FAI-FUNCTIONAL ADEQUACY INDEX OF PAVEMENT (DIM)
* TVMH-TOTAL VEHICLE MILES OF HIGHWAY (VEH-MI)
* TVMHN-TOTAL VEHICLE MILES OF HIGHWAY NORMAL (VEH-MI)
```

5.3.3 Bridge Management Subsystem (BMS)

The bridge management subsystem in the model can be subdivided into two parts. The first part deals with the physical assets of highway bridges, and the second part addresses the functional performance of bridges. The Physical Bridge Management Subsystem, referring to the first part of the BMS, builds a framework for managing and improving the physical condition of bridges. The systematic mechanism for preventive maintenance, repair, rehabilitation, and replacement of bridges is methodized. The Functional Bridge Management Subsystem, the second part of the BMS, models the functional adequacy of the facility by calculating the number of functionally obsolescent bridges over time. The functionally obsolescent bridge refers to a bridge that is unable to manage the traffic demand, even though it is structurally sound.

It should be noted that both subsystems are not separable from each other. In other words, one bridge that is in very good condition could be functionally obsolescent at the same time, or vice versa. Hence, the total number of bridges should not be sorted out as physical bridges or functional bridges. Functionally obsolescent bridges will only be generated from bridges in the Physical Bridge Management Subsystem which do not satisfy the volume of traffic. The causal diagrams provided in Appendix would be helpful in understanding the underlying ideas and the following explanations about the model.

- **Physical Bridge Management Subsystem**

The physical conditions of bridges that are classified in the BMS model fall into five hierarchical levels: Bridges in Preferred Condition (BPFC), Bridges in Good Condition (BGC), Bridges in Poor Condition (BPC), Bridges in Serious Condition (BSC), and Bridges in Critical Condition (BCC). This classification is based on decision guidelines for a bridge condition rating suggested by Minor, et al. [Minor, et al. 1988]. These five conditions of bridges constitute five level variables, each of which is related to aging rates and maintenance rates, as shown in the following.

```
L BPFC.K(H)=BPFC.J(H)+(DT)(CRB.JK(H)+PVMB.JK(H)+RRRB.JK(H)+RHRB.JK(H)+^
                RPRB.JK(H)-ERB.JK(H))
NOTE BPFC-BRIDGES IN PREFERRED CONDITION (BRIDGES)
L BGC.K(H)=BGC.J(H)+(DT)(ERB.JK(H)-PVMB.JK(H)-ARB.JK(H))
NOTE BGC-BRIDGES IN GOOD CONDITION (BRIDGES)
L BPC.K(H)=BPC.J(H)+(DT)(ARB.JK(H)-RRRB.JK(H)-DRB.JK(H))
NOTE BPC-BRIDGES IN POOR CONDITION (BRIDGES)
L BSC.K(H)=BSC.J(H)+(DT)(DRB.JK(H)-RHRB.JK(H)-SDRB.JK(H))
NOTE BSC-BRIDGES IN SERIOUS CONDITION (BRIDGES)
L BCC.K(H)=BCC.J(H)+(DT)(SDRB.JK(H)-RPRB.JK(H))
NOTE BCC-BRIDGES IN CRITICAL CONDITION (BRIDGES)
* CRB-CONSTRUCTION RATE OF BRIDGE (BRIDGES/YR)
* ERB-EXPOSURE RATE OF BRIDGE (BRIDGES/YR)
```

* ARB-AGING RATE OF BRIDGE (BRIDGES/YR)
* DRB-DETERIORATION RATE OF BRIDGE (BRIDGES/YR)
* SDRB-SERIOUS DETERIORATION RATE OF BRIDGE (BRIDGES/YR)
* PVMB-PREVENTIVE MAINTENANCE RATE OF BRIDGE (BRIDGES/YR)
* RRRB-REPAIR RATE OF BRIDGE (BRIDGES/YR)
* RHRB-REHABILITATION RATE OF BRIDGE (BRIDGES/YR)
* RPRB-REPLACEMENT RATE OF BRIDGE (BRIDGES/YR)

For the maintenance of bridges, four types of maintenance rates are applied to the corresponding level variables to upgrade the deteriorated conditions of bridges to a preferred condition. The rates of maintenance are obtained from the expenditures on a bridge divided by the unit maintenance cost. The source of expenditures can be found in the BMS Budget (BMSB), which is also generated from the revenue generation process in the Finance Subsystem. The form of each equation for the maintenance rates follows a similar shape, as shown in the following equation for the preventive maintenance rate.

R PVMB.KL(H)=MIN(PMEB.K(H)/PMCB.K(H),BGC.K(H))
NOTE PVMB-PREVENTIVE MAINTENANCE RATE OF BRIDGE (BRDGS/YR)
A PMEB.K(H)=BMSB.K(H)*FBPM.K(H)
NOTE PMEB-PREVENTIVE MAINTENANCE EXPENDITURE ON BRIDGES ($/YR)
* BMSB-BMS BUDGET
* FBPM-FRACTION OF BMSB TO PREVENTIVE MAINTENANCE (DIM)

The state-dependent prioritization strategy applied in the PMS is also used to determine the allocation fractions of the BMS budget for each management activity. For example, the fraction of the BMS budget allocated to preventive maintenance is a proportion of the number of bridges in good condition over the total number of bridges, as provided in the following equations. Utilizing these equations, the fractions of the budget allocated to other maintenance activities can be obtained by replacing the nominator by the corresponding level variables.

```
A FBBC.K(H)=CLIP(0,BPFC.K(H)/(TNB.K(H)+TNFOB.K(H)),0,HCE.K(H))
NOTE FBBC-FRACTION OF BMS BUDGET TO CONSTRUCTION (DIM)
A FBPM.K(H)=BGC.K(H)/(TNB.K(H)+TNFOB.K(H))
NOTE FBPM-FRACTION OF BUDGET TO PREVENTIVE MAINT (DIM)
NOTE TNB-TOTAL NUMBER OF BRIDGES (BRDGS)
NOTE TNFOB-TOTAL NUMBER OF FUNC OBSOLESCENT BRDGS (BRDGS)
```

The aging time of bridges is calculated by estimating the Total Service life (TSL) of bridges. The TSL of bridges over the highway network varies with the types of bridges. For example, the service life of concrete-deck arch bridges is as high as 77 years, whereas that of timber stringer bridges drops down to 47 years [Klaiber, et al. 1987]. In the BMS, an average TSL needs to be calculated to compromise the diversity of the service life of bridges. In order to obtain the TSL averaged over the network, the following statistics from the National Bridge Inventory (NBI) as shown in Table 5.6, have been used. The NBI contains records for more than 575,000 highway bridges in the nation, following a coding guide from the FHWA [FHWA 1979].

Table 5.6 Statistics for the most common bridge types

Main Structure Type	Percentage of bridges (%)	Anticipated Retirements (yr)
Steel Stringer	27.2	57
Timber Stringer	12.0	47
Concrete Slab	8.8	64
Steel Through-Truss	6.5	73
Concrete Tee	5.6	67
Concrete Stringer	3.5	54
Steel-Girder Floor Beam	1.9	61
Concrete-Deck Arch	1.3	77

Source: Klaiber, et al. 1987

It should be noted that the TSL varies with bridges because of the many factors that affect the life of bridges. Service life can be extended by consistent and timely maintenance activities, and can be reduced by severe traffic loads. A study by Klaiber, et al. shows that extensive rehabilitation and replacement of bridges would extend their remaining service life [Klaiber, et al. 1987]. The following program calculates the TSL of bridges by adopting NBI statistics along with maintenance and traffic factors.

```
A TSL.K(H)=TSLN*(1+BRHB.K(H)/TNB.K(H))*(1+BRPL.K(H)/TNB.K(H))*TSLM.K(H)
NOTE TSL-TOTAL SERVICE LIFE OF BRIDGES (YRS)
NOTE TSLN-TOTAL SERVICE LIFE NORMAL (YRS)
A TSLM.K(H)=TABLE(TSLMT,DCRH.K(H),0,1.0,0.1)
T TSLMT=1/0.95/0.90/0.85/0.80/0.75/0.70/0.65/0.60/0.55/0.50
NOTE TSL-TOTAL SERVICE LIFE MULTIPLIER (DIM)
NOTE BRHB-BRIDGES REHABILITATED (BRIDGES)
NOTE BRPL-BRIDGES REPLACED (BRIDGES)
```

As the condition of a bridge worsens, the service life remaining to the bridge is shortened. In order to estimate the Remaining Service Life (RSL), the fractions of the RSL from the TSL are first defined for the five categories of bridges, and they are multiplied by the TSL to get the RSL of each level of bridge. Shown as an example, as follows, is the calculation of the RSL for bridges in poor condition.

```
A RSLBPC.K(H)=RTBPC*TSL.K(H)
NOTE RSLBPC-REMAINING SERVICE LIFE OF BPC (YRS)
NOTE RTBPC-REMAINING TO TOTAL SERVICE LIFE RATIO OF BPC (DIM)
```

The remaining service life of bridges calculated so far is utilized to estimate the aging time of bridges. For example, the Exposure Time of Bridges (ETB), which is the transition time from the BPFC to the BGC, can be obtained by subtracting the remaining service life of the BGC from the remaining service life of the BPFC. Then, the exposure rate of bridges is calculated by dividing the BPFC by the ETB. This example is shown in the following equation.

```
A ETB.K(H)=RSLBPFC.K(H)-RSLBGC.K(H)
NOTE ETB-EXPOSURE TIME OF BRIDGES (YRS)
R ERB.KL(H)=BPFC.K(H)/ETB.K(H)
NOTE ERB-EXPOSURE RATE OF BRIDGE (BRIDGES/YR)
* RSLBPFC-REMAINING SERVICE LIFE OF BPFC (YRS)
* RSLBGC- REMAINING SERVICE LIFE OF BGC (YRS)
```

The performance of the physical condition of bridges over the network is measured by a Physical Sufficiency Index for Bridges (PSIB). The following equation calculates the PSIB with weighting factors for the five levels of bridges.

```
A PSIB.K(H)=(BPFC.K(H)*WFBPFC+BGC.K(H)*WFBGC+BPC.K(H)*WFBPC+^
      BSC.K(H)*WFBSC+BCC.K(H)*WFBCC)/TNB.K(H)
NOTE PSIB-PHYSICAL SUFFICIENCY INDEX OF BRIDGES (DIM)
NOTE WFBPFC-WEIGHTING FACTOR FOR BPFC (DIM)
NOTE WFBGC-WEIGHTING FACTOR FOR BGC (DIM)
NOTE WFBPC-WEIGHTING FACTOR FOR BPC (DIM)
NOTE WFBSC-WEIGHTING FACTOR FOR BSC (DIM)
NOTE WFBCC-WEIGHTING FACTOR FOR BCC (DIM)
```

- **Functional Bridge Management Subsystem**

The functional conditions of bridges fall into the following hierarchical levels: Functionally Obsolescent Bridges in Preferred Condition (FOBPFC), Functionally Obsolescent Bridges in Good Condition (FOBGC), Functionally Obsolescent Bridges in Poor Condition (FOBPC), and Functionally Obsolescent Bridges in Serious Condition (FOBSC). In addition to these levels, the bridges in critical condition is regarded as functionally inadequate because of its worst physical condition.

The number of functionally obsolescent bridges increases in accordance with obsolete rates and decreases by widening rates, as shown in the following.

```
L FOBPFC.K(H)=FOBPFC.J(H)+(DT)(ORBPFC.JK(H)-WBPFC.JK(H))
NOTE FOBPFC-FUNCTIONALLY OBSOLESCENT BPFC (BRDGS)
L FOBGC.K(H)=FOBGC.J(H)+(DT)(ORBGC.JK(H)-WBGC.JK(H))
NOTE FOBGC-FUNCTIONALLY OBSOLESCENT BGC (BRDGS)
L FOBPC.K(H)=FOBPC.J(H)+(DT)(ORBPC.JK(H)-WBPC.JK(H))
NOTE FOBPC-FUNCTIONALLY OBSOLESCENT BPC (BRDGS)
L FOBSC.K(H)=FOBSC.J(H)+(DT)(ORBSC.JK(H)-WBSC.JK(H))
NOTE FOBSC-FUNCTIONALLY OBSOLESCENT BSC (BRDGS)
* ORBPFC-OBSOLESCENCE RATE OF BPFC (BRIDGES/YR)
* ORBGC-OBSOLESCENCE RATE OF BGC (BRIDGES/YR)
* ORBPC-OBSOLESCENCE RATE OF BPC (BRIDGES/YR)
* ORBSC-OBSOLESCENCE RATE OF BSC (BRIDGES/YR)
* WBPFC-WIDENING RATE OF BPFC (BRIDGES/YR)
* WBGC-WIDENING RATE OF BGC (BRIDGES/YR)
* WBPC-WIDENING RATE OF BPC (BRIDGES/YR)
* WBSC-WIDENING RATE OF BSC (BRIDGES/YR)
```

Those bridges in the Physical Bridge Management Subsystem whose traffic loads exceed specified volume/capacity ratios would be classified as functionally obsolescent. If the traffic load of a bridge is under the specified ratios, its obsolescence rate would be zero. The following shows an example of the estimation of the obsolescence rate for the BPFC.

```
R ORBPFC.KL(H)=(BPFC.K(H)*FOFBPFC.K(H))/OTBPFC
A FOFBPFC.K(H)=CLIP(0,1,MTBPFC(H),DCRH.K(H))
NOTE FOFBPFC-FUNC OBSOLESCENCE FACTOR FOR BPFC (DIM)
NOTE MTBPFC-MARGINAL TRAFFIC INTENSITY OF BPFC (DIM)
NOTE OTBPFC-OBSOLESCENCE TIME OF BPFC (YR)
```

Widening is an efficient remedy for bridges to manage an increasing volume of traffic. Widening rates are calculated as widening expenditures over widening costs. Widening expenditures are parts of the BMS budget, and each share for functionally obsolescent bridges is determined as the proportion of the corresponding condition of bridges over the total number of bridges. An example of the calculation of the fraction of the BMS budget to BPFC widening is provided as follows.

A FWBPFC.K(H)=FOBPFC.K(H)/(TNB.K(H)+TNFOB.K(H))
NOTE FWBPFC-FRACTION OF BMS BUDGET TO BPFC WIDENING (DIM)

Functional adequacy of bridges is measured using a functional obsolescence rate of bridges (FORB), which computes the proportion of the number of functionally obsolescent bridges over the total number of bridges. This part of the equation is provided as follows.

A FORB.K(H)=NFOB.K(H)/TNB.K(H)
NOTE FORB-FUNCTIONALLY OBSOLESCENT RATE OF BRIDGES (DIM)
A NFOB.K(H)=TNFOB.K(H)+BCC.K(H)
NOTE NFOB-NUMBER OF FUNCTIONALLY OBSOLESCENT BRIDGES (BRIDGES)

5.3.4 Travel Demand Subsystems

The investment in transportation infrastructures such as highways, mass transit, ports, and airports improves their serviceability and as a result, induces more traffic. In the area where a high growth rate of traffic exists, its volume/capacity ratio is most likely increasing. The following grounds can be seen as a cause for this tendency. The improvement of transportation infrastructure, or transportation capacity, is limited for many reasons: budget constraints, land availability, difficulty of land acquisition, laws and policies, and many others. This “rigid” nature of the infrastructure is often outgrown by the increasing traffic demand in many areas, which causes higher volume/capacity ratios over time.

On the other hand, the increasing volume of traffic would require more improved transportation infrastructure that is capable of managing the traffic demand. The decision as to the development of the infrastructure that satisfies the requirement must be made very prudently, and the improvement plan must be scientifically quantified so as not to waste the available budget. Adopted in a formula for travel time estimation, the volume/capacity ratio can be used to provide a basis for the quantification of and a perception about the performance of transportation facilities. Hence, the measurement or estimation of the volume/capacity ratio is an essential procedure for any type of transportation project.

The Travel Demand Subsystems consist of two parts: the Travel Demand Subsystem A and the Travel Demand Subsystem B. The Travel Demand Subsystem A predicts daily vehicle demand for general purpose trips, which include home-based shopping trips, home-based social and recreational trips, home-based other trips, and non-home based trips. Daily commuter and truck demands are estimated in the Travel Demand Subsystem B. In this model, the travel demands of other modes such as bus, motorcycle, and bicycle, are neglected because their portions of the total travel demand are very small. The following sections describe each of the subsystems in detail. Referring to the causal diagrams provided in Appendix would be helpful for clarification.

- **Travel Demand Subsystem A**

In transportation planning, traffic generation is estimated separately for each of a number of trip purposes, typically including work trips, shopping trips, school trips, and social or recreational trips. The reason that traffic generation is separated for each trip purpose is because the travel behavior of trip-makers depends on the trip purpose [Papacostas 1987]. In the model, the method of generating the daily traffic demand for general purpose trips is associated with trip-rate analysis on a household basis. In other words, trip generation rates for each trip purpose and household unit are applied to estimate daily trips. The selection of trip generation rates should be carefully made, because they determine the amount of traffic volume utilized for the rest of the forecasting processes. Using improper rates will mislead analysts as to the interpretation of results. Trip generation rates applied in this model were obtained from research conducted by the Federal Highway Administration [FHWA 1994]. The research is based on data from the 1990 Nationwide Personal Transportation Survey (NPTS), and contains various characteristics of urban travel patterns, including trip generation rates. The rates provided in Table 5.7 are the results of the survey and are used for estimating daily trips. The subsequent equation calculates the daily home-based shopping trips.

Table 5.7 Daily Trip Rates per Household by Trip Purpose

Trip Purpose	Trip Rate (trips/household-day)
Home-based Shopping	0.76
Home-based Social and Recreational	0.98
Home-based Other	1.84
Non-home-based	1.52
All	5.10

Source: FHWA 1994

```
A  DHST.K=HV.K*HSTR
NOTE  DHST-DAILY HOME-BASED SHOPPING TRIPS (TRIPS/DAY)
NOTE  HSTR-HOME-BASED SHOPPING TRIP RATE (TRIPS/HH-DAY)
* HV-HOUSEHOLDS IN VIRGINIA (HOUSEHOLDS)
```

The daily trips obtained are utilized to calculate the person-demand, i.e. the number of person trips per day. The conversion to person-demand can be made by adopting daily trip rates per person. According to a survey, daily trips per person using privately owned vehicles are 3.26 trips [FHWA 1994]. Based on this rate, daily trips per person for the four trip purposes were calculated by applying each proportion of trip rates per household.

Table 5.8 contains the daily trip rates. Daily person-demand for each of the trip purposes can be estimated by dividing daily trips by daily trip rates per person. The following equations compute daily person demand for home-based shopping trips.

A DHSPD.K=DHST.K/DHSTP
NOTE DHSPD-DAILY H.B. SHOPPING PERSON DEMAND (PERSONS/DAY)
NOTE DHSTP-DAILY H.B. SHOPPING TRIPS PER PERSON (TRIPS/PERSON)

Table 5.8 Daily Trip Rates per Person by Trip Purpose

Trip Purpose	Trip Rate (trips/household-day)
Home-based Shopping	0.49
Home-based Social and Recreational	0.63
Home-based Other	1.18
Non-home-based	0.97
All	3.27

Source: FHWA 1994

Highway traffic should be expressed in terms of vehicles, and thus the daily person-demand calculated so far needs to be converted into vehicle units. This conversion can be made by dividing the daily person-demand by the average vehicle occupancy. As for the trip rates per household or person, the average vehicle occupancy is different for each of the trip purposes. Usually, work-related trips have a low occupancy, whereas social and recreational trips have a higher occupancy. Details of the average occupancy by trip purpose are provided in Table 5.9. In the model, average vehicle occupancies were regrouped and averaged for the four trip purposes based on the data in Table 5.9. The following equation calculates daily vehicle demand for home-based shopping trips.

A DHSVD.K=DHSPD.K/AVOHS
NOTE DHSVD-DAILY H.B. SHOPPING VEHICLE DEMAND (VEHS/DAY)
NOTE AVOHS-AVERAGE VEHICLE OCCUPANCY FOR H.B.S. TRIP (PERSONS/VEH)

The total vehicle demand for general purpose trips is obtained by adding together the demands for the four trip categories. It should be noted that this total demand is applied to all levels of highways, including interstate, primary, urban, and secondary highways. Thus, the final demand should be distributed to each category of the highways.

Table 5.9 Average Vehicle Occupancy by Trip Purpose

Trip Purpose	Average Occupancy
Earning a Living	
To or From Work	1.12
Work-Related Business	1.32
Family and Personal Business	
Shopping	1.51
Other Family/Personal Business	1.65
Civic/Educational/Religious	1.76
Social and Recreational	
Vacation/Pleasure Driving	2.22
Visit Friends/Relatives	1.59
Other Social/Recreational	1.93
Other	1.55
All	1.51

Source: FHWA 1994

```
A  DVDGP.K=DHSVD.K+DHSRVD.K+DHOVD.K+DNHVD.K
NOTE  DVDGP-DAILY VEHICLE DEMAND FOR GENERAL PURPOSE (VEHS/DAY)
NOTE  DHSRVD-DAILY H.B. SOCIAL AND RECRE. VEHICLE DEMAND (VEHS/DAY)
NOTE  DHOVD-DAILY H.B. OTHER VEHICLE DEMAND (VEHS/DAY)
NOTE  DNHVD-DAILY N.H.B. VEHICLE DEMAND (VEHS/DAY)
A  DVDGPH.K(H)=DVDGP.K*(HMSGP(H)+TTPH(H))*HAM.K
NOTE  DVDGPH-DAILY VEHICLE DEMAND FOR G.P. OF HIGHWAY (VEHS/DAY)
NOTE  HMSGP-HIGHWAY MODAL SPLIT FOR G.P. TRIP (DIM)
NOTE  TTPH-THRU TRAFFIC PORTION ON A HIGHWAY (DIM)
NOTE  HAM-HIGHWAY ATTRACTION MULTIPLIER (DIM)
```

The calculation of the daily travel distance for each type of trip is a prerequisite for computing vehicle miles of travel for general purpose trips. It can be estimated by multiplying the number of daily trips by average trip length. The average trip length surveyed by the FHWA shows various trip lengths for different trip purposes, as shown in Table 5.10.

Table 5.10 Average Trip Length by Trip Purpose

Trip Purpose	Average Trip Length*
Earning a Living	
To or From Work	10.14
Work-Related Business	9.25
Family and Personal Business	
Shopping	5.10
Other Family/Personal Business	6.50
Civic/Educational/Religious	4.95
Social and Recreational	
Vacation/Pleasure Driving	19.77
Visit Friends/Relatives	8.26
Other Social/Recreational	8.00
Other	6.70
All	1.51

* in unit of miles per trip
Source: FHWA 1994

The estimation of daily travel distance is based on the use of unit values in Table 5.10, with an adoption of the annual growth rate. The following equations show the computation of daily travel distance for home-based shopping trips.

```
A  DTDHS.K=DHST.K*ATLHS.K
NOTE  DTDHS-DAILY TRAVEL DISTANCE FOR H.B.S. TRIP (MILES/DAY)
A  ATLHS.K=ATLHSN*(1+0.002833)**TIME.K
NOTE  ATLHS-AVERAGE TRIP LENGTH FOR H.B.S. TRIP (MILES/TRIP)
NOTE  ATLHSN-ATLHS NORMAL (MILES/TRIP)
```

The average distance traveled per vehicle per day can be simply calculated from daily travel distance divided by daily vehicle demand. Then, vehicle miles of travel on highways are obtained by multiplying the average travel distance by the daily vehicle demand on the highways.

```
A  DTDGP.K=DTDHS.K+DTDHSR.K+DTDHO.K+DTDNH.K
NOTE  DTDGP-DAILY TRAVEL DISTANCE FOR GEN. PURPOSE (MILES/DAY)
NOTE  DTDHSR-DAILY TRAVEL DISTANCE FOR H.B.S.R. TRIP (MILES/DAY)
NOTE  DTDHO-DAILY TRAVEL DISTANCE FOR H.B.O. TRIP (MILES/DAY)
NOTE  DTDNH-DAILY TRAVEL DISTANCE FOR N.H.B. TRIP (MILES/DAY)
A  ATDGP.K=DTDGP.K/DVDGP.K
NOTE  ATDGP-AVERAGE TRAVEL DISTANCE FOR GEN. PUR. TRIP (MI)
A  VMGPH.K(H)=DVDGPH.K(H)*ATDGP.K
NOTE  VMGPH-VEH MILES PER DAY FOR G.P. TRIP ON A HIGHWAY (VEH-MI/DAY)
```

- **Travel Demand Subsystem B**

In addition to demand generated for general purpose trips, commuter and truck demands constitute other major components of travel demand. Commuter demand cannot be neglected in transportation planning. Commuter demand affects the volume and flow of a highway network on a regular basis. In particular, in the morning and evening peak periods in urban areas, its contribution to traffic congestion is significant. Various efforts to reduce the impact of commuter demand are being considered, e.g. travel demand management such as variable work hours, restrictions in parking at the work place, congestion fees, carpools, and so on. Another factor impacting network traffic is truck demand. Trucking is a major mode of freight movement, and its portion of all traffic continues to increase because of industrialization. Also, due to its heavy and slow characteristics, it negatively affects the movement of other traffic, and results in an inefficient flow in the whole network.

Both commuter and truck demands are derived in accordance with the development of the regional economy. A new industry or the expansion of existing industries create new employment, and thus, many job opportunities. As a result, new industries or the expansion of existing industries produce more work-related traffic, including commuter traffic, around the region. Furthermore, as the regional economy is developed, the productivity of industries also increases, and generates a large amount of freight for transportation to other regions. Therefore, the regional economy is a major source of traffic generation.

The number of persons commuting during peak periods can be derived by considering the total amount of employment in a region. The total amount of employment in Virginia is estimated as an output of the Regional Economy Subsystem. Now, the subsystem is related to Travel Demand Subsystem B in order to figure the number of commuters per period. As not every employee reports to his/her workplace every day because of illness, vacation, accidents, family matters, and other reasons, a Workplace Report Rate (WRR), the portion of workers actually reporting in a day among the total number of employees, is applied to estimate the number of commuters per period. Having obtained the number of commuters, they should be assigned to their chosen mode of transportation. Commuters have several options, including driving alone, using carpools, using mass transit, walking, or using other modes of transportation. Statistics show that a dominant number of commuters use their private cars to commute.

In the model, transportation modes for commuters are categorized as three types, which are: driving alone, carpools, and other modes. Based on the statistics and under the assumption that the dominant trend of using private cars will persist in the future, the fractions of commuters driving alone, using carpools, and using other modes were assumed as 0.7, 0.2, and 0.1, respectively. Using these fractions, the number of commuters in each mode is calculated, as shown in the following equations.

```
A  C.K=E.K*WRR
NOTE  C-COMMUTERS (PERSONS/PERIOD)
NOTE  WRR-WORKPLACE REPORT RATE (DIM)
```

```
A  CDA.K=C.K*FCDA
NOTE  CDA-COMMUTERS DRIVING ALONE (PERSONS/PERIOD)
NOTE  FCDA-FRACTION OF COMMUTERS DRIVING ALONE (DIM)
A  CMCP.K=C.K*FCCP
NOTE  CCP-COMMUTERS IN CARPOOL (PERSONS/PERIOD)
NOTE  FCCP-FRACTION OF COMMUTERS IN CARPOOL (DIM)
A  COM.K=C.K-(CDA.K+CMCP.K)
NOTE  COM-COMMUTERS USING OTHER MODES (PERSONS/PERIOD)
```

The following equation calculates vehicular demand for commuting per period. Then, daily commuter demand is obtained by multiplying commuter demand per period by the number of commuting periods, i.e., morning and evening peak periods.

```
A  DACD.K=CDA.K/AVODA
NOTE  AVODA-AVERAGE VEHICLE OCCUPANCY FOR D.A. TRAFFIC (PERSONS/VEH)
A  CPCD.K=CMCP.K/AVOCP
NOTE  CPCD-CARPOOL COMMUTER DEMAND (VEHS/PERIOD)
N  AVOCP=(1.22*(FCDA+FCCP)-FCDA*AVODA)/FCCP
NOTE  AVOCP-AVERAGE VEHICLE OCCUPANCY IN CARPOOL (PERSONS/VEH)
A  CVDP.K=DACD.K+CPCD.K
NOTE  CVDP-COMMUTER VEHICLE DEMAND PER PERIOD (VEHS/PERIOD)
A  DCVD.K=CVDP.K*NCP
NOTE  DCVD-DAILY COMMUTER VEHICLE DEMAND (VEHS/DAY)
NOTE  NCP-NUMBER OF COMMUTING PERIOD (PERIODS/DAY)
```

The daily vehicle miles for commuting are calculated as a product of the daily commuter vehicle demand and the average travel distance for commuting. The average travel distance for commuting trips tends to increase over time. Research shows that average travel distance has increased at an annual growth rate of 3.31 percent over the period from 1983 through 1990 [FHWA 1994]. The following program reflects this tendency, along with the calculations of commuter vehicle-miles.

A VMCH.K(H)=DCVDH.K(H)*ATDC.K
NOTE VMCH-VEHICLE MILES FOR COMMUTING ON A HIGHWAY (VEH-MI/DAY)
A ATDC.K=ATDCN*(1+ATDGR)**TIME.K
NOTE ATDC-AVERAGE TRAVEL DISTANCE FOR COMMUTING (MI)
NOTE ATDCN-AVERAGE TRAVEL DISTANCE FOR COMMUTING NORMAL (MI)
NOTE ATDGR-AVERAGE TRAVEL DISTANCE GROWTH RATE (DIM)
* DCVDH-DAILY COMMUTER VEHICLE DEMAND OF HIGHWAY (VEHS/DAY)

Similarly to the demand generation process for commuter traffic, the regional economy produces a significant amount of freight and, thus, truck traffic. On rural interstate routes in 1990, truck volume, including heavy single unit trucks, 3- and 4-axle combination trucks, and 5-axle or more combination trucks, accounted for 22 percent of the average daily traffic volumes [FHWA 1992]. However, because this statistic did not include the volume of light trucks, the portion of all types of trucks over the whole traffic on the interstate would be much greater once light trucks are included.

The number of trucks generated from industries relies on the amount of output produced by industries. In other words, the more the industrial output, the more truck traffic would be generated. One of the ways to estimate the number of trucks used to transport outputs is to consider the unit capacity of a truck in terms of dollars. The truck capacity would vary depending on the output or freight characteristics, such as weight, volume, or price, etc. However, itemizing the vast amount of freight would require an extensive and time-consuming investigation, and that itemization goes beyond the scope of this research. For simplification, in the model, a truck is assumed to carry an industrial output worth 200,000 dollars, on average. This unit capacity, then, divides the total industrial output produced by regional economic activities, and derives the total number of trucks used to transport the outputs.

One of the important steps in the transportation planning or demand forecasting processes is to estimate the origin and destination of traffic. Origin refers to the place from which a travel unit is generated, and the destination is the place where the journey of the unit is terminated. As is the case with any other traffic, a truck also follows an origin/destination pattern. Most likely, industries that make products would be the origins of the truck traffic, and the destinations of those products would be final sites of the journey. However, after unloading products at the destination site, a truck could operate empty on its way back to the origin site or to other destinations, unless it is loaded with new freight. From this viewpoint, it can be seen that there is the possibility that not every truck would carry freight. Thus, an inefficient rotation of freight transportation causes a number of empty trucks on highways, and those numbers should be addressed in the demand forecasting processes. In the model, due to the difficulty of obtaining data about empty trucks, it is assumed that 10 percent of trucks generated from industries would operate empty in the course of their journeys. The following program calculates the annual number of trucks and the daily number of trucks, by taking into account the above considerations.

```
A  ATIO.K=SIO.K*TIO
NOTE  ATIO-ANNUAL TRUCKS FROM INDUSTRIAL OUTPUT (TRUCKS/YR)
NOTE  TIO-TRUCKS PER INDUSTRIAL OUTPUT (TRUCKS/$)
A  AET.K=ATIO.K*ETF
NOTE  AET-ANNUAL EMPTY TRUCKS (TRUCKS/YR)
NOTE  ETF-EMPTY TRUCK FACTOR
A  AT.K=ATIO.K+AET.K
NOTE  AT-ANNUAL TRUCKS (TRUCKS/YR)
A  DTR.K=AT.K/CFDT
NOTE  DTR-DAILY TRUCKS (TRUCKS/DAY)
NOTE  CFDT-CONVERSION FACTOR TO DAILY TRUCKS (DIM)
* SIO-SUM OF INDUSTRIAL OUTPUTS ($)
```

Because of differences in the size and performance of trucks compared to other modes of transportation, a passenger car equivalent factor is applied to obtain an equal unit of vehicles. Then, the truck demand in units of vehicles per day is assigned to each of the highway categories, along with the addition of through-traffic volumes. Finally, vehicle miles of trucks on the highways are calculated from the daily truck demand multiplied by the average travel distance of a truck. National statistics about average miles traveled per truck show that no steady growth patterns have been found over past years from 1980 to 1995 [FHWA 1960-1980 & 1985-1995]. According to the statistics, the annual travel distance of a truck was 16,863 miles, on average, during the period between 1980 and 1995. The model uses this average travel distance for the estimation of vehicle miles of trucks.

```
A  DTD.K=DTR.K*PCET
NOTE  DTD-DAILY TRUCK DEMAND (VEHS/DAY)
NOTE  PCET-PASSENGER CAR EQUIVALENTS FOR TRUCK (VEHS/TRUCK)
A  DTDH.K(H)=DTD.K*(HMST(H)+TTTPH(H))
NOTE  DTDH-DAILY TRUCK DEMAND ON HIGHWAY (VEHS/DAY)
NOTE  IMST-INTERSTATE MODAL SPLIT FOR TRUCK (DIM)
NOTE  TTTPH-TRUCK THRU TRAFFIC PORTION ON HIGHWAY (DIM)
A  VMTH.K(H)=DTDH.K(H)*ATDT
NOTE  VMTH-VEHICLE MILES FOR TRUCK ON HIGHWAY (VEH-MI/DAY)
NOTE  ATDT-AVERAGE TRAVEL DISTANCE FOR TRUCK (MI)
```

5.3.5 Transportation Subsystem

The Transportation Subsystem contains routines to calculate a demand capacity ratio of the whole network based on the outputs from the Travel Demand Subsystems A and B. The objective of the Transportation Subsystem is to estimate the average travel time of highway traffic. First, the volume of the average annual daily traffic (AADT) is calculated from the total vehicle miles of travel on the highway. Then, the demand capacity ratio of the highway is estimated, along with the highway capacity. Finally, the average travel time of traffic is calculated using a formulation for travel time estimation. The following sections describe details of the process.

In the model, vehicle miles on highways have been calculated as a product of the daily traffic generation and the average travel distance. Another form of the equation used to obtain vehicle miles can be written as [VDOT 1980-1995]:

$$\text{Vehicle Miles} = \text{AADT} \times \text{Highway Segment Length}. \qquad (5.1)$$

The AADT can be defined as the "*average 24-hour traffic volume at a given location over a full 365-day year* [McShane and Roess 1990]." In order to know the AADT for a highway, the total vehicle miles should first be determined. The total vehicle miles of traffic on a highway are the sum of three types of vehicle miles, i.e. the vehicle miles of general purpose trips, of commuting, and of trucks. Having obtained the total vehicle miles, the AADT can then be calculated using the above Equation (5.1). The following program explains this part of the model.

```
A  TVMH.K(H)=VMGPH.K(H)+VMCH.K(H)+VMTH.K(H)
NOTE  TVMH-TOTAL VEHICLE MILES ON HIGHWAY (VEH-MI/DAY)
A  AADTH.K(H)=TVMH.K(H)/MH.K(H)
NOTE  AADTH-ANNUAL AVERAGE DAILY TRAFFIC OF HIGHWAY (VEHS/DAY)
NOTE  MH-MILEAGE OF HIGHWAY (MI)
NOTE VMGPH-VEHICLE MILES OF GENERAL-PURPOSE TRIPS
NOTE VMCH-VEHICLE MILES OF COMMUTING
NOTE VMTH-VEHICLE MILES OF TRUCKS
```

In calculating a demand capacity ratio, the numerator of the ratio needs to be expressed as the hourly volume, because the capacity of a highway is expressed in a vehicles per hour unit. Daily traffic volumes vary during the course of a 24-hour day, usually with periods of maximum volume occurring during the morning and evening peak hours. Usually, the peak-hour volume is used for transportation planning, highway design, and many types of traffic operational analysis because any transportation infrastructure must be designed to serve adequately the peak-hour traffic volume. In order to calculate the peak-hour volume, the following equation can be used [McShane and Roess 1990]:

$$DDHV = AADT \times K \times D \quad (5.2)$$

where, DDHV = directional design hour volume,

K = the proportion of daily traffic occurring during the peak hour, and

D = the proportion of peak-hour traffic traveling in the peak direction.

General ranges for K and D factors in terms of facility types are given in Table 5.11.

Table 5.11 General Ranges for K and D factors

Facility type	K factor	D factor
Rural	0.15-0.25	0.65-0.80
Suburban	0.12-0.15	0.55-0.65
Urban	0.07-0.12	0.50-0.55

Source: McShane and Roess 1990

The K factors applied in the model are assumed based on the general ranges provided in this Table. The effect of the D factor is neglected in the model because the model adopts macroscopic and comprehensive views of the whole highway system and is not confined to traffic operations on a local scale. The following explains the computation of the design hour volume along with average annual volume on highway.

```
A  DHVH.K(H)=AADTH.K(H)*KF(H)
NOTE  DHVH-DESIGN HOUR VOLUME ON HIGHWAY (VEHS/HR)
NOTE  KF-K FACTOR (DIM)
A  AATH.K(H)=AADTH.K(H)*360
NOTE AATH-AVERAGE ANNUAL TRAFFIC ON HIGHWAY (VEHS/YR)
```

The capacity of a highway is obtained by multiplying the average number of lanes of the highway by the lane capacity. The average number of lanes is calculated from the total lane miles divided by highway length or mileage. The demand capacity ratio is expressed as the design hour volume over highway capacity. It should be noted that the ratio represents the functional performance of transportation facilities.

```
A  ANLH.K(H)=TLMH.K(H)/MH.K(H)
NOTE  ANLH-AVERAGE NUMBER OF LANES OF HIGHWAY (LANES)
A  CAPH.K(H)=ANLH.K(H)*LCH(H)
NOTE  CAPH-CAPACITY OF HIGHWAY (VEHS/HR)
NOTE  LCH-LANE CAPACITY OF HIGHWAY (VEHS/HR-LANE)
A  DCRH.K(H)=DHVH.K(H)/CAPH.K(H)
NOTE DCRH-DEMAND CAPACITY RATIO OF HIGHWAY (DIM)
```

Travel time along a certain link is affected by various types of link impedance, which are also influenced by the amount of traffic using the transportation infrastructures. The modeling of link transportation impedance attempts to include this relationship. Although travel times along the same route are often highly variable, even for similar road traffic conditions, the model assumes an overall average traffic flow-dependent function.

The non-linear relationship between traffic flow-dependent travel times and transportation facilities has been studied extensively, but the following are the most likely to be encountered in transportation studies. The first, proposed by Davidson [Davidson 1966] is as follows:

$$T_q = T_0 \frac{1-(1-j)q/Q}{1-q/Q} \qquad (5.3)$$

where, T_q = travel time at traffic volume q,

T_0 = free-flow or zero-flow travel time,

j = level of service parameter,

q = traffic volume, and

Q = saturation traffic volume.

The level of the service parameter is related to the type of road, road surface conditions, road widths, the frequency of traffic signals and pedestrian crossings and parked vehicles. In the absence of authentic data, Blunden [Blunden 1971] suggests a range of j values for various types of highways. A method for the estimation of free-flow travel times and saturation flows is described by Taylor [Taylor 1977].

The estimation of travel time on highways using the flow-dependent formulation (5.3) requires two conceptual inputs, traffic demand and transportation supply. One of the inputs is the demand capacity ratio calculated in the previous steps. The other input for the equation is the level of the service parameter. The level of the service parameter explains the current status of transportation infrastructure conditions. The values of the parameter range from zero, the ideal condition, close to one, the worst condition. In the model, the parameter is estimated based on the pavement and bridge conditions of highways.

5.3.6 Regional Economy Subsystem

Economic activities in a region are directly related not only to the welfare of the region, but also to the financial base for transportation systems. In order to maintain transportation systems in an acceptable condition, a certain level of investment is required. The investment in the system is provided by transportation revenue, and thus is limited in amount within the revenue. Hence, the amount of transportation revenue eventually determines the capability of a region in managing transportation infrastructures.

Economic activities can be represented by the industrial productivity of a region. If the industrial productivity increases, more revenue is generated. An increase in the revenue of a region would also cause an increase in transportation revenue. An increase in transportation revenue leads to improvements in the condition of the transportation infrastructure. This series of relationships among the regional economy, transportation revenue, and the transportation infrastructure should be examined in any civil infrastructure model that deals with management and planning issues.

The regional economy also functions as a crucial sector for a demand-side approach to the transportation planning process. Industrial activities within a regional economy system create a significant number of induced traffic demands. These demands include two types of major travel demands: a freight demand and a commuter demand. The commodity flows caused by mass production and work trips in the morning and the evening peak periods produce serious traffic impacts in industrial regions. Hence, on the transportation demand side, the quantification of output produced by the regional economy should be identified and analyzed in modeling.

The objective of the Regional Economy Subsystem is to estimate the Gross State Product and the number of employees in Virginia. The GSP estimates provide a basis for calculating the freight demand, and the number of employees is used to estimate the commuter demand. The estimations of both demands are explained the Travel Demand Subsystem B. The size of the GSP also affects the generation processes of the transportation revenue in the Finance Subsystem. The framework of the model of this subsystem is described in the following sections.

The modeling of the regional economy begins with the perception of a capital formation process in each industrial sector. Industrial capital refers to the monetary value of the total means of industrial activities, which include the buildings and equipment. It increases with annual investments of capital, and decreases with the depreciation of capital. Following the analysis method selected for this model, industrial capital should be estimated for each industry. The U.S. Department of Commerce's Bureau of Economic Analysis (BEA) prepares gross product estimates for 61 industries which fall within 10 sectors, as shown in Table 5.12.

The following DYNAMO equations provide a capital formation process as described above.

```
L  IC.K(S)=IC.J(S)+(DT)(CI.JK(S)-CD.JK(S))
NOTE  IC-INDUSTRIAL CAPITAL ($)
NOTE  CI-CAPITAL INVESTMENT ($/YR)
NOTE  CD-CAPITAL DEPRECIATION ($/YR)
NOTE  S-GSP SECTORS
```

Table 5.12 Industries in GSP sectors

Industrial Sector	Number of Industries
1. Agriculture, forestry, and fisheries	2
2. Mining	4
3. Construction	1
4. Manufacturing	21
5. Transportation and public utilities	9
6. Wholesale trade	1
7. Retail trade	1
8. Finance, insurance, and real estate	6
9. Services	13
10. Government	3
Total	61

Source: Bureau of Economic Analysis, U.S. DoC

The value of capital declines over the time of use. The rate of capital depreciation can be calculated from industrial capital divided by the average lifetime of the capital, as shown in the following equations.

R CD.KL(S)=IC.K(S)/ALC.K(S)
NOTE CD-CAPITAL DEPRECIATION ($/YR)
A ALC.K(S)=ALCN*ALCM.K(S)
NOTE ALC-AVERAGE LIFETIME OF CAPITAL (YR)
NOTE ALCN-AVERAGE LIFETIME OF CAPITAL NORMAL (YR)
A ALCM.K(S)=ICN(S)/IC.K(S)
NOTE ALCM-AVERAGE LIFETIME OF CAPITAL MULTIPLIER (YR)

The industrial output is a result of industrial activities using industrial capital. It increases with an increase in industrial capital, and decreases with an increase in the capital-output ratio. The capital-output ratio indicates the amount of capital required to produce a unit output. A different capital-output ratio is assumed for each industry because the characteristics of an industry determine a ratio that is different from those of other companies.

A IO.K(S)=IC.K(S)/COR(S)
NOTE IO-INDUSTRIAL OUTPUT ($/YR)
NOTE COR-CAPITAL OUTPUT RATIO (YR)

The product of each sector refers to industrial output with a productivity factor. The productivity factor ranges from zero, zero productivity, to one, perfect productivity. In reality, the factor cannot reach one because some friction factors are involved and obstruct perfect operation. In the model, a fraction of industrial output to input and a transportation friction indicator are assumed to be major factors that affect productivity. The fraction of industrial output to input is interpreted as the amount of input required to produce a unit of output. The bigger values of the fraction unfavorably affect the productivity of an industry. The transportation friction indicator is obtained from the physical sufficiency index from the Pavement Management Subsystem. The higher the values of the index, the lower the transportation friction indicator. In other words, highways' good pavement condition insures efficient transportation activity with minimal obstruction. Both the fraction and the indicator decrease productivity from a point of one. The equation for this part of the model is presented in the following.

```
A  PS.K(S)=IO.K(S)*PDT.K
NOTE  PS-PRODUCT BY EACH SECTOR ($/YR)
A  PDT.K=1-FIOI*TFIH.K
NOTE  PDT-PRODUCTIVITY (DIM)
NOTE  FIOI-FRACTION OF IO TO INPUTS (DIM)
NOTE  TFIH-TRANSPORT FRICTION INDICATOR (DIM)
```

The amount of capital investment depends on the amount of production and the acquisition of profits from production. A portion of the profit produced should be reinvested in capital so as to maintain or improve the current economic activities in an industry. The following equations describe the investment formations.

```
R  CI.KL(S)=PS.K(S)*FPSCI(S)
NOTE  CI-CAPITAL INVESTMENT ($/YR)
NOTE  FPSCI-FRACTION OF PS TO CI (DIM)
```

The GSP is the market value of the goods and services produced by labor and property located in a state [Cutts and Knapp 1992]. Broadly speaking, the methods of estimating gross product can be summarized in two categories. First, gross product can be measured as the sum of expenditures, including consumer spending, investment, net exports, and government purchases. Second, it can be measured as the sum of the "value added" in each industry. The term of "value" refers to the subtraction of the value of intermediate input from gross output. In theory, the method used should not affect the result. The way that the GSP is measured in this model follows the second method, i.e. GSP by the industrial sector, for the following reason. A disadvantage in using the first method is that it does not address nor differentiate the characteristics of each industry because the gross product is estimated not by the net product of each industry, but by the total value of a state. As indicated in the following equation, the gross state product is expressed as a sum of the products created by the ten industrial sectors in Table 5.12.

```
A  GSP.K=SUMV(PS.K(*),1,10)
NOTE  GSP-GROSS STATE PRODUCT ($/YR)
```

The number of employees in industries is determined by the scale and characteristics of the industries. The scale of an industry can be measured by the amount of products it creates, and the characteristics of an industry can be addressed by modeling in terms of ten industrial sectors. In the model, the product of each sector performs as a representative term in the scale, and product labor ratios are applied to explain the characteristics of the industries. The product labor ratio expresses total monetary values of products created by a worker in a year. In most cases, the ratio increases over time because of an efficient operation of capital and technological progress. Also, the ratio is affected positively by labor productivity, which provides different magnitudes over the ten sectors. An increase in the product/labor ratio results in a decrease in the number of employees, as shown in the following equations. It should be noted, however, that past data prove an increasing trend in employment in Virginia. This trend can be verified by observing the following causal chains: The development of the regional economy resulted in an improved production rate. In turn, mass production caused the existing industry to expand. Finally, the expansion of the industry created more opportunities for employment over the state. This causal link can also be examined by observing the following equations.

```
A  ES.K(S)=(PS.K(S)/PLR.K(S))
NOTE  ES-EMPLOYMENT IN EACH SECTOR (WORKERS)
A  PLR.K(S)=PLRN(S)*(1+LP(S))**TIME.K
NOTE  PLR-PRODUCT LABOR RATIO (($/YR)/WORKER)
NOTE  PLRN-PRODUCT LABOR RATIO NORMAL (($/YR)/WORKER)
NOTE  LP-LABOR PRODUCTIVITY (DIM)
A  E.K=SUMV(ES.K(*),1,10)
NOTE  E-EMPLOYMENT (WORKERS)
```

5.3.7 Functional Subsystem

The Functional Subsystem provides various cost items for the Pavement Management Subsystem and the Bridge Management Subsystem. For the PMS, maintenance costs for deficient highways, maintenance costs for deteriorated highways, and construction costs are estimated. For the BMS, the unit costs for the following management activities are calculated: preventive maintenance costs, repair costs, rehabilitation costs, replacement costs, widening costs, and construction costs.

In order to estimate maintenance, repair, and rehabilitation (MR&R) costs of bridges, detailed tasks for each category of maintenance activities are identified, and unit costs for the tasks are surveyed. The identification of the maintenance tasks and the unit costs is based on previous research on the highway management system for the Virginia Department of Transportation [de la Garza, et al. 1996]. Table 5.13 specifies the unit cost items for the management tasks that are surveyed and considered in the TPMSHM.

The management costs are estimated by using the same format of equations as shown in the following example of preventive maintenance costs for bridges. The costs for the MR&R activities for bridges are obtained by averaging the unit costs of maintenance tasks. The unit costs increase with an expansion of the corresponding facilities, i.e. pavement sections and bridges, and this relationship is reflected by adopting cost multipliers, PMCBM for the following example. Also, the effect of inflation is considered in calculating future costs.

```
N PMCBN(H)=(CEJM(H)+CPGM(H)+CSC(H)+CSDC(H)+CSP(H))/5
NOTE PMCBN-PREVENTIVE MAINTENANCE COST FOR BRIDGE NORMAL ($/BRDG)
NOTE CEJM-COST OF EXPANSION JOINT MAINTENANCE ($/BRDG)
NOTE CPGM-COST OF PARAPET GUARD RAIL MAINTENANCE ($/BRDG)
NOTE CSC-COST OF SCOUR ($/BRDG)
NOTE CSDC-COST OF SEALING DECK/CRACK ($/BRDG)
NOTE CSP-COST OF SPOT PAINTING ($/BRDG)
A PMCB.K(H)=PMCBN(H)*PMCBM.K(H)*(1+INFL*DT)**TIME.K
```

NOTE PMCB-PREVENTIVE MAINTENANCE COST FOR BRIDGE ($/BRDG)
NOTE PMCBM-PREVENTIVE MAINT COST FOR BRIDGE MULTIPLIER (DIM)
NOTE INFL-INFLATION FACTOR (DIM)

Table 5.13 Unit Cost Items for the Highway Management Tasks

<table>
<tr><th>Subsystem</th><th colspan="2">Unit Cost Items</th></tr>
<tr><td>PMS</td><td colspan="2">• Maintenance Costs For Deficient Highway
• Maintenance Costs For Deteriorated Highway
• Construction Costs</td></tr>
<tr><td rowspan="6">BMS</td><td>• Preventive Maintenance Costs</td><td>Expansion Joint Maintenance
Parapet Guard Rail Maint
Scour
Sealing Deck/Crack
Spot Painting</td></tr>
<tr><td>• Repair Costs</td><td>Structural Steel Second Member Replace & Repair
Repainting
Patching
Expansion Joint Replacement
Drainage System Replacement & Repair
Deck Overlay
Deck Edge Repair
Cathodic Protection
Concrete Diaphragm Repair
Bearing & Anchor Bolt Replacement
Concrete Beam End Repair
Deck Replacement
Superstructure Replacement</td></tr>
<tr><td>• Rehabilitation Costs</td><td>Repair Of Collision Damage
Repair Of Abutment
Replacement Of Abutment
Repair Of Pier
Replacement Of Pier</td></tr>
<tr><td colspan="2">• Replacement Costs</td></tr>
<tr><td colspan="2">• Widening Costs</td></tr>
<tr><td colspan="2">• Construction Costs</td></tr>
</table>

5.3.8 Finance Subsystem

The physical condition of the transportation infrastructure is determined by many factors, which include the level of management, policy, traffic load, traffic characteristics, weather, and socioeconomic impact, etc. Managing an appropriate level of highway condition can be viewed as a counteraction responding to a natural or forced deterioration process caused by these factors. The magnitude of the counteraction is inevitably confined for many reasons: the available work-force, the environmental or local traffic impact, and the available highway budget, etc. Of these, the highway budget would be a major deciding factor for decision-makers to implement highway management programs. Any infrastructure management or improvement plans would not be possible to carry out without minimal investment in those plans. Hence, the transportation budgeting process should be the first consideration for management programs. In the model, the Finance Subsystem comprises a generation process of transportation revenue and a budget allocation process in the state.

- **State Revenue Generation**

State revenue is collected to form the two types of fund groups, the Highway Maintenance and Operating Fund (HMOF) and the Transportation Trust Fund (TTF) [Miller 1995]. Major revenue sources for the HMOF can derive from various types of vehicle user fees, such as motor vehicle fuels tax, motor vehicle sales and use tax, motor vehicle licenses fees, and other miscellaneous fees and tolls. Another significant portion of the HMOF comes from federal aid. The following equation explains the revenue sources for the HMOF.

```
A  HMOF.K=RMFTH.K+RMLFH.K+RMSUTH.K+FR.K+MRH.K
NOTE RMFTH-REVENUE FROM MOTOR VEH FUELS TAX FOR HMOF ($)
NOTE RMLFH-REVENUE FROM MOTOR VEH LICENSE FEES FOR HMOF ($)
```

NOTE RMSUTH-REVENUE FROM MOTOR VEH SALES & USE TAX FOR HMOF ($)
NOTE FR-FEDERAL AID REVENUE ($)
NOTE MRH-MISCELLANEOUS REVENUE FOR HMOF ($)

Major state sources of revenue for the TTF are the motor vehicle fuels tax, the state sales tax, the motor vehicle sales and use tax, the motor vehicle license fee, and other miscellaneous fees, as shown in the following DYNAMO equation. Even though some sources are identical to those for the HMOF, different portions of the budget are allocated to the corresponding fund group. Table 5.14 summarizes the rates of the taxes and fees levied to vehicle users for the formation of HMOF and TTF.

A TTF.K=RMFTT.K+RMLFT.K+RMSUTT.K+RSST.K+MRT.K
NOTE TTF-TRANSPORTATION TRUST FUND ($)
NOTE RMFTT-REVENUE FROM MOTOR VEH FUELS TAX FOR TTF ($)
NOTE RMLFT-REVENUE FROM MOTOR VEH LICENSE FEES FOR TTF ($)
NOTE RMSUTT-REVENUE FROM MOTOR VEH SALES & USE TAX FOR TTF ($)
NOTE RSST-REVENUE FROM STATE SALES TAX ($)
NOTE MRT-MISCELLANEOUS REVENUE FOR TTF ($)

As indicated in Table 5.14, most portions of the taxes and fees belong to the HMOF and the TTF. The units of taxes and fees provide essential information for estimating the total state revenue. The revenues for the HMOF and the TTF can be generated from the same form of equations for the following revenue sources: the motor vehicle fuels tax, the motor vehicle sales and use tax, and motor vehicle licenses fees. The only difference in the equations would be the respective rates for the two fund groups. The following paragraphs explain the calculation forms of these categories of revenue sources.

The estimation of the motor vehicle fuels tax for both fund groups utilizes the corresponding rates, along with related auxiliary variables., as shown in the following equations.

A RMFT.K=MFT*VMT.K/ADTG.K

NOTE RMFT-REVENUE FROM MOTOR VEH FUELS TAX ($)

NOTE MFT-MOTOR VEHICLE FUELS TAX ($/GAL)

NOTE ADTG-AVERAGE DISTANCE TRAVELED PER GALLON (MI/GAL)

Table 5.14 Major State Sources of Revenue

Revenue Source	Rate	Fund
Motor Vehicle Fuels Tax	14.85 cents/gallon 2.50 cents/gallon 0.15 cents/gallon 0.20 cents/gallon	HMOF TTF Division of Motor Vehicles Leakage Underground Storage Tanks
Motor Vehicle Sales and Use Tax	2.0 % 1.0 %	HMOF TTF
State Sales and Use Tax	3.0 % 1.0 % 0.5 %	State General Fund Localities TTF
Motor Vehicle License Fee	16.00 dollars/vehicle 4.00 dollars/vehicle 3.00 dollars/vehicle 2.00 dollars/vehicle 1.50 dollars/vehicle	HMOF Division of Motor Vehicles TTF Rescue Squads State Police

Source: Miller 1995

A VMT.K=VR.K*AMTV.K

NOTE VMT-VEHICLE MILES TRAVELED (VEH-MI)

NOTE VR-VEHICLE REGISTRAIONS (VEHICLES)

NOTE AMTV-AVERAGE MILES TRAVELED PER VEHICLE (MI/VEH)

Revenue from the collection of motor vehicle license fee is proportionally increasing with an increase in the number of vehicles registered.

A RMLF.K=VR.K*MLF

NOTE MLF-MOTOR VEHICLE LICENSE FEES ($/VEH)

NOTE RMLF-REVENUE FROM MOTOR VEH LICENSE FEES ($)

Motor vehicle sales and use tax is levied to the vehicle owner when he/she registers his/her new or used vehicle with the state. Currently, the tax rate in Virginia is 3.0% of the vehicle purchase-price. In order to obtain annual revenues from this source, it is necessary to know the total number of new and used vehicles newly registered, and the respective prices of the vehicles. From these records, the total price paid for vehicles in a year can be found, and in turn, the total tax collected from these purchases can be calculated. The following equation explains the calculation.

```
A  RMSUT.K=MSUT*(NVT.K*ANVP.K+UVT.K*AUVP.K)
NOTE RMSUT-REVENUE FROM MOTOR VEHICLE SALES AND USE TAX ($)
NOTE MSUT-MOTOR VEHICLE SALES & USE TAX (DIM)
NOTE NVT-NEW VEHICLES TITLED (VEHICLES)
NOTE ANVP-AVERAGE PRICE OF NEW VEHICLES ($/VEHICLE)
NOTE UVT-USED VEHICLES TITLED (VEHICLES)
NOTE AUVP-AVERAGE PRICE OF USED VEHICLES ($/VEHICLE)
```

Revenue from state sales and use tax constitutes a major source for the TTF. The rate of sales tax differs among the states, and sales tax in Virginia is 4.5% of the purchase price. In this percentage of tax, 0.5 percent is reserved for the TTF revenue. The total amount of state sales depends on the size of the population and the annual spending on purchases.

```
A  RSST.K=PV.K*SST*APRP
NOTE RSST-REVENUE FROM STATE SALES TAX ($)
NOTE SST-STATE SALES TAX (DIM)
NOTE APRP-AVERAGE PURCHASE RATE PER PERSON ($)
```

The amount of financial support at the federal level depends on the amount of federal funding projects. Past financial data show that federal aid has been increasing at an annual rate of 4.8 percent from 1988 to 1996 [VDOT annual]. However, the data also indicate that a significant fluctuation in the amount of federal aid has been observed between 1989 and

1990. This inconsistency in the pattern of increase was caused by the different sizes and numbers of federal programs each year. However, in the model, because of the difficulty of predicting federal programs it is assumed that the past growth pattern will be maintained in the future with the same annual rate.

```
A  FR.K=FRN*(1+FRIF)**TIME.K
NOTE FR-FEDERAL AID REVENUE ($)
NOTE FRN-FEDERAL AID REVENUE NORMAL ($)
NOTE FRIF-FEDERAL AID REVENUE INCREASING FACTOR (DIM)
```

Miscellaneous revenues for the HMOF and the TTF include a number of revenue sources, as shown in Table 5.15. The contribution of each source to the two fund groups is relatively small, so they are grouped into the category of miscellaneous revenues.

Table 5.15 Miscellaneous Revenue Sources for the HMOF and the TTF

HMOF	TTF
Road Tax International Registration Plan Overload Permits Mileage Permits Hauling Permit Fees Highway Permit Fees Bridge and Ferry Tolls Weighing Fees Liquidated Damages Motor Carrier Registration Fee Transfers	Road Tax Aviation Fuels Tax Motor Vehicle Rental Tax Transportation Improvement District Fund Alternative Fuels Revolving Fund Transit Special Formula Operating General Fund Trust and Agency

Source: VDOT annual

It should be noted that the amount of miscellaneous revenue would be affected by the economic status of the state. In other words, the economic performance, represented by the GSP, will positively influence the amount of state revenue. In the model, this linkage is realized by adopting a multiplier, which is proportional to an increase in the GSP of Virginia. The following equation for the TTF explains this relationship.

```
A  MRT.K=MRTN*MRTM.K
NOTE MRT-MISCELLANEOUS REVENUE FOR TTF ($)
NOTE MRTN-MISCELLANEOUS REVENUE FOR TTF NORMAL ($)
A  MRTM.K=TABLE(MRTMT,GSP.K,15E10,65E10,5E10)
T  MRTMT=1.04/1.06/1.08/1.10/1.12/1.14/1.16/1.18/1.20/1.22/1.24
NOTE MRTM-MISCELLANEOUS REVENUE FOR TTF MULTIPLIER ($)
```

- **Budget Allocation**

Once the HMOF and the TTF are formulated, they are spent on various transportation systems, including highways, mass transit, and ports and airports. In 1995, for example, Virginia's total transportation revenue was allocated to each system, with different allocation portions as shown in Figure 5.5.

As shown in Figure 5.5, a major portion of the revenue, 85 percent, was allocated to highway-related projects. This 85 percent of the highway budget is spent on comprehensive activities related to highways, which include administrative services, planning and research, highway system acquisition, and construction and management, etc. Among these activities, the portion of the highway budget allocated to construction and management was 84.86 percent in 1996 [VDOT annual].

The construction and management budget is further divided in terms of the highways' administration systems, i.e. the interstate system, the primary system, the secondary system, and the urban system. In 1996, for example, the construction and management budget was distributed to each system in the following percentages [VDOT annual].

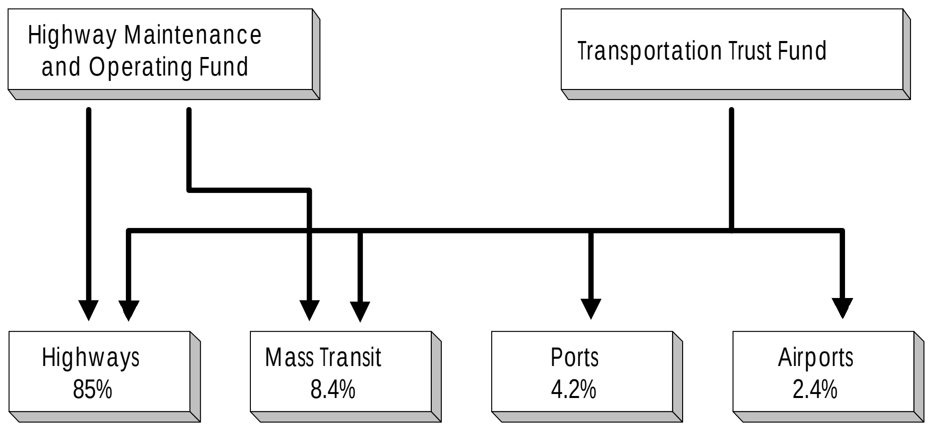

Figure 5.5 Allocation of Transportation Funds
Source: VDOT 1995

Table 5.16 Distribution of Construction and Management Budget

Highway System	Budget Allocation
Interstate Highway System	19.2 %
Primary Highway System	27.0 %
Secondary Highway System	31.1 %
Urban Highway System	22.7 %

Source: VDOT annual

The following DYNAMO equations figure the size of the budgets utilized for the PMS and the BMS. The tree-type budget flows described above are mathematically modeled. The final outputs of this portion of the model are the PMS budget (PMSB) and the BMS budget (BMSB), which are also necessary inputs for the PMS and the BMS, respectively.

```
A  HRA.K=TR.K*FTRH
NOTE HRA-HIGHWAY REVENUE ALLOCATED ($)
NOTE TR-TOTAL TRANSPORTATION REVENUE ($)
NOTE FTRH-FRACTION OF TOTAL REVENUE TO HIGHWAYS (DIM)
A  CMBH.K=HRA.K*FHRACM
```

```
NOTE CMBH-CONSTRUCTION & MAINTENANCE BUDGET FOR ALL HIGHWAYS ($)
NOTE FHRACM-FRACTION OF HRA TO CONSTRUCTION & MAINTENANCE (DIM)
A  ICMB.K(H)=CMBH.K*FCMBI(H)
NOTE ICMB-CONSTRUCTION & MAINT BUDGET FOR EACH CATEGORY ($)
NOTE FCMBI-FRACTION OF CMBH TO HIGHWAY (DIM)
A  PMSB.K(H)=ICMB.K(H)*PMSP
NOTE PMSB-PAVEMENT MANAGEMENT SUBSYSTEM BUDGET ($)
A  BMSB.K(H)=ICMB.K(H)-PMSB.K(H)
NOTE BMSB-BRIDGE MANAGEMENT SUBSYSTEM BUDGET ($)
```

5.3.9 Appraisal Subsystem

Improvement programs for transportation infrastructure not only affect and change the existing conditions of the infrastructure, but they also impact economic, environmental, and social factors in related areas. The assessment of the consequences of a project accounting for those factors involves more vague and challenging tasks than an assessment of physical impacts. No single method commonly recognized and proven has been established to address all three factors. Thus, in current research, the investigation of these factors is selective and separated.

On the other hand, the appraisal of transportation improvements is emphasized in the quantification of direct user-benefits. These benefits should not be confused with the economic impact of improvements. Economic impact measures the indirect or secondary effects of expenditures on the transportation infrastructure. This impact could include employment, income, and production of goods, etc. In this research, the economic impact is addressed by investigating the variations in employment, the state product, and revenue generation over the years. Presented in this section is the appraisal process of direct user-benefits realized by infrastructure management. Direct user-benefits can be categorized as follows: reductions in operating costs, reductions in time costs, and reductions in accident costs [BPR 1965]. The reductions in operating costs refer to changes in road users' vehicle operating costs due to improvements. Reductions in time costs account for change in users' travel time costs due to improvements. The change in costs of fatal, personal injury, and property damage accidents is referred to as "accident cost savings." The quantification of these benefits can be accomplished by deriving the monetary value of each benefit. Details of the analytical processes used in estimating user-benefits are provided in the subsequent sections.

- **Vehicle Operating Costs**

Vehicle operating costs comprise fuel, oil, tire, maintenance and depreciation costs. They can be estimated as a function of vehicle class, average vehicle speed, road surface and pavement conditions, horizontal and vertical alignment, and volume capacity ratio. The annual vehicle operating costs pertaining to the base and project cases may be derived from the vehicle unit operating costs. The vehicle unit operating costs vary per mile of travel. Generally, the more miles a vehicle travels in a year, the more the cost per mile decreases. Thus, the unit cost should be a function of vehicle miles of travel. The following table shows the cost of operating a vehicle per year based on 10,000 miles per year.

Table 5.17 Vehicle Operating Cost

Year	Total Cost per 10,000 Miles (current dollars / 10,000 miles)	Total Cost per Mile (current cents / mile)
1980	2,795	28.0
1985	2,582	25.8
1990	3,932	39.3
1991	4,505	45.1
1992	4,743	47.4
1993	4,705	47.0
1994	4,834	48.3
1995	5,062	50.6
1996	5,260	52.6
Annual Growth Rate	4.03%	4.02%

Source: AAA annual

In the model, the annual values of the initial vehicle operating costs are first estimated based on the data shown in Table 5.17. This estimation is performed by using the annual growth rate of 4.02 percent, and is based on the assumption of 10,000 miles of vehicle travel. Then, the basic vehicle operating costs reflecting various vehicle miles are computed. As a preliminary step, the annual value of vehicle miles is calculated from the total number of vehicle miles of travel, which was previously predicted in the Transportation Subsystem. The equation for the basic vehicle operating costs can be obtained from the estimation conducted by the American Automobile Association. It is estimated that the annual cost of operating a vehicle in 1995 ranged from 50.6 cents per mile, if 10,000 miles were traveled, to 37.0 cents per mile, if 20,000 miles were traveled [AAA annual].

```
A IVOC.K=IVOCN*(1+IVOCG)**TIME.K
NOTE IVOC-INITIAL VEHICLE OPERATING COSTS (CENTS/VEH-MI)
NOTE IVOCN-IVOC NORMAL (CENTS/VEH-MI)
C IVOCG=0.040194
NOTE IVOCG-IVOC GROWTH RATE (DIM)
A TAVMH.K=TVMH.K*360
NOTE TAVMH-TOTAL ANNUAL VEHICLE MILES OF HIGHWAYS (VEH-MI)
NOTE TVMH-TOTAL VEHICLE MILES OF HIGHWAYS (VEH-MI/DAY)
A BVOC.K=IVOC.K-0.00136*(AMTV.K-10000)
NOTE BVOC-BASIC VEHICLE OPERATING COSTS (CENTS/VEH-MI)
```

Vehicle operating costs also vary according to the operating speed, the demand capacity ratio, and the pavement condition. Higher vehicle operating speeds in excess of approximately 30 to 40 miles per hour result in reduced vehicle efficiency and increased operating costs [Seskin 1990]. As the demand capacity ratio increases, the costs also increases. The condition of the road surface also affects operating costs. When there is a transition in the surface from gravel to a sealed condition, or from poor to good condition, the costs decrease. The following program addresses the adjusted vehicle operating costs as a function of the three affecting factors. Both the operating speed and the demand capacity ratio are the outputs of the Transportation Subsystem, and the pavement condition can be assessed from the analysis of the Pavement Management Subsystem.

```
A ABVOC.K(H)=BVOC.K*OSF.K(H)*DCRF.K(H)*PVCF.K(H)
NOTE ABVOC-ADJUSTED BVOC (CENTS/VEH-MI)
A OSF.K(1)=TABLE(OSFTI,OPS.K(1),10,80,10)
T OSFTI=1.1/1.0/0.95/0.95/0.98/1.0/1.02/1.04
NOTE OSF-OPERATING SPEED FACTOR (DIM)
A DCRF.K(1)=TABLE(DCRFTI,DCRH.K(1),0.0,1.0,0.1)
T DCRFTI=0.50/0.60/0.70/0.80/0.90/1.00/1.10/1.20/1.30/1.40/1.50
NOTE DCRF-DEMAND CAPACITY RATIO FACTOR (DIM)
A PVCF.K(1)=TABLE(PVCFTI,PSIH.K(1),0.66,0.80,0.02)
T PVCFTI=2.5/2.3/2.1/1.9/1.7/1.5/1.4/1.1
NOTE PVCF-PAVEMENT CONDITION FACTOR (DIM)
A VOC.K(H)=((TAVMH.K(H)*ABVOC.K(H)/100)/(1+DSCR)**TIME.K)
NOTE VOC-VEHICLE OPERATING COSTS OF HIGHWAY ($)
NOTE DSCR-DISCOUNT RATE (DIM)
```

- **Accident Costs**

The change in the incidence of accidents that would follow a road improvement may be estimated by using relationships between accident rates and road and traffic characteristics. The use of site-specific data is not recommended because limited, statistically unreliable results are likely to be obtained, which would lead to inconsistent results. Accidents can be categorized into three types in terms of their characteristics: the fatal accident, the personal injury accident, and the property damage accident. The calculation of accident costs per vehicle miles can be performed by using the following equation.

$$ACVM_i = \sum_{i=1}^{3} \left(P_n \cdot BAR_i \cdot ACT_n \right) \qquad (5.4)$$

where, $ACVM_i$ = accident costs per vehicle mile for year i (\$/veh-mi),

P_n = proportion of total accidents to accident type n,

n = accident type,

BAR_i = basic accident rates for year i (accidents/veh-mi), and

ACT_n = accident cost for type n accident (\$/accident).

In order to calculate accident costs, the basic accident rates with regard to the accident types need to be known. Table 5.18 summarizes the rates of vehicle fatalities, injuries, and property damages per 100 million vehicle miles.

Table 5.18 Accident Types and Associated Rates*

Year	Fatality	Personal Injury	Property Damage
1990	2.1	151	302
1991	1.9	143	282
1992	1.7	137	267
1993	1.7	136	266
1994	1.7	136	275
1995	1.7	140	273

* Rates per 100 million vehicle miles

Source: BTS 1997

The proportion of total accidents to each type of accident is assumed to be 3.5 percent, 18.5 percent, and 78 percent for fatal accidents, personal injury accidents, and property damage accidents, respectively. The determination of the cost of each type of accident is based on the estimation conducted by the National Highway Traffic Safety Administration, as shown in Table 5.19.

Table 5.19 Accident Costs

Accident Type	Accident Costs
Fatal accident	$ 268,700 per fatality
Personal injury accident	$ 2,280 per injury
Property damage accident	$ 530 per accident

Source: NHTSA 1983

A good pavement condition would contribute to the reduction of accident rates, because of an increase in maneuverability, as long as the speed limit is maintained by the drivers. The following equation accounts for this aspect by relating the pavement condition factor to the accident rates.

```
A PVCFA.K=TABLE(PVCFAT,PSIH.K,0.8,1.0,0.02)
T PVCFAT=1.25/1.20/1.15/1.1/1.05/1.0/0.96/0.92/0.88/0.84/0.80
NOTE PVCFA-PAVEMENT CONDITION FACTOR FOR ACCIDENTS (DIM)
A ABFAR.K=BFAR*PVCFA.K
NOTE ABFAR-ADJUSTED BFAR (ACCIDENTS/VEH-MI)
NOTE BFAR-BASIC FATAL ACCIDENT RATE (ACCIDENTS/VEH-MI)
A ACVM.K=(0.035*ABFAR.K*FAC+0.185*ABPIAR.K*PIC+0.78*ABPDAR.K*PDC)
NOTE ACVM-ACCIDENT COSTS PER VEHICLE MILE ($/VEH-MI)
NOTE ABPIAR-ADJUSTED BPIAR (ACCIDENTS/VEH-MI)
NOTE ABPDAR-ADJUSTED BPDAR (ACCIDENTS/VEH-MI)
NOTE FAC-FATAL ACCIDENT COST ($)
NOTE PIC-PERSONAL INJURY COST ($)
NOTE PDC-PROPERTY DAMAGE COST ($)
```

Annual accident costs can be obtained by multiplying the accident costs per vehicle mile by the total annual vehicle miles. The costs then are discounted over future years.

```
A ACST.K=TAVMH.K*ACVM.K*(1+DSCR)**TIME.K
NOTE ACST-ACCIDENT COSTS ($)
NOTE TAVMH-TOTAL ANNUAL VEHICLE MILES OF HIGHWAYS (VEH-MI)
```

- **Travel Time Cost**

The major benefit arising from the construction and maintenance of highways is the reduction in travel time for vehicles. The monetary value of travel time savings is not directly available, but has to be derived from behavioral research, statistical and economical analysis of travel data, and the values of time for other activities. The value of time saving depends on the purpose and the time of the trip during the day. However, these differences are not always taken into account in economic analysis. The selection of a monetary value for travel time in this model is based on the average hourly earnings of the driver, and a time value of seven dollars per hour is used [Seskin 1990]. The estimation of travel time costs is performed by using the following equation. Both travel time and average annual daily traffic are generated in the Transportation Subsystem.

```
A TTC.K=(TT.K/60)*VOT*AADTH.K*360*(1+DSCR)**TIME.K
NOTE TTC-TRAVEL TIME COST ($)
NOTE VOT-VALUE OF TIME ($/HR)
NOTE TT-TRAVEL TIME (MIN)
NOTE AADTH-AVERAGE ANNUAL DAILY TRAFFIC (VEH)
```

The three costs incurred to highway users analyzed so far constitute the total user costs. The user benefits can be estimated by utilizing the concept of consumer surplus, which is explained as follows: Traffic flow can be considered as the travel demand, which provides inverse relationship with travel costs, as shown in Figure 5.6. The transportation supply function is represented by the travel time, or the travel cost, versus the traffic flow relationship. As the flow increases, travel cost increases. In Figure 5.6, the original supply curve represents an existing condition of highways with relatively high travel costs. Point C shows the equilibrium in that situation, with q1 as traffic volume and c1 as travel cost. If an improvement is proposed, it may be represented by the revised supply curve providing lower travel costs. As a result of the improvement, the travel demand will increase and a new equilibrium point will be reached at point E, with q2 as traffic volume and c2 as travel cost. As transportation costs are lowered, more trips are induced. The generated traffic is q2 minus q1. The user-benefits, or consumer surplus, are represented by the area ABDEC. The benefits for original users correspond to the rectangle ABCD, and those for the new users to the triangle CDE. Hence, the total change in the consumer surplus can be calculated by the formulae (5.5).

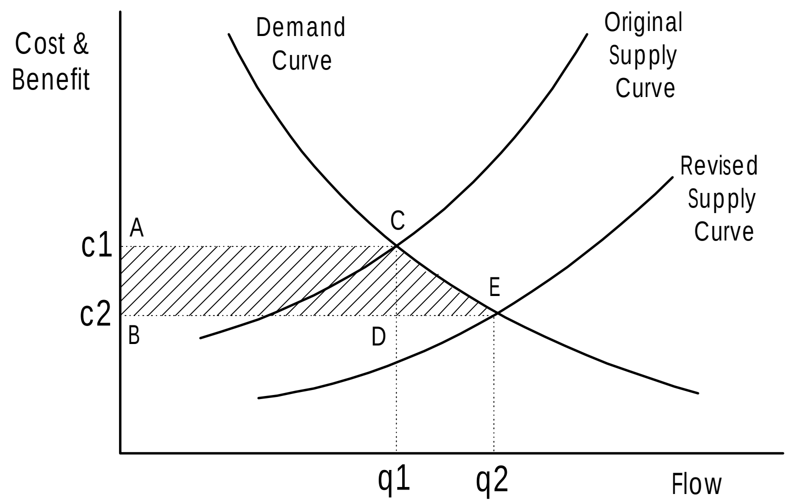

Figure 5.6 Concept of Consumer Surplus

$$\Delta CS = (c1 - c2) \cdot \frac{q1 + q2}{2} \qquad (5.5)$$

where, ΔCS = change in consumer surplus,

q1 = travel demand on base case,

q2 = travel demand on project case,

c1 = travel costs on base case, and

c2 = travel costs on project case.

This conceptual approach is appropriate for evaluating various types of transportation infrastructure improvements. The following equations calculate the total user costs and user benefits for an improvement scenario, compared to the base scenario.

```
A TUC.K=VOC.K+ACST.K+TTC.K
NOTE TUC-TOTAL USER COSTS ($)
A UBH.K=(TUCN-TUC.K)*(AATHN+AATH.K)/2
NOTE UBH-USER BENEFIT OF HIGHWAY ($)
NOTE  AATH-ANNUAL AVERAGE TRAFFIC VOLUME ON HIGHWAY (VEH)
```

As a criterion for the assessment of highway improvements, the benefit cost ratio is estimated. As implied by its name, the benefit cost ratio is a straightforward calculation of the ratio of the present value of benefits to present value of costs. The ratio applied in this research is expressed in the following form.

$$BCR = \frac{R - E}{C \cdot r}(1 - e^{-rt}) \tag{5.6}$$

where, BCR = benefit cost ratio,

R = annual revenues,

E = annual expenditures,

C = capital costs,

r = interest rate, and

t = life-span of the project.

The following DYNAMO equation calculates the benefit cost ratio by using Equation (5.6).

```
A BCR.K(H)=((LTRBH.K(H)-AEH.K(H))/(CAPCH.K(H)*DSCR))*(1-EXP(-DSCR*N))
NOTE BCR-BENEFIT COST RATIO (DIM)
NOTE LTRBH-ACCUMULATED TOTAL REVENUE ($)
NOTE AEH-ACCUMULATED EXPENDITURES ON HIGHWAY ($)
```

NOTE CAPCH-CAPITAL COSTS OF HIGHWAY ($)
NOTE N-SERVICE LIFE (YR)

The TPMSHM described in this chapter should be validated for observed conditions in order to examine the credibility of the model. The model validation process is presented in the next chapter.

CHAPTER 6
MODEL VERIFICATION

6.1 Model Validation

In transportation analysis, the purpose of systems modeling in representing the transportation infrastructure system is twofold: to gain a better conception of how the system functions, and to predict the future behavior of the system [Black 1981]. The achievement of this purpose is not possible without a reasonable modeling procedure. The modeling procedure can be represented by the following sequential and feedback steps:

- Identification of the system under consideration,
- Identification of the system components,
- Investigation of the relationships among the components,
- Construction of a model,
- Model calibration,
- Model validation, and
- Prediction of future behavior of the system.

The first three steps require the modeler to understand the structure of the model in its entirety, including its working mechanisms. The construction of a model is based on this understanding, but the model is not complete at this stage. Once the model is constructed, it should be calibrated through parameter estimation, and tested for validity and reliability. Both the calibration and validation processes are accomplished by scrutinizing the observed, “real-world” data. As a final step in the modeling procedure, the objectives of the systems model are realized, i.e. future forecasting, which includes the perception and the anticipation of how the system would work in the future.

In order to draw inferences about the future behavior of the system from results obtained from the simulation, the model should be a reasonably valid representation of the real system. However, the process of model validation is often overlooked or even left out of the modeling process. One should not be over-confident that the model is accurate if it has not been verified with observations in the real world. Furthermore, future estimates predicted by the use of an incomplete model cannot be representations of the future behavior of the system. Model validation is a process that should not be neglected.

For model validity, Drew [1996] states that the validity or significance of a model is dependent on its suitability for a particular purpose, its ability to forecast macro-behavior, its scope, the defense of the details of the model structure and variable interactions, and the validity and precision of the sources from which the contents of model are drawn.

In the validation procedure, the values of the parameters constituting the model are estimated by investigating the relationships among the observed data gained from the real world. The parameter estimation continues until the gap between the observations and the estimates falls within a specified level of confidence. However, the presentation of validation comparisons between the estimated and the observed data always show the range of unavoidable uncertainty that is inherent in the observed data. Hence, the credibility of the model is limited to some extent, even though the model passes the validation test under certain sets and variations of conditions [Kobayashi 1978].

In summary, the model validation is accomplished by comparing the model output with the observed data so as to ensure that [IHT 1987]:

- the degree of accuracy of the model is adequate for the decisions which need to be taken,
- the decision-makers understand the quality of the information with which they are presented, and
- the inherent uncertainties can be taken into account in reaching decisions.

The following section describes the parameter estimation procedure for the validation of the model developed in this research.

6.2 Parameter Estimation

From a general and simplified viewpoint, a model can be represented by two characteristics: variables and constants. A variable is a quantity to which one is able to assign different numerical values. On the other hand, a constant, as its name implies, is a fixed value that is not subject to change under any conditions. In the mathematical form of a model, a variable is divided into a dependent variable and an independent variable. The dependent variable is computed if the numerical values of the independent variable are known. Then, the model can be simply written as a combination of the dependent variables, the independent variables, and the constants. Here, the term for this combination should be properly defined in the course of modeling task.

The first task of model construction is to configure the relationship between the variables by investigating the specific sphere of interest. Then, the second task involves estimating realistic numerical values for the constants to describe the relationship between the dependent and the independent variables. These constants are referred to as the parameters of the model. The process of estimating the parameters is also known as "model calibration." The objective of model calibration is to obtain the best correspondence between the model estimates and data representing the real world. Model calibration can be initiated by investigating observed data. This observation is then employed to estimate the numerical values of the model parameters that enable the proposed model to replicate the observed data.

The modeling task in the validation stage necessarily accompanies repeated attempts to find appropriate values for the parameters. The parameter estimation in this research is implemented for two broad cases: the base case, and the future case. This case-by-case estimation is based on the fact that the values of the parameters are not constant over all cases under consideration, but unique to each particular case. The estimation of the parameters for the base case follows the model calibration process. For the future case, even though most values of the parameters are assumed to persist in the future, some modifications for the values of the future case are made. These modifications are based on the perceptions gained from the prediction of future trends and the planning philosophy of the modeler.

The following section measures model performance as a result of model calibration. This measurement is verified by comparing the estimates to the observations for each of the selected key variables in the model.

6.3 Model Performance

The assessment or decision as to whether or not a model performs properly and reliably should be made in the course of the modeling procedure. If the model accommodates the perception gained from the real system, it can be used to predict the future behavior of the system. The prediction should be accompanied by reasonable estimations of future parameters affecting the future system. On the other hand, if the model does not fully explain the existing system, it should be modified or reproduced until the outputs of the model represent the real world. This modification is usually performed by an iterative process; this process should not be overlooked because it is an essential part of the whole modeling task.

The transportation planning model for state highway management developed and explained in Chapter 5 is examined by investigating the major variables on which the model is based. In the course of modeling, these variables constitute key elements to produce the final outcomes of the model. The variables examined are:

- Population,
- Vehicle registration,
- Gross state product,
- Employment,
- Transportation revenue, and
- Vehicle miles of travel.

The following table illustrates the relationships between the above variables and the subsystems with which the variables are directly associated.

Table 6.1 Key Variables and Related Subsystems

Key Variable	Subsystem
Population	Travel Demand Subsystem A Finance Subsystem Demography Subsystem
Vehicle registration	Finance Subsystem Demography Subsystem
Gross state product	Regional Economy Subsystem Finance Subsystem
Employment	Regional Economy Subsystem Travel Demand Subsystem B
Transportation revenue	Finance Subsystem Pavement Management Subsystem Bridge Management Subsystem
Vehicle miles of travel	Transportation Subsystem Pavement Management Subsystem Appraisal Subsystem

The validation of the model is performed by comparing estimates of the key variables with the observed data for each of the variables. This task is performed with repeated iterations. Presented in this section are the final outputs of the processes. The measurement as to how close the estimates are to the observed data is conducted by analyzing the correlation between them. The correlation analysis measures the relationship between two data sets by means of a single number, called a correlation coefficient. The coefficient calculated in this analysis is represented by the covariance of two data sets divided by the product of their standard deviations [Walpole and Myers 1993]. The scale of a correlation coefficient ranges from 0, i.e. no correlation between two data sets, to 1, i.e. perfect correlation.

$$\rho_{X,Y} = \frac{Cov(X,Y)}{\sigma_X \cdot \sigma_Y} \tag{6.1}$$

where, $\rho_{X,Y}$ = correlation coefficient of two data sets X and Y,

Cov(X,Y) = covariance of X and Y,

σ_X = standard deviation of X, and

σ_Y = standard deviation of X.

The covariance and standard deviations can be expressed as follows:

$$Cov(X,Y) = E(XY) - \mu_X \mu_Y \tag{6.2}$$

$$\sigma_X = \sqrt{\sum (X_i - \mu_X)^2 / n} \tag{6.3}$$

$$\sigma_Y = \sqrt{\sum (Y_i - \mu_Y)^2 / n} \tag{6.4}$$

where, E(XY) = expected value of XY,

μ_X , μ_Y = mean of X and Y, respectively, and

n = number of data points in each data set.

The subsequent sections show the performance of the model by providing results of correlation analysis for each of the variables. Each variable is investigated with a different period of comparison due to data availability.

6.3.1 Population

The population in Virginia has been increasing at an annual rate of 1.4 percent since 1980, as shown in Table 6.2. This steady increase is caused by relatively high birth rates and in-migration rates. The estimates generated by the model demonstrate a high correlation between the observed and the estimated population, as indicated by the correlation coefficient in Table 6.2.

Table 6.2 Validation of Population (persons)

Year	Observed*	Estimated
1980	5,346,800	5,347,000
1981	5,430,600	5,426,000
1982	5,485,200	5,506,000
1983	5,555,900	5,587,000
1984	5,635,500	5,669,000
1985	5,702,000	5,752,000
1986	5,795,000	5,837,000
1987	5,914,000	5,923,000
1988	6,015,000	6,010,000
1989	6,098,000	6,099,000
1990	6,189,000	6,189,000
1991	6,287,000	6,280,000
1992	6,389,000	6,373,000
1993	6,473,000	6,467,000
1994	6,552,000	6,562,000
1995	6,615,234	6,658,000
1996	6,675,451	6,757,000
Correlation Coefficient	0.99825	

* Source: CPS annual

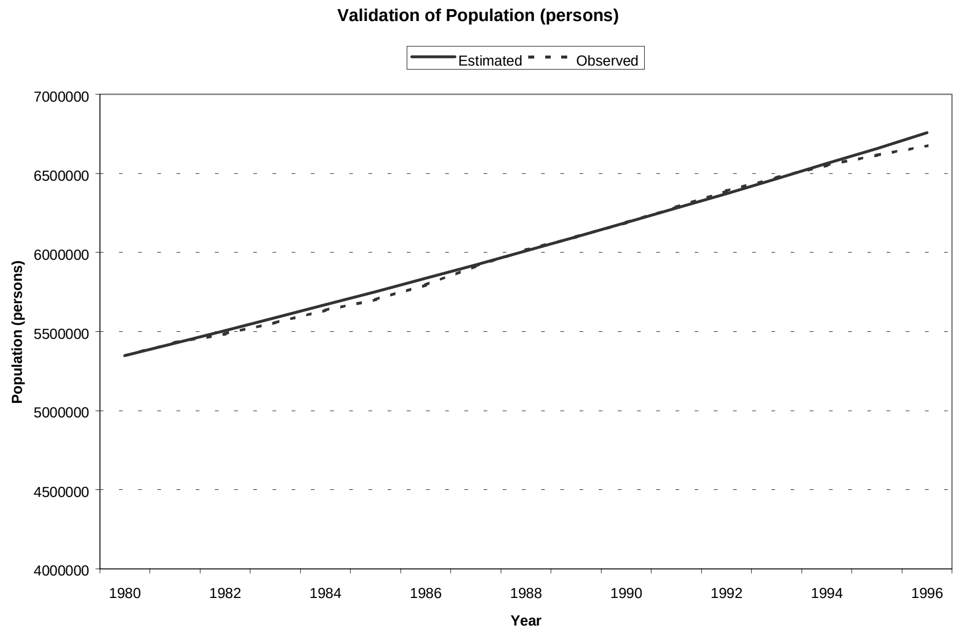

Figure 6.1 Validation of Population

6.3.2 Vehicle Registration

The number of vehicles registered in Virginia has increased with an annual growth rate of 2.86 percent since 1980. This growth affects the revenue size for transportation funds as well affecting traffic generation. The estimation of vehicle registration shows a value of 0.988 as a correlation coefficient. Figure 6.2 also shows the comparison between observed and estimated vehicles registered.

6.3.3 Gross State Product

The annual growth rate of 9.90 percent was observed for the amount of the gross state product over the period between 1980 and 1989. Economic development and inflation would be major contributors to the high rate of increase. The estimates of the gross state product shown in Table 6.4 are the sums of products created by ten industry sectors. The annual growth rate for the estimated values is calculated as 9.96 percent.

Table 6.3 Validation of Vehicle Registration (vehicles)

Year	Observed*	Estimated
1980	3,626,000	3,674,000
1981	3,741,400	3,786,000
1982	3,856,800	3,901,000
1983	3,925,600	4,018,000
1984	4,128,300	4,138,000
1985	4,253,000	4,260,000
1986	4,514,000	4,385,000
1987	4,660,700	4,513,000
1988	4,752,300	4,644,000
1989	4,887,600	4,777,000
1990	4,985,400	4,914,000
1991	5,023,700	5,053,000
1992	5,124,900	5,196,000
1993	5,229,000	5,342,000
1994	5,383,500	5,490,000
Correlation Coefficient	0.98806	

* Source: CPS annual

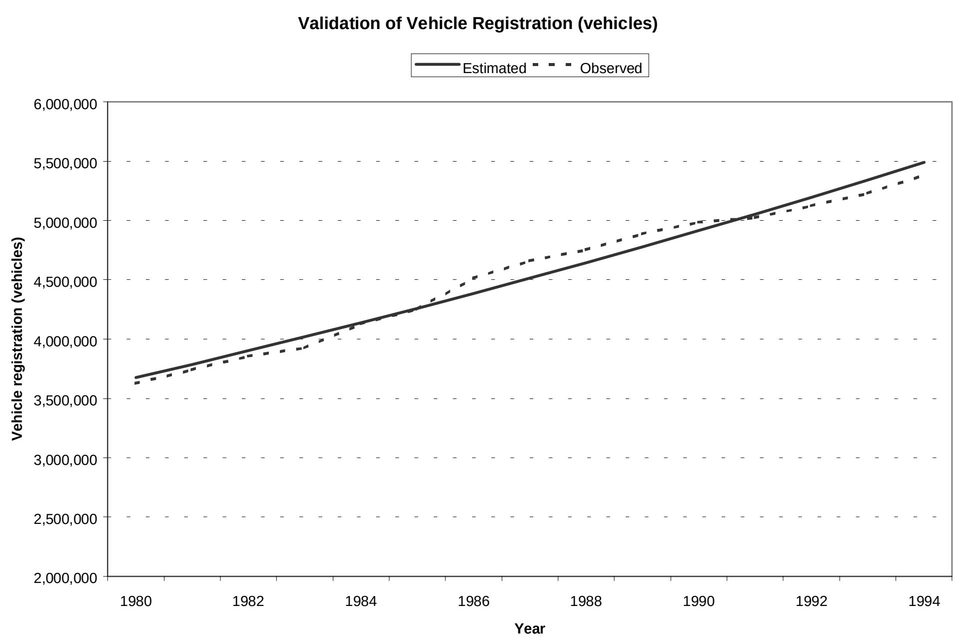

Figure 6.2 Validation of Vehicle Registration

Table 6.4 Validation of Gross State Product (million current dollars)

Year	Observed*	Estimated
1980	58,401	57,870
1981	65,592	64,700
1982	70,244	72,110
1983	78,634	80,080
1984	87,898	88,560
1985	96,009	97,500
1986	105,509	106,800
1987	115,882	116,400
1988	126,667	126,200
1989	136,497	136,000
Correlation Coefficient	0.99928	

* Source: Cutts and Knapp 1992

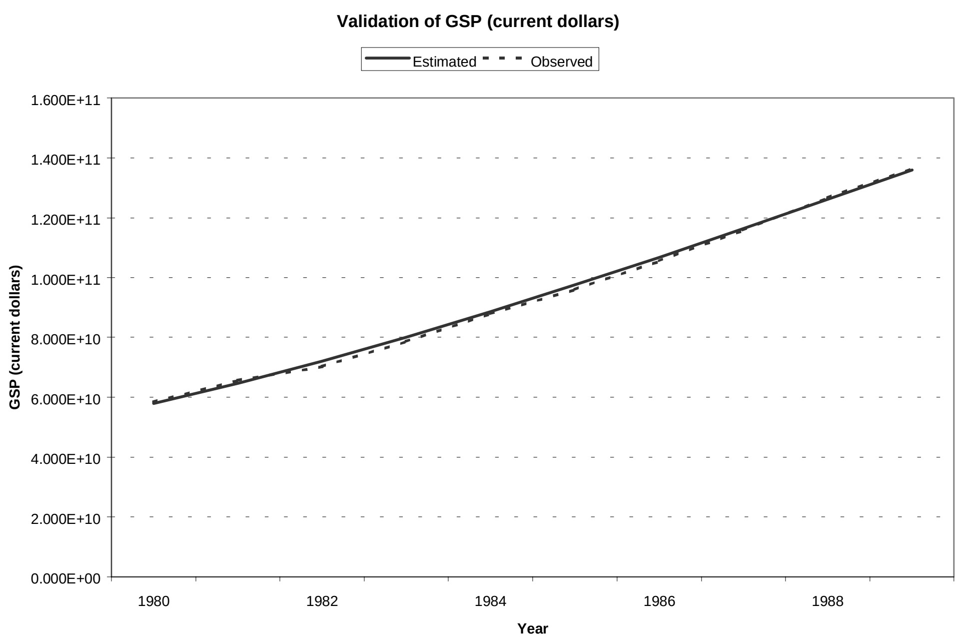

Figure 6.3 Validation of Gross State Product

6.3.4 Employment

The number of employees in Virginia increased with an annual growth rate of 2.83 percent over the period between 1980 and 1990. The estimated employment is very close to the observed employment, with an annual rate of 2.92 percent. This correspondence can also be verified by observing Figure 6.4.

6.3.5 Transportation Revenue

Transportation revenue is obtained from both the transportation trust fund and the highway maintenance and operating fund. Past revenues formulated over the period between 1988 and 1996 showed an annual growth rate of 3.21 percent. However, high fluctuations in the amount of revenue were observed between 1990 and 1992, as shown in Table 6.6 and Figure 6.5. This case can be interpreted from the fact that the size of the revenue partly depends on the number of state and federal funded projects, which are not consistent over time. The validation results of transportation revenue show a relatively low correlation, due to fluctuations in the size of revenue over the period between 1988 and 1996.

6.3.6 Vehicle Miles of Travel

The estimates of vehicle miles of travel are very close to the observed data as shown in Table 6.7 and Figure 6.6. The annual increasing rates for the observations and estimates are shown as 4.78 percent and 4.57 percent, respectively.

Table 6.5 Validation of Employment (workers)

Year	Observed*	Estimated
1980	2,348,400	2,318,000
1981	2,446,095	2,420,000
1982	2,445,950	2,520,000
1983	2,555,958	2,614,000
1984	2,698,000	2,702,000
1985	2,757,800	2,781,000
1986	2,820,700	2,849,000
1987	2,863,462	2,904,000
1988	2,972,373	2,945,000
1989	3,022,345	3,015,000
1990	3,103,943	3,090,000
Correlation Coefficient	0.98990	

* Source: CPS annual, and Cutts and Knapp 1992

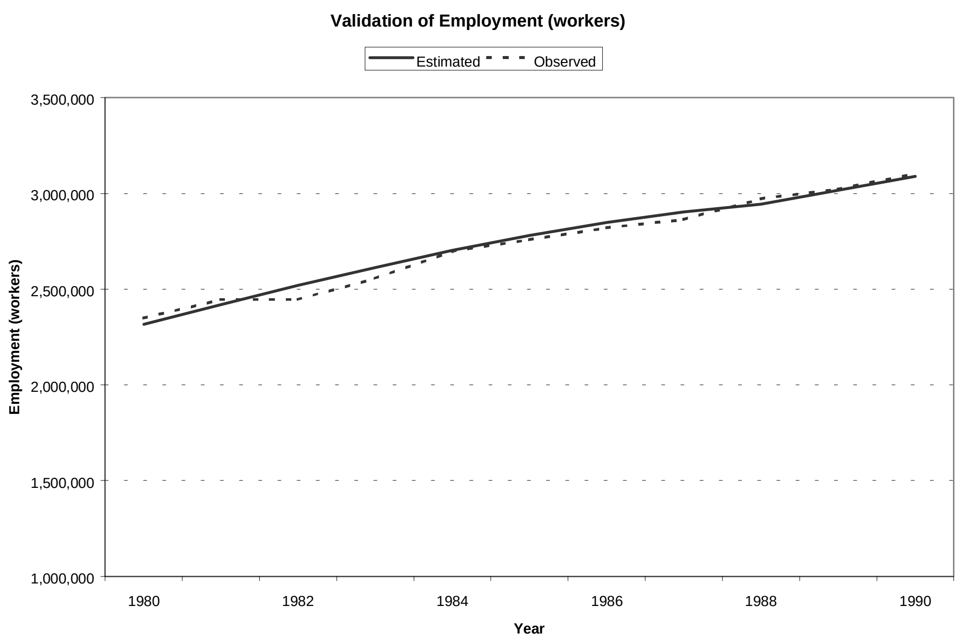

Figure 6.4 Validation of Employment

Table 6.6 Validation of Transportation Revenue (million current dollars)

Year	Observed*	Estimated
1988	1,692.7	1,698.0
1989	1,814.2	1,752.0
1990	1,844.8	1,807.0
1991	2,048.6	1,864.0
1992	1,824.3	1,924.0
1993	1,891.3	1,985.0
1994	2,046.9	2,048.0
1995	2,136.1	2,114.0
1996	2,178.8	2,182.0
Correlation Coefficient	0.86942	

* Source: VDOT annual, and Zagardo and Smith 1993

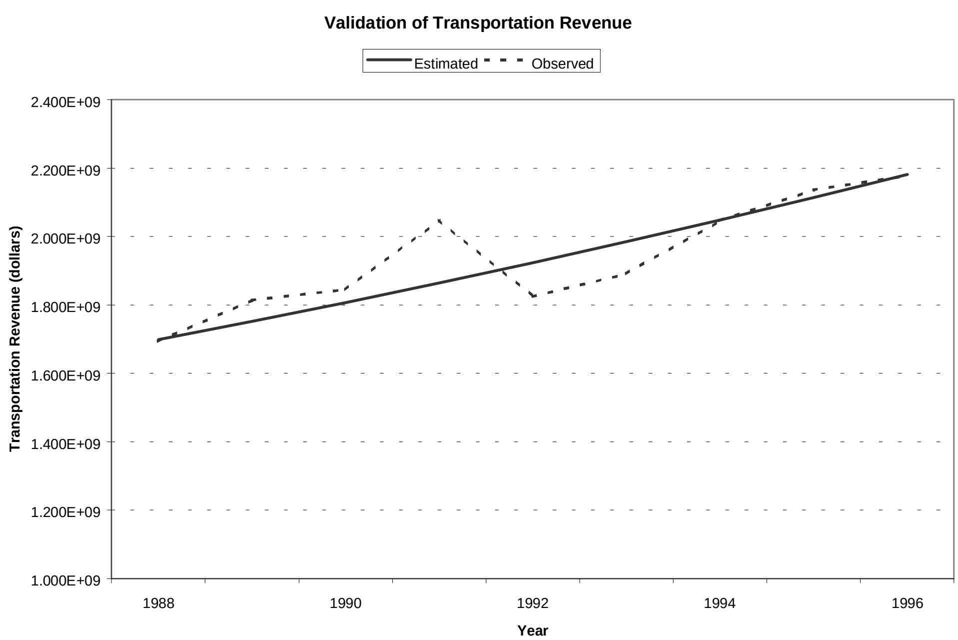

Figure 6.5 Validation of Transportation Revenue

Table 6.7 Validation of Vehicle Miles of Travel (thousand vehicle miles)

Year	Observed*	Estimated
1980	26,027.5	26,270.0
1981	27,271.6	27,450.0
1982	28,575.2	28,670.0
1983	29,941.1	29,930.0
1984	31,372.3	31,450.0
1985	32,871.9	32,780.0
1986	34,443.2	34,600.0
1987	36,089.5	35,970.0
1988	37,814.6	37,850.0
1989	39,622.2	39,510.0
1990	41,516.1	41,690.0
1991	43,500.6	43,910.0
1992	45,579.9	45,890.0
1993	47,758.6	47,890.0
1994	50,041.5	49,620.0
1995	52,433.5	51,350.0
Correlation Coefficient	0.99929	

Source: VDOT 1980-1995

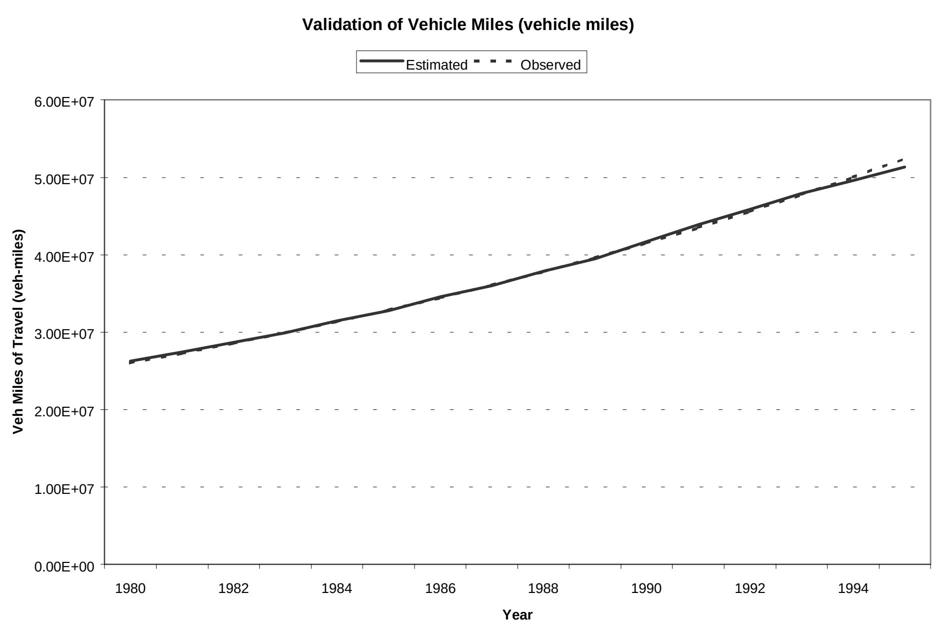

Figure 6.6 Validation of Vehicle Miles of Travel

CHAPTER 7
FUTURE SIMULATION AND ANALYSIS

7.1 Overview

This chapter provides and interprets the simulation results of the TPMSHM for various scenarios. First, the basic parameters of the TPMSHM are forecast. Utilizing these estimates, then, simulation and analysis are implemented as a base case. The significance of the prioritization scheme embedded in the TPMSHM is also discussed in this simulation. Next, as a policy analysis, the impact of raising the fuel tax is examined. Finally, the cost sensitivity inherent in the TPMSHM is discussed.

In a series of analyses, the effectiveness of the prioritization method developed in this research is measured by using several indicators of physical, functional, and economic conditions of highways. These indicators include a physical sufficiency index (PSI), a functional adequacy index (FAI), a functional obsolescence rate of bridges (FORB), a benefit cost ratio (BCR), and a user benefit index (UBI).

7.2 Forecasting of Basic Parameters

The future prediction of the behavioral patterns of highway conditions begins from the estimation of the basic parameters by which the physical characteristics of highways are determined. The deviated estimates from the actual future values will generate unreliable analysis outputs and will mislead the analysts and the public in their understanding and expectations of future transportation systems. However, the future statistics are unknown, and the judgement as to the accuracy of future estimates is difficult to make until the future comes. Given this uncertainty, a reasonable approach to predicting the future is to refer to past trends. This reference could lead to a simple extrapolation of the observed statistics in prediction, or a nonlinear growth pattern.

In the previous chapter, the following key variables were selected to examine the model performance: population, vehicle registration, vehicle miles of travel, gross state product, employment, and transportation revenue. The future estimation of these basic parameters was based on the observation of past data, and from this observation appropriate prediction methods were identified, as provided in Chapter 5. The following summarizes the results of the forecasts. In forecasting, the estimates of each parameter were compared to those predicted by other related research in order to reduce possible errors. Tables 7.1 and 7.2 contain future forecasts of the six parameters.

7.2.1 Population

It is estimated that in the year 2,000 the population of Virginia will be as high as over 7 million persons. The population increases almost linearly during the next two decades following the year 2,000. This growth pattern results in a 0.77 percent annual increase rate.

7.2.2 Vehicle Registration

In the year 2000, the number of vehicles registered in Virginia will exceed 6.3 million vehicles. The future increase pattern of vehicle registration shows a steady growth, with a 0.84 percent increase annually. Close to the year 2010, the number of vehicles will approach 7 million, and in the year 2020, the vehicle registration will record about 7.5 million vehicles. The number of vehicles per capita, or vehicle ownership, also will increase from 0.899 vehicle/capita in the year 2000, to 0.913 vehicle/capita in the year 2020.

7.2.3 Vehicle Miles of Travel

The estimates of vehicle miles of travel show a 2.96 percent annual growth rate. Compared to other demographics such as population and vehicle registration, vehicle miles of travel will increase at a higher rate. This high increase is due to an increase in trip lengths, numbers of employees, and regional economic productivity. Near to the year 2020, travel mileage exceeds 100 million vehicle miles.

7.2.4 Gross State Product

The high growth pattern of the GSP that has persisted in past years in Virginia implies consistent growth in the future, as long as a sudden “bailout” does not occur. The increase in the GSP can be related to an increase in productivity and employment opportunities. In the year 2000, the GSP is estimated at about 218.1 billion current dollars, and it increases at 5.49 percent annually.

7.2.5 Employment

In the year 2000, it is estimated that the number of employees will be as high as 4 million persons. This number increases at a 2.89 percent annual growth rate until the number of employees reaches up to 7 million persons in the year 2020. This growth can be interpreted by the fact that a growth in industrial scale, represented by the GSP, creates more opportunities for employment.

7.2.6 Transportation Revenue

The amount of transportation revenue, which comprise the TTF and the HMOF, will increase by 2.78 percent annually. This growth corresponds to an increase in demographics, such as population and vehicle registration. It is estimated that the transportation revenue will increase up to 2.3 billion dollars in the year 2000 from the present year. In the year 2020, the amount of transportation revenue is expected to be as high as 4 billion dollars.

Table 7.1 Demographics estimates (I)

Year	Population (persons)	Vehicle Registration (vehicles)	Vehicle Miles of Travel (vehicle miles)
2000	7,048,000	6,336,000	58,210,000
2001	7,102,000	6,389,000	60,030,000
2002	7,157,000	6,443,000	61,930,000
2003	7,212,000	6,498,000	63,900,000
2004	7,267,000	6,553,000	65,940,000
2005	7,323,000	6,608,000	68,030,000
2006	7,379,000	6,664,000	70,160,000
2007	7,435,000	6,720,000	72,320,000
2008	7,493,000	6,777,000	74,510,000
2009	7,550,000	6,834,000	76,710,000
2010	7,608,000	6,891,000	78,920,000
2011	7,666,000	6,949,000	81,420,000
2012	7,725,000	7,008,000	83,950,000
2013	7,785,000	7,067,000	86,500,000
2014	7,844,000	7,127,000	89,050,000
2015	7,904,000	7,187,000	91,610,000
2016	7,965,000	7,247,000	94,170,000
2017	8,026,000	7,309,000	96,720,000
2018	8,088,000	7,370,000	99,270,000
2019	8,150,000	7,432,000	101,800,000
2020	8,213,000	7,495,000	104,400,000

Table 7.2 Demographics estimates (II)

Year	Gross State Product (million current dollars)	Employment (persons)	Transportation Revenue (million current dollars)
2000	218,100	4,010,000	2,307
2001	238,900	4,124,000	2,358
2002	260,900	4,245,000	2,413
2003	283,900	4,369,000	2,470
2004	307,900	4,494,000	2,529
2005	332,500	4,617,000	2,592
2006	357,600	4,734,000	2,657
2007	382,800	4,844,000	2,726
2008	408,000	4,943,000	2,798
2009	432,800	5,030,000	2,873
2010	457,000	5,103,000	2,952
2011	480,600	5,365,000	3,035
2012	503,100	5,616,000	3,122
2013	524,400	5,853,000	3,213
2014	544,400	6,075,000	3,309
2015	563,000	6,282,000	3,409
2016	580,100	6,473,000	3,515
2017	595,900	6,648,000	3,626
2018	610,300	6,807,000	3,743
2019	623,400	6,953,000	3,866
2020	635,300	7,084,000	3,995

7.3 Simulation and Analysis

The simulation of the TPMSHM is implemented for the period from the year 2000 to the year 2020. In the base run, the physical condition of highways is estimated for this period by utilizing forecasts of future demographics and current policies such as fuels tax, vehicle license fees, vehicle sales and use tax, and state sales tax. This simulation is performed for each category of state highway and the nine districts in Virginia. The following sections describe the simulation results and interpretations.

7.3.1 Pavement Condition of State Highways

The variations in pavement condition over time are expressed in terms of lane miles of sufficient highways (HSF), deficient highways (HDF), and deteriorated highways (HDT). The following interprets simulation results for each highway system.

- **Interstate Highways**

Figure 7.1 shows trajectories of pavement conditions of interstate highways for the simulation period along with fractions of PMS budget to maintenance and construction, FPMSB and FPMSC, respectively. At the base year, the year 2000, it is assumed that the lane miles of the three conditions of highways are the same. In the early period of simulation, the HSF decreases, whereas the HDT continues to increase. The HSF, then, begins to increase very slightly until the year 2010. From the time of the year 2010, when construction is terminated, the HSF shows a greater increase. As the year 2020 approaches, the marginal increase decreases. On the other hand, the HDT increases from the base year until the construction termination time, and then drops rapidly after the year 2010.

This output implies the significance of construction. During the construction period, a large amount of the available PMS budget is dedicated to high-cost construction, and as a result, the portion of the budget allocated for maintenance activities becomes relatively small, which causes low rates of maintenance. However, the state-dependent prioritization contributes to an increase in the fractions of budget to maintenance during this period, as shown in Figure 7.1. After the construction period, a large amount of the budget, which has been allocated to new construction, is devoted to maintenance activities, which results in an improvement of the overall pavement condition of interstate highways.

The changes in the HDF show different patterns from those of the HSF and the HDT. The HDF increases during the first year, and then begins to decrease until the year 2011. An increase in the HDF during the first year is due to its aging time and because maintenance activities do not occur until the year 2001. A decrease after the year 2001 is caused by the fact that the maintenance costs for the HDF are not as high as those for the HDT, and therefore, the maintenance rates for the HDF are higher than those for the HDT. A sudden fall in the HDF during the first year is due to construction termination. The HDF, then, starts increasing in an asymptotic manner until the year 2020. This increase is a result of the prioritized allocations of the budget to the worst condition of highways, i.e. the HDT. These allocations can be verified by a significant decrease in the HDT and a significant increase in the HSF during this period.

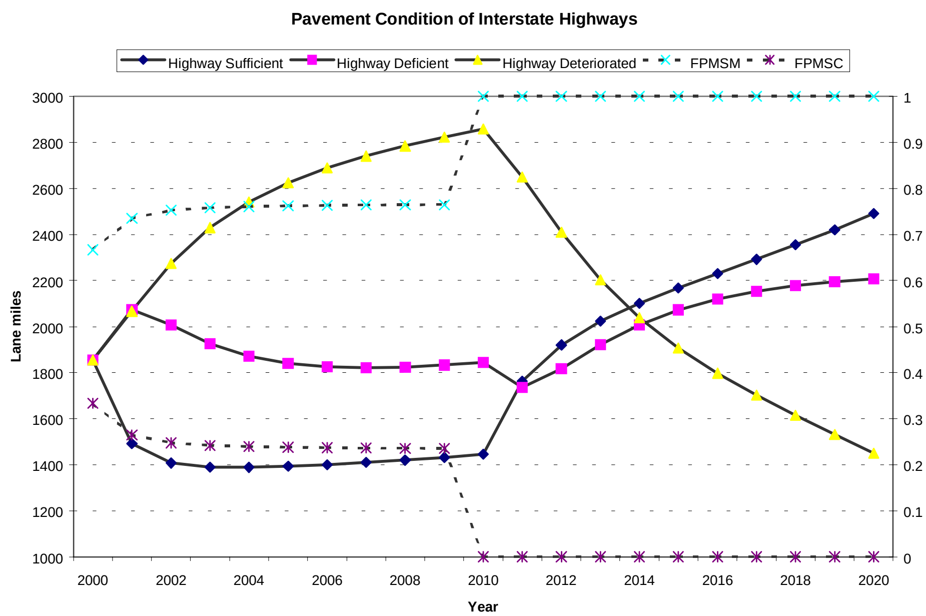

Figure 7.1 Pavement Condition of Interstate Highways

- **Primary Highways**

The changing pattern of the pavement conditions of primary highways is similar to that of interstate highways, except for the scale of each condition, as shown in Figure 7.2. Marginal decreases in the HDT and marginal increases in the HSF after the year 2010 are smaller than for interstate highways. These moderate changes are due to the fact that the total lane miles of primary highways are far more than those of interstate highways, and therefore there are more sections of highway that should be maintained. Also, relatively low maintenance rates compared to the long lane miles contribute to this moderate change. However, the overall pavement conditions improve after the termination of construction.

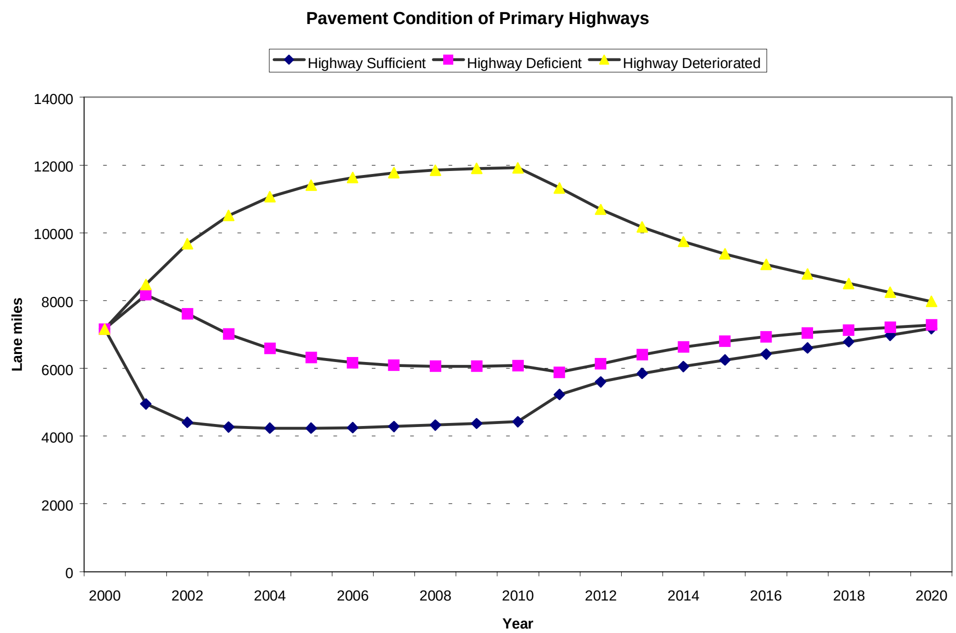

Figure 7.2 Pavement Condition of Primary Highways

- **Secondary Highways**

The lane miles of the secondary highways are the longest among the four highway systems. Their lengths are almost eight times those of interstate highways, and over four times those of primary highways. The large scale of highway miles requires a more intense management level than for interstate and primary highways. However, the maintenance rates for secondary highways are inevitably limited because of a limited budget. This disequilibrium between demand, i.e. highways in need of maintenance, and supply, i.e.

maintenance rates, causes deteriorating pavement conditions, even though the conditions improve slightly after the termination of construction, as shown in Figure 7.3.

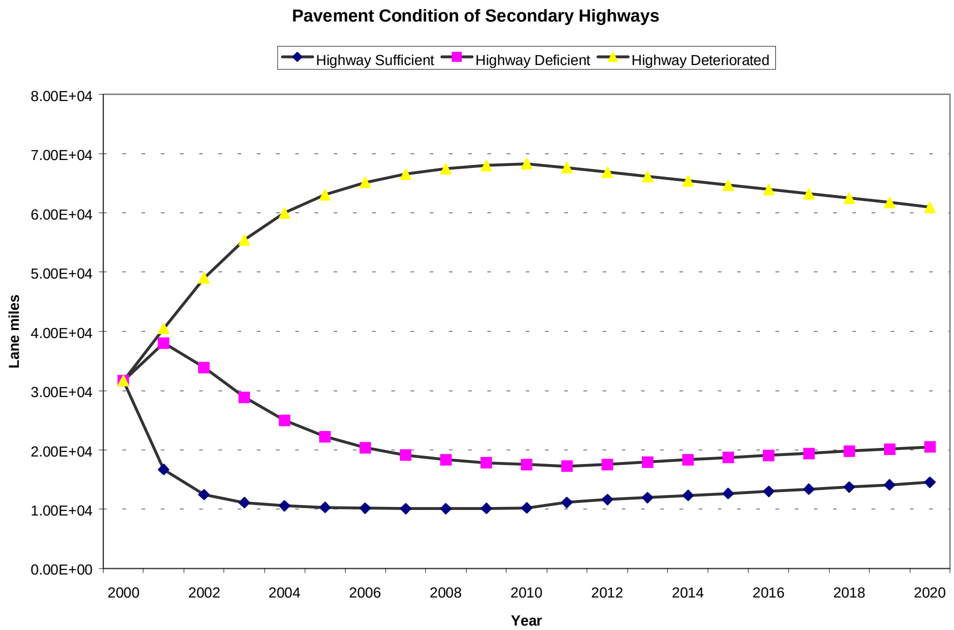

Figure 7.3 Pavement Condition of Secondary Highways

- **Urban Highways**

The pavement conditions of urban highways change in a similar pattern to those of primary highways, as shown in Figure 7.4. This similarity arises from the fact that the scale of urban highways and their maintenance costs are similar to those of primary highways.

7.3.2 Pavement Condition Indices of State Highways

The measurements of pavement conditions are performed by adopting two indices: a physical sufficiency index (PSI), and a functional adequacy index (FAI).

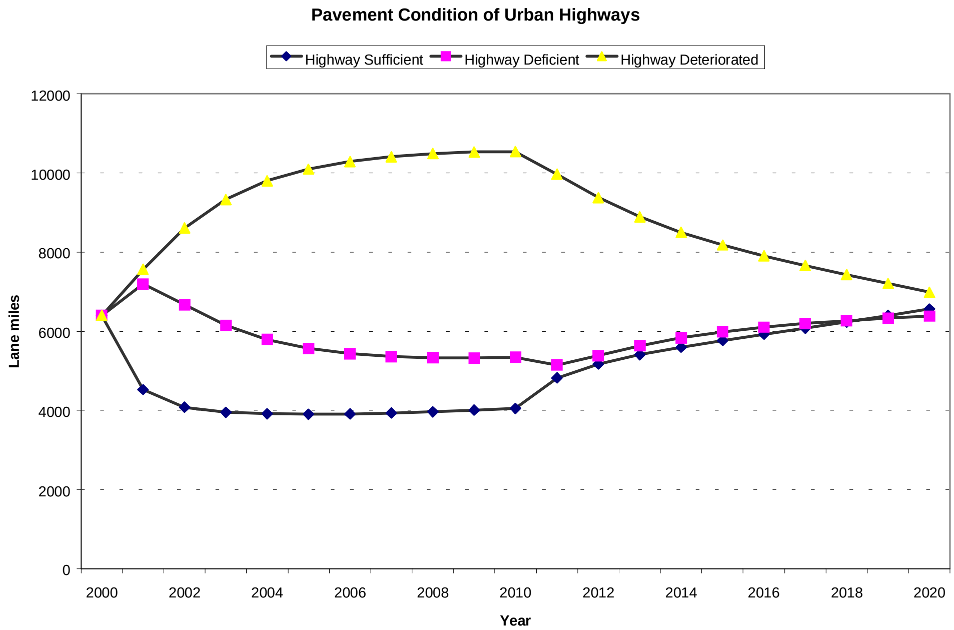

Figure 7.4 Pavement Condition of Urban Highways

- **Physical Sufficiency Index**

Figure 7.5 summarizes variations in pavement condition for the four highway categories in terms of PSI values. During the construction period between the year 2000 and the year 2010, the PSI drops in the early years and then stabilizes at a fixed value near to the year 2010. This stabilization is due to the allocation scheme modeled in this research. The scheme realizes the prioritized allocation of the budget by utilizing a state-dependent fraction formula, as described in Chapter 5 in detail. This scheme reduces further deterioration of highways by decreasing marginal decreases in the PSI over time, as shown in Figure 7.5. Without this allocation scheme, the PSI of each category of highway will drop to 0.5, the worst pavement condition.

After the termination of construction, the PSI values begin to increase because of increased maintenance activities. The interstate highways provide the highest pavement condition, and the secondary highways the lowest. The reason that the PSI of the interstate highways is the highest is that the lane miles of interstates are comparatively short, and thus, maintenance rates for interstates are relatively high. Also, a marginal increase in the PSI for interstate highways is the greatest, whereas the secondary highways show a slight increase.

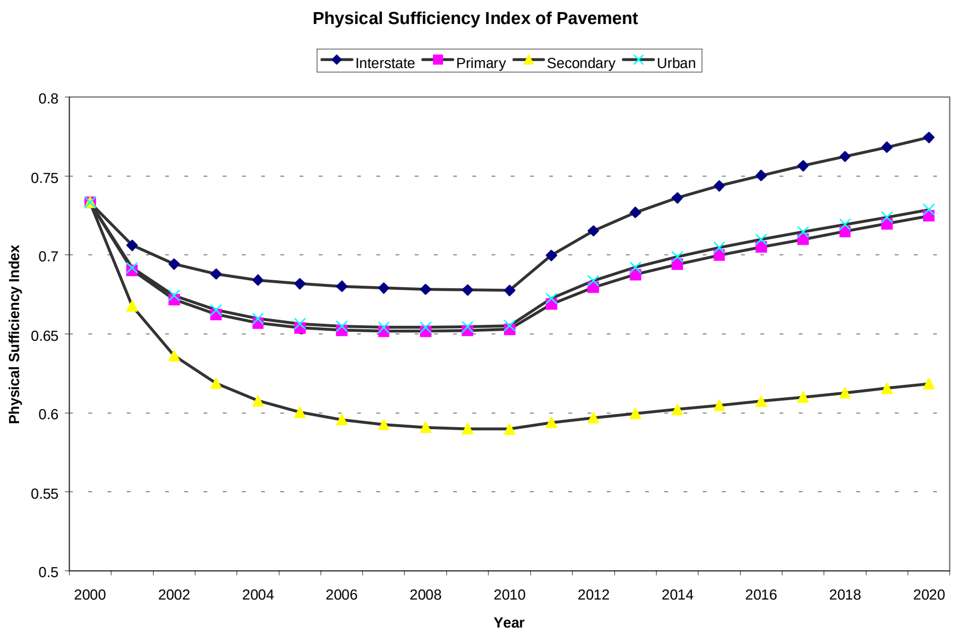

Figure 7.5 Physical Sufficiency Indices of Pavement

- **Functional Adequacy Index**

The functional capability of highways can be indicated by the value of the FAI. This capability is determined by an interaction between supply and demand. If the basic demographics such as population and the number of vehicles increase, the travel demand on highways also increases. To meet this growing demand, transportation facilities need to be improved in many ways, including construction or expansion. However, unlike the demand-side of transportation, the transportation supply is inevitably confined to its service due to limited resources. Thus, in most areas, a disequilibrium between supply and demand is observed, and leads to a reduction in the functional capability of transportation.

Figure 7.6 represents the FAI values for all highway levels obtained from the base run. For interstate highways, because of an expansion of highway lane miles during construction, the FAI moderately increases, even though travel demand also increases during this period. However, after construction, it decreases because no more lane miles are constructed on this facility and travel demand grows continuously. On the other hand, the values of the FAI for other facilities, i.e. primary, secondary, and urban highways, drop over the entire simulation time. This result is caused by relatively low construction rates. In other words, only small portions of highways are expanded, compared to their long lane-mile configurations.

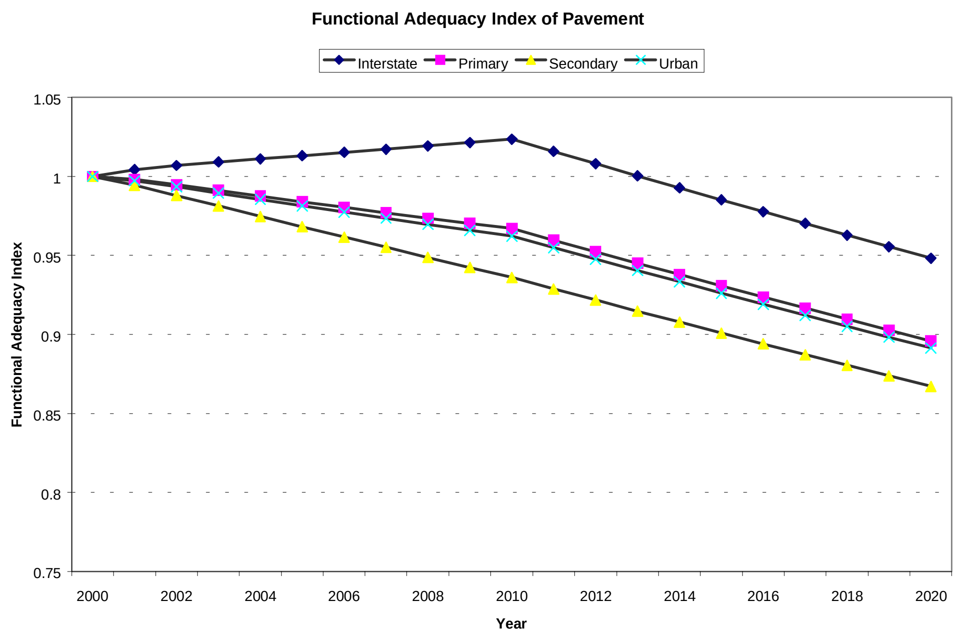

Figure 7.6 Functional Adequacy Indices of Pavement

7.3.3 Bridge Conditions of State Highways

The variations in bridge conditions over time are expressed in terms of the numbers of bridges in preferred condition (BPFC), in good condition (BGC), in poor condition (BPC), in serious condition (BSC), and in critical condition (BCC). The following interprets simulation results for each highway system.

- **Interstate Highways**

Because bridges are parts of highway sections, the construction of bridges is subject to the construction of the main pavement sections of the highway. Thus, during construction, the number of bridges also increases. Figure 7.7 shows trajectories of the bridge conditions of interstate highways before and after the construction termination time. At the beginning of the simulation, the BPFC increases significantly due to the new construction of bridges. The BCC also increases because of a lack in the maintenance budget. The prioritized allocation scheme applied in the BMS reduces the marginal increase in the BPFC and decreases the BCC. This scheme also realizes the increase in the BGC, which had been dropping initially. After the termination of construction, the conditions of bridges begin to stabilize because of an increase in maintenance rates.

- **Primary Highways**

The bridge conditions of primary highways are worse than interstate highways, because there are more bridges to be maintained and the maintenance budget is not sufficient to cover all bridges. However, the prioritization method realizes a stabilization in all condition levels of bridges, as shown in Figure 7.8. It should be noted that the worst level of bridge condition increases during the construction period because a large amount of the budget is invested in construction rather than maintenance. This deterioration becomes more serious for the secondary highways.

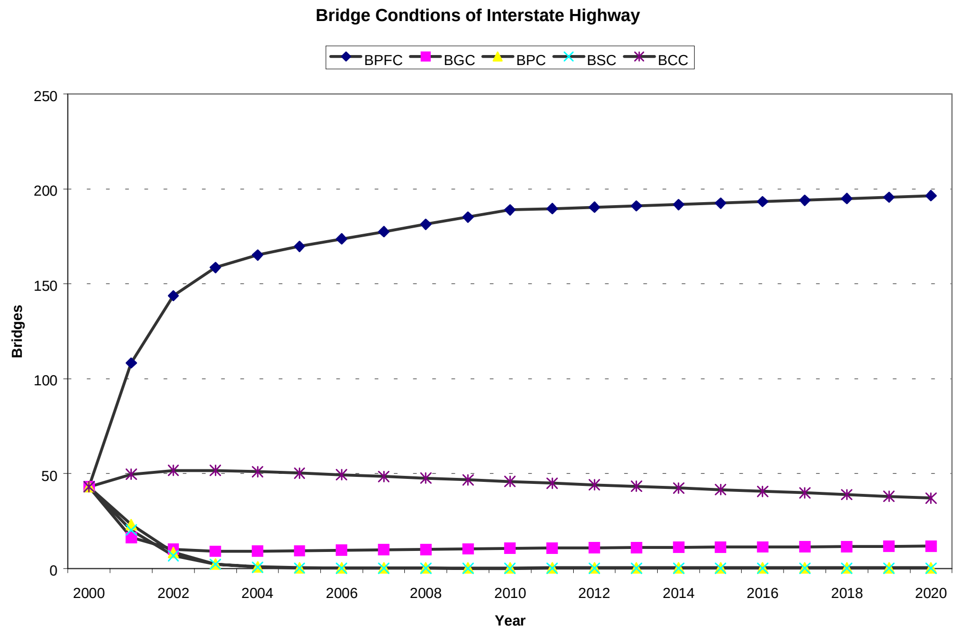

Figure 7.7 Bridge Conditions of Interstate Highways

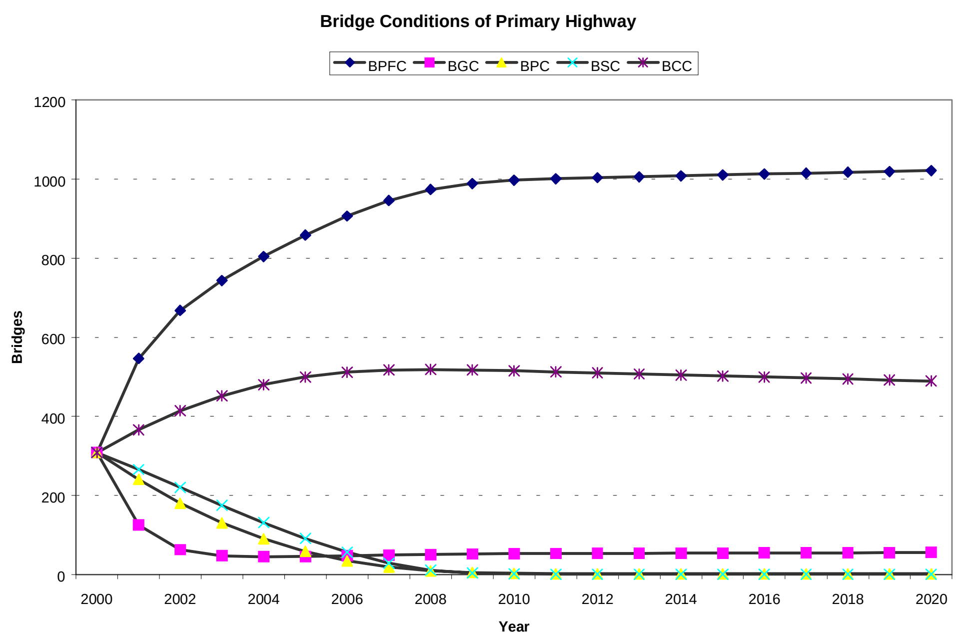

Figure 7.8 Bridge Conditions of Primary Highways

- **Secondary Highways**

The greater number of bridges on secondary highways and the low maintenance rate result in the worst conditions, as shown in Figure 7.9. Noticeable in this result is that the BCC increases almost as much as the BPFC during the construction period. The increase in the BPFC is due to the new bridges constructed, and the increase in the BCC is caused by the shortage in the maintenance budget, and in turn, in maintenance activities for bridges. However, due to prioritization, the deterioration speed is reduced as time passes. Also, it is observed that the BGC increases slightly, and the BPC and the BSC decrease.

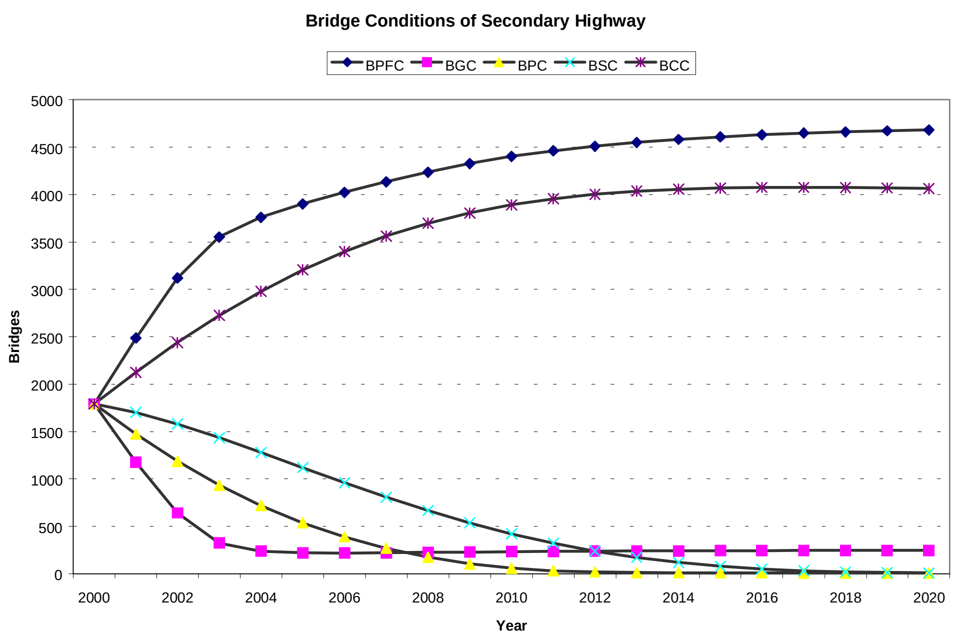

Figure 7.9 Bridge Conditions of Secondary Highways

- **Urban Highways**

The bridge conditions of urban highways show similar trajectories to those of primary highways, because both facilities have similar numbers of bridges and they are provided similar levels of maintenance. Figure 7.10 shows the variations in bridge conditions over the analysis period.

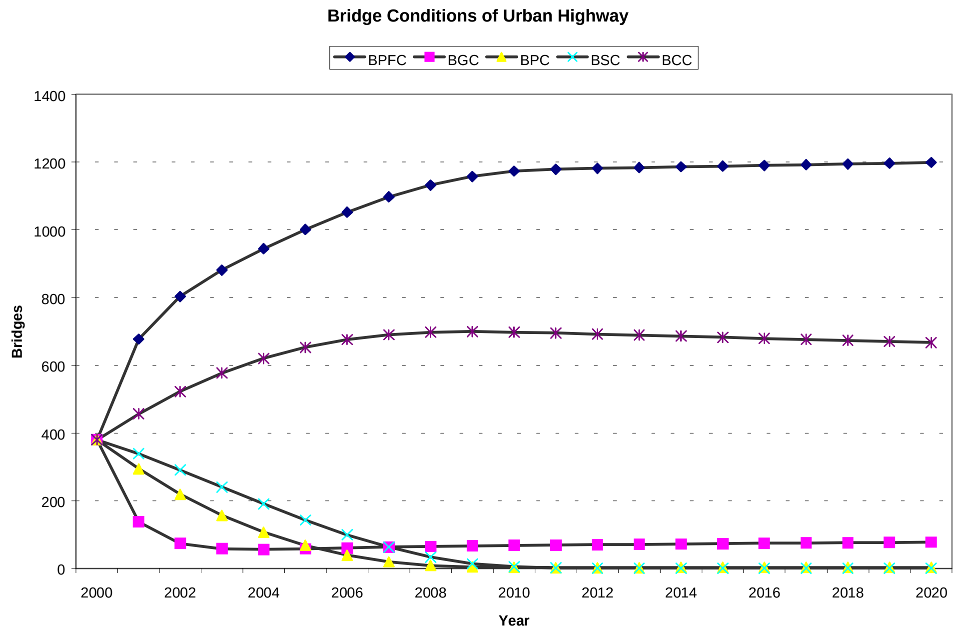

Figure 7.10 Bridge Conditions of Urban Highways

7.3.4 Bridge Condition Indices of State Highways

The measurements of bridge conditions are performed by adopting two indices: a physical sufficiency index of bridges (PSIB) and a functional obsolescence rate of bridges (FORB).

- **Physical Sufficiency Index of Bridges**

Figure 7.11 summarizes the overall bridge conditions of the four highway categories. In the construction period, the PSIB values of primary, secondary, and urban highways increases slightly. As expected, bridges on the interstate highways are the most responsive to maintenance activities, and their PSIB values are higher than other highways. The bridges on the primary and urban highways provide similar condition levels, and the bridges on the secondary highways have the lowest condition. It should be noted that a moderate increase in the physical sufficiency of bridges during construction is caused primarily by an increase in new bridges. On the other hand, the bridges in the worst condition also increase in this period, as shown in Figures 7.7 through 7.10, because of the deterioration of the existing bridges. This increase in the BCC lowers the level of the PSIB, which would have been even higher without the adverse impact of construction.

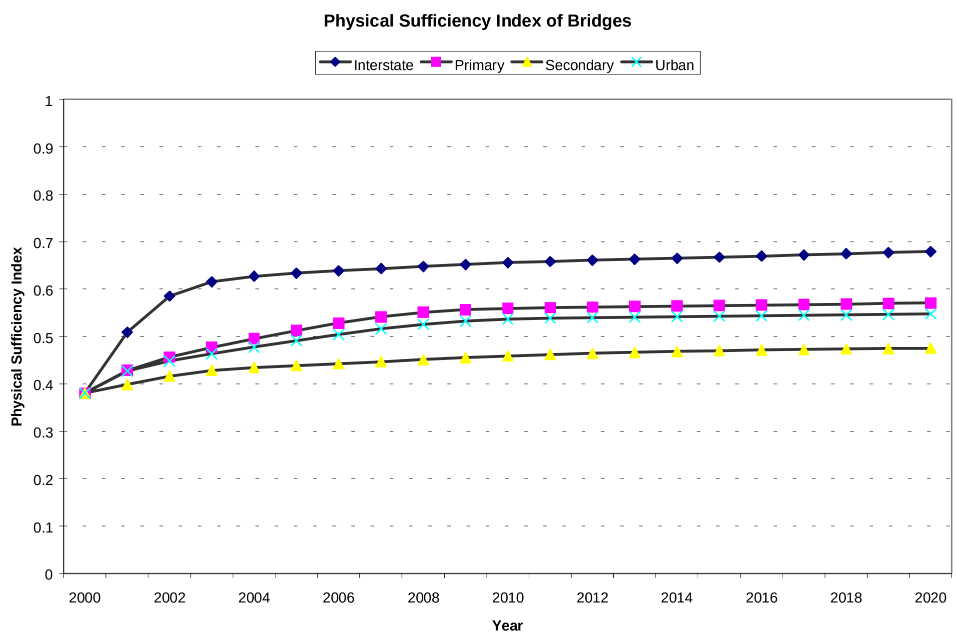

Figure 7.11 Physical Sufficiency Indices of Bridges

- **Functional Obsolescence Rate of Bridges**

Figure 7.12 shows the values of the FORB for the bridges on the highways. The decision as to whether or not a bridge is functionally adequate is dependent on the traffic load of the bridge. If a bridge is functionally inadequate, the expansion of the bridge is an assured alternative to reducing its volume capacity ratio. As seen in Figure 7.12, the FORB of interstate highways is reduced during the construction period. After this period, the rate increases due to a growing travel demand. However, because of the prioritization scheme, the marginal increase of the rate decreases, and the rate begins stabilizing at 0.29. The rates of primary and secondary highways provide similar transition patterns, except that their rates are higher than the interstate highway's. The cause of these high rates can be found in the fact that the widening rates determined by the limited budget are not high enough to manage all the bridges on the highway system. The FORB of the secondary highways represents the number of bridges in critical condition, which is regarded as a part of the functionally obsolescent categories in this research. The traffic load on secondary highways is negligibly small, so the traffic factor does not provide significance to the functionality of bridges.

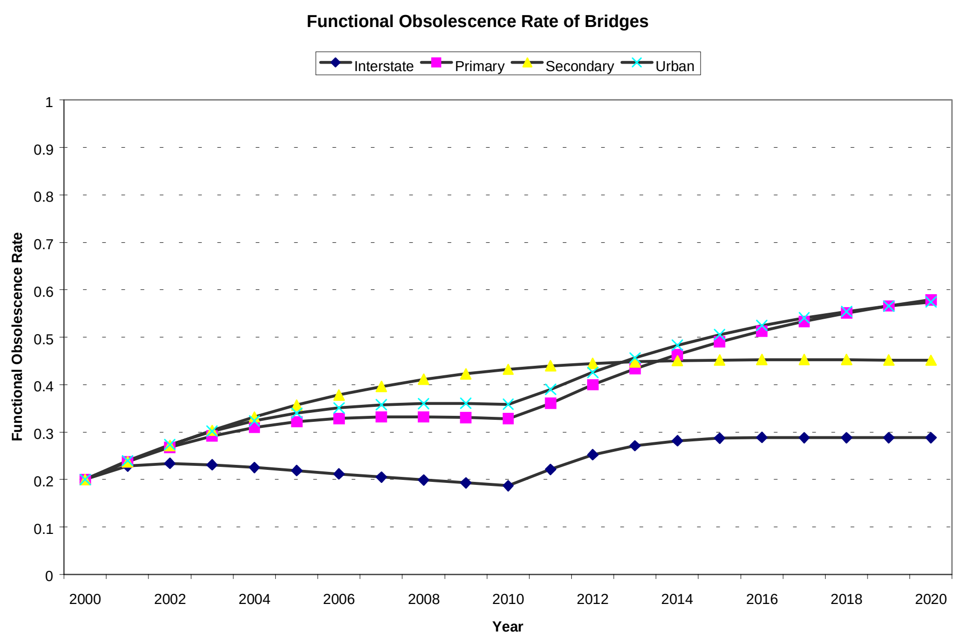

Figure 7.12 Functional Obsolescence Rate of Bridges

7.3.5 Benefit Cost Ratio

An improvement in the transportation infrastructure benefits the transportation user and the agency in terms of cost savings. A good physical condition of the highway system also contributes to these savings. The level of savings can be measured by adopting a benefit cost ratio. Figure 7.13 provides the benefit cost ratios for interstate highways over the analysis period. At the beginning of this period, construction and maintenance activities help produce a ratio as high as 2.64. Then, this ratio decreases slightly during the construction period, and drops to 2.55 in the year 2010. However, after the termination of construction, it increases significantly up to 3.91 in the year 2020. Noticeable in this figure is that the growth pattern of the benefit cost ratio follows a similar pattern to the physical sufficiency index presented in Figure 7.5. Thus, the benefit cost ratio provides a positive relationship with the physical condition of highways.

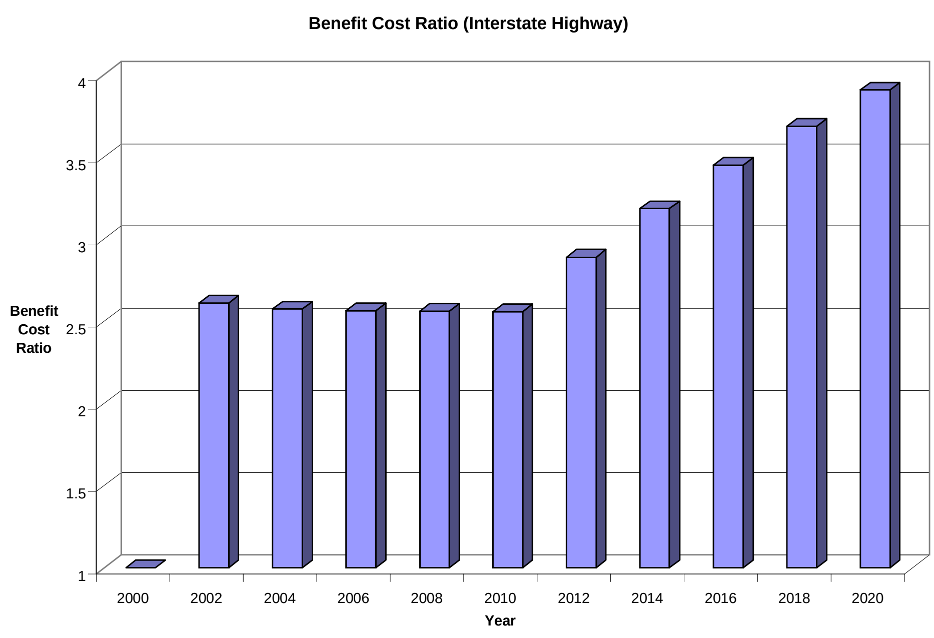

Figure 7.13 Benefit Cost Ratio of Interstate Highways

7.3.6 Physical Conditions of District Highways

To be able to simulate the physical conditions of highways for nine construction districts in Virginia, the TPMSHM needs to be expanded by adding one more dimension to the corresponding parameters. This addition increases the four elements of state highways to thirty-six elements, and requires the extension of the current program capacity to as much as nine times that presently shown. However, the DYNAMO program used in this research, Professional Dynamo 4.0 for Windows, is limited in its capacity to expand this dimension. The current TPMSHM consists of about 500 parameters and ten sub-programs, and it already consumes 95 percent of the program's capacity when it is compiled and simulated. Further expansion exceeds its 100 percent capacity and causes the generation of run errors. To overcome this limitation, nine separate simulations for the nine districts need to be implemented. Several parameters should be changed in their values to reflect the characteristics of each district. The major parameters are:

- Highway lane miles for each category of the highway system,
- Number of bridges for each category of the highway system, and
- Allocation shares of transportation revenue by construction district.

The first two parameters can be obtained easily from various survey documents [FHWA annual, CPS annual, DTS annual]. The estimation of the third parameter can be facilitated by surveying the past history of allocation shares. Table 7.3 summarizes allocation percentages by each construction district during the period between 1988 and 1993 [Smith 1993]. In the simulation of the future highway conditions for each district, the average shares over this period are used under the assumption that these shares are not changed during the analysis period.

Table 7.3 Allocation Shares of Transportation Revenue by Construction District

District	1988	1989	1990	1991	1992	1993	Average
Bristol	9.1	8.6	9.4	9.5	8.8	8.6	**9.0**
Culpeper	5.2	4.7	5.2	5.0	5.0	4.9	**5.0**
Fredericksburg	6.1	5.2	5.8	5.3	4.9	5.1	**5.4**
Lynchburg	6.5	6.4	6.9	6.6	6.4	6.6	**6.6**
No.Virginia	17.3	17.3	18.4	20.1	27.3	24.0	**20.8**
Richmond	14.1	15.0	13.3	13.2	12.0	13.1	**13.5**
Salem	9.3	9.1	9.6	9.3	8.7	9.1	**9.2**
Staunton	7.3	7.2	7.8	7.3	6.8	6.8	**7.2**
Suffolk	25.1	26.3	23.7	23.7	20.1	21.8	**23.5**

Source: Smith 1993

Figure 7.14 shows one of the simulation results, the pavement condition of urban highways in the Salem district. This pattern of system behavior is similar to that of urban highways at the state level, as seen in Figure 7.4. The changes in the physical sufficiency indices for the four highway systems in the Salem district are shown in Figure 7.15. The interstate highway provides the highest level of physical sufficiency among other systems, and this sufficiency increases even higher during the non-construction period. The good condition of the interstate highway is caused by higher budget shares for interstate highways of Salem than those of other districts and its shortest mileage among the highways in Salem district.

The trajectories of the bridge conditions in the Salem district over the 20-year period also provide similar patterns to those found in the state conditions. Figures 7.16 and 7.17 represent the variations in the physical condition of bridges on the urban highways.

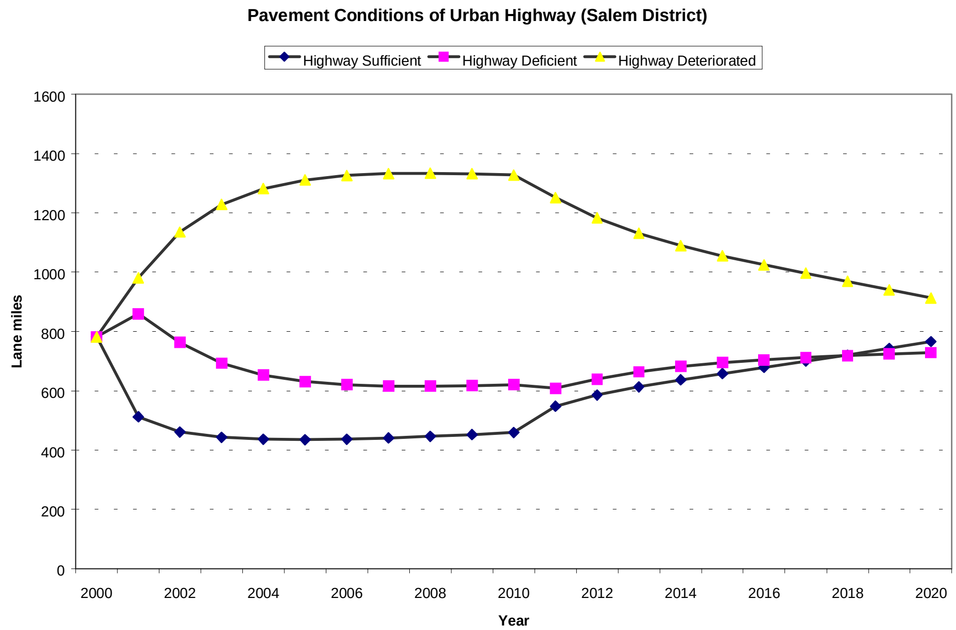

Figure 7.14 Physical Conditions of the Urban Highways (Salem District)

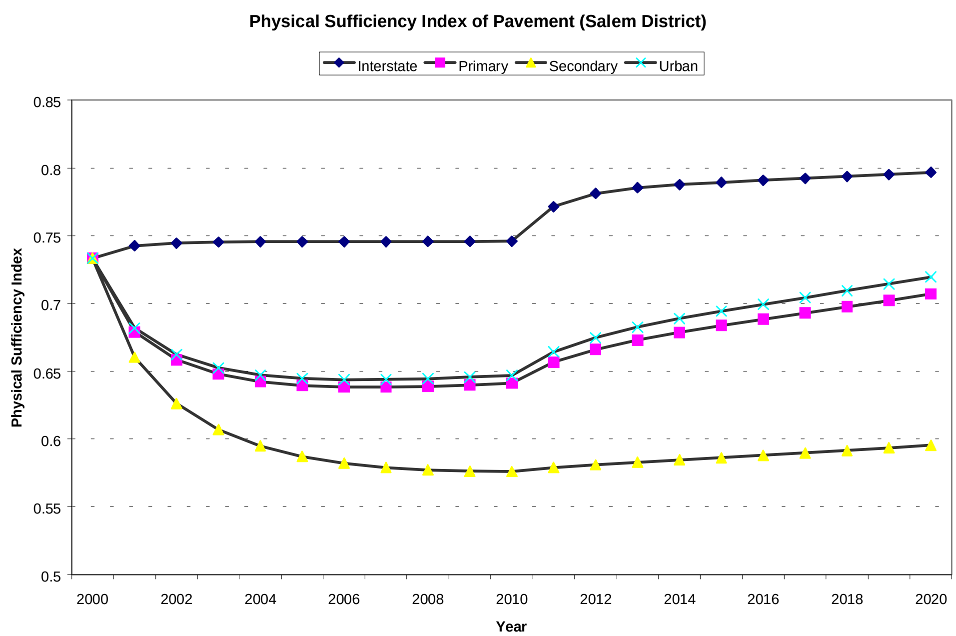

Figure 7.15 Physical Sufficiency Index of Pavement (Salem District)

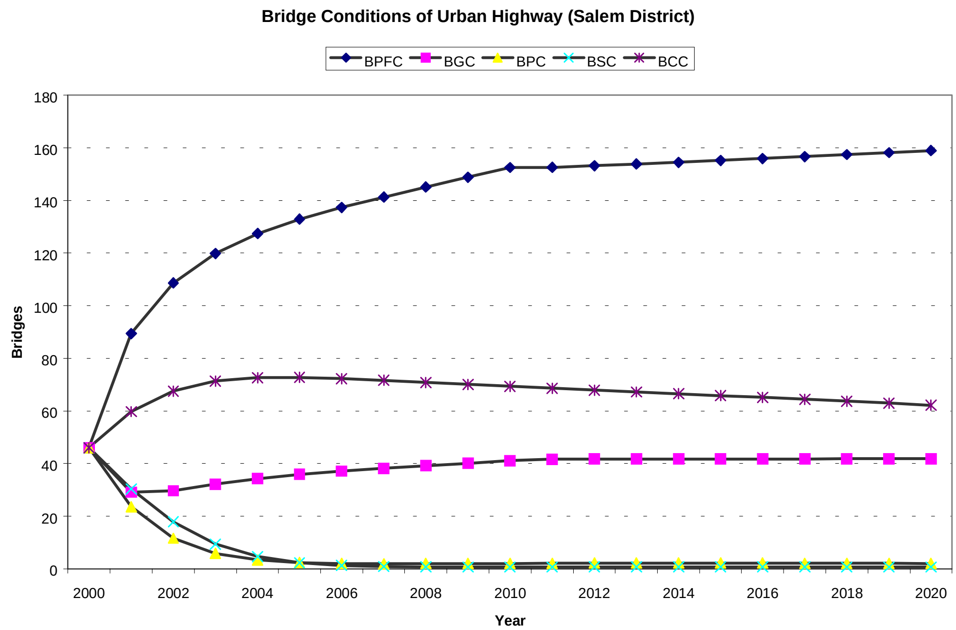

Figure 7.16 Bridge Conditions of the Urban Highways (Salem District)

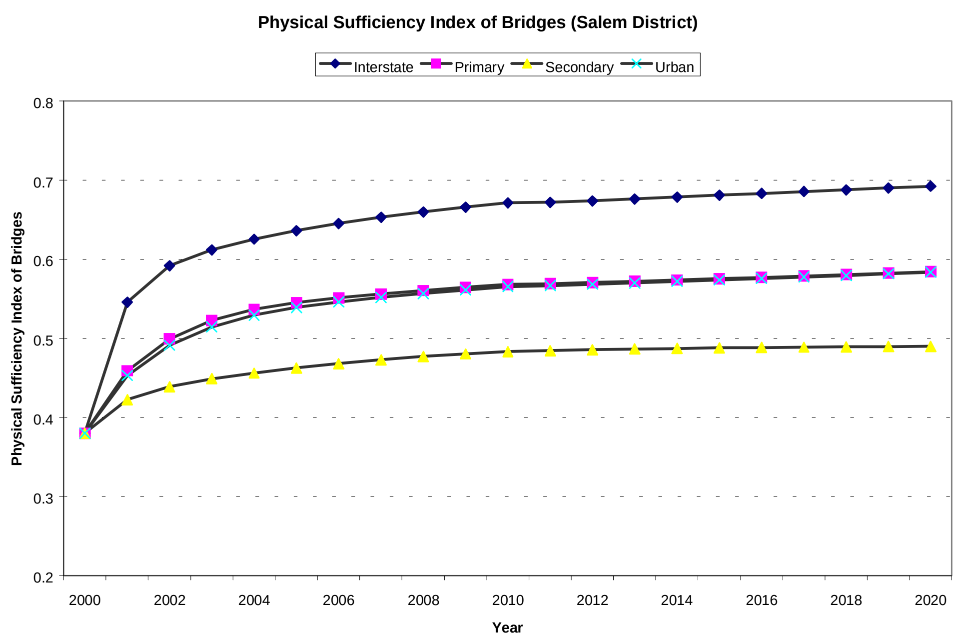

Figure 7.17 Physical Sufficiency Index of Bridges (Salem District)

7.4 Analysis of Fuels Tax Policy

As indicated by the behavioral patterns of highways observed in the base run, the level of highway condition is determined by the magnitude of highway management activities. The magnitude is also determined by the size of the state transportation revenue. Thus, establishing a sufficient transportation revenue should be essential in maintaining the state highway system in good condition. As described in the revenue generation process in the Finance Subsystem of the TPMSHM, several political factors affect revenue size: motor fuels tax, vehicle sales and use tax, vehicle license fees, and state sales tax. In Virginia, raising the state's fuels tax is a recent issue that has the potential for overcoming the annual shortfall in transportation revenue [Roanoke Times 1997]. The problem with raising the fuels tax is that it is difficult to anticipate its impact on transportation revenue, and eventually on highway conditions. The following analysis concentrates on this issue, and strives to visualize the anticipated effects on highways in terms of its benefits and costs.

To investigate various rates of fuels tax, a term for a fuels tax ratio is adopted. The fuels tax ratio expresses the ratio of the assumed rate of fuels tax over the current rate, 17.35 cents per gallon for the HMOF and the TTF. In this analysis, the fuels tax ratios ranging from 1.0, i.e. the current rate, through 3.0, i.e. three times the current rate, are considered with a 0.25 increment.

First, changes in the amount of transportation revenue according to different fuels tax ratios are examined. Figure 7.18 shows the relationships between the transportation revenue and the fuels tax ratio for selected years. As seen in this figure, the revenue increases until the fuels tax ratio reaches 2.0. Then, the revenue decreases with a further increase in the tax ratio. This result implies that an increase in the fuels tax does not necessarily guarantee an increase in the revenue at some rate of fuels tax. This relationship can be explained as a human reaction to the increasing price. That is, because of a high gasoline price, people are less willing to buy a new or used car or to drive in daily life. This reluctance affects and reduces vehicle registration and vehicle miles of travel. This reduction, then, negatively affects the revenue generation process, and decreases the amount of state revenue.

The changes in the revenue size also affect the physical condition of the highway system. Figure 7.19 shows variations in the PSI of interstate highways with regard to several ratios of fuels tax for the years 2010 and 2020. If the fuels tax is doubled from the current rate, the values of the PSI are raised to their maximums, i.e. 0.692 in the year 2010 and 0.793 in the year 2020. The further increase in fuels tax results in a decrease in the PSI, or the deterioration of highway conditions. The behavioral pattern observed in this figure can be interpreted as a response to the budget changes shown in Figure 7.18. In other words, the size of the budget directly affects the physical condition of highways.

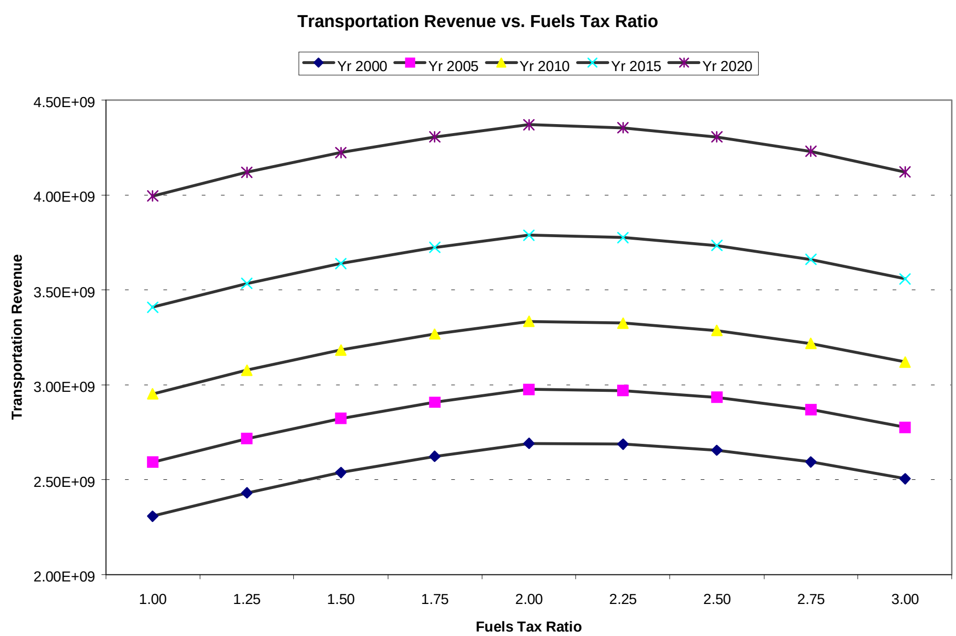

Figure 7.18 Total Revenue vs. Fuels Tax Ratio

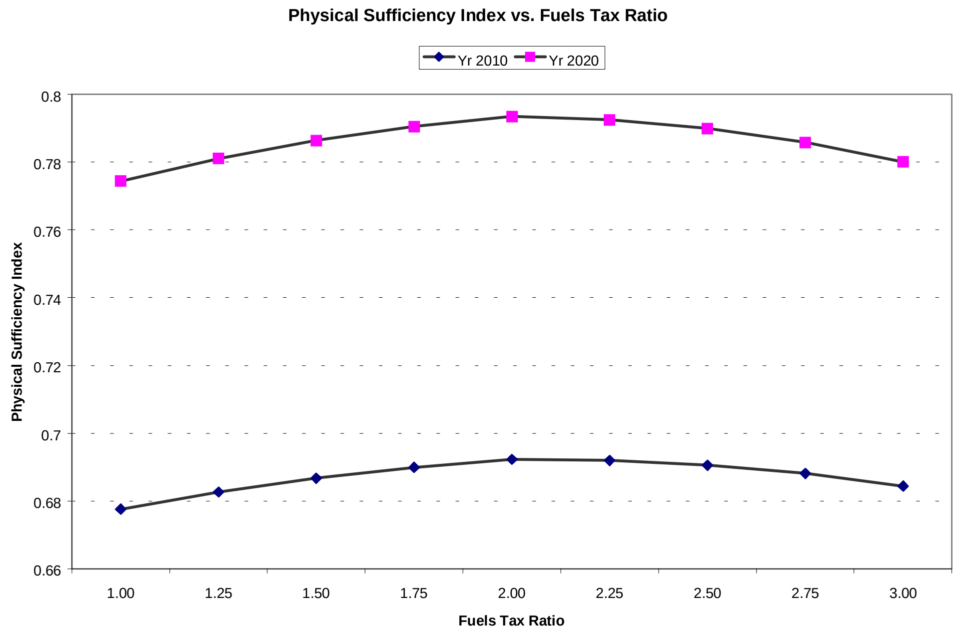

Figure 7.19 Physical Sufficiency Index vs. Fuels Tax Ratio

The highway user benefits increase with the reduction of travel time and the savings in accident costs and vehicle operating costs. The improvement of the physical condition of highways contributes to the increase in user benefits because of reduced friction on the road, an improved fuel efficiency, and reduced damage to vehicles. The user benefit index, as a measure of effectiveness for highway user benefits, reflects how much the physical condition of highways contribute to an increase or a decrease in the user costs.

The user benefit index (UBI) is calculated as

$$UBI = \frac{(TUC_0 - TUC_n) \cdot (ATV_0 + ATV_n)/2}{CPC_n + AE_n - (CPC_0 + AE_0)} \qquad (7.1)$$

where,

$TUC_{0,n}$: total user costs of the base and alternative cases, respectively,

$ATV_{0,n}$: annual traffic volumes of the base and alternative cases, respectively,

$CPC_{0,n}$: capital costs of the base and alternative cases, respectively, and

$AE_{0,n}$: annual expenditures of the base and alternative cases, respectively.

The numerator represents the annual amount of user cost savings due to highway improvements. The denominator expresses the difference in the annual investment between the base case and the improvement alternative. This index represents the amount of user savings that can be achieved with additional investments for the alternatives to the base case. The higher the UBI, the more cost-effective the alternative.

Figure 7.20 shows measures of the UBI of interstate highways as functions of the fuels tax ratio. The UBI increases with an increase in the fuels tax until the ratio reaches 2.0. At this tax ratio, a maximum UBI is achieved. However, a further increase in the fuels tax causes a decrease in the UBI. The reason that the UBI drops is that physical sufficiency is reduced in these high tax ranges because of the shortage of transportation revenue.

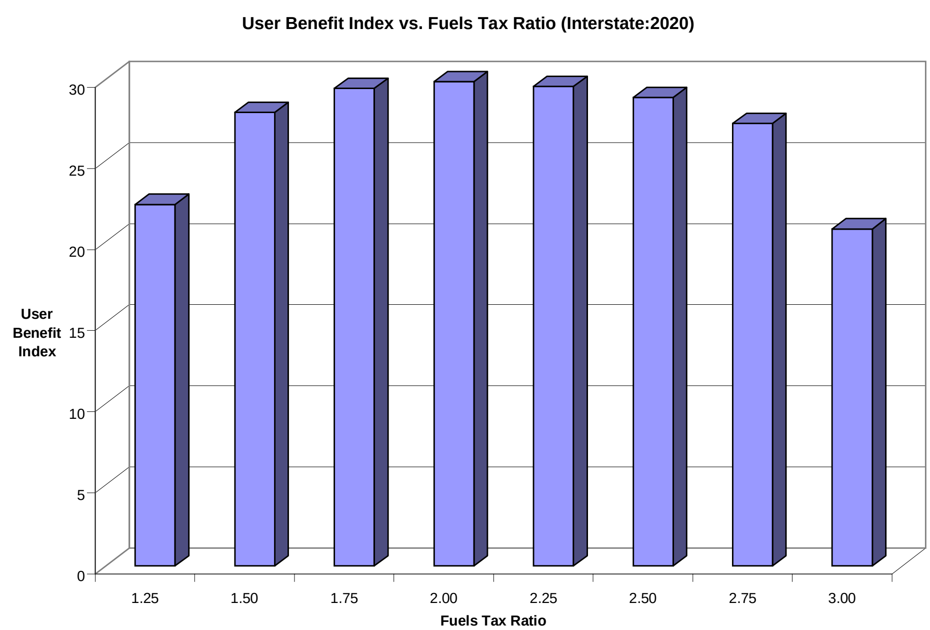

Figure 7.20 User Benefit Index vs. Fuels Tax Ratio (Interstate: Year 2020)

Figure 7.21 provides another example of the relationship between user benefits and fuels tax for urban highways in the year 2020. A similar shape of the results of changes in user benefits to Figure 7.20 is observed in this result, except for the scale of the UBI. The UBI for urban highways is calculated as 9.8 at its maximum, whereas the interstate highways generate a UBI as high as 29.9. This difference in user benefits should be related to the difference in physical sufficiency between the highway systems, as shown in Figure 7.22. This figure compares the UBI values of the four highway categories for the selected years. It also implies the significance of the construction termination time, from which a marginal growth in user benefits increases.

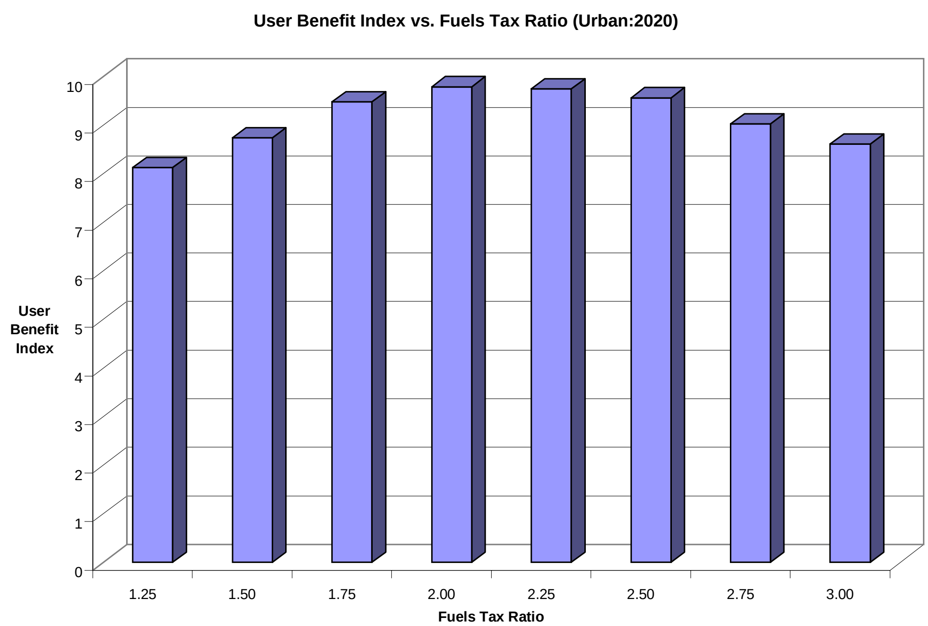

Figure 7.21 User Benefit Index vs. Fuels Tax Ratio (Urban: Year 2020)

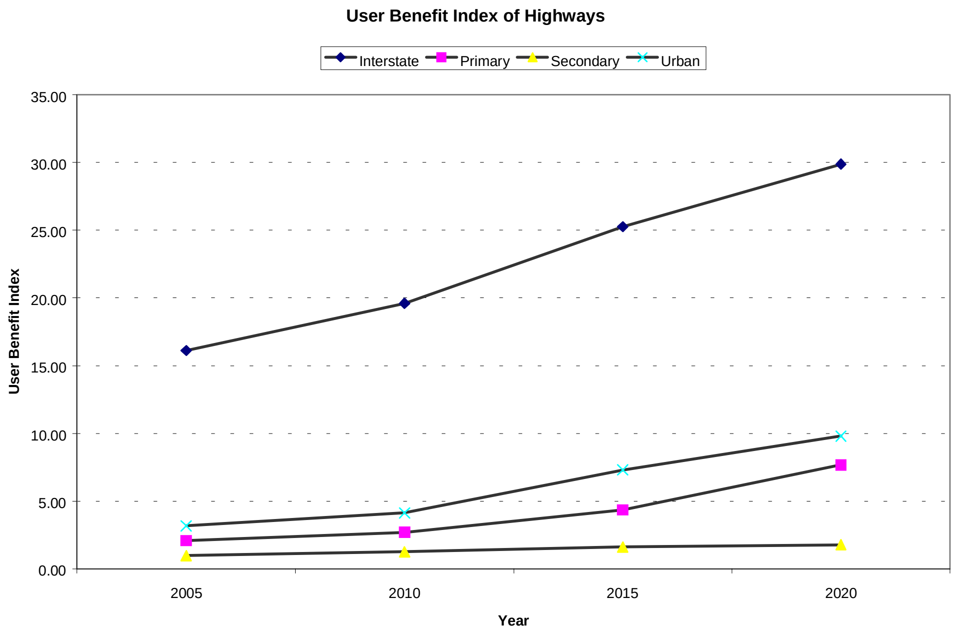

Figure 7.22 User Benefit Index of Highways

In the figures from Figure 7.18 through Figure 7.22, similar patterns to the system reaction to the amounts of fuels tax are observed. There is a fuels tax optimum rate, which maximizes the state revenue, the highway conditions, and the user benefits. Further, it is found that there are a series of positive relationship among transportation revenue, the physical condition of highways, and the highway user benefits. Basically, the transportation revenue plays an essential role in determining the quality of the highway system.

7.5 Cost Sensitivity of the TPMSHM

This research utilizes various unit-cost items, such as construction, replacement, expansion, and maintenance costs, based on the data surveyed in previous research [de la Garza et al.]. Most of these costs have been calculated for general practices under the some assumptions, so that actual management costs applied in the field could deviate from these averaged costs. If different costs from those used in this research are considered, the TPMSHM could generate a different system behavior. Thus, the cost sensitivity of this model should be investigated. This section examines the impacts of a 10 percent increase in the maintenance costs of highways. Figure 7.23 shows changes in user benefits for the four highway systems as final outputs of the simulation. For the case of twice the current fuels tax in the year 2020, the UBI of interstate highways decreases by as much as 23.7 percent, i.e. from 29.9 to 22.8, with a 10 percent increase in unit costs. For urban highways, the UBI is reduced by 23.5 percent. These results are caused by the reduction of maintenance rates due to the increase unit cost. Figure 7.23 indicates the significance of data accuracy. In other words, the use of the wrong data could cause the system to be inaccurately interpreted, because it generates deviated results. Data accuracy can be achieved by the selection of appropriate data collection methods. These methods could vary from the investigation of the maintenance history to the expert's estimation. No matter what type of collection is utilized, the importance of data acquisition should always be emphasized in the course of analysis.

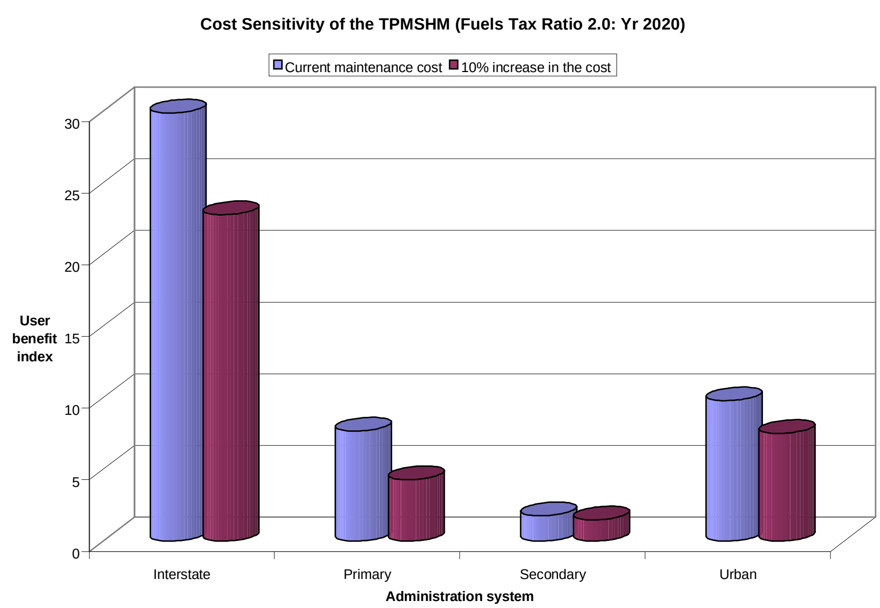

Figure 7.23 Cost Sensitivity of the TPMSHM

CHAPTER 8
DATA AND DISPLAY BASES

8.1 Data Base for TPMSHM

Once the model has been formulated, it must be fitted to the particular situation under study. This means that the parameters of the equations are estimated in order to represent the available data as closely as possible. Model development and data collection progress together and, in principle, are never complete. The refinement of the model should follow analysis of the data and facilitate the subsequent collection of more accurate data. A frequent mistake is to collect data and then analyze them without knowing the relationship between the parameters of an MBMS and the objectives of the study, which require particular data collection and interpretation. The type of data and the number of variables should be determined and collected after the model is formulated, in order to develop the model further.

In research, the collection of data means measurements and observations, and once these are made, they must be organized, evaluated, and interpreted. Moreover, whenever measurements and observations are made, inevitably, errors are made. Because no measurement or observation is free of error, steps must be taken to evaluate their precision and their accuracy. Precision is descriptive of the degree of care and refinement employed in making measurements or observations; accuracy is descriptive of the correctness of the results. Precision can be regarded as indicative of the degree of care employed in the operation; accuracy can be regarded as indicative of the exactness of the result.

The central problem in discovering new knowledge in the real world consists of observing a portion of the real world, termed a sample, and on this basis statements are made about the whole based on an observation of a part. This routine operation is a part of the discipline of statistics. Statistics is also concerned with many elements relevant to the design of a DSS, including data collection, data reduction, data processing, parameter estimation, and confidence analysis.

The types of data used in TPMSHM range from basic demographics to transportation-related parameters. Because the evolution patterns of socioeconomic data are uncertain and irregular in their nature, the exact prediction of future behavior is almost impossible. The effort, then, is to concentrate on reducing deviations from the observed pattern and further, from the expected pattern. The observed behavior of data examined in this research falls into two categories: highly fluctuating growth and persistent growth with moderate fluctuation.

The former case can be exemplified by using hypothetical data, as shown in Figure 8.1. In this case, the selection of a data point causes high deviations from actual values in other data points. One method used to minimize these errors for all of the data points is to apply a fitted regression line [Walpole and Myers 1993]. This line is characterized by a regression equation such as

$$\hat{y} = a + bx \tag{8.1}$$

where, the estimates a and b represent the y intercept and slope, respectively. In this equation, each pair of observations satisfies the relation

$$y_i = a + bx_i + e_i \tag{8.2}$$

where, e_i is called a residual and describes the error in the fit of the model at the i th data point. By using the method with the least squares, the parameters a and b can be found so that the sum of the squares of the residuals is a minimum.

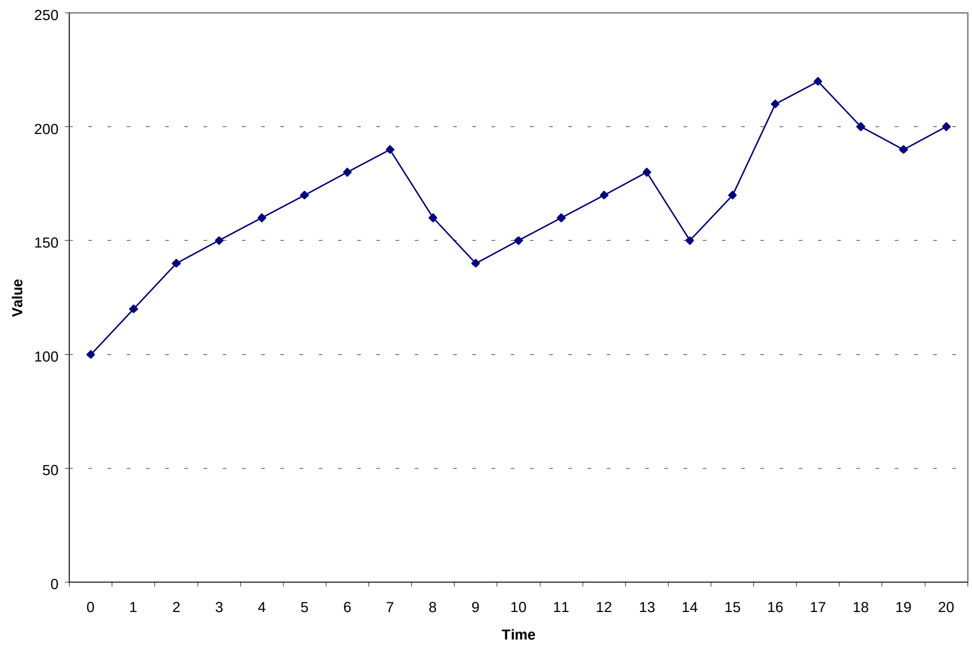

Figure 8.1 Hypothetical data with highly fluctuated growth

Figure 8.2 depicts the line fit to the hypothetical set of data using regression analysis. In this research, the estimated trend represented by the fitted regression line is used for the estimation of a parameter.

The latter case can be exemplified using hypothetical data, as shown in Figure 8.3. Compared to Figure 8.1, the growth pattern is somewhat moderate rather than highly fluctuating. In this case, it is useful to apply an annual growth rate to fit the observed data. The annual growth rate can be obtained from the following formulation:

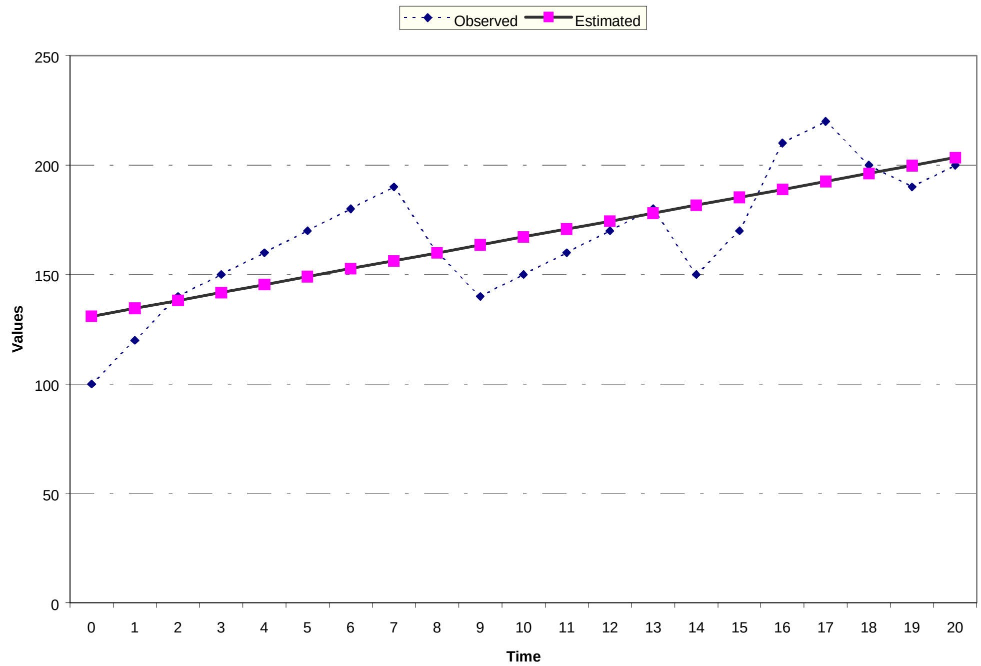

Figure 8.2 Regression fit for data with highly fluctuated growth

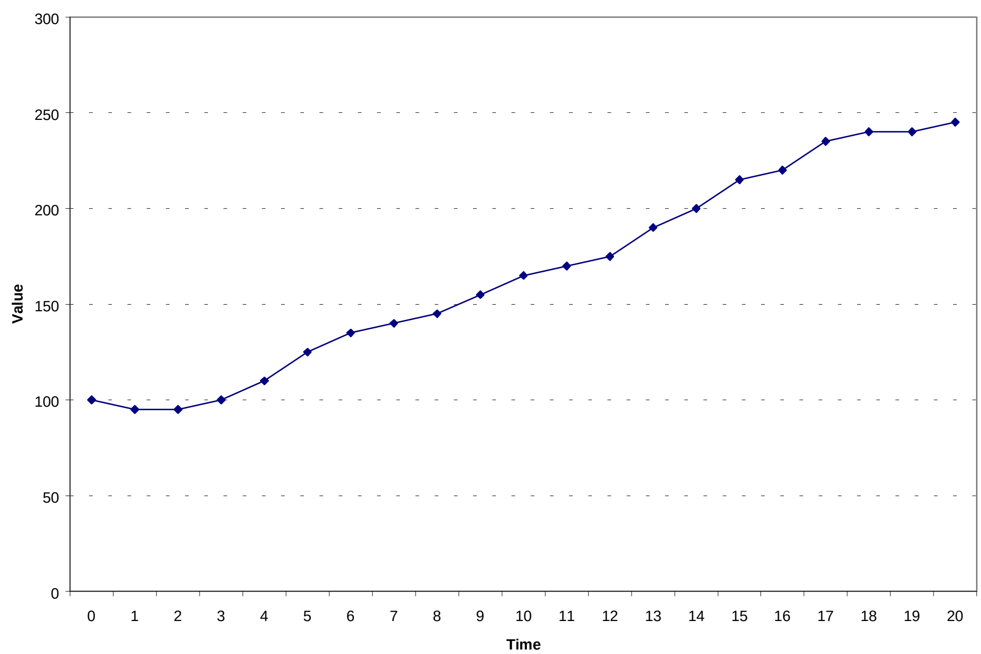

Figure 8.3 Hypothetical data with moderately fluctuated growth

$$r = (O_t/O_0)^{\frac{1}{t}} - 1 \tag{8.3}$$

where O_t and O_0 are values of observed data at times t and 0, respectively. The annual growth rate, r, can then be used to calculate estimated values as shown in Equation 8.4. It should be noted that, in predicting the future values of a parameter, this annual rate is assumed to persist in the future.

$$E_t = E_0 \cdot (1 + r)^t \tag{8.4}$$

where E_t and E_0 are values of estimated data at times t and 0, respectively. Figure 8.4 depicts the comparison between observed data and estimated data that have been calculated using Equations 8.3 and 8.4.

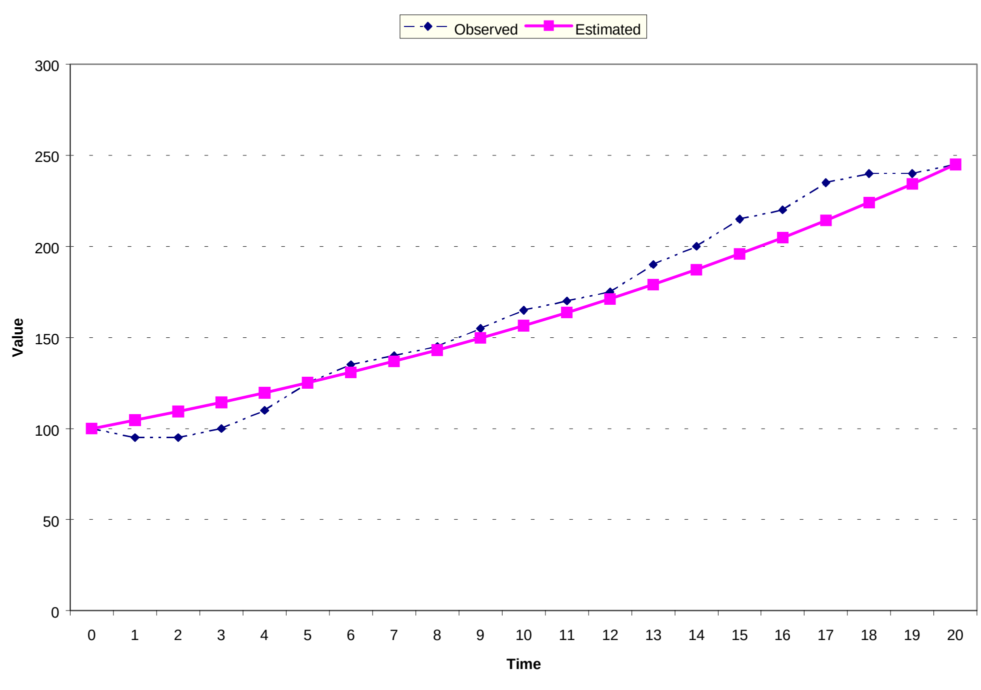

Figure 8.4 Data estimation using annual growth rate

The DBMS in this research defines data that should be routinely collected and processed into information so as to automatically update parameter values in the various subsystems of the TPMSHM. The design of the data base for TPMSHM is performed by defining fields and records. The field represents a column of data with a common data type and a common set of properties. The data type refers to the characteristics of a variable that determine what kind of data the variable can hold. The major types include text, numeric, binary, float, decimal, currency, time, or user-defined types. The record is a set of related data about various parameter items. Each record is composed of a set of related fields. Each field defines one attribute of information for the record. Taken together, a record defines one specific unit of retrievable information in a data base.

The construction of a data base can be facilitated by using various commercial data base programs such as dBase, FoxPro, and MS Access. These programs allow the user to design the structure of a data base, to retrieve desired data, to organize data, and to generate a data report table in an easy and efficient manner. They are also capable of storing large-scale data groups in timesaving and organized ways. Common to these programs is that their organizations of data are based on a relational structure consisting of a series of fields and records. They are able to relate the common characteristics of fields and records, and produce abstract reports by synthesizing the common data. This function provides a powerful asset in data management, which could be time-consuming and tedious if manually implemented.

Data base programs have been upgrading their features in terms of graphical capability, speed improvement, and compatibility with other software. Their platform of computer environment has also evolved from DOS based to Windows based in accordance with the popular trends of other types of computer programs toward a Windows operating system. In this research, as one of data base tools, Microsoft® Access 97 was used to build a data base for TPMSHM.

Using MS Access, the user can manage the desired information from a single data base file. Within the file, the user can perform the following data management functions using the corresponding data base object:

- Input data into separate storage containers, called tables,
- View, add, and update table data using online forms,
- Find and retrieve the data the user requests using queries, and
- Analyze or print data in a specific layout using reports.

The design of a data base for TPMSHM is based on the following definitions of nine field components. Each set of these field components represents a variable or a constant, which constitutes the TPMSHM when taken together.

- *SUBSYSTEM*, specifies the subsystem of TPMSHM where a record belongs.
- *ACRONYM*, contains the parameter names that are used in each subsystem of TPMSHM. Each record can be identified and distinguished by these names, and they are used as variables in DYNAMO source codes of TPMSHM.
- *NAME*, provides description of each ACRONYM.
- *VALUE*, contains the numerical values of ACRONYMs that are defined as constants.
- *UNIT*, identifies the unit of each ACRONYM or variable in the DYNAMO code.
- *TDP*, specifies records that are time-dependent.
- *TIDP*, specifies records that are time-independent. These records are also characterized by their fixed values.
- *TYPE*, specifies the characteristics of each record in terms of data research, model generation, and user definition. The type of data research implies that the value of the corresponding variable is obtained according to a literature survey, current legislation, or observed trends. The variable that is computed by an algorithm in the model belongs to the type of model generation. The values of the variables of user definition types are estimated by statistical methods or by identification of relationships between variables.
- *SOURCE*, specifies the source of each variable where its information can be obtained.

An example of the constructed data structure using these nine fields is provided in Figure 8.5. A complete list of data is provided in the Appendix. This figure shows the actual computer screen in the MS Access data base program. The first field suggests that this part of the data base is used in the Finance Subsystem. In the value field, the time-dependent or model-generated variables, which do not provide a fixed number, are denoted as minus signs. The data type of both TDP and TIDP is defined as a Yes/No or an On/Off type. The last field provides the source of each record by identifying the references, which can be found in the reference lists at the end of this dissertation.

A data sheet as shown in Figure 8.5 is designed by setting the field name, data type, and description of records. These settings can be facilitated by using another function of MS Access, as shown in Figure 8.6, which provides a design view of the data base. This function also allows the user to define a primary key for the data set. The primary key specifies one or more fields whose value or values are uniquely identified in each table in a record. This key provides a reference point among the various types of inquiries.

The type of data needed to build a DBMS is extracted by interpreting the TPMSHM. It should be noted that if the TPMSHM is to be changed in its contents, the data base should also be modified and fitted to the model. In MS Access, any modifications, including adding, deleting, or editing of each data item can be easily implemented. It can also generate various formats of data structure through the arrangement of records and the macro function.

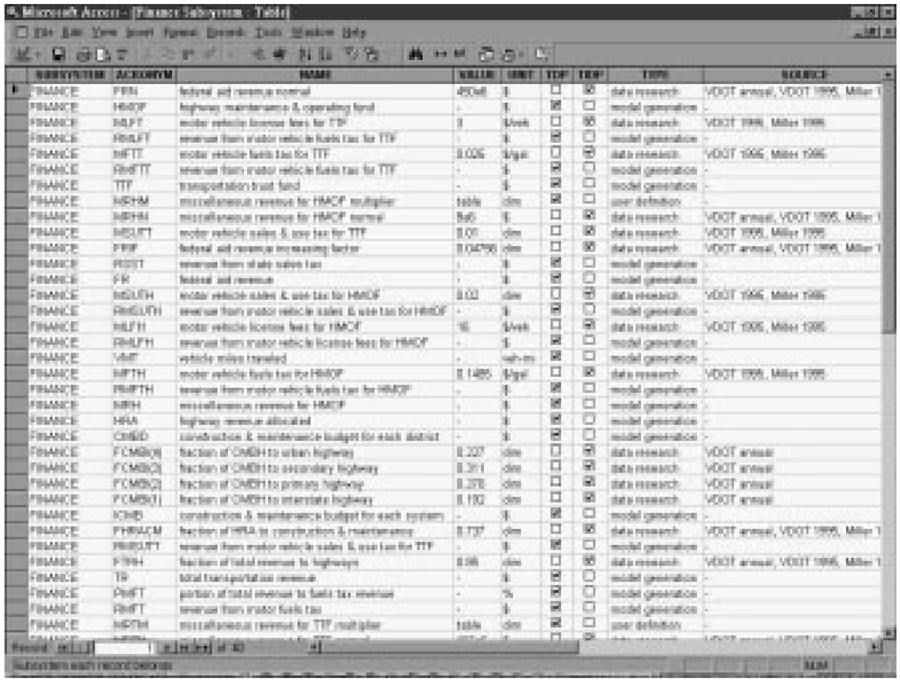

Figure 8.5 Data sheet view of a data base for TPMSHM

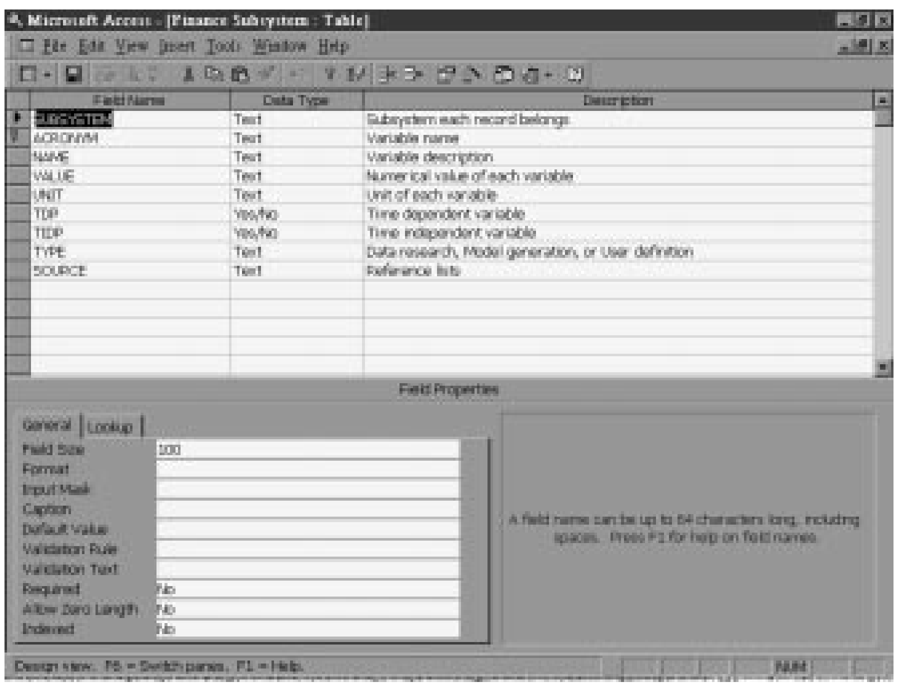

Figure 8.6 Design sheet view of a data base for TPMSHM

8.2 Display Base for TPMSHM

The eventual and primary users of the DSS incorporating TPMSHM are decision makers who are involved in various types of decision making regarding highway management. Whereas the role of transportation planners is to develop an appropriate methodology that is applicable to certain issues or problems related to transportation, that of decision makers is to set the direction of planning or engineering actions by utilizing the methodology. In most cases, not all decision makers are familiar with the details of the methodology being used. Rather, they see the anticipated effects of the actions that are caused by inputs of various policies or plans. The purpose of the user interface is to facilitate this human/machine conversation in easy and efficient ways. The basic requirements of the interface are that it be interactive, easy, and explicit.

Much of the system dynamics software, as described in Chapter 4, is being developed to realize these requirements. The DYNAMO language itself is not capable of providing a DSS architecture, although it provides a large-scale modeling capability as a solid model base. As a possible application tool, Powersim software is examined. Powersim is a Windows-based system dynamics program that facilitates model building, various types of result presentations, and interactive simulation. The following paragraphs present the general features of Powersim in comparison to DYNAMO elements.

The construction of TPMSHM was based on the use of DYNAMO codes. DYNAMO is a suitable language for TPMSHM because the model consists of many subprograms and arrays, and DYNAMO is capable of dealing with those large-scale dimensions. Instead of using TPMSHM, a simple model for life-cycle planning for sustainable development (LCPSD), presented in Chapter 3, is used for the purpose of feature comparison between DYNAMO and Powersim.

First, LCPSD has been built by using simple DYNAMO codes, as shown in Figure 8.7. This figure contains a partial list of programs on the editor screen of Professional DYNAMO 4.0 for Windows [Pugh-Roberts Associates 1994]. A complete list has been provided in Chapter 3. The editor features a series of pull-down menus and several buttons that are required to create, edit, compile, and simulate a system dynamics model. This program can be coded under either a DOS or Windows environment using respective versions of DYNAMO. In this environment, coding should follow a predefined grammar by understanding the terminology and working mechanisms of system dynamics. Thus, working with this mathematical representation would not be an easy task without a knowledge of system dynamics. Also, unlike the development of this model containing only a few variables, the construction of a large-scale model such as TPMSHM, which contains hundreds of variables, requires time-consuming and repetitive effort because all texts must be manually typed.

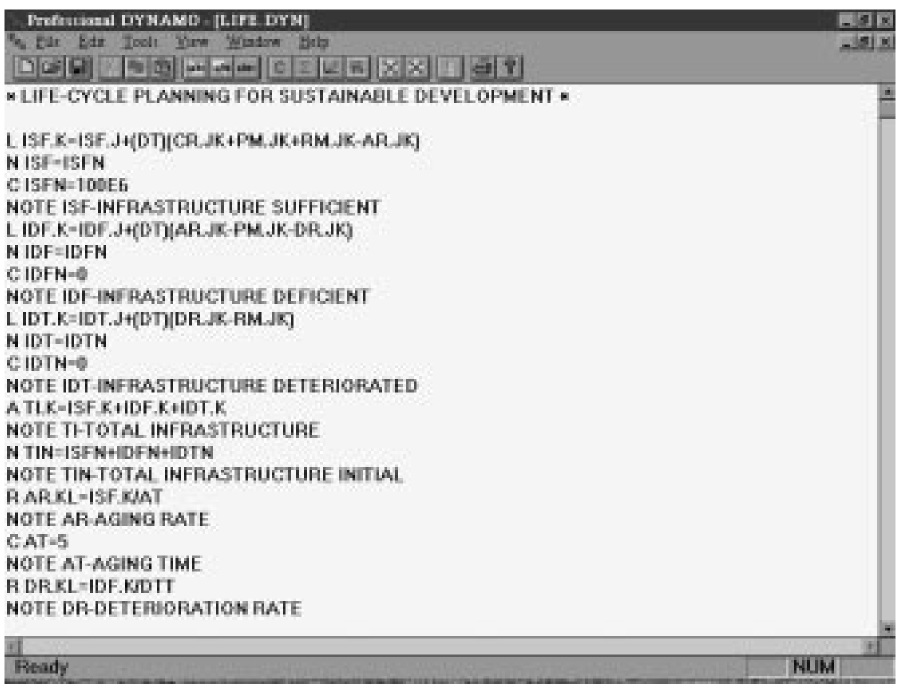

Figure 8.7 Editor Screen of DYNAMO containing LCPSD model

Compared to the shortcomings inherent in DYNAMO, Powersim provides a convenient way to build a model. Under a distinct graphic environment, as a modeler draws a causal diagram of the model, Powersim automatically leads the user to construct systems equations simultaneously. All the user needs to do is to fill in parameter values and to relate variables to complete system dynamics equations. On the other hand, DYNAMO does not provide the graphical capability to produce a causal diagram. The diagram must be constructed by utilizing standalone graphic software such as CAD, CANVAS, and VISIO, and the coding task is done separately.

Due to the separate modeling steps required to produce causal diagrams and systems equations, modeling under the DYNAMO environment is time-consuming and inefficient. In this context, the convenience of using Powersim saves time in model building. This convenience can be also found in other system dynamics software, such as STELLA. However, the disadvantage of interpreting the causal diagram is that the diagram does not show the explicit relationships among variables, due to missing polarities and complex symbols. This disadvantage could cause serious problems in understanding a model if the model consists of hundreds of variables and several submodels, such as TPMSHM.

Figures 8.8 and 8.9 represent a causal diagram and a part of the systems equations for life-cycle planning for a sustainable development model using Powersim. In the causal diagram, different types of symbols according to level, rate, auxiliary, and exogenous variables are shown. The screen shown in Figure 8.9 is a main editor of Powersim under the Windows environment, which consists of pull-down menus and symbolic buttons.

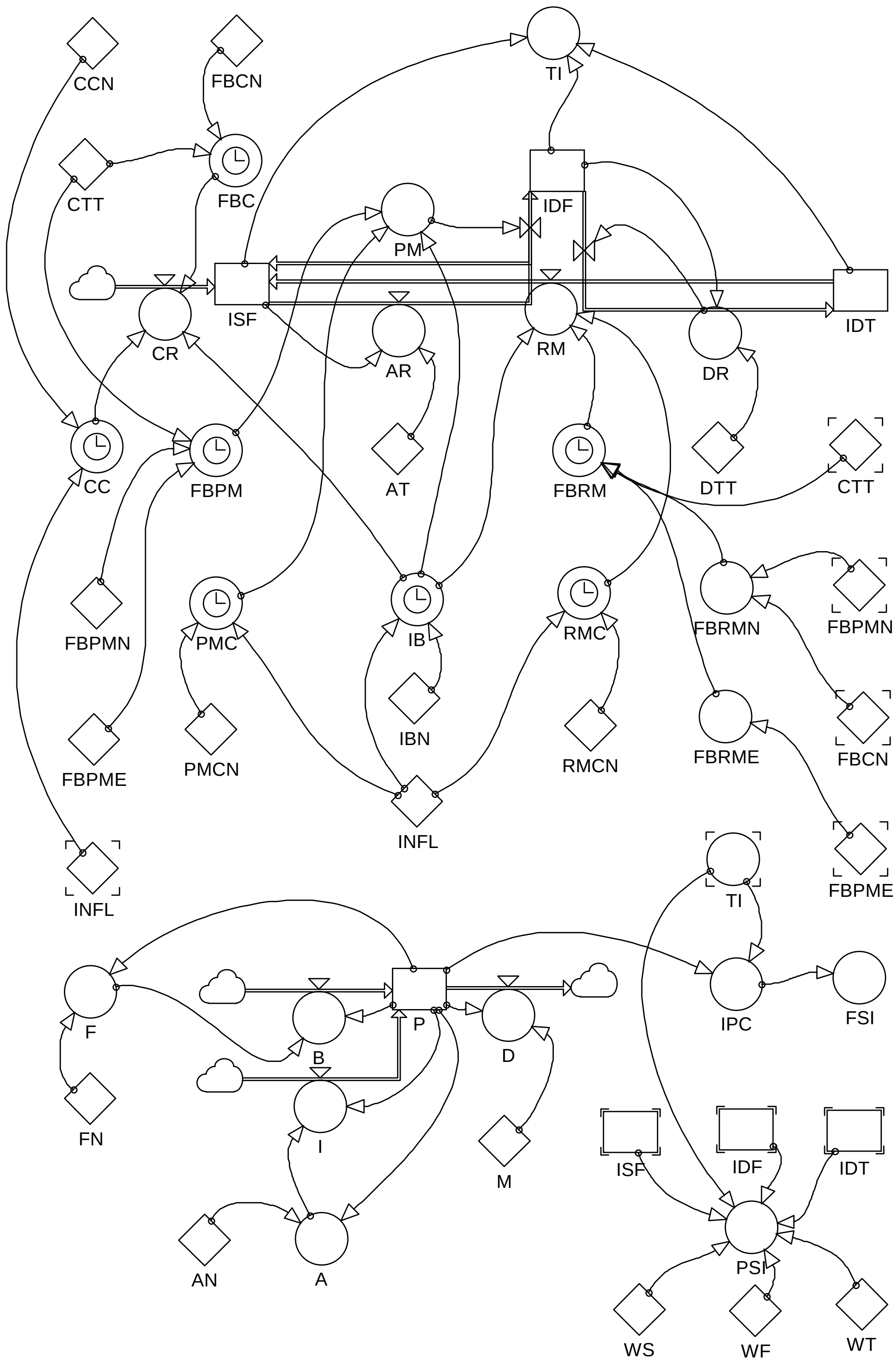

Figure 8.8 Causal diagram of LCPSD model using Powersim

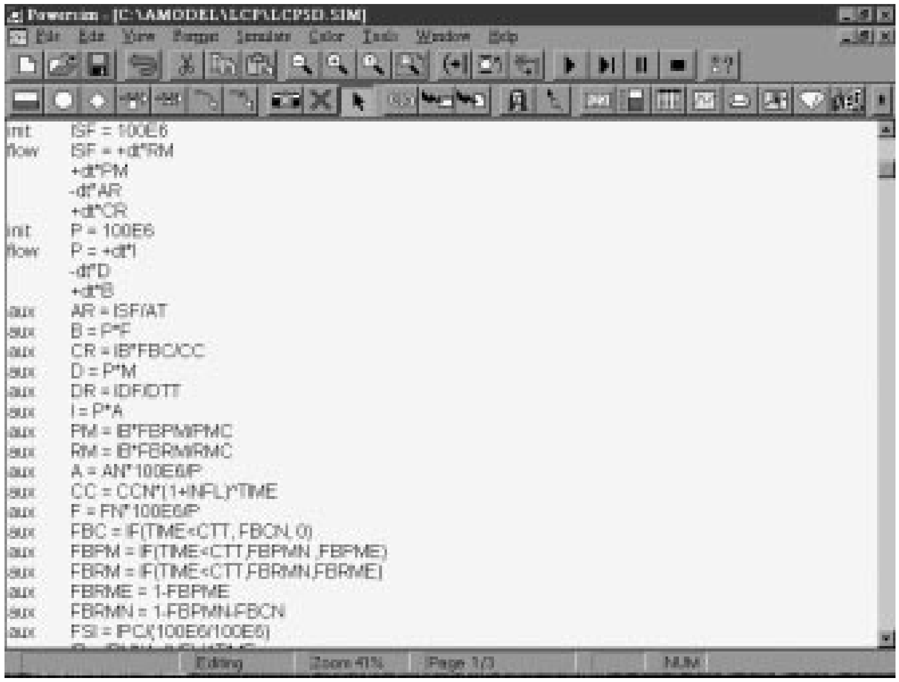

Figure 8.9 Systems equation of LCPSD model using Powersim

The simulation results of the life-cycle planning model can be plotted to indicate changes in the behavioral pattern of an infrastructure system over a preset time period. Three level variables, i.e. ISF, infrastructure sufficient, IDF, infrastructure deficient, and IDT, infrastructure deteriorated, represent each state of the system. Figure 3.3 provided in Chapter 3 is a graphical representation generated from DYNAMO which shows the changes in infrastructure condition with regard to these three state variables. Figure 3.4 in the same Chapter shows system performances over the simulation time period through a physical sufficiency index, PSI, and a functional sufficiency index, FSI.

DYNAMO is capable of presenting simulation results in terms of PLOT and REPORT formats [Pugh-Roberts Associates 1994]. The PLOT function facilitates the expression of time changes in variables or relationships between two variables. The REPORT function represents simulation results in a text format, usually in the form of tables. These functions are not parts of the primary DYNAMO programs that express models, but are parts of separate user-defined files, termed DYNAMO RepW Script, or .DRS, files. Thus, to be able to see a number of results either in plots or in tables, a user should build as many .DRS files as required, compile the main model, and simulate both the main model and the .DRS files. These processes require that the user have knowledge about the DYNAMO environment, and could be inconvenient for a user who is not familiar with computer simulation techniques.

Whereas result presentation in DYNAMO is limited to two major types, Powersim provides nine types of result presentation:

- *Number*: displays the simulation results of selected variables in a numeric format,
- *Slide/Bar*: displays the current value of certain variables as bars and/or slider buttons along a horizontal or vertical value axis,
- *Time Table*: presents the time series history of certain variables, in columns or rows,
- *Time Graph*: displays a two-dimensional graph of one or more variables' development over time,
- *Scatter Graph*: displays the relationship between two variables in a two-dimensional graph by using one variable as the X-coordinate and the other as the Y-coordinate,
- *Button*: displays the current value of certain variables as one of the button states which are set, clear, or other,
- *Array Graph*: displays the current value of several parameters as a line graph or as a series of bars,
- *Gauge*: is an input/output object that displays a model variable as a moving bar or needle, and
- *Multimedia*: is a multi purpose presentation that is capable of presenting video, animation, sound, text, pictures, and message boxes based on the state of a simulation.

Figures 8.10 through 8.15 present various types of result presentations. Unlike the simulation pattern of DYNAMO, Powersim shows step-by-step procedures and changing patterns of the system during the simulation. Thus, the user is able to stop the run of the program in the middle of simulation, and to change, for example, parameter values if desired. These figures represent the final outputs of the simulation.

Figure 8.10 shows the values of PSI and FSI at the end of the simulation in the forms of bar and number.

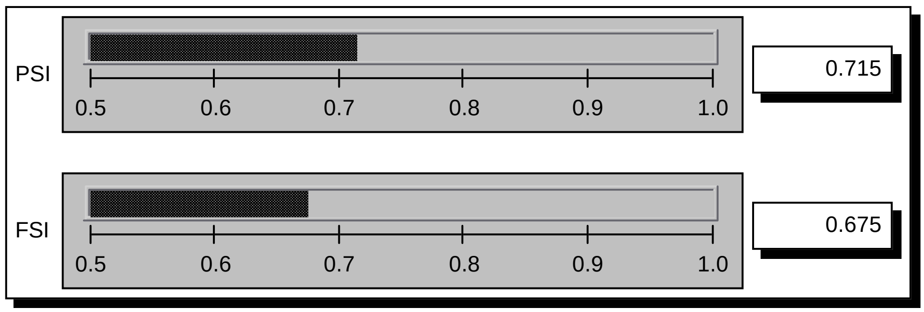

Figure 8.10 Performance indices of LCPSD using Powersim (Bar and Number Type)

Figure 8.11 presents the final status and value of IPC, i.e. infrastructure per capita, at the end of the simulation.

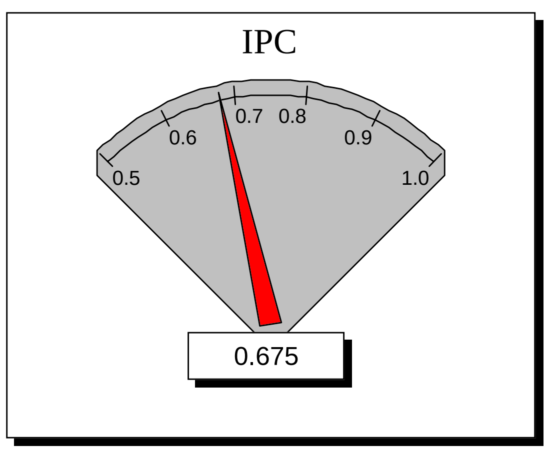

Figure 8.11 Infrastructure/capita of LCPSD using Powersim (Gauge and Number Type)

Figure 8.12 represents changes in infrastructure conditions over the simulation time, and Figure 8.13 plots the simulation results in time graph type.

Time	ISF	IDF	IDT
0	100,000,000	0.00	0.00
10	33,421,145.2	68,836,027.3	13,742,827.5
20	24,410,393.1	68,758,701.9	38,830,905.0
30	23,190,882.0	63,050,753.1	61,758,365.0
40	23,025,833.9	58,822,543.3	82,151,622.9
50	23,003,496.3	56,154,312.0	100,842,192
60	23,000,473.2	54,521,914.3	118,477,613
70	23,000,064.0	53,529,915.7	135,470,020
80	23,000,008.7	52,927,981.0	152,072,010
90	23,000,001.2	52,562,854.4	168,437,144
100	23,001,855.6	52,339,761.6	184,658,122
110	72,285,918.9	27,413,827.7	160,299,993
120	78,955,979.8	43,258,464.6	137,785,295
130	79,858,702.8	57,059,220.9	123,081,816
140	79,980,876.9	65,996,943.1	114,021,920
150	79,997,411.9	71,494,702.2	108,507,625
160	79,999,649.7	74,839,650.0	105,160,440
170	79,999,952.6	76,869,869.4	103,129,918
180	79,999,993.6	78,101,450.0	101,898,296
190	79,999,999.1	78,848,467.1	101,151,273
200	79,999,999.9	79,301,559.4	100,698,180

Figure 8.12 Infrastructure Condition of LCPSD using Powersim (Time Table Type)

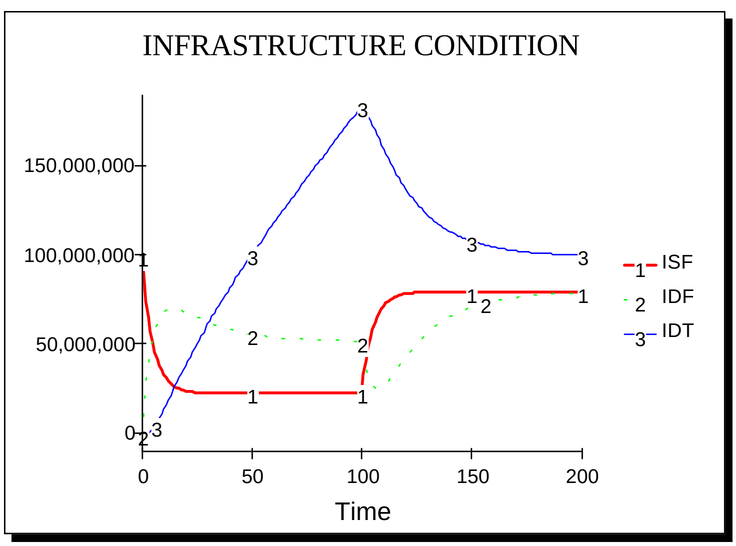

Figure 8.13 State variations of LCPSD using Powersim (Time Graph Type)

Figure 8.14 shows both physical and functional sufficiency indices in time graph type, and Figure 8.15 provides a scatter graph that shows the relationship between PSI and population.

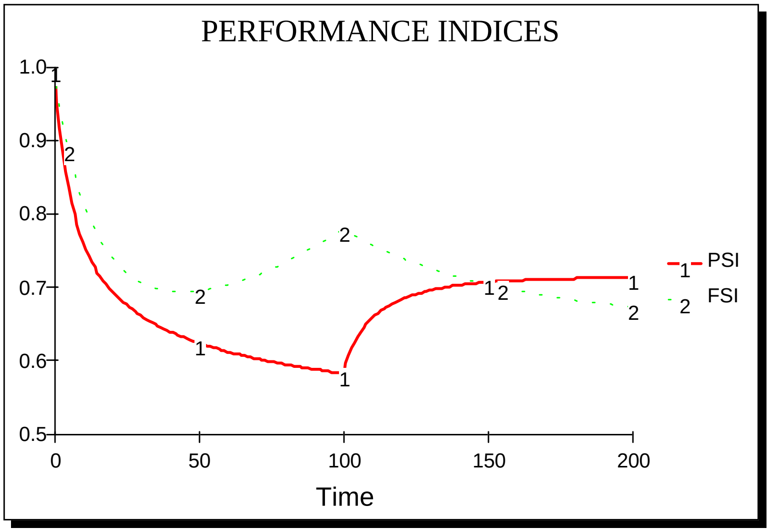

Figure 8.14 Performance indices of LCPSD using Powersim (Time Graph Type)

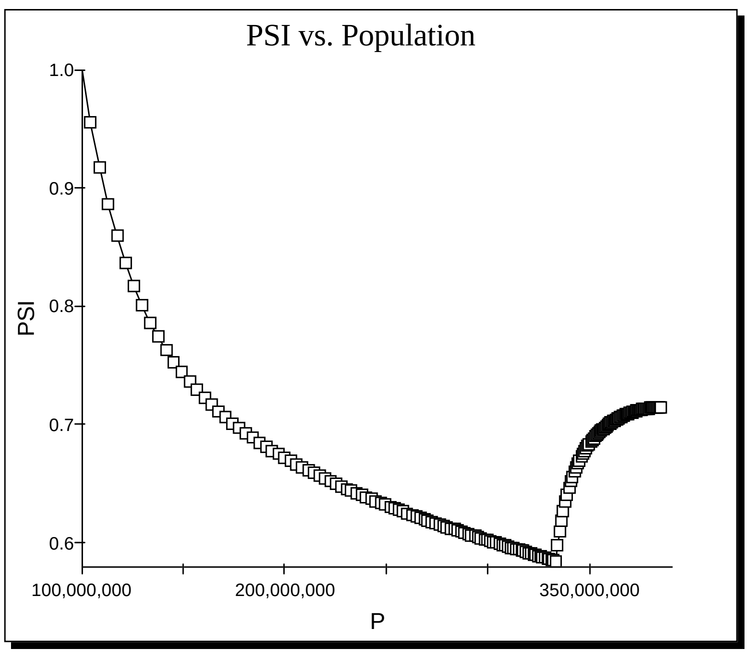

Figure 8.15 PSI vs. Population of LCPSD using Powersim (Scatter Graph Type)

The extensive capability of result presentation inherent in Powersim allows the user to select the desired forms of simulation outputs. Moreover, these types of results do not require the user to produce additional files and rerun the model. Another advantage is that the user is able to see all of these results at the same time as the simulation on the screen by freely resizing and arranging each reporting type.

Powersim also facilitates the interaction between the user and the model. In a case where the decision maker wants to see the impact of changes in some policy variables under the DYNAMO environment, he/she must access its compiler and simulator, or even the source code. In this case, Powersim provides a convenient and spontaneous way to analyze policy through the use of a slider tool. Figure 8.16 shows the features of the sliders. By using this function, the user is able to select the policy variables that have been initially defined as fixed values, and to change the initial value directly by dragging the slider button while a simulation is running. The slider also allows the user to see the precise numerical value as he/she adjusts variables. By giving the desired inputs to a model via selected parameters, the user can see the different results of the changes instantaneously. This user interface is easy and efficient in that it does not require the user to have detailed knowledge about the model and computer, and about how to access the model itself. It also reduces the time of policy analysis that, in most cases, requires repetitive effort.

The overall features of the user interface can be summarized as shown in Figure 8.17. This integrated user interface contains a causal diagram of the LCPSD model, selected types of result presentations, and the sliders for various inputs. The user can easily change and add to the screen format, the parameters, and the reporting types. This simple interface can be further extended to the TPMSHM to help achieve DSS functions.

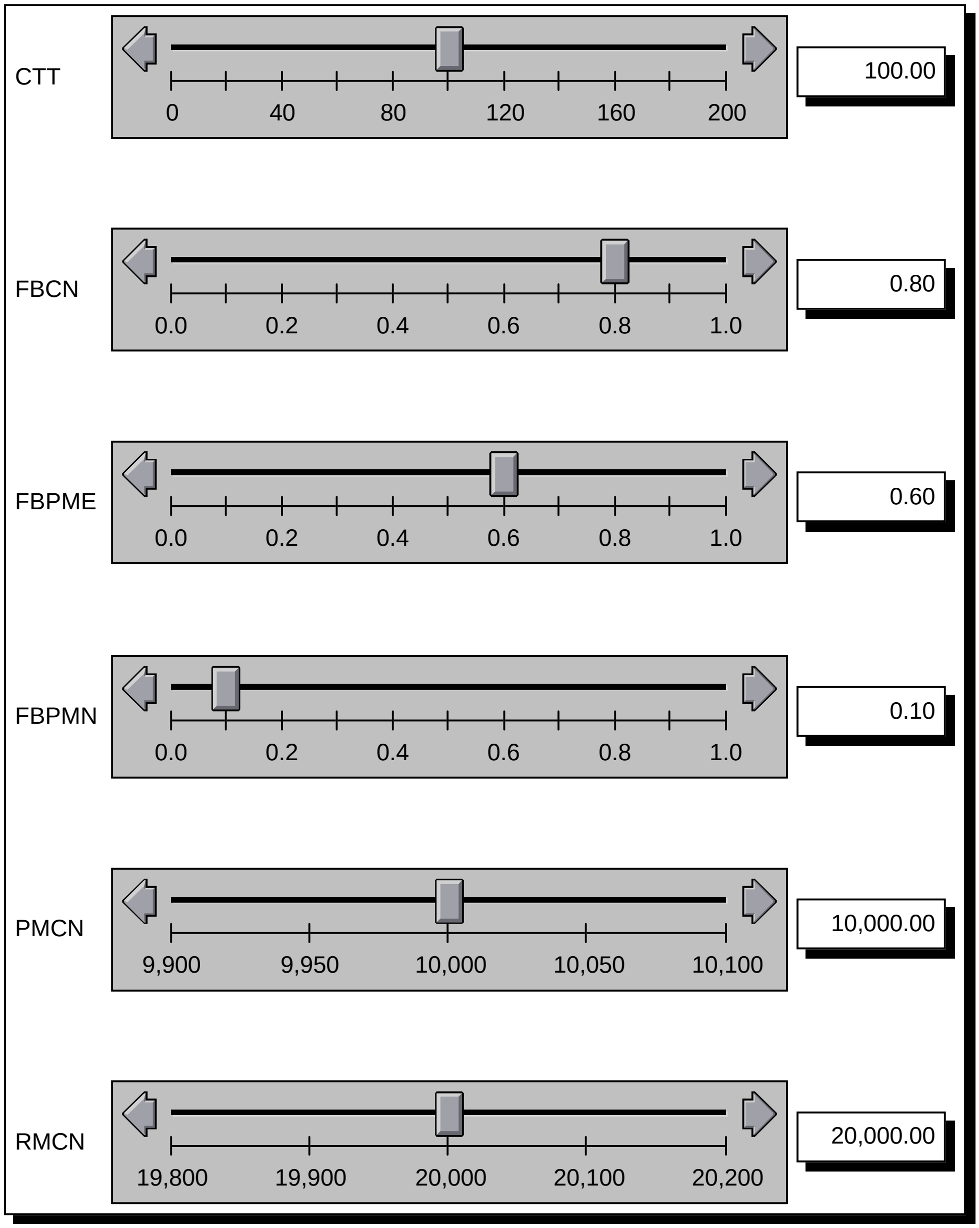

Figure 8.16 Slider tool for selected parameters in LCPSD model

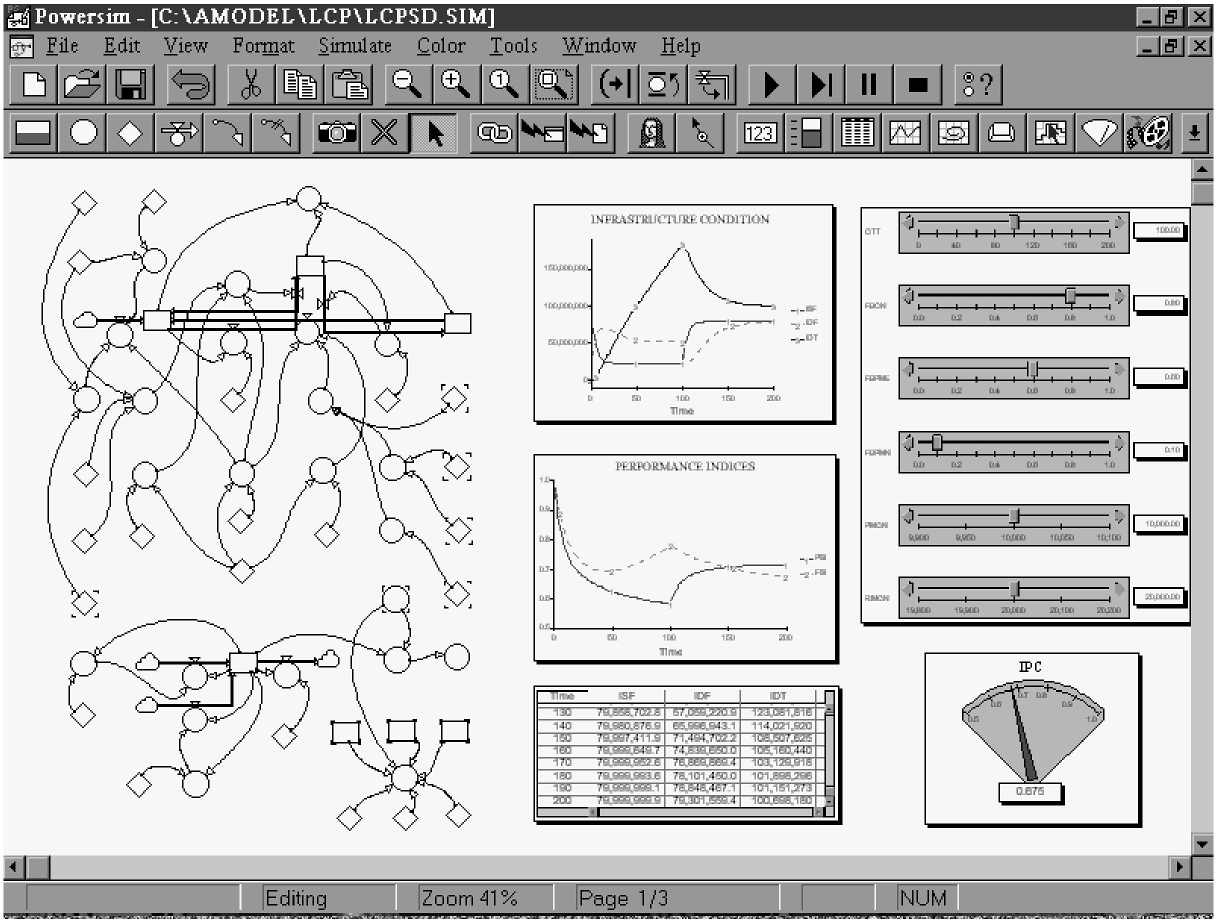

Figure 8.17 The integrated user interface of LCPSD using Powersim

CHAPTER 9
CONCLUSION

9.1 Research Summary

The realization of the current status of transportation infrastructure and the necessity for developing an infrastructure improvement strategy, as raised by the ISTEA in 1991, applies to almost every field of transportation. In particular, the importance of the highway system to the nation's socioeconomic activities is emphasized because the system constitutes the fundamental arteries in the nation's transportation network. The establishment of a highway management system is a response to the increasing awareness of the deteriorating conditions of highways in the United States.

This research has been designed to formulate a transportation planning model for state highway management and to frame a decision support system through use of the model. The following summarizes the distinct features of the TPMSHM and the decision support system.

- The TPMSHM provides a comprehensive view of a highway management system. The model is not restricted to the analysis of the PMS and the BMS, but encompasses even broader systems that are causally related to the physical system. These systems include transportation, demography, finance, and the regional economy systems that play an essential role in determining the level of the physical condition of highways.
- The TPMSHM is characterized by a state-dependent prioritization strategy. The fraction of the budget for construction investment is obtained as a proportion of highways in sufficient condition over the whole highway network. The remaining fraction of the budget is devoted to maintenance activities. As the highway system deteriorates over time, highways in sufficient condition diminish, and thus the fraction

for construction investment is reduced. On the other hand, investments in maintenance activities are increasing, resulting in an improvement of the highway system. Thus, it is suggested that management give priority to budget allocations to highways in the worst condition.

- To address statewide highway management issues, the model validates the state's revenue generation and allocation processes and identifies a clear relationship between the amount of revenue and the physical level of highways. The Finance Subsystem corrects an error made in the existing model, validates past and current revenues, and forecasts future revenues.
- The TPMSHM is verified as to its credibility for several basic demographic categories. These key parameters include population, vehicle registration, vehicle miles, employment, gross state product, and transportation revenue.
- An emphasis is given to model travel demand generation in the state. Three major categories of demand sources, specifically travel demand for general-purpose trips, commuter demand, and truck demand, are considered and modeled in detail.
- The architecture of a decision support system is demonstrated. A Data Base is constructed by listing all the parameters needed in the TPMSHM. Using MS Access, the data base is designed in terms of the records and fields that express the characteristics of the parameters. A Display Base is demonstrated using Powersim software for system dynamics. The capability of the software in representing simulation results in various graphic formats is examined. Also, a convenient feature of the user interface that enables the user to comprehend the system's behavior in an interactive and spontaneous manner is identified.

Based on these features of the TPMSHM, this research forecasts variations in the future condition of pavement and bridges for the 20-year period from the year 2000 through the year 2020. The significance of sustainable development is emphasized in this forecast. A need for qualitative development by improving current conditions rather than through the expansion of the highway system becomes apparent in the course of the simulation and analysis.

This research suggests important implications about prioritized management and sustainable development. Throughout this study, the following salient results have been found.

- Highway construction detrimentally affects the pavement condition of highways. The physical sufficiency indices for all levels of highways decrease during the construction period. The reduction of the maintenance budget due to the high-cost of construction is a primary cause of the decrease in physical sufficiency.
- For bridges, the bridges in critical condition, i.e. the worst condition, increase significantly during the construction period, although the physical sufficiency index of bridges increases because of an increase in new bridges. A shortage in the maintenance budget leads to this deterioration in existing bridges.
- The negative impact of construction on the physical condition of highways is seen in the decrease in the benefit cost ratio over the construction period.
- During construction, the state-dependent prioritization method inherent in the TPMSHM realizes a reduction in further deterioration of pavement condition and an improvement in the overall condition of bridges.
- State-dependent prioritization also contributes to maintaining or stabilizing highways at their highest levels of condition after the construction termination time. This effect is caused by the determination of efficient budget shares by physical condition level of highways.
- The interstate highway is the greatest beneficiary in this highway management system. Its shortest lane miles, fewest bridges, and the relatively high maintenance rates for these infrastructure configurations result in the highest condition among other highways. On the other hand, the physical condition of secondary highways is the lowest because the maintenance rates are not high enough to manage its huge scale of infrastructure.
- The increase in the fuels tax contributes to an increase in transportation revenue, but there is a tradeoff between the tax increase and demand. The excessive increase in the

fuels tax only results in the reduction of transportation revenue because of the reduced demand. In this research, when the fuels tax doubles from the current rate, the maximum level of revenue is achieved.

- There are positive relationships among transportation revenue, the physical condition of highways, and user benefits. In other words, the growth in transportation revenue intensifies maintenance activities, and the increase in intensity improves highway conditions. Highway users receive benefits from the improvements in terms of cost savings.
- The importance of the data collection process is identified through the analysis of the cost sensitivity of the TPMSHM. The model is sensitive to the use of different unit costs from the originally calculated or assumed values. Thus, data accuracy should be achieved from the selection of an appropriate data acquisition method for the various parameters in the model.
- The TPMSHM can be best implemented within the framework of a decision support system to help decision makers in their decisions on various highway management tasks. The computer programs utilized in constructing a Data Base and demonstrating a Display Base are useful in managing a large amount of data, to comprehend the system's behavior in an interactive and instantaneous way, and to represent its behavior in various forms of graphics.

9.2 Implications for Further Research

An emphasis in this research is the development of a model for state highway management as a Model Base for a steering component of the decision support system. The TPMSHM governs the development stages of the other two components of the DSS. Thus, having developed the model, further research should be devoted to establishing a highway management decision support system (HMDSS) by embedding the complete features of a Data Base and a Display Base. Possible formats for these two components have been suggested in this research, and the following refinements and development need to be addressed in further research.

In the decision support system conceptualized in this research, the TPMSHM and the Data Base function as isolated entities. In other words, if changes in parameter values occur in the Data Base, those changes are not made automatically in the TPMSHM. In this case, the user or modeler should manually correct the parameter in reference to the Data Base. The contents of the Data Base are to be updated over time, so the bridge connecting the Data Base to the TPMSHM needs to be established for efficient, timely modification.

The Display Base demonstrated through a simple model should be extended to incorporate the TPMSHM. Powersim demonstrates its graphical capability in the result presentation and useful interfaces, but any system dynamics program that provides powerful array functions and convenient user interfaces can be used for this DSS. In addition, a program that provides multi-dimensional capabilities should be employed in modeling so as to incorporate all features of the district highways into a single model.

The necessity for a data model should be emphasized. The major function that should be implemented by a data model in this DSS is that of manipulating data inputted by the user, identifying the relationships among data, and estimating the necessary socioeconomic parameters. One example of this procedure in the TPMSHM can be found in forecasting future demographics by calculating annual growth rates from the observed data. This calculation is performed manually in this research as a separate forecasting process. This process needs to be facilitated by using a data model.

In order to manage the district highways in an efficient way, it is necessary to develop a distribution model for sharing the state budget by each district. The distribution model realizes a prioritized budget allocation for the districts whose highway conditions are worse than the conditions of other districts. Also, this research can be further extended by incorporating a nonlinear optimization algorithm in the model so as to find optimal levels of budget allocations which minimize the management costs and maximize the road user benefits.

9.3 Conclusion

Throughout this research, emphasis has been placed on dynamic simulation models to show the types of trajectories of highway conditions that, if put into practice, lead to sustainable development options rather than remaining on an unsustainable path of development by maintaining the status quo. From the dynamic behavior of the highway system observed through the simulation, an adverse impact of new expansions of the highway system on sustainable development has been identified. The concept of sustainability embedded in this research is conveyed by achieving qualitative development of the state highway system for the construction and non-construction period.

The issue of utilizing limited resources in an efficient manner in highway management has been reflected through the development of a state-dependent prioritization method. The use of this prioritization scheme for infrastructure management is encouraging in that it realizes qualitative development by reducing the deterioration rates during construction and improving physical conditions after construction.

As infrastructure problems arise from a shortage of financial resources, a solution to the problem is often initiated by an increase in the infrastructure budget. But, how? Much of the research in this area strives to determine methods of increasing current revenues, including raising fuels tax. A caution, however, should be given concerning implementing this fuels tax policy. Travel demand is negatively affected by an increase in the fuels tax, and an excessive fuels tax increase will cause a reduction in revenue.

Any strategies for maintaining highway conditions at an acceptable level through the efficient use of limited resources or the improvement of financial status should aim for achieving sustainable development. The engineer's role in the management of civil infrastructure systems is often regarded as developing a technocratic ideology. This technocratic ideology is exaggerated in its assumption that the engineer is supremely able to understand and control events to suit the engineer's purposes [O'Riordan 1988]. Although ideology surely constitutes a vital component in the improvement of the infrastructure system, it cannot prevent a catastrophe in the civil infrastructure. Sustainable development consolidates the foundation of civil infrastructure through qualitative development, and technological evolution should be deployed within a framework of sustainable development so as to prevent "*fragile foundations*."

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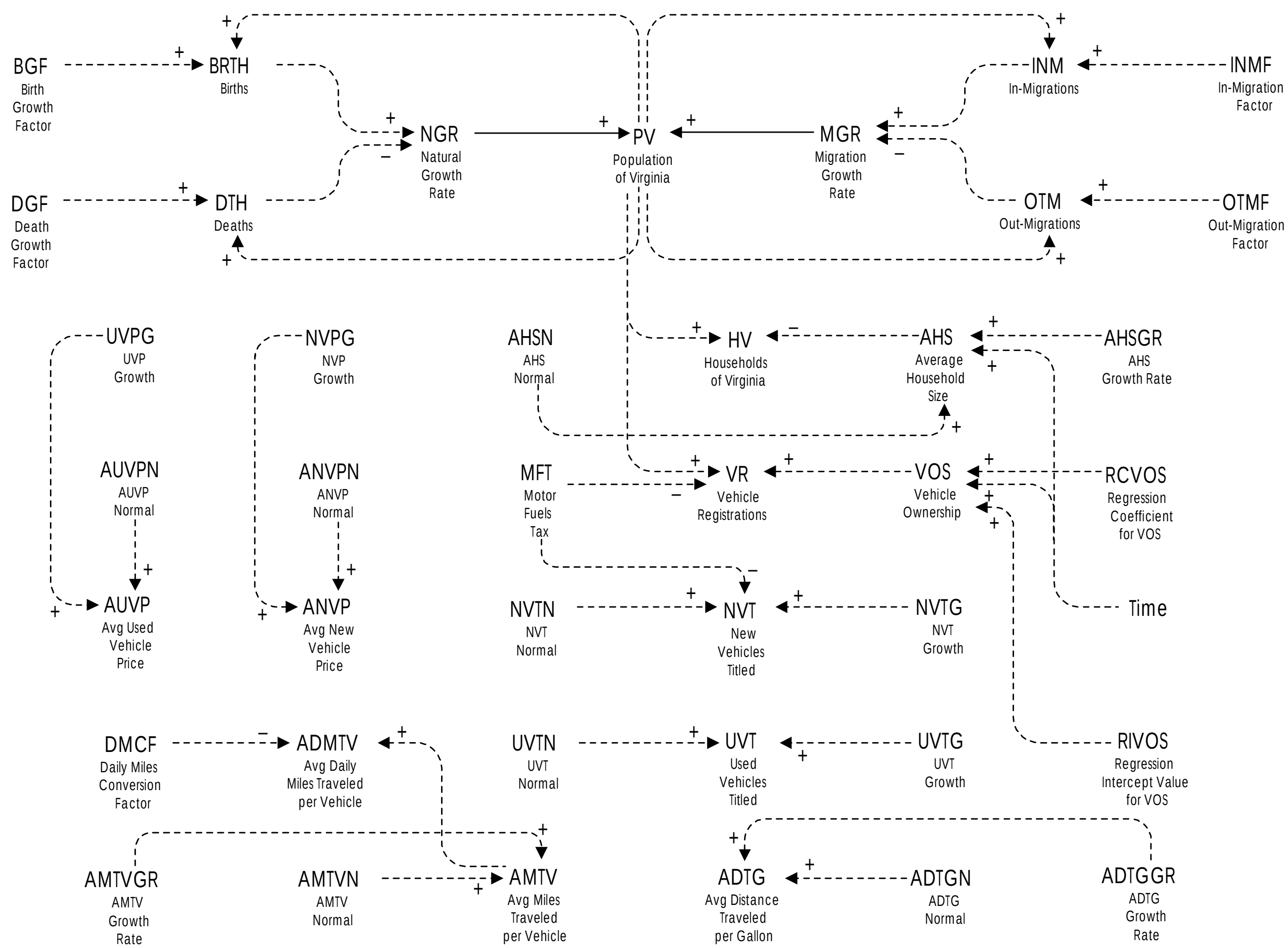
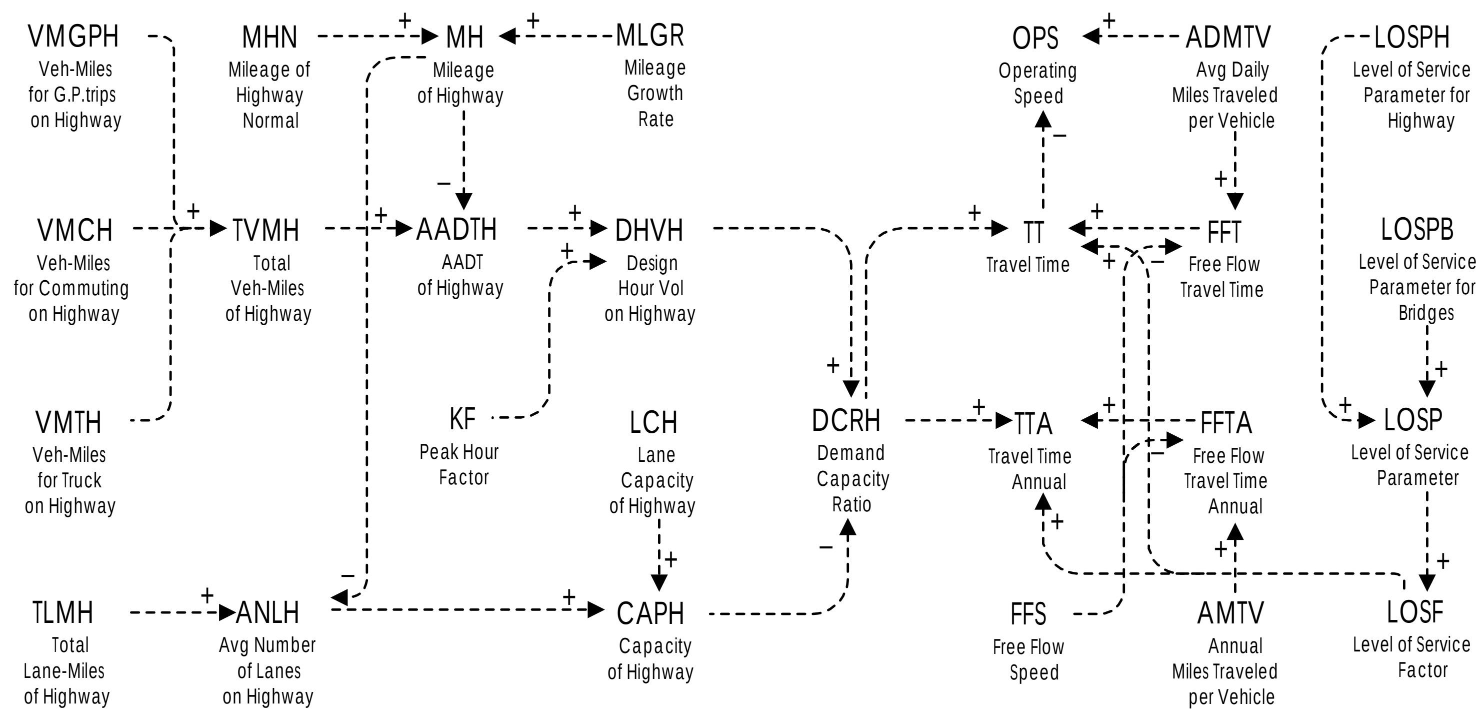
APPENDIX A

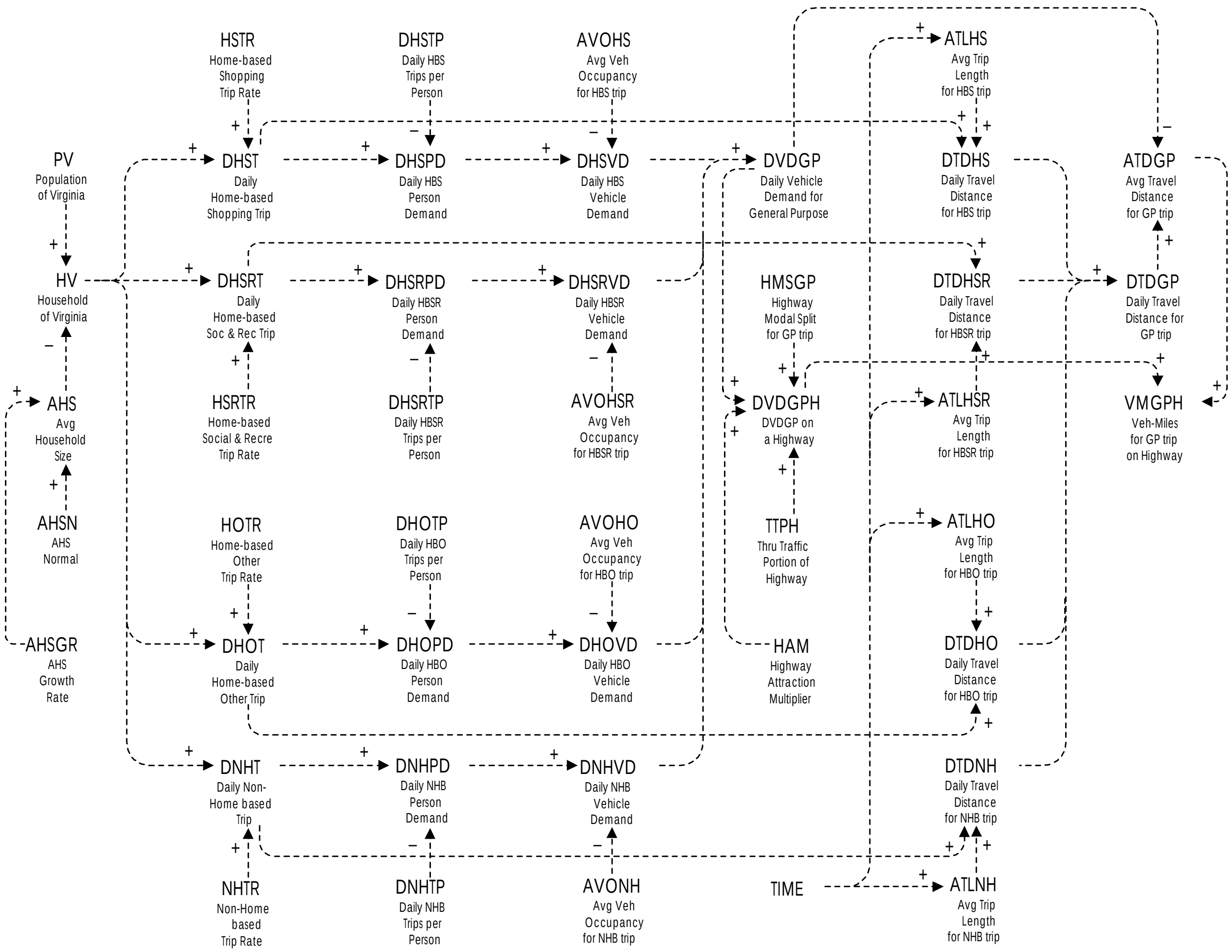
Causal Diagrams of the TPMSHM



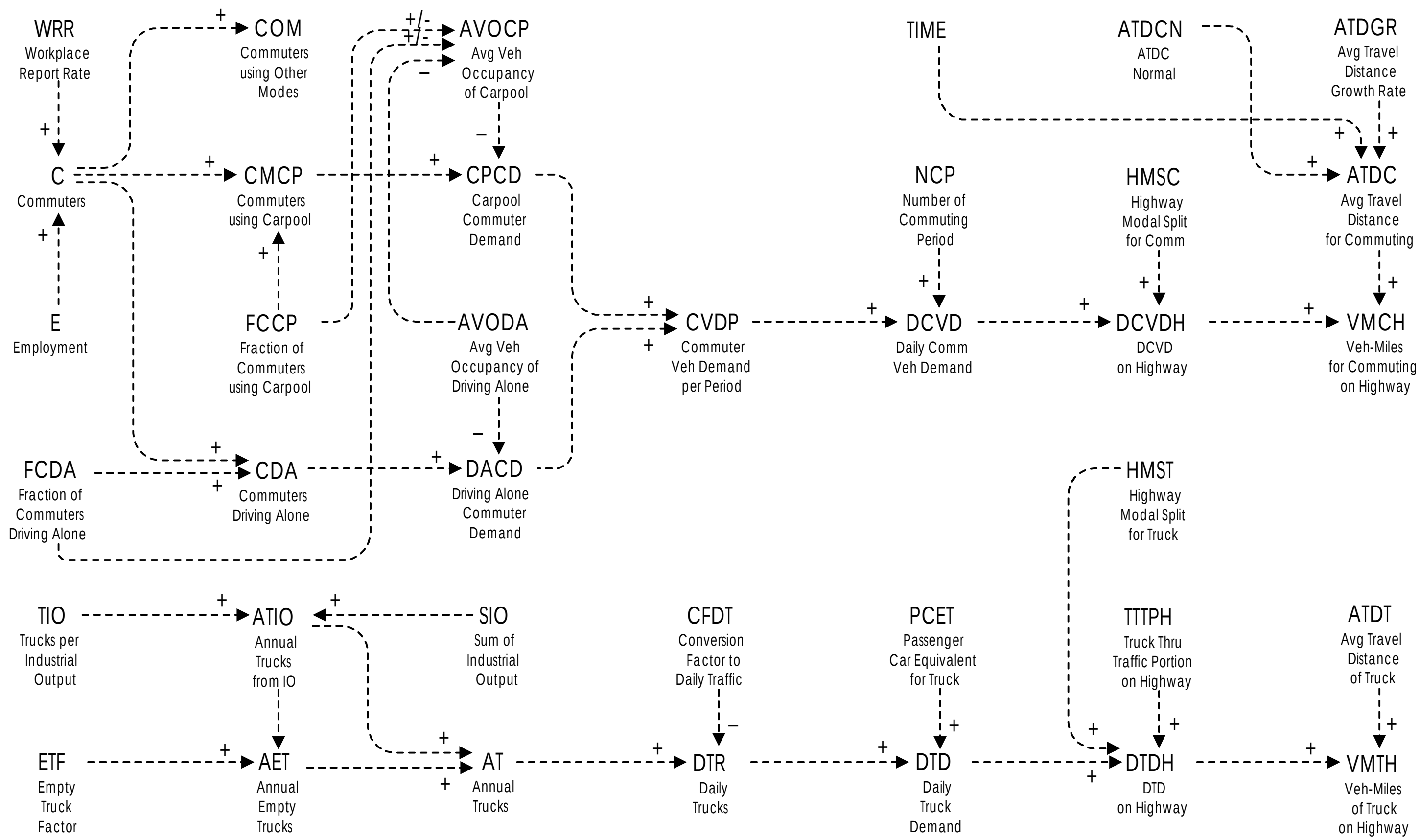
Demography Subsystem



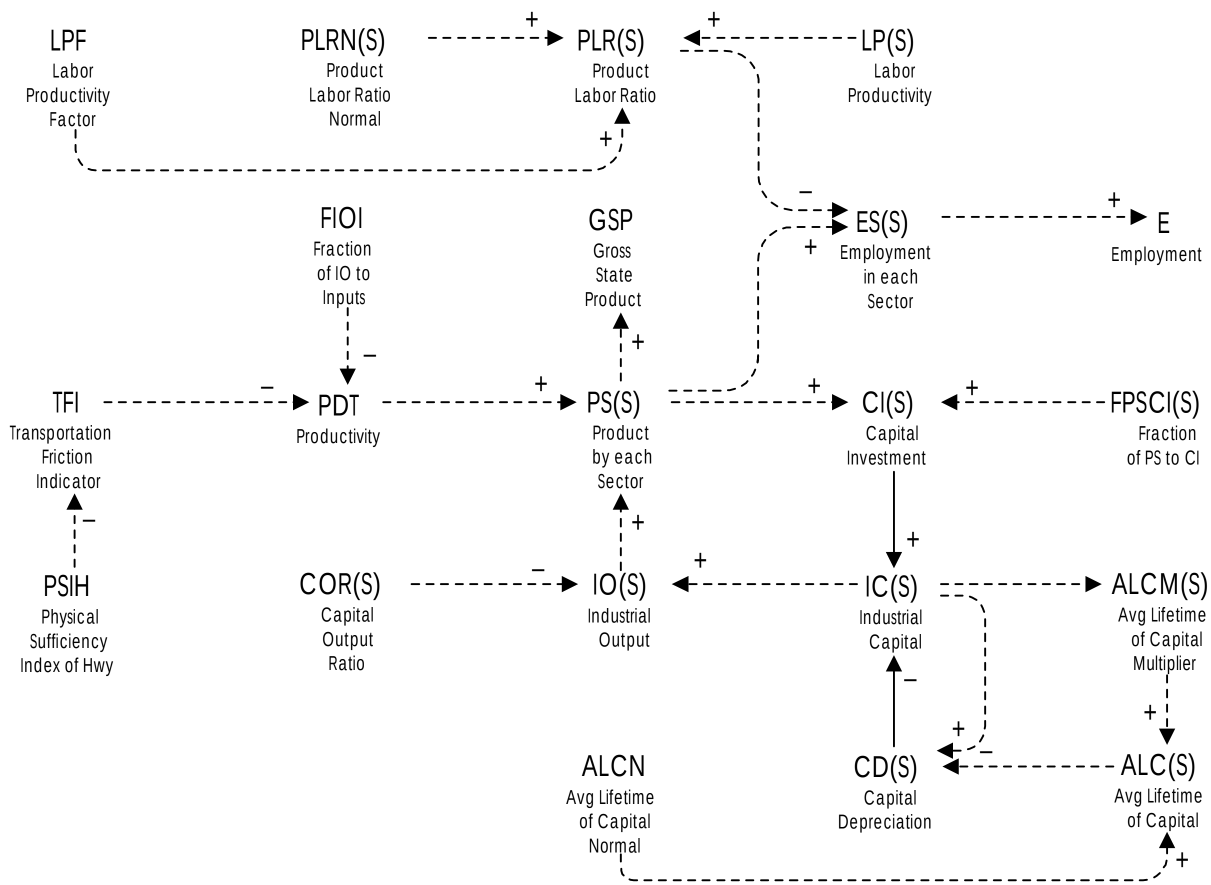
Transportation Subsystem



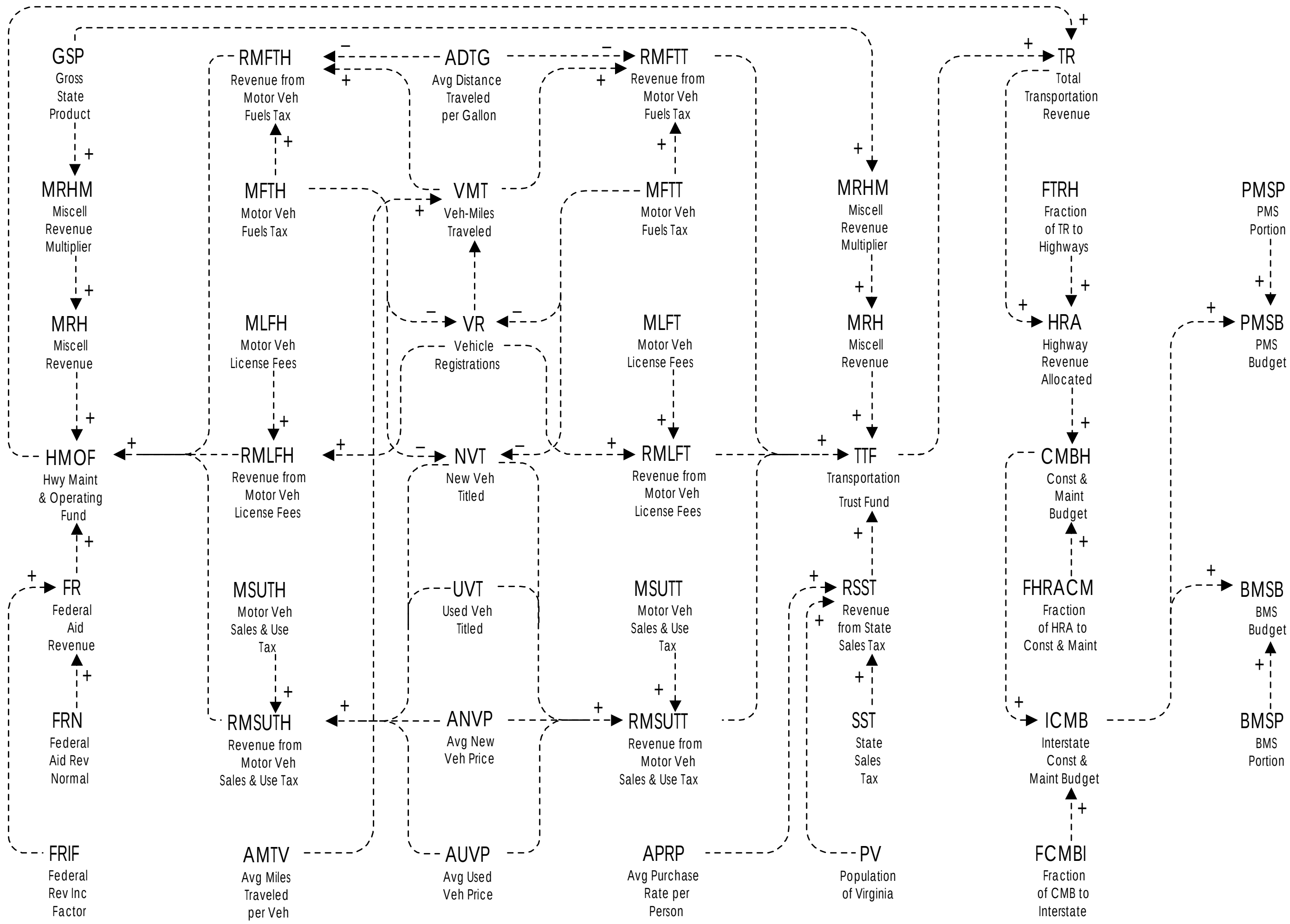
Travel Demand Subsystem A



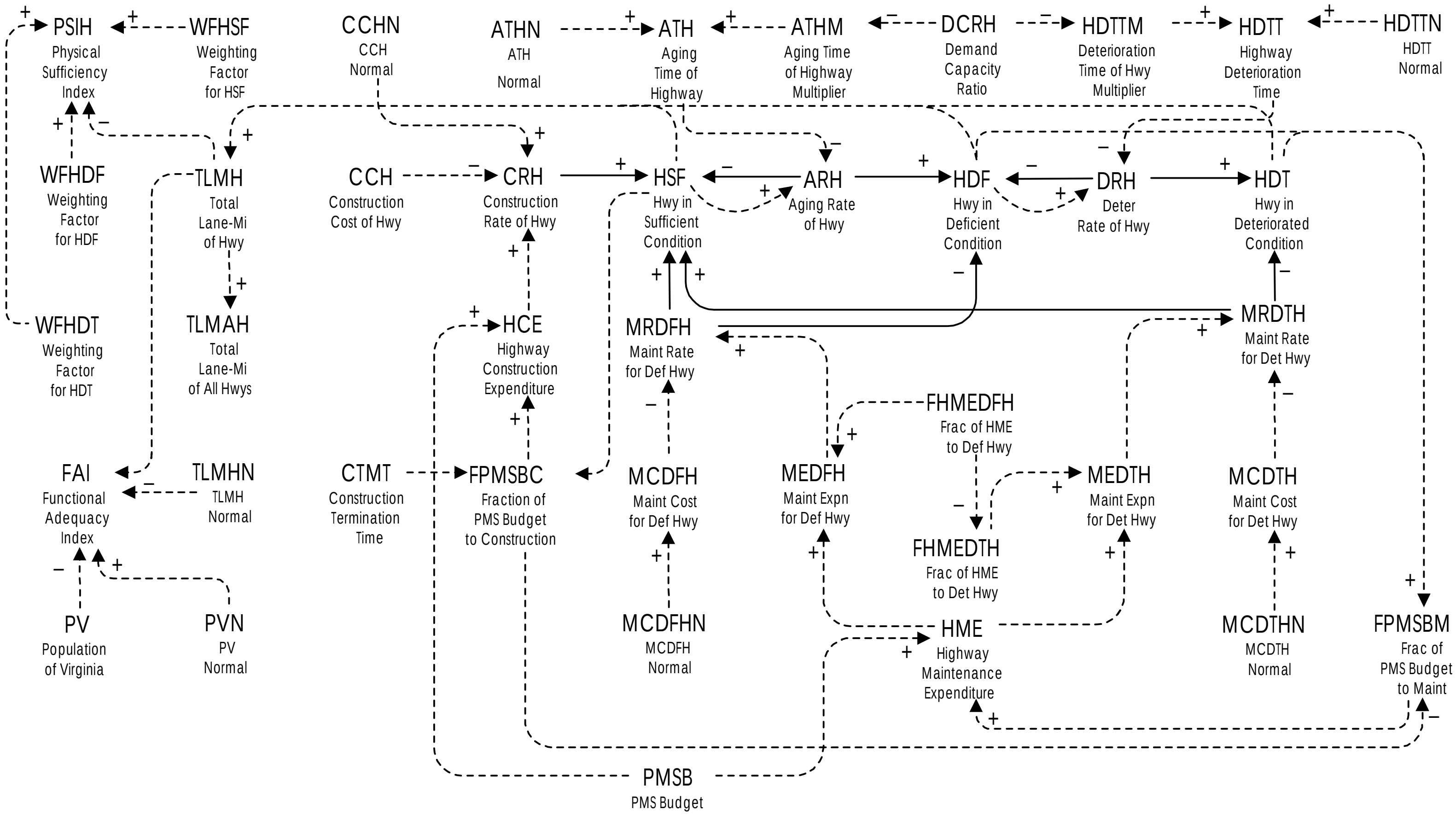
Travel Demand Subsystem B



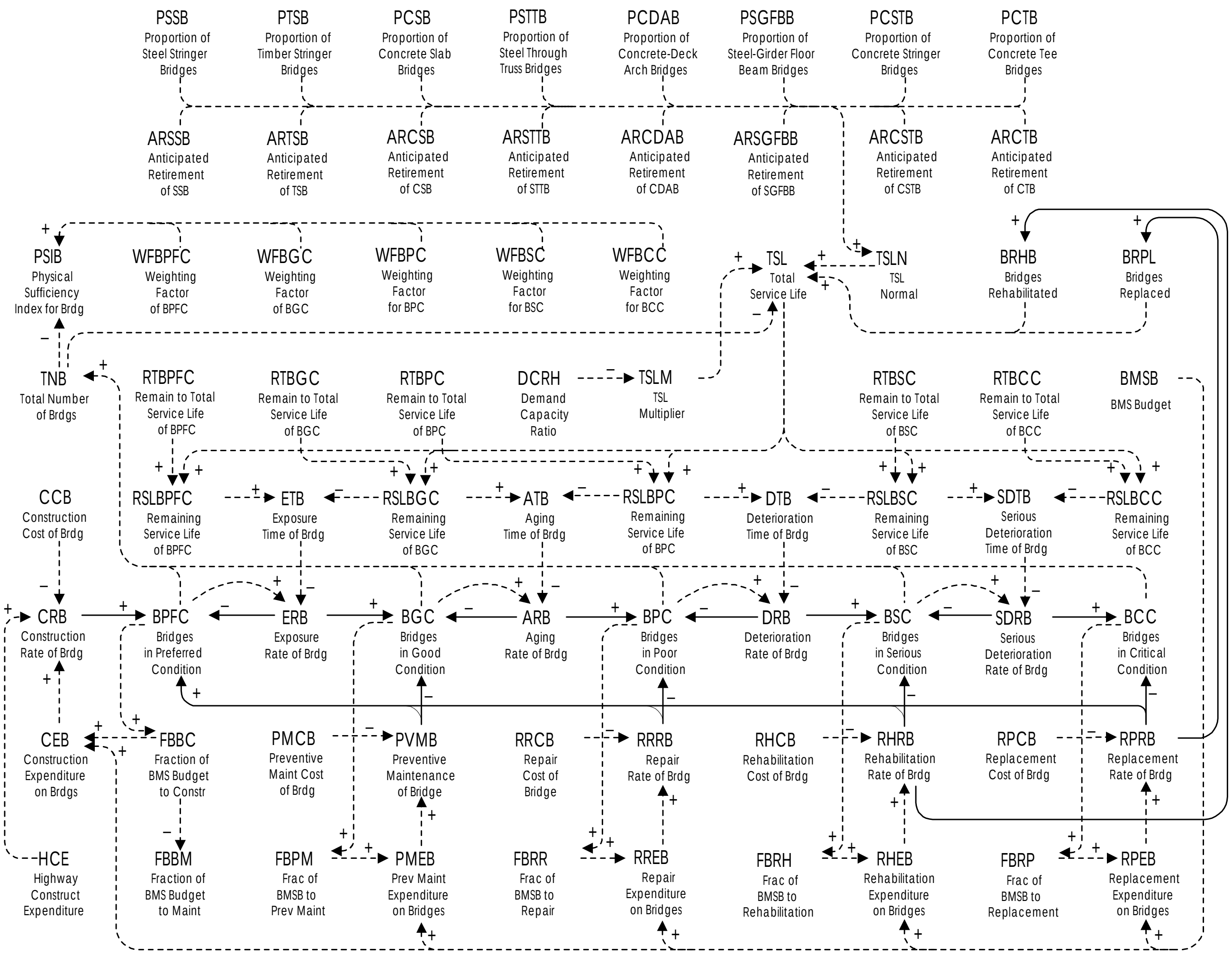
Regional Economy Subsystem



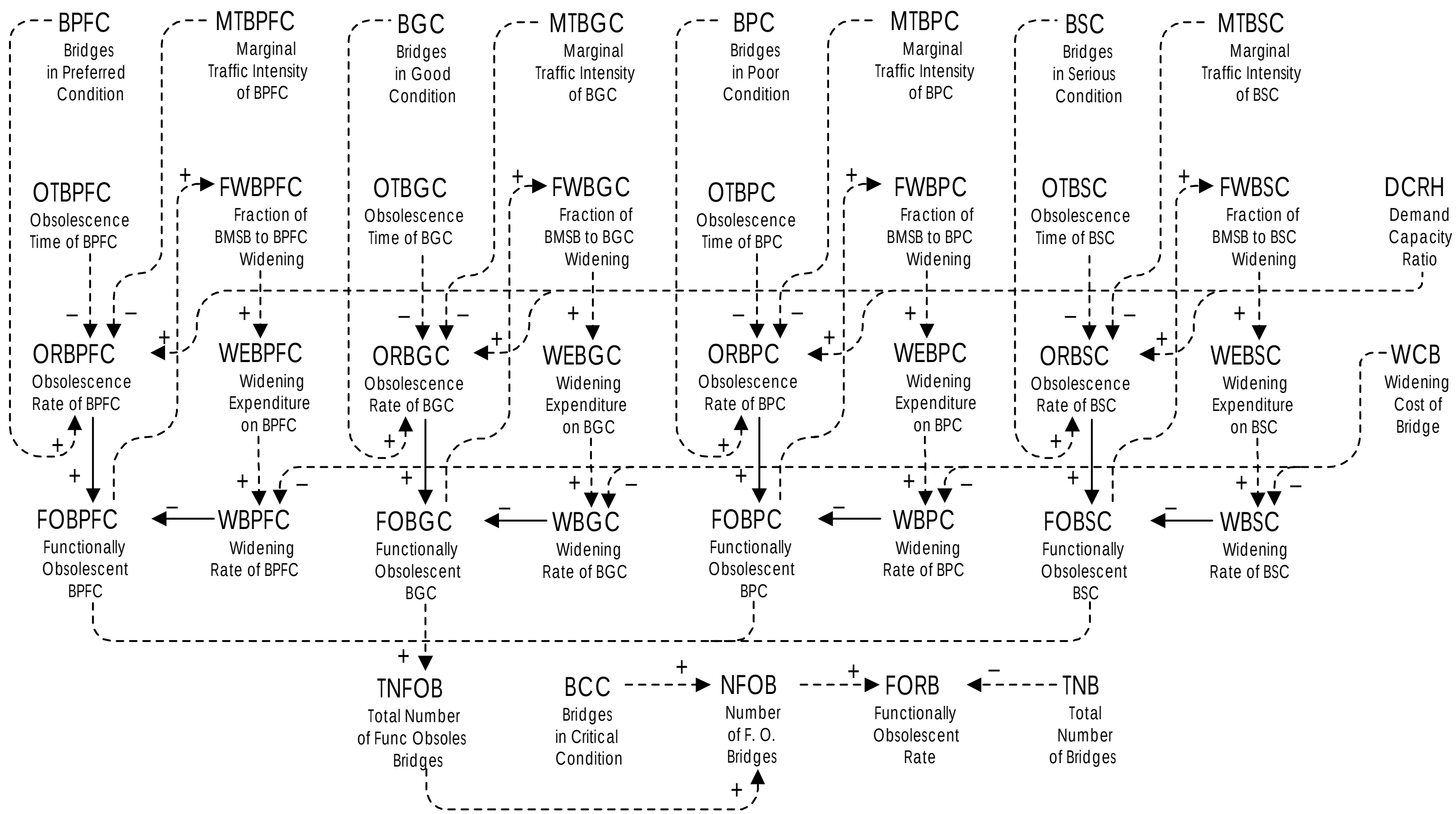
Finance Subsystem



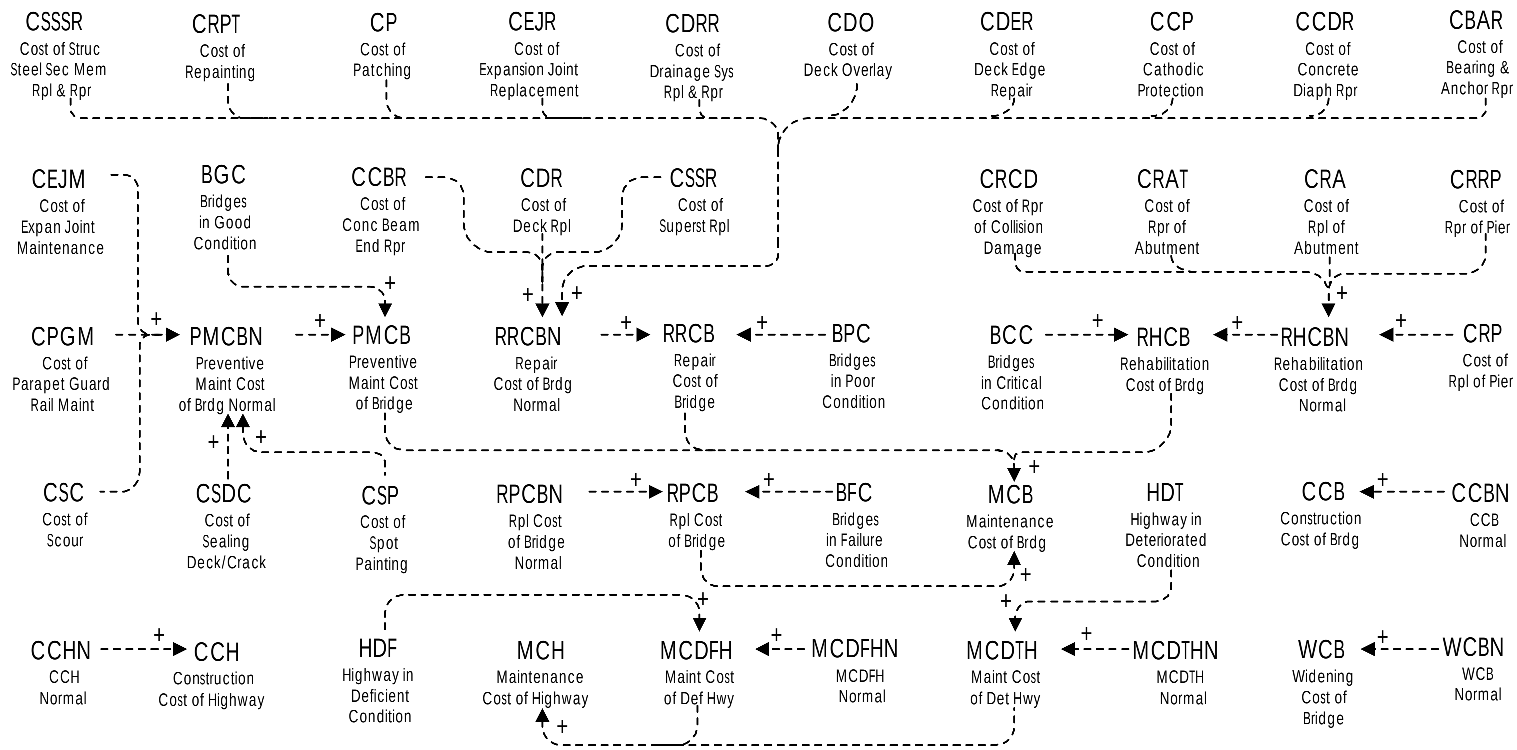
Pavement Management Subsystem



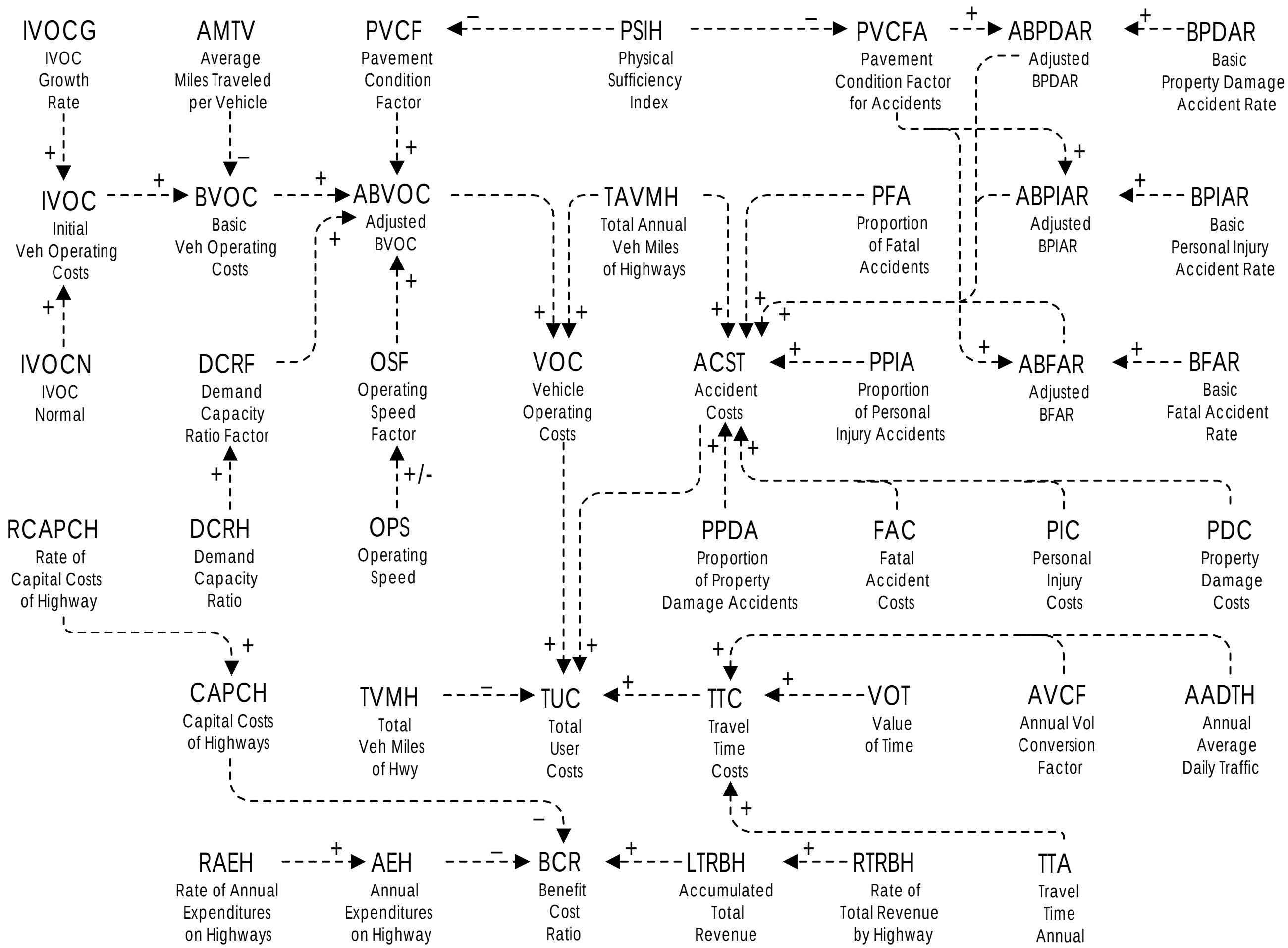
Bridge Management Subsystem (Physical)



Bridge Management Subsystem (Functional)



Functional Subsystem



Appraisal Subsystem

APPENDIX B

Complete Listing of DYNAMO Program

MAIN PROGRAM

```
* TRANSPORTATION PLANNING MODEL *
* FOR STATE HIGHWAY MANAGEMENT  *
* (     T     P     M     S     H     M     ) *

* PROGRAMMED BY  KYEIL KIM
* MODELING DATE :  10/31/97
* COPYRIGHT 1998, KYEIL KIM

FOR H=1,4

* H - ADMINISTRATION SYSTEMS
* H = 1 : INTERSTATE HIGHWAY
* H = 2 : PRIMARY HIGHWAY
* H = 3 : SECONDARY HIGHWAY
* H = 4 : URBAN HIGHWAY

INSERT DMGP
INSERT TRPH
INSERT TRPA
INSERT TRPB
INSERT RECN
INSERT FIN
INSERT PMS
INSERT BMS
INSERT FUNC
INSERT APR

SPEC  DT=0.25/LENGTH=20/SAVPER=1

SAVE  PV,HV,VR,TR,TVMH,GSP,E
SAVE  HSF,HDF,HDT,FAI
SAVE  BPFC,BGC,BPC,BSC,BCC,PSIB
SAVE  FOBPFC,FOBGC,FOBPC,FOBSC
SAVE  VOC,ACST,TTC,LOSP,DCRH,OPS
SAVE  CAPCH,AEH,AATH,TUC,PSIH,FORB
```

DEMOGRAPHY SUBSYSTEM

```
L PV.K=PV.J+(DT)(NGR.JK+MGR.JK)
NOTE PV-POPULATION OF VIRGINIA (PERSONS)
N PV=PVN
C PVN=7048E3
NOTE PVN-POPULATION OF VIRGINIA INITIAL (2000) (PERSONS)
R NGR.KL=BRTH.K-DTH.K
NOTE NGR-NATURAL GROWTH RATE (PERSONS/YR)
A BRTH.K=PV.K*BGF
NOTE BRTH-BIRTHS (PERSONS/YR)
C BGF=0.010293
NOTE BGF-BIRTH GROWTH FACTOR (DIM)
A DTH.K=PV.K*DGF
NOTE DTH-DEATHS (PERSONS/YR)
C DGF=0.007837
NOTE DGF-DEATH GROWTH FACTOR (DIM)
R MGR.KL=INM.K-OTM.K
NOTE MGR-MIGRATION RATE (PERSONS/YR)
A INM.K=PV.K*INMF
NOTE INM-IN-MIGRATIONS (PERSONS/YR)
C INMF=0.034840
NOTE INMF-IN-MIGRATION FACTOR (DIM)
A OTM.K=PV.K*OTMF
NOTE OTM-OUT-MIGRATIONS (PERSONS/YR)
C OTMF=0.029643
NOTE OTMF-OUT-MIGRATION FACTOR (DIM)
A  HV.K=PV.K/AHS.K
NOTE  HV-HOUSEHOLDS IN VIRGINIA (HOUSEHOLDS)
A  AHS.K=AHSN*(1+AHSGR)**TIME.K
NOTE  AHS-AVERAGE HOUSEHOLD SIZE (PERSONS/HOUSEHOLD)
C  AHSN=2.47
NOTE  AHSN-AVERAGE HOUSEHOLD SIZE NORMAL (PERSONS/HOUSEHOLD)
C  AHSGR=-0.007515
NOTE  AHSGR-AVERAGE HOUSEHOLD SIZE GROWTH RATE (DIM)
A VR.K=PV.K*VOS.K*MFTF
NOTE VR-VEHICLE REGISTRATIONS IN VIRGINIA (VEHICLES)
A VOS.K=RCVOS*TIME.K+RIVOS
NOTE VOS-VEHICLE OWNERSHIP IN VIRGINIA (VEHICLE/PERSON)
C RCVOS=0.000682
NOTE RCVOS-REGRESSION COEFFICIENT OF VEH OWNERSHIP (DIM)
C RIVOS=0.898978
NOTE RIVOS-REGRESSION INTERCEPT VALUE OF VEH OWNERSHIP (DIM)
N MFTF=TABLE(MFTFT,MFT,0.1735,0.5205,0.08675)
T MFTFT=1.0/0.90/0.80/0.65/0.50
NOTE MFTF-MOTOR FUELS TAX FACTOR (DIM)
A NVT.K=(NVTN*(1+NVTG)**TIME.K)*MFTF
NOTE NVT-NEW VEHICLES TITLED (VEHICLES)
N NVTN=344817
NOTE NVTN-NEW VEHICLES TITLED NORMAL (VEHICLES)
C NVTG=-0.007929
NOTE NVTG-NEW VEHICLES TITLED GROWTH FACTOR (DIM)
A UVT.K=UVTN*(1+UVTG)**TIME.K
```

```
NOTE UVT-USED VEHICLES TITLED (VEHICLES)
N UVTN=1077300
NOTE UVTN-USED VEHICLES TITLED NORMAL (VEHICLES)
C UVTG=0.0148555
NOTE UVTG-USED VEHICLES TITLED GROWTH FACTOR (DIM)
A ANVP.K=ANVPN*(1+NVPG)**TIME.K
NOTE ANVP-AVERAGE NEW VEHICLE PRICE ($)
N ANVPN=23777
NOTE ANVPN-AVERAGE NEW VEHICLE PRICE NORMAL ($)
C NVPG=0.034783
NOTE NVPG-NEW VEHICLE PRICE GROWTH FACTOR (DIM)
A AUVP.K=AUVPN*(1+UVPG)**TIME.K
NOTE AUVP-AVERAGE USED VEHICLE PRICE ($)
N AUVPN=6333
NOTE AUVPN-AVERAGE USED VEHICLE PRICE NORMAL ($)
C UVPG=0.058251
NOTE UVPG-USED VEHICLE PRICE GROWTH FACTOR (DIM)
A AMTV.K=AMTVN*(1+AMTVGR)**TIME.K
NOTE AMTV-AVERAGE MILES TRAVELED PER VEHICLE (MI/VEH-YR)
N AMTVN=12704
NOTE AMTVN-AVERAGE MILES TRAVELED PER VEHICLE NORMAL (MI/VEH-YR)
C AMTVGR=0.010864
NOTE AMTVGR-AMTV GROWTH RATE (DIM)
A ADMTV.K=AMTV.K/360
NOTE ADMTV-AVERAGE DAILY MILES TRAVELED PER VEHICLE (MI/VEH-DAY)
N ADMTVN=AMTVN/360
NOTE ADMTVN-AVERAGE DAILY MILES TRAVELED PER VEHICLE NORMAL (MI/VEH-DAY)
A ADTG.K=ADTGN*(1+ADTGGR)**TIME.K
NOTE ADTG-AVERAGE DISTANCE TRAVELED PER GALLON (MI/GAL)
N ADTGN=18.32
NOTE ADTGN-AVERAGE DISTANCE TRAVELED PER GALLON NORMAL (MI/GAL)
C ADTGGR=0.016189
NOTE ADTGGR-ADTG GROWTH RATE (DIM)
```

TRANSPORTATION SUBSYSTEM

A TVMH.K(H)=VMGPH.K(H)+VMCH.K(H)+VMTH.K(H)
NOTE TVMH-TOTAL VEHICLE MILES ON HIGHWAY (VEH-MI/DAY)
A AADTH.K(H)=TVMH.K(H)/MH.K(H)
NOTE AADTH-ANNUAL AVERAGE DAILY TRAFFIC OF HIGHWAY (VEHS/DAY)
A MH.K(H)=MHN(H)*(1+MLGR(H))**TIME.K
NOTE MH-MILEAGE OF HIGHWAY (MI)
T MHN=1155.82/8001.51/47210.20/10467.73
NOTE MHN-MILEAGE OF HIGHWAY NORMAL (MI)
T MLGR=0.0189/0.00067/0.0037/0.0125
NOTE MLGR-MILEAGE GROWTH RATE (DIM)
A DHVH.K(H)=AADTH.K(H)*KF(H)
NOTE DHVH-DESIGN HOUR VOLUME ON HIGHWAY (VEHS/HR)
T KF=0.08/0.15/0.15/0.15
NOTE KF-K FACTOR (DIM)
A AATH.K(H)=AADTH.K(H)*360
NOTE AATH-AVERAGE ANNUAL TRAFFIC ON HIGHWAY (VEHS/YR)
A ANLH.K(H)=TLMH.K(H)/MH.K(H)
NOTE ANLH-AVERAGE NUMBER OF LANES OF HIGHWAY (LANES)
A CAPH.K(H)=ANLH.K(H)*LCH(H)
NOTE CAPH-CAPACITY OF HIGHWAY (VEHS/HR)
T LCH=2400/2200/2000/2500
NOTE LCH-LANE CAPACITY OF HIGHWAY (VEHS/HR-LANE)
A DCRH.K(H)=DHVH.K(H)/CAPH.K(H)
NOTE DCRH-DEMAND CAPACITY RATIO OF HIGHWAY (DIM)
A LOSPH.K(H)=(HSF.K(H)*1+HDF.K(H)*3+HDT.K(H)*5)/TLMH.K(H)
NOTE LOSPH-LEVEL OF SERVICE PARAMETER FOR HIGHWAYS (DIM)
A LOSPB.K(H)=(BPFC.K(H)*1+BGC.K(H)*2+BPC.K(H)*4+BSC.K(H)*8+BCC.K(H)*16)/TNB.K(H)
NOTE LOSPB-LEVEL OF SERVICE PARAMETER FOR BRIDGES (DIM)
A LOSP.K(H)=PMSP*LOSPH.K(H)+(1-PMSP)*LOSPB.K(H)
NOTE LOSP-LEVEL OF SERVICE PARAMETER FOR HMS (DIM)
A LOSF.K(1)=TABLE(LOSFTI,LOSP.K(1),1.0,5.0,0.5)
T LOSFTI=0.05/0.1/0.15/0.2/0.25/0.3/0.35/0.4/0.45
A LOSF.K(2)=TABLE(LOSFTP,LOSP.K(2),1.0,6.4,0.6)
T LOSFTP=0.05/0.1/0.2/0.3/0.4/0.5/0.6/0.7/0.8/0.9
A LOSF.K(3)=TABLE(LOSFTS,LOSP.K(3),1.0,6.4,0.6)
T LOSFTS=0.05/0.1/0.2/0.3/0.4/0.5/0.6/0.7/0.8/0.9
A LOSF.K(4)=TABLE(LOSFTU,LOSP.K(4),1.0,6.4,0.6)
T LOSFTU=0.05/0.1/0.2/0.3/0.4/0.5/0.6/0.7/0.8/0.9
NOTE LOSF-LEVEL OF SERVICE FACTOR FOR HMS (DIM)
A FFT.K(H)=(ADMTV.K/FFS(H))*60
NOTE FFT-FREE FLOW TIME (MIN)
A FFTA.K(H)=(AMTV.K/FFS(H))*60
NOTE FFTA-FREE FLOW TIME ANNUAL (MIN)
T FFS=80/70/50/60
NOTE FFS-FREE FLOW SPEED (MI/HR)
A TT.K(H)=FFT.K(H)*((1-(1-LOSF.K(H))*DCRH.K(H))/(1-DCRH.K(H)))
NOTE TT-TRAVEL TIME (MIN)
A TTA.K(H)=FFTA.K(H)*((1-(1-LOSF.K(H))*DCRH.K(H))/(1-DCRH.K(H)))
NOTE TTA-TRAVEL TIME ANNUAL (MIN)
A OPS.K(H)=(ADMTV.K/TT.K(H))*60
NOTE OPS-OPERATING SPEED (MI/HR)

TRAVEL DEMAND SUBSYSTEM A

A DHST.K=HV.K*HSTR
NOTE DHST-DAILY HOME-BASED SHOPPING TRIPS (TRIPS/DAY)
C HSTR=0.76
NOTE HSTR-HOME-BASED SHOPPING TRIP RATE (TRIPS/HH-DAY)
A DHSRT.K=HV.K*HSRTR
NOTE DHSRT-DAILY HOME-BASED SOCIAL AND RECRE. TRIPS (TRIPS/DAY)
C HSRTR=0.98
NOTE HSRTR-HOME-BASED SOCIAL AND RECRE. TRIP RATE (TRIPS/HH-DAY)
A DHOT.K=HV.K*HOTR
NOTE DHOT-DAILY HOME-BASED OTHER TRIPS (TRIPS/DAY)
C HOTR=1.84
NOTE HOTR-HOME-BASED OTHER TRIP RATE (TRIPS/HH-DAY)
A DNHT.K=HV.K*NHTR
NOTE DNHT-DAILY NON-HOME-BASED TRIPS (TRIPS/DAY)
C NHTR=1.52
NOTE NHTR-NON-HOME-BASED TRIP RATE (TRIPS/HH-DAY)
A DHSPD.K=DHST.K/DHSTP
NOTE DHSPD-DAILY H.B. SHOPPING PERSON DEMAND (PERSONS/DAY)
C DHSTP=0.49
NOTE DHSTP-DAILY H.B. SHOPPING TRIPS PER PERSON (TRIPS/PERSON)
A DHSRPD.K=DHSRT.K/DHSRTP
NOTE DHSRPD-DAILY H.B. SOCIAL AND RECRE. PERSON DEMAND (PERSONS/DAY)
C DHSRTP=0.63
NOTE DHSRTP-DAILY H.B. SOCIAL AND RECRE. TRIPS PER PERSON (TRIPS/PERSON)
A DHOPD.K=DHOT.K/DHOTP
NOTE DHOPD-DAILY H.B. OTHER PERSON DEMAND (PERSONS/DAY)
C DHOTP=1.18
NOTE DHOTP-DAILY H.B. OTHER TRIPS PER PERSON (TRIPS/PERSON)
A DNHPD.K=DNHT.K/DNHTP
NOTE DNHPD-DAILY N.H.B. PERSON DEMAND (PERSONS/DAY)
C DNHTP=0.97
NOTE DNHTP-DAILY N.H.B. TRIPS PER PERSON (TRIPS/PERSON)
A DHSVD.K=DHSPD.K/AVOHS
NOTE DHSVD-DAILY H.B. SHOPPING VEHICLE DEMAND (VEHS/DAY)
C AVOHS=1.51
NOTE AVOHS-AVERAGE VEHICLE OCCUPANCY FOR H.B.S. TRIP (PERSONS/VEH)
A DHSRVD.K=DHSRPD.K/AVOHSR
NOTE DHSRVD-DAILY H.B. SOCIAL AND RECRE. VEHICLE DEMAND (VEHS/DAY)
C AVOHSR=1.91
NOTE AVOHSR-AVERAGE VEHICLE OCCUPANCY FOR H.B.S.R. TRIP (PERSONS/VEH)
A DHOVD.K=DHOPD.K/AVOHO
NOTE DHOVD-DAILY H.B. OTHER VEHICLE DEMAND (VEHS/DAY)
C AVOHO=1.65
NOTE AVOHO-AVERAGE VEHICLE OCCUPANCY FOR H.B.O. TRIP (PERSONS/VEH)
A DNHVD.K=DNHPD.K/AVONH
NOTE DNHVD-DAILY N.H.B. VEHICLE DEMAND (VEHS/DAY)
C AVONH=1.32
NOTE AVONH-AVERAGE VEHICLE OCCUPANCY FOR N.H.B. TRIP (PERSONS/VEH)
A DVDGP.K=DHSVD.K+DHSRVD.K+DHOVD.K+DNHVD.K
NOTE DVDGP-DAILY VEHICLE DEMAND FOR GENERAL PURPOSE (VEHS/DAY)
A DVDGPH.K(H)=DVDGP.K*(HMSGP(H)+TTPH(H))*HAM.K

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NOTE  DVDGPH-DAILY VEHICLE DEMAND FOR G.P. OF HIGHWAY (VEHS/DAY)
T  HMSGP=0.25/0.25/0.25/0.25
NOTE  HMSGP-HIGHWAY MODAL SPLIT FOR G.P. TRIP (DIM)
T  TTPH=0.10/0.10/0.06/0.02
NOTE  TTPH-THRU TRAFFIC PORTION ON A HIGHWAY (DIM)
A  HAM.K=TABLE(HAMT,TIME.K,0,20,2)
T  HAMT=1.06/1.07/1.08/1.09/1.10/1.11/1.10/1.09/1.08/1.07/1.06
NOTE  HAM-HIGHWAY ATTRACTION MULTIPLIER (DIM)
A  DTDHS.K=DHST.K*ATLHS.K
NOTE  DTDHS-DAILY TRAVEL DISTANCE FOR H.B.S. TRIP (MILES/DAY)
A  ATLHS.K=ATLHSN*(1+0.002833)**TIME.K
NOTE  ATLHS-AVERAGE TRIP LENGTH FOR H.B.S. TRIP (MILES/TRIP)
C  ATLHSN=5.25
NOTE  ATLHSN-AVERAGE TRIP LENGTH NORMAL FOR H.B.S. TRIP (MILES/TRIP)
A  DTDHSR.K=DHSRT.K*ATLHSR.K
NOTE  DTDHSR-DAILY TRAVEL DISTANCE FOR H.B.S.R. TRIP (MILES/DAY)
A  ATLHSR.K=ATLHSRN*(1+0.009853)**TIME.K
NOTE  ATLHSR-AVERAGE TRIP LENGTH FOR H.B.S.R. TRIP (MILES/TRIP)
C  ATLHSRN=13.25
NOTE  ATLHSRN-AVERAGE TRIP LENGTH NORMAL FOR H.B.S.R. TRIP (MILES/TRIP)
A  DTDHO.K=DHOT.K*ATLHO.K
NOTE  DTDHO-DAILY TRAVEL DISTANCE FOR H.B.O. TRIP (MILES/DAY)
A  ATLHO.K=ATLHON*(1+0.011966)**TIME.K
NOTE  ATLHO-AVERAGE TRIP LENGTH FOR H.B.O. TRIP (MILES/TRIP)
C  ATLHON=6.81
NOTE  ATLHON-AVERAGE TRIP LENGTH NORMAL FOR H.B.O. TRIP (MILES/TRIP)
A  DTDNH.K=DNHT.K*ATLNH.K
NOTE  DTDNH-DAILY TRAVEL DISTANCE FOR N.H.B. TRIP (MILES/DAY)
A  ATLNH.K=ATLNHN*(1-0.007928)**TIME.K
NOTE  ATLNH-AVERAGE TRIP LENGTH FOR N.H.B. TRIP (MILES/TRIP)
C  ATLNHN=8.55
NOTE  ATLNHN-AVERAGE TRIP LENGTH NORMAL FOR N.H.B. TRIP (MILES/TRIP)
A  DTDGP.K=DTDHS.K+DTDHSR.K+DTDHO.K+DTDNH.K
NOTE  DTDGP-DAILY TRAVEL DISTANCE FOR GEN. PURPOSE (MILES/DAY)
A  ATDGP.K=DTDGP.K/DVDGP.K
NOTE  ATDGP-AVERAGE TRAVEL DISTANCE FOR GEN. PUR. TRIP (MI)
A  VMGPH.K(H)=DVDGPH.K(H)*ATDGP.K
NOTE  VMGPH-VEH MILES PER DAY FOR G.P. TRIP ON A HIGHWAY (VEH-MI/DAY)
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TRAVEL DEMAND SUBSYSTEM B

A C.K=E.K*WRR
NOTE C-COMMUTERS (PERSONS/PERIOD)
C WRR=0.9
NOTE WRR-WORKPLACE REPORT RATE (DIM)
A CDA.K=C.K*FCDA
NOTE CDA-COMMUTERS DRIVING ALONE (PERSONS/PERIOD)
C FCDA=0.70
NOTE FCDA-FRACTION OF COMMUTERS DRIVING ALONE (DIM)
A CMCP.K=C.K*FCCP
NOTE CCP-COMMUTERS IN CARPOOL (PERSONS/PERIOD)
C FCCP=0.20
NOTE FCCP-FRACTION OF COMMUTERS IN CARPOOL (DIM)
A COM.K=C.K-(CDA.K+CMCP.K)
NOTE COM-COMMUTERS USING OTHER MODES (PERSONS/PERIOD)
A DACD.K=CDA.K/AVODA
NOTE DACD-DRIVING ALONE COMMUTER DEMAND (VEHS/PERIOD)
C AVODA=1.0
NOTE AVODA-AVERAGE VEHICLE OCCUPANCY FOR D.A. TRAFFIC (PERSONS/VEH)
A CPCD.K=CMCP.K/AVOCP
NOTE CPCD-CARPOOL COMMUTER DEMAND (VEHS/PERIOD)
N AVOCP=(1.22*(FCDA+FCCP)-FCDA*AVODA)/FCCP
NOTE AVOCP-AVERAGE VEHICLE OCCUPANCY IN CARPOOL (PERSONS/VEH)
A CVDP.K=DACD.K+CPCD.K
NOTE CVDP-COMMUTER VEHICLE DEMAND PER PERIOD (VEHS/PERIOD)
A DCVD.K=CVDP.K*NCP
NOTE DCVD-DAILY COMMUTER VEHICLE DEMAND (VEHS/DAY)
C NCP=2
NOTE NCP-NUMBER OF COMMUTING PERIOD (PERIODS/DAY)
A DCVDH.K(H)=DCVD.K*HMSC(H)
NOTE DCVDH-DAILY COMMUTER VEHICLE DEMAND OF HIGHWAY (VEHS/DAY)
T HMSC=0.15/0.15/0.10/0.60
NOTE HMSC-HIGHWAY MODAL SPLIT FOR COMMUTING (DIM)
A VMCH.K(H)=DCVDH.K(H)*ATDC.K
NOTE VMCH-VEHICLE MILES FOR COMMUTING ON A HIGHWAY (VEH-MI/DAY)
A ATDC.K=ATDCN*(1+ATDGR)**TIME.K
NOTE ATDC-AVERAGE TRAVEL DISTANCE FOR COMMUTING (MI)
C ATDCN=14.54
NOTE ATDCN-AVERAGE TRAVEL DISTANCE FOR COMMUTING NORMAL (MI)
C ATDGR=0.0231
NOTE ATDGR-AVERAGE TRAVEL DISTANCE GROWTH RATE (DIM)
A ATIO.K=SIO.K*TIO
NOTE ATIO-ANNUAL TRUCKS FROM INDUSTRIAL OUTPUT (TRUCKS/YR)
C TIO=0.000005
NOTE TIO-TRUCKS PER INDUSTRIAL OUTPUT (TRUCKS/$)
A AET.K=ATIO.K*ETF
NOTE AET-ANNUAL EMPTY TRUCKS (TRUCKS/YR)
C ETF=0.1
NOTE ETF-EMPTY TRUCK FACTOR
A AT.K=ATIO.K+AET.K
NOTE AT-ANNUAL TRUCKS (TRUCKS/YR)
A DTR.K=AT.K/CFDT

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NOTE  DTR-DAILY TRUCKS (TRUCKS/DAY)
C  CFDT=360
NOTE  CFDT-CONVERSION FACTOR TO DAILY TRUCKS (DIM)
A  DTD.K=DTR.K*PCET
NOTE  DTD-DAILY TRUCK DEMAND (VEHS/DAY)
C  PCET=3
NOTE  PCET-PASSENGER CAR EQUIVALENTS FOR TRUCK (VEHS/TRUCK)
A  DTDH.K(H)=DTD.K*(HMST(H)+TTTPH(H))
NOTE  DTDH-DAILY TRUCK DEMAND ON HIGHWAY (VEHS/DAY)
T  HMST=0.4/0.4/0.1/0.1
NOTE  IMST-INTERSTATE MODAL SPLIT FOR TRUCK (DIM)
T  TTTPH=0.3/0.2/0.1/0.05
NOTE  TTTPH-TRUCK THRU TRAFFIC PORTION ON HIGHWAY (DIM)
A  VMTH.K(H)=DTDH.K(H)*ATDT
NOTE  VMTH-VEHICLE MILES FOR TRUCK ON HIGHWAY (VEH-MI/DAY)
C  ATDT=48.18
NOTE  ATDT-AVERAGE TRAVEL DISTANCE FOR TRUCK (MI)
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REGIONAL ECONOMY SUBSYSTEM

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FOR  S=1,10
NOTE  S-GSP SECTORS
NOTE  1-AGRICULTURE, FORESTRY, AND FISHERIES
NOTE  2-MINING
NOTE  3-CONSTRUCTION
NOTE  4-MANUFACTURING
NOTE  5-TRANSPORTATION, COMMUNICATION, AND PUBLIC UTILITIES
NOTE  6-WHOLESALE TRADE
NOTE  7-RETAIL TRADE
NOTE  8-FINANCE, INSURANCE, AND REAL ESTATE
NOTE  9-SERVICES
NOTE  10-GOVERNMENT
L  IC.K(S)=IC.J(S)+(DT)(CI.JK(S)-CD.JK(S))
N  IC(S)=ICN(S)
NOTE  IC-INDUSTRIAL CAPITAL ($)
T  ICN=18200E6/5895E6/23710E6/39870E6/87530E6/12110E6/16990E6/121500E6/71560E6/65880E6
NOTE  ICN-INDUSTRIAL CAPITAL NORMAL ($)
A  SIC.K=SUMV(IC.K(*),1,10)
NOTE  SIC-SUM OF INDUSTRIAL CAPITAL OF EACH SECTOR ($)
N  SICN=SUMV(ICN(*),1,10)
NOTE  SIC-INITIAL SUM OF INDUSTRIAL CAPITAL OF EACH SECTOR ($)
R  CI.KL(S)=PS.K(S)*FPSCI(S)
NOTE  CI-CAPITAL INVESTMENT ($/YR)
T  FPSCI=0.72/0.065/0.13/0.125/0.62/0.122/0.125/0.55/0.345/0.21
NOTE  FPSCI-FRACTION OF PS TO CI (DIM)
R  CD.KL(S)=IC.K(S)/ALC.K(S)
NOTE  CD-CAPITAL DEPRECIATION ($/YR)
A  ALC.K(S)=ALCN*ALCM.K(S)
NOTE  ALC-AVERAGE LIFETIME OF CAPITAL (YR)
C  ALCN=25
NOTE  ALCN-AVERAGE LIFETIME OF CAPITAL NORMAL (YR)
A  ALCM.K(S)=ICN(S)/IC.K(S)
NOTE  ALCM-AVERAGE LIFETIME OF CAPITAL MULTIPLIER (YR)
A  PS.K(S)=IO.K(S)*PDT.K
NOTE  PS-PRODUCT BY EACH SECTOR ($/YR)
A  PDT.K=1-FIOI*TFIH.K
NOTE  PDT-PRODUCTIVITY (DIM)
C  FIOI=0.45
NOTE  FIOI-FRACTION OF IO TO INPUTS (DIM)
A  TFIH.K=TFI.K(1)
A  TFI.K(1)=TABLE(TFIT,PSIH.K(1),0.5,1.0,0.05)
T  TFIT=1.01/1.009/1.008/1.007/1.006/1.005/1.004/1.003/1.002/1.001/1.00
NOTE  TFIH-TRANSPORT FRICTION INDICATOR (DIM)
A  GSP.K=SUMV(PS.K(*),1,10)
NOTE  GSP-GROSS STATE PRODUCT ($/YR)
A  IO.K(S)=IC.K(S)/COR(S)
NOTE  IO-INDUSTRIAL OUTPUT ($/YR)
T  COR=3.5/0.98/0.5/0.65/2.5/0.6/0.6/2.0/1.05/1.0
NOTE  COR-CAPITAL OUTPUT RATIO (YR)
A  SIO.K=SUMV(IO.K(*),1,10)
NOTE  SIO-SUM OF INDUSTRIAL OUTPUT OF EACH SECTOR ($)
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A  ES.K(S)=(PS.K(S)/PLR.K(S))
NOTE  ES-EMPLOYMENT IN EACH SECTOR (WORKERS)
A  PLR.K(S)=PLRN(S)*(1+LP(S)*LPF.K)
NOTE  PLR-PRODUCT LABOR RATIO (($/YR)/WORKER)
T  PLRN=30629/63269/50705/53066/69404/57545/41554/99409/45214/50218
NOTE  PLRN-PRODUCT LABOR RATIO NORMAL (($/YR)/WORKER)
T  LP=0.1128/0.0612/0.0661/0.0652/0.0605/0.0577/0.0479/0.0679/0.0649/0.0688
NOTE  LP-LABOR PRODUCTIVITY (DIM)
A  LPF.K=CLIP(10,TIME.K,TIME.K,10)
NOTE  LPF-LABOR PRODUCTIVITY FACTOR (DIM)
A  E.K=SUMV(ES.K(*),1,10)
NOTE  E-EMPLOYMENT (WORKERS)
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FINANCE SUBSYSTEM

A HMOF.K=RMFTH.K+RMLFH.K+RMSUTH.K+FR.K+MRH.K
NOTE HMOF-HIGHWAY MAINTENANCE & OPERATING FUND ($)
A RMFTH.K=MFTH*VMT.K/ADTG.K
NOTE RMFTH-REVENUE FROM MOTOR VEH FUELS TAX FOR HMOF ($)
N MFTH=0.1485
NOTE MFTH-MOTOR VEHICLE FUELS TAX FOR HMOF ($/GAL)
A VMT.K=VR.K*AMTV.K
NOTE VMT-VEHICLE MILES TRAVELED (VEH-MI)
A RMLFH.K=VR.K*MLFH
NOTE RMLFH-REVENUE FROM MOTOR VEH LICENSE FEES FOR HMOF ($)
C MLFH=16
NOTE MLFH-MOTOR VEHICLE LICENSE FEES FOR HMOF ($/VEH)
A RMSUTH.K=MSUTH*(NVT.K*ANVP.K+UVT.K*AUVP.K)
NOTE RMSUTH-REVENUE FROM MOTOR VEH SALES & USE TAX FOR HMOF ($)
C MSUTH=0.02
NOTE MSUTH-MOTOR VEHICLE SALES & USE TAX FOR HMOF (DIM)
A FR.K=FRN*(1+FRIF)**TIME.K
NOTE FR-FEDERAL AID REVENUE ($)
N FRN=450E6
NOTE FRN-FEDERAL AID REVENUE NORMAL ($)
C FRIF=0.0475606
NOTE FRIF-FEDERAL AID REVENUE INCREASING FACTOR (DIM)
A MRH.K=MRHN*MRHM.K
NOTE MRH-MISCELLANEOUS REVENUE FOR HMOF ($)
N MRHN=8.0E6
NOTE MRHN-MISCELLANEOUS REVENUE FOR HMOF NORMAL ($)
A MRHM.K=TABLE(MRHMT,GSP.K,15E10,65E10,5E10)
T MRHMT=1.15/1.40/1.80/2.20/2.60/3.00/3.40/3.80/4.20/4.60/5.0
NOTE MRHM-MISCELLANEOUS REVENUE FOR HMOF MULTIPLIER ($)
A TTF.K=RMFTT.K+RMLFT.K+RMSUTT.K+RSST.K+MRT.K
NOTE TTF-TRANSPORTATION TRUST FUND ($)
A RMFTT.K=MFTT*VMT.K/ADTG.K
NOTE RMFTT-REVENUE FROM MOTOR VEH FUELS TAX FOR TTF ($)
N MFTT=0.025
NOTE MFTT-MOTOR VEHICLE FUELS TAX FOR TTF ($/GAL)
A RMLFT.K=VR.K*MLFT
NOTE RMLFT-REVENUE FROM MOTOR VEH LICENSE FEES FOR TTF ($)
C MLFT=3
NOTE MLFT-MOTOR VEHICLE LICENSE FEES FOR TTF ($/VEH)
A RMSUTT.K=MSUTT*(NVT.K*ANVP.K+UVT.K*AUVP.K)
NOTE RMSUTT-REVENUE FROM MOTOR VEH SALES & USE TAX FOR TTF ($)
C MSUTT=0.01
NOTE MSUTT-MOTOR VEHICLE SALES & USE TAX FOR TTF (DIM)
A RSST.K=PV.K*SST*APRP
NOTE RSST-REVENUE FROM STATE SALES TAX ($)
C SST=0.005
NOTE SST-STATE SALES TAX (DIM)
C APRP=9500
NOTE APRP-AVERAGE PURCHASE RATE PER PERSON ($)
A MRT.K=MRTN*MRTM.K
NOTE MRT-MISCELLANEOUS REVENUE FOR TTF ($)

N MRTN=165E6
NOTE MRTN-MISCELLANEOUS REVENUE FOR TTF NORMAL ($)
A MRTM.K=TABLE(MRTMT,GSP.K,15E10,65E10,5E10)
T MRTMT=1.04/1.06/1.08/1.10/1.12/1.14/1.16/1.18/1.20/1.22/1.24
NOTE MRTM-MISCELLANEOUS REVENUE FOR TTF MULTIPLIER ($)
A RMFT.K=RMFTH.K+RMFTT.K
NOTE RMFT-REVENUE FROM MOTOR FUELS TAX ($)
A PMFT.K=(RMFT.K/TR.K)*100
NOTE PMFT-PROPORTION OF TOTAL REVENUE TO FUELS TAX REVENUE (%)
N MFT=MFTH+MFTT
NOTE MFT-MOTOR FUEL TAX FOR BOTH HMOF & TTF ($/GAL)
A TR.K=HMOF.K+TTF.K
NOTE TR-TOTAL TRANSPORTATION REVENUE ($)
A TRBH.K(H)=TR.K*FCMBI(H)
NOTE TRBH-TOTAL REVENUE BY HIGHWAYS ($)
A HRA.K=TR.K*FTRH
NOTE HRA-HIGHWAY REVENUE ALLOCATED ($)
C FTRH=0.85
NOTE FTRH-FRACTION OF TOTAL REVENUE TO HIGHWAYS (DIM)
A CMBH.K=HRA.K*FHRACM
NOTE CMBH-CONSTRUCTION & MAINTENANCE BUDGET FOR HIGHWAYS ($)
C FHRACM=0.737
NOTE FHRACM-FRACTION OF HRA TO CONSTRUCTION & MAINTENANCE (DIM)
A ICMB.K(H)=CMBH.K*FCMBI(H)
NOTE ICMB-CONSTRUCTION & MAINT BUDGET ($)
T FCMBI=0.192/0.270/0.311/0.227
NOTE FCMBI-FRACTION OF CMBH TO HIGHWAY (DIM)
A PMSB.K(H)=ICMB.K(H)*PMSP
NOTE PMSB-PAVEMENT MANAGEMENT SUBSYSTEM BUDGET ($)
C PMSP=0.80
NOTE PMSP-PMS PORTION (DIM)
A BMSB.K(H)=ICMB.K(H)-PMSB.K(H)
NOTE BMSB-BRIDGE MANAGEMENT SUBSYSTEM BUDGET ($)

PAVEMENT MANAGEMENT SUBSYSTEM

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L  HSF.K(H)=HSF.J(H)+(DT)(CRH.JK(H)+MRDFH.JK(H)+MRDTH.JK(H)-ARH.JK(H))
N  HSF(H)=HSFN(H)
T  HSFN=1854.69/7160.4/31677.18/6396.11
NOTE  HSF-HIGHWAY IN SUFFICIENT CONDITION (LANE-MI)
L  HDF.K(H)=HDF.J(H)+(DT)(ARH.JK(H)-MRDFH.JK(H)-DRH.JK(H))
N  HDF(H)=HDFN(H)
T  HDFN=1854.69/7160.4/31677.18/6396.11
NOTE  HDF-HIGHWAY IN DEFICIENT CONDITION (LANE-MI)
L  HDT.K(H)=HDT.J(H)+(DT)(DRH.JK(H)-MRDTH.JK(H))
N  HDT(H)=HDTN(H)
T  HDTN=1854.69/7160.4/31677.18/6396.11
NOTE  HDT-HIGHWAY IN DETERIORATED CONDITION (LANE-MI)
R  CRH.KL(H)=HCE.K(H)/CCH.K(H)
NOTE  CRH-CONSTRUCTION RATE OF HIGHWAY (LANE-MI/YR)
R  ARH.KL(H)=HSF.K(H)/ATH.K(H)
NOTE  ARH-AGING RATE OF HIGHWAY (LANE-MI/YR)
A  ATH.K(H)=ATHN*ATHM.K(H)
NOTE  ATH-AGING TIME OF HIGHWAY (YR)
N  ATHN=1
NOTE  ATHN-AGING TIME OF HIGHWAY NORMAL (YR)
A  ATHM.K(H)=TABLE(ATHMT,DCRH.K(H),0.0,1.0,0.1)
T  ATHMT=1.0/0.98/0.96/0.94/0.92/0.90/0.88/0.86/0.84/0.82/0.80
NOTE  ATHM-AGING TIME OF HIGHWAY MULTIPLIER (DIM)
R  DRH.KL(H)=HDF.K(H)/HDTT.K(H)
NOTE  DRH-DETERIORATING RATE OF HIGHWAY (LANE-MI/YR)
A  HDTT.K(H)=HDTTN*HDTTM.K(H)
NOTE  HDTT-HIGHWAY DETERIORATION TIME (YR)
N  HDTTN=3
NOTE  HDTTN-HIGHWAY DETERIORATION TIME NORMAL (YR)
A  HDTTM.K(H)=TABLE(HDTTMT,DCRH.K(H),0.0,1.0,0.1)
T  HDTTMT=1.0/0.98/0.96/0.94/0.92/0.90/0.88/0.86/0.84/0.82/0.80
NOTE  HDTTM-HIGHWAY DETERIORATION TIME MULTIPLIER (DIM)
R  MRDFH.KL(H)=MIN(MEDFH.K(H)/MCDFH.K(H),HDF.K(H))
NOTE  MRDFH-MAINTENANCE RATE FOR DEFICIENT HIGHWAY (LANE-MI/YR)
A  MEDFH.K(H)=HME.K(H)*FHMEDFH.K(H)/MAX(FHMEDFH.K(H)+FHMEDTH.K(H),1E-6)
NOTE  MEDFH-MAINTENANCE EXPENDITURE FOR DEFICIENT HIGHWAY ($/YR)
R  MRDTH.KL(H)=MIN(MEDTH.K(H)/MCDTH.K(H),HDT.K(H))
NOTE  MRDTH-MAINTENANCE RATE FOR DETERIORATED HIGHWAY (LANE-MI/YR)
A  MEDTH.K(H)=HME.K(H)*FHMEDTH.K(H)/MAX(FHMEDFH.K(H)+FHMEDTH.K(H),1E-6)
NOTE  MEDTH-MAINTENANCE EXPENDITURE FOR DETERIORATED HIGHWAY ($/YR)
A  HCE.K(H)=PMSB.K(H)*FPMSBC.K(H)
NOTE  HCE-HIGHWAY CONSTRUCTION EXPENDITURE ($/YR)
A  HME.K(H)=PMSB.K(H)*FPMSBM.K(H)
NOTE  HME-HIGHWAY MAINTENANCE EXPENDITURE ($/YR)
A  TLMH.K(H)=MAX(HSF.K(H)+HDF.K(H)+HDT.K(H),1E-6)
NOTE  TLMH-TOTAL LANE-MILEAGE OF HIGHWAY (LANE-MI)
N  TLMHN(H)=HSFN(H)+HDFN(H)+HDTN(H)
NOTE  TLMHN-TOTAL LANE-MILEAGE OF HIGHWAY INITIAL (LANE-MI)
A  FPMSBC.K(H)=CLIP(0,HSF.K(H)/TLMH.K(H),TIME.K,CTMT)
NOTE  FPMSBC-FRACTION OF PMS BUDGET TO CONSTRUCTION (DIM)
C  CTMT=10
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NOTE CTMT-CONSTRUCTION TERMINATION TIME (YR)
A FPMSBM.K(H)=1-FPMSBC.K(H)
NOTE FPMSBM-FRACTION OF PMS BUDGET TO MAINTENANCE (DIM)
A FHMEDFH.K(H)=CLIP(FPMSBM.K(H)*HDF.K(H)/MAX(HDF.K(H)+HDT.K(H),1E-6),0,HDF.K(H),0)
NOTE FHMEDFH-FRACT OF MAINT EXPENDITURE TO DEFICIENT HIGHWAY (DIM)
A FHMEDTH.K(H)=FPMSBM.K(H)-FHMEDFH.K(H)
NOTE FHMEDTH-FRACT OF MAINT EXPENDITURE TO DETERIORATED HIGHWAY (DIM)
C WFHSF=1.0
NOTE WFHSF-WEIGHTING FACTOR FOR HSF (DIM)
C WFHDF=0.7
NOTE WFHDF-WEIGHTING FACTOR FOR HDF (DIM)
C WFHDT=0.5
NOTE WFHDT-WEIGHTING FACTOR FOR HDT (DIM)
A PSIH.K(H)=(HSF.K(H)*WFHSF+HDF.K(H)*WFHDF+HDT.K(H)*WFHDT)/TLMH.K(H)
NOTE PSIH-PHYSICAL SUFFICIENCY INDEX OF HIGHWAY (DIM)
N PSIHN(H)=(HSFN(H)*WFHSF+HDFN(H)*WFHDF+HDTN(H)*WFHDT)/TLMHN(H)
NOTE PSIHN-PHYSICAL SUFFICIENCY INDEX OF HIGHWAY NORMAL (DIM)
A FAI.K(H)=(TLMH.K(H)/PV.K)/(TLMHN(H)/PVN)
NOTE FAI-FUNCTIONAL ADEQUACY INDEX OF PAVEMENT (DIM)

BRIDGE MANAGEMENT SUBSYSTEM

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L BPFC.K(H)=BPFC.J(H)+(DT)(CRB.JK(H)+PVMB.JK(H)+RRRB.JK(H)+RHRB.JK(H)+^
  RPRB.JK(H)-ERB.JK(H))
N BPFC(H)=BPFCN(H)
T BPFCN=43/308/1791/380
NOTE BPFC-BRIDGES IN PREFERRED CONDITION (BRIDGES)
L BGC.K(H)=BGC.J(H)+(DT)(ERB.JK(H)-PVMB.JK(H)-ARB.JK(H))
N BGC(H)=BGCN(H)
T BGCN=43/308/1791/380
NOTE BGC-BRIDGES IN GOOD CONDITION (BRIDGES)
L BPC.K(H)=BPC.J(H)+(DT)(ARB.JK(H)-RRRB.JK(H)-DRB.JK(H))
N BPC(H)=BPCN(H)
T BPCN=43/308/1791/380
NOTE BPC-BRIDGES IN POOR CONDITION (BRIDGES)
L BSC.K(H)=BSC.J(H)+(DT)(DRB.JK(H)-RHRB.JK(H)-SDRB.JK(H))
N BSC(H)=BSCN(H)
T BSCN=43/308/1791/380
NOTE BSC-BRIDGES IN SERIOUS CONDITION (BRIDGES)
L BCC.K(H)=BCC.J(H)+(DT)(SDRB.JK(H)-RPRB.JK(H))
N BCC(H)=BCCN(H)
T BCCN=43/308/1791/380
NOTE BCC-BRIDGES IN CRITICAL CONDITION (BRIDGES)
R ERB.KL(H)=BPFC.K(H)/ETB.K(H)
NOTE ERB-EXPOSURE RATE OF BRIDGE (BRIDGES/YR)
R ARB.KL(H)=BGC.K(H)/ATB.K(H)
NOTE ARB-AGING RATE OF BRIDGE (BRIDGES/YR)
R DRB.KL(H)=BPC.K(H)/DTB.K(H)
NOTE DRB-DETERIORATION RATE OF BRIDGE (BRIDGES/YR)
R SDRB.KL(H)=BSC.K(H)/SDTB.K(H)
NOTE SDRB-SERIOUS DETERIORATION RATE OF BRIDGE (BRIDGES/YR)
R CRB.KL(H)=CEB.K(H)/CCB.K(H)
NOTE CRB-CONSTRUCTION RATE OF BRIDGE (BRDGS/YR)
A CEB.K(H)=BMSB.K(H)*FBBC.K(H)
NOTE CEB-CONSTRUCTION EXPENDITURE ON BRIDGES ($/YR)
R PVMB.KL(H)=MIN(PMEB.K(H)/PMCB.K(H),BGC.K(H))
NOTE PVMB-PREVENTIVE MAINTENANCE RATE OF BRIDGE (BRDGS/YR)
A PMEB.K(H)=BMSB.K(H)*FBPM.K(H)
NOTE PMEB-PREVENTIVE MAINTENANCE EXPENDITURE ON BRIDGES ($/YR)
R RRRB.KL(H)=MIN(RREB.K(H)/RRCB.K(H),BPC.K(H))
NOTE RRRB-REPAIR RATE OF BRIDGE (BRDGS/YR)
A RREB.K(H)=BMSB.K(H)*FBRR.K(H)
NOTE RREB-REPAIR EXPENDITURE ON BRIDGES ($/YR)
R RHRB.KL(H)=MIN(RHEB.K(H)/RHCB.K(H),BSC.K(H))
NOTE RHRB-REHABILITATION RATE OF BRIDGE (BRDGS/YR)
A RHEB.K(H)=BMSB.K(H)*FBRH.K(H)
NOTE RHEB-REHABILITATION EXPENDITURE ON BRIDGES ($/YR)
R RPRB.KL(H)=MIN(RPEB.K(H)/RPCB.K(H),BCC.K(H))
NOTE RPRB-REPLACEMENT RATE OF BRIDGE (BRDGS/YR)
A RPEB.K(H)=BMSB.K(H)*FBRP.K(H)
NOTE RPEB-REPLACEMENT EXPENDITURE ON BRIDGES ($/YR)
N PSSB=0.272
NOTE PSSB-PROPORTION OF STEEL STRINGER BRIDGES (DIM)
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N ARSSB=57
NOTE ARSSB-ANTICIPATED RETIREMENT OF SSB (YRS)
N PTSB=0.12
NOTE PTSB-PROPORTION OF TIMBER STRINGER BRIDGES (DIM)
N ARTSB=47
NOTE ARTSB-ANTICIPATED RETIREMENT OF TSB (YRS)
N PCSB=0.088
NOTE PCSB-PROPORTION OF CONCRETE SLAB BRIDGES (DIM)
N ARCSB=64
NOTE ARCSB-ANTICIPATED RETIREMENT OF CSB (YRS)
N PSTTB=0.065
NOTE PSTTB-PROPORTION OF STEEL THROUGH-TRUSS BRIDGES (DIM)
N ARSTTB=73
NOTE ARSTTB-ANTICIPATED RETIREMENT OF STTB (YRS)
N PCDAB=0.013
NOTE PCDAB-PROPORTION OF CONCRETE-DECK ARCH BRIDGES (DIM)
N ARCDAB=77
NOTE ARCDAB-ANTICIPATED RETIREMENT OF CDAB (YRS)
N PSGFBB=0.019
NOTE PSGFBB-PROPORTION OF STEEL-GIRDER FLOOR BEAM BRIDGES (DIM)
N ARSGFBB=61
NOTE ARSGFBB-ANTICIPATED RETIREMENT OF SGFBB (YRS)
N PCSTB=0.035
NOTE PCSTB-PROPORTION OF CONCRETE STRINGER BRIDGES (DIM)
N ARCSTB=54
NOTE ARCSTB-ANTICIPATED RETIREMENT OF CSTB (YRS)
N PCTB=0.056
NOTE PCTB-PROPORTION OF CONCRETE TEE BRIDGES (DIM)
N ARCTB=67
NOTE ARCTB-ANTICIPATED RETIREMENT OF CTB (YRS)
A TSL.K(H)=TSLN*(1+BRHB.K(H)/TNB.K(H))*(1+BRPL.K(H)/TNB.K(H))*TSLM.K(H)
NOTE TSL-TOTAL SERVICE LIFE OF BRIDGES (YRS)
A TSLM.K(H)=TABLE(TSLMT,DCRH.K(H),0,1.0,0.1)
T TSLMT=1/0.95/0.90/0.85/0.80/0.75/0.70/0.65/0.60/0.55/0.50
NOTE TSLM-TOTAL SERVICE LIFE MULTIPLIER (DIM)
N TSLN=(PSSB*ARSSB+PTSB*ARTSB+PCSB*ARCSB+PSTTB*ARSTTB+PCDAB*^
    ARCDAB+PSGFBB*ARSGFBB+PCSTB*ARCSTB+PCTB*ARCTB)/^
    (PSSB+PTSB+PCSB+PSTTB+PCDAB+PSGFBB+PCSTB+PCTB)
NOTE TSLN-TOTAL SERVICE LIFE NORMAL (YRS)
L BRHB.K(H)=BRHB.J(H)+(DT)(RHRB.JK(H))
N BRHB(H)=BRHBN(H)
T BRHBN=0/0/0/0
NOTE BRHB-BRIDGES REHABILITATED (BRIDGES)
L BRPL.K(H)=BRPL.J(H)+(DT)(RPRB.JK(H))
N BRPL(H)=BRPLN(H)
T BRPLN=0/0/0/0
NOTE BRPL-BRIDGES REPLACED (BRIDGES)
A RSLBPFC.K(H)=RTBPFC*TSL.K(H)
NOTE RSLBPFC-REMAINING SERVICE LIFE OF BPFC (YRS)
C RTBPFC=1.0
NOTE RTBPFC-REMAINING TO TOTAL SERVICE LIFE RATIO OF BPFC (DIM)
A RSLBGC.K(H)=RTBGC*TSL.K(H)
NOTE RSLBGC-REMAINING SERVICE LIFE OF BGC (YRS)
C RTBGC=0.70
NOTE RTBGC-REMAINING TO TOTAL SERVICE LIFE RATIO OF BGC (DIM)
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A RSLBPC.K(H)=RTBPC*TSL.K(H)
NOTE RSLBPC-REMAINING SERVICE LIFE OF BPC (YRS)
C RTBPC=0.20
NOTE RTBPC-REMAINING TO TOTAL SERVICE LIFE RATIO OF BPC (DIM)
A RSLBSC.K(H)=RTBSC*TSL.K(H)
NOTE RSLBSC-REMAINING SERVICE LIFE OF BSC (YRS)
C RTBSC=0.10
NOTE RTBSC-REMAINING TO TOTAL SERVICE LIFE RATIO OF BSC (DIM)
A RSLBCC.K(H)=RTBCC*TSL.K(H)
NOTE RSLBCC-REMAINING SERVICE LIFE OF BCC (YRS)
C RTBCC=0.01
NOTE RTBCC-REMAINING TO TOTAL SERVICE LIFE RATIO OF BCC (DIM)
A ETB.K(H)=RSLBPFC.K(H)-RSLBGC.K(H)
NOTE ETB-EXPOSURE TIME OF BRIDGES (YRS)
A ATB.K(H)=RSLBGC.K(H)-RSLBPC.K(H)
NOTE ATB-AGING TIME OF BRIDGES (YRS)
A DTB.K(H)=RSLBPC.K(H)-RSLBSC.K(H)
NOTE DTB-DETERIORATION TIME OF BRIDGES (YRS)
A SDTB.K(H)=RSLBSC.K(H)-RSLBCC.K(H)
NOTE SDTB-SERIOUS DETERIORATION TIME OF BRIDGES (YRS)
A TNB.K(H)=BPFC.K(H)+BGC.K(H)+BPC.K(H)+BSC.K(H)+BCC.K(H)
NOTE TNB-TOTAL NUMBER OF BRIDGES (BRDGS)
N TNBN(H)=BPFCN(H)+BGCN(H)+BPCN(H)+BSCN(H)+BCCN(H)
NOTE TNBN-TOTAL NUMBER OF BRIDGES NORMAL (BRDGS)
A TNFOB.K(H)=FOBPFC.K(H)+FOBGC.K(H)+FOBPC.K(H)+FOBSC.K(H)
NOTE TNFOB-TOTAL NUMBER OF FUNC OBSOLESCENT BRDGS (BRDGS)
A FBBC.K(H)=CLIP(0,BPFC.K(H)/(TNB.K(H)+TNFOB.K(H)),0,HCE.K(H))
NOTE FBBC-FRACTION OF BMS BUDGET TO CONSTRUCTION (DIM)
A FBPM.K(H)=BGC.K(H)/(TNB.K(H)+TNFOB.K(H))
NOTE FBPM-FRACTION OF BUDGET TO PREVENTIVE MAINT (DIM)
A FBRR.K(H)=BPC.K(H)/(TNB.K(H)+TNFOB.K(H))
NOTE FBRR-FRACTION OF BUDGET TO REPAIRS (DIM)
A FBRH.K(H)=BSC.K(H)/(TNB.K(H)+TNFOB.K(H))
NOTE FBRH-FRACTION OF BUDGET TO REHABILITATION (DIM)
A FBRP.K(H)=BCC.K(H)/(TNB.K(H)+TNFOB.K(H))
NOTE FBRP-FRACTION OF BUDGET TO REPLACEMENT (DIM)
A PSIB.K(H)=(BPFC.K(H)*WFBPFC+BGC.K(H)*WFBGC+BPC.K(H)*WFBPC+^
                BSC.K(H)*WFBSC+BCC.K(H)*WFBCC)/TNB.K(H)
NOTE PSIB-PHYSICAL SUFFICIENCY INDEX OF BRIDGES (DIM)
C WFBPFC=0.8
NOTE WFBPFC-WEIGHTING FACTOR FOR BPFC (DIM)
C WFBGC=0.5
NOTE WFBGC-WEIGHTING FACTOR FOR BGC (DIM)
C WFBPC=0.3
NOTE WFBPC-WEIGHTING FACTOR FOR BPC (DIM)
C WFBSC=0.2
NOTE WFBSC-WEIGHTING FACTOR FOR BSC (DIM)
C WFBCC=0.1
NOTE WFBCC-WEIGHTING FACTOR FOR BCC (DIM)
L DFOBPFC.K(H)=DFOBPFC.J(H)+(DT)(ORBPFC.JK(H)-WBPFC.JK(H))
N DFOBPFC(H)=DFBPFCN(H)
T DFBPFCN=0/0/0/0
A FOBPFC.K(H)=MIN(DFOBPFC.K(H),BPFC.K(H))
NOTE FOBPFC-FUNCTIONALLY OBSOLESCENT BPFC (BRDGS)
L DFOBGC.K(H)=DFOBGC.J(H)+(DT)(ORBGC.JK(H)-WBGC.JK(H))
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N DFOBGC(H)=DFOBGCN(H)
T DFOBGCN=0/0/0/0
A FOBGC.K(H)=MIN(DFOBGC.K(H),BGC.K(H))
NOTE FOBGC-FUNCTIONALLY OBSOLESCENT BGC (BRDGS)
L DFOBPC.K(H)=DFOBPC.J(H)+(DT)(ORBPC.JK(H)-WBPC.JK(H))
N DFOBPC(H)=DFOBPCN(H)
T DFOBPCN=0/0/0/0
A FOBPC.K(H)=MIN(DFOBPC.K(H),BPC.K(H))
NOTE FOBPC-FUNCTIONALLY OBSOLESCENT BPC (BRDGS)
L DFOBSC.K(H)=DFOBSC.J(H)+(DT)(ORBSC.JK(H)-WBSC.JK(H))
N DFOBSC(H)=DFOBSCN(H)
T DFOBSCN=0/0/0/0
A FOBSC.K(H)=MIN(DFOBSC.K(H),BSC.K(H))
NOTE FOBSC-FUNCTIONALLY OBSOLESCENT BSC (BRDGS)
R ORBPFC.KL(H)=(BPFC.K(H)*FOFBPFC.K(H))/OTBPFC
NOTE ORBPFC-OBSOLESCENCE RATE OF BPFC (BRDGS/YR)
A FOFBPFC.K(H)=CLIP(0,1,MTBPFC(H),DCRH.K(H))
NOTE FOFBPFC-FUNC OBSOLESCENCE FACTOR FOR BPFC (DIM)
T MTBPFC(H)=0.43/0.24/0.2/0.38
NOTE MTBPFC-MARGINAL TRAFFIC INTENSITY OF BPFC (DIM)
C OTBPFC=15
NOTE OTBPFC-OBSOLESCENCE TIME OF BPFC (YR)
R ORBGC.KL(H)=(BGC.K(H)*FOFBGC.K(H))/OTBGC
NOTE ORBGC-OBSOLESCENCE RATE OF BGC (BRDGS/YR)
A FOFBGC.K(H)=CLIP(0,1,MTBGC(H),DCRH.K(H))
NOTE FOFBGC-FUNC OBSOLESCENCE FACTOR FOR BGC (DIM)
T MTBGC(H)=0.43/0.24/0.2/0.38
NOTE MTBGC-MARGINAL TRAFFIC INTENSITY OF BGC (DIM)
C OTBGC=8
NOTE OTBGC-OBSOLESCENCE TIME OF BGC (YR)
R ORBPC.KL(H)=(BPC.K(H)*FOFBPC.K(H))/OTBPC
NOTE ORBPC-OBSOLESCENCE RATE OF BPC (BRDGS/YR)
A FOFBPC.K(H)=CLIP(0,1,MTBPC(H),DCRH.K(H))
NOTE FOFBPC-FUNC OBSOLESCENCE FACTOR FOR BPC (DIM)
T MTBPC=0.43/0.24/0.2/0.38
NOTE MTBPC-MARGINAL TRAFFIC INTENSITY OF BPC (DIM)
C OTBPC=6
NOTE OTBPC-OBSOLESCENCE TIME OF BPC (YR)
R ORBSC.KL(H)=(BSC.K(H)*FOFBSC.K(H))/OTBSC
NOTE ORBSC-OBSOLESCENCE RATE OF BSC (BRDGS/YR)
A FOFBSC.K(H)=CLIP(0,1,MTBSC(H),DCRH.K(H))
NOTE FOFBSC-FUNC OBSOLESCENCE FACTOR FOR BSC (DIM)
T MTBSC=0.43/0.24/0.2/0.38
NOTE MTBSC-MARGINAL TRAFFIC INTENSITY OF BSC (DIM)
C OTBSC=4
NOTE OTBSC-OBSOLESCENCE TIME OF BSC (YR)
R WBPFC.KL(H)=WEBPFC.K(H)/WCB.K(H)
NOTE WBPFC-WIDENING RATE OF BPFC (BRDGS/YR)
A WEBPFC.K(H)=BMSB.K(H)*FWBPFC.K(H)
NOTE WEBPFC-WIDENING EXPENDITURE ON BPFC ($/YR)
R WBGC.KL(H)=WEBGC.K(H)/WCB.K(H)
NOTE WBGC-WIDENING RATE OF BGC (BRDGS/YR)
A WEBGC.K(H)=BMSB.K(H)*FWBGC.K(H)
NOTE WEBGC-WIDENING EXPENDITURE ON BGC ($/YR)
R WBPC.KL(H)=WEBPC.K(H)/WCB.K(H)
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NOTE WBPC-WIDENING RATE OF BPC (BRDGS/YR)
A WEBPC.K(H)=BMSB.K(H)*FWBPC.K(H)
NOTE WEBPC-WIDENING EXPENDITURE ON BPC ($/YR)
R WBSC.KL(H)=WEBSC.K(H)/WCB.K(H)
NOTE WBSC-WIDENING RATE OF BSC (BRDGS/YR)
A WEBSC.K(H)=BMSB.K(H)*FWBSC.K(H)
NOTE WEBSC-WIDENING EXPENDITURE ON BSC ($/YR)
A FWBPFC.K(H)=FOBPFC.K(H)/(TNB.K(H)+TNFOB.K(H))
NOTE FWBPFC-FRACTION OF BMS BUDGET TO BPFC WIDENING (DIM)
A FWBGC.K(H)=FOBGC.K(H)/(TNB.K(H)+TNFOB.K(H))
NOTE FWBGC-FRACTION OF BMS BUDGET TO BGC WIDENING (DIM)
A FWBPC.K(H)=FOBPC.K(H)/(TNB.K(H)+TNFOB.K(H))
NOTE FWBPC-FRACTION OF BMS BUDGET TO BPC WIDENING (DIM)
A FWBSC.K(H)=FOBSC.K(H)/(TNB.K(H)+TNFOB.K(H))
NOTE FWBSC-FRACTION OF BMS BUDGET TO BSC WIDENING (DIM)
A NFOB.K(H)=TNFOB.K(H)+BCC.K(H)
NOTE NFOB-NUMBER OF FUNCTIONALLY OBSOLESCENT BRIDGES (BRIDGES)
A FORB.K(H)=NFOB.K(H)/TNB.K(H)
NOTE FORB-FUNCTIONALLY OBSOLESCENT RATE OF BRIDGES (DIM)

FUNCTIONAL SUBSYSTEM

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T CEJM=2051.34/1326.99/502.59/756.38
NOTE CEJM-COST OF EXPANSION JOINT MAINT ($/BRDG)
T CPGM=3412.98/2482.17/1045.13/1045.13
NOTE CPGM-COST OF PARAPET GUARD RAIL MAINT ($/BRDG)
T CSC=1197.43/1032.82/586.77/588.71
NOTE CSC-COST OF SCOUR ($/BRDG)
T CSDC=42882.66/26899.99/6434.74/6434.74
NOTE CSDC-COST OF SEALING DECK/CRACK ($/BRDG)
T CSP=5850.42/3039.18/511.98/1732.33
NOTE CSP-COST OF SPOT PAINTING ($/BRDG)
N PMCBN(H)=(CEJM(H)+CPGM(H)+CSC(H)+CSDC(H)+CSP(H))/5
NOTE PMCBN-PREVENTIVE MAINT COST FOR BRIDGE NORMAL ($/BRDG)
A PMCBM.K(1)=TABLE(PMCBMI,BGC.K(1),0,150,15)
T PMCBMI=1.0/2.5/4.0/5.5/7.0/8.5/10.0/11.5/13.0/14.5/16.0
A PMCBM.K(2)=TABLE(PMCBMP,BGC.K(2),0,500,50)
T PMCBMP=1.0/2.5/4.0/5.5/7.0/8.5/10.0/11.5/13.0/14.5/16.0
A PMCBM.K(3)=TABLE(PMCBMS,BGC.K(3),0,2000,200)
T PMCBMS=1.0/2.5/4.0/5.5/7.0/8.5/10.0/11.5/13.0/14.5/16.0
A PMCBM.K(4)=TABLE(PMCBMU,BGC.K(4),0,500,50)
T PMCBMU=1.0/2.5/4.0/5.5/7.0/8.5/10.0/11.5/13.0/14.5/16.0
NOTE PMCBM-PREVENTIVE MAINT COST FOR BRIDGE MULTIPLIER (DIM)
A PMCB.K(H)=PMCBN(H)*PMCBM.K(H)*(1+INFL*DT)**TIME.K
NOTE PMCB-PREVENTIVE MAINT COST FOR BRIDGE ($/BRDG)
T CSSSR=19071.03/9246.56/973.32/5270.54
NOTE CSSSR-COST OF STRUCTURAL STEEL SEC MEMBER RPL & RPR ($/BRDG)
T CRPT=23316.08/12112.25/2039.95/6903.98
NOTE CRPT-COST OF REPAINTING ($/BRDG)
T CP=47553.19/29829.78/7135.58/17002.97
NOTE CP-COST OF PATCHING ($/BRDG)
T CEJR=4168.09/2696.33/1021.23/1536.91
NOTE CEJR-COST OF EXPANSION JOINT REPLACEMENT ($/BRDG)
T CDRR=5849.29/5849.29/5849.29/3334.09
NOTE CDRR-COST OF DRAINAGE SYSTEM RPL & RPR ($/BRDG)
T CDO=102319.82/64184.49/15353.56/53685.16
NOTE CDO-COST OF DECK OVERLAY ($/BRDG)
T CDER=4555.65/3313.20/1395.03/1888.52
NOTE CDER-COST OF DECK EDGE REPAIR ($/BRDG)
T CCP=485186.67/304354.15/72804.51/173481.87
NOTE CCP-COST OF CATHODIC PROTECTION ($/BRDG)
T CCDR=3633.36/1761.63/185.43/1004.13
NOTE CCDR-COST OF CONCRETE DIAPHRAGM REPAIR ($/BRDG)
T CBAR=8984.51/4492.26/1123.06/2560.59
NOTE CBAR-COST OF BEARING & ANCHOR BOLT RPL ($/BRDG)
T CCBR=14248.88/6785.18/1357.04/3867.55
NOTE CCBR-COST OF CONCRETE BEAM END REPAIR ($/BRDG)
T CDR=135759.18/85160.77/20371.30/48541.64
NOTE CDR-COST OF DECK REPLACEMENT ($/BRDG)
T CSSR=473525.49/277829.44/63065.37/158362.78
NOTE CSSR-COST OF SUPERSTRUCTURE REPLACEMENT ($/BRDG)
N RRCBN(H)=(CSSSR(H)+CRPT(H)+CP(H)+CEJR(H)+CDRR(H)+CDO(H)+CDER(H)^
    +CCP(H)+CCDR(H)+CBAR(H)+CCBR(H)+CDR(H)+CSSR(H))/13
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NOTE RRCBN-REPAIR COST OF BRIDGE NORMAL ($/BRDG)
A RRCBM.K(1)=TABLE(RRCBMI,BPC.K(1),0,100,10)
T RRCBMI=1.0/2.5/4.0/5.5/7.0/8.5/10.0/11.5/13.0/14.5/16.0
A RRCBM.K(2)=TABLE(RRCBMP,BPC.K(2),0,500,50)
T RRCBMP=1.0/2.5/4.0/5.5/7.0/8.5/10.0/11.5/13.0/14.5/16.0
A RRCBM.K(3)=TABLE(RRCBMS,BPC.K(3),0,2000,200)
T RRCBMS=1.0/2.5/4.0/5.5/7.0/8.5/10.0/11.5/13.0/14.5/16.0
A RRCBM.K(4)=TABLE(RRCBMU,BPC.K(4),0,500,50)
T RRCBMU=1.0/2.5/4.0/5.5/7.0/8.5/10.0/11.5/13.0/14.5/16.0
A RRCB.K(H)=RRCBN(H)*RRCBM.K(H)*(1+INFL*DT)**TIME.K
NOTE RRCB-REPAIR COST OF BRIDGE ($/BRDG)
T CRCD=116985.86/116985.86/116985.86/116985.86
NOTE CRCD-COST OF REPAIR OF COLLISION DAMAGE ($/BRDG)
T CRAT=9204.97/7939.54/4510.64/4525.54
NOTE CRAT-COST OF REPAIR OF ABUTMENT ($/BRDG)
T CRA=21328.18/18396.15/10451.28/10485.81
NOTE CRA-COST OF REPLACEMENT OF ABUTMENT ($/BRDG)
T CRRP=76184.22/33241.30/11080.43/18947.54
NOTE CRRP-COST OF REPAIR OF PIER ($/BRDG)
T CRP=99423.31/42936.46/14312.15/24473.78
NOTE CRP-COST OF REPLACEMENT OF PIER ($/BRDG)
N RHCBN(H)=(CRCD(H)+CRAT(H)+CRA(H)+CRRP(H)+CRP(H))/5
NOTE RHCBN-REHABILITATION COST OF BRIDGE NORMAL ($/BRDG)
A RHCBM.K(1)=TABLE(RHCBMI,BSC.K(1),0,100,10)
T RHCBMI=1.0/2.5/4.0/5.5/7.0/8.5/10.0/11.5/13.0/14.5/16.0
A RHCBM.K(2)=TABLE(RHCBMP,BSC.K(2),0,500,50)
T RHCBMP=1.0/2.5/4.0/5.5/7.0/8.5/10.0/11.5/13.0/14.5/16.0
A RHCBM.K(3)=TABLE(RHCBMS,BSC.K(3),0,2000,200)
T RHCBMS=1.0/2.5/4.0/5.5/7.0/8.5/10.0/11.5/13.0/14.5/16.0
A RHCBM.K(4)=TABLE(RHCBMU,BSC.K(4),0,500,50)
T RHCBMU=1.0/2.5/4.0/5.5/7.0/8.5/10.0/11.5/13.0/14.5/16.0
A RHCB.K(H)=RHCBN(H)*RHCBM.K(H)*(1+INFL*DT)**TIME.K
NOTE RHCB-REHABILITATION COST OF BRIDGE ($/BRDG)
T RPCBN=1700000.0/1237600.0/618800.0/707200.0
NOTE RPCBN-REPLACEMENT COST OF BRIDGE NORMAL ($/BRDG)
A RPCBM.K(1)=TABLE(RPCBMI,BCC.K(1),0,100,10)
T RPCBMI=1.0/2.5/4.0/5.5/7.0/8.5/10.0/11.5/13.0/14.5/16.0
A RPCBM.K(2)=TABLE(RPCBMP,BCC.K(2),0,1000,100)
T RPCBMP=1.0/2.5/4.0/5.5/7.0/8.5/10.0/11.5/13.0/14.5/16.0
A RPCBM.K(3)=TABLE(RPCBMS,BCC.K(3),0,5000,500)
T RPCBMS=1.0/2.5/4.0/5.5/7.0/8.5/10.0/11.5/13.0/14.5/16.0
A RPCBM.K(4)=TABLE(RPCBMU,BCC.K(4),0,1000,100)
T RPCBMU=1.0/2.5/4.0/5.5/7.0/8.5/10.0/11.5/13.0/14.5/16.0
A RPCB.K(H)=RPCBN(H)*RPCBM.K(H)*(1+INFL*DT)**TIME.K
NOTE RPCB-REPLACEMENT COST OF BRIDGE ($/BRDG)
A BMC.K(H)=PMCB.K(H)+RRCB.K(H)+RHCB.K(H)+RPCB.K(H)
NOTE BMC-BRIDGE MR&R COST ($/BRDG)
T WCBN=584929.28/425828.52/243330.58/242722.26
NOTE WCBN-WIDENING COST OF BRIDGE NORMAL ($/BRDG)
A WCB.K(H)=WCBN(H)*(1+INFL*DT)**TIME.K
NOTE WCB-WIDENING COST OF BRIDGE ($/BRDG)
T CCBN=1800000.0/1310400.0/655200.0/749000.0
NOTE CCBN-CONSTRUCTION COST OF BRIDGE NORMAL ($/BRDG)
A CCBDM.K(1)=TABLE(CCBDMI,BPFC.K(1),0,500,50)
T CCBDMI=1.0/3.0/5.0/7.0/9.0/11.0/12.0/13.0/14.0/15.0/16.0
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A CCBDM.K(2)=TABLE(CCBDMP,BPFC.K(2),0,1400,140)
T CCBDMP=1.0/3.0/5.0/7.0/9.0/11.0/12.0/13.0/14.0/15.0/16.0
A CCBDM.K(3)=TABLE(CCBDMS,BPFC.K(3),0,5000,500)
T CCBDMS=1.0/2.5/4.0/5.5/7.0/8.5/10.0/11.5/13.0/14.5/16.0
A CCBDM.K(4)=TABLE(CCBDMU,BPFC.K(4),0,1600,160)
T CCBDMU=1.0/2.5/4.0/5.5/7.0/8.5/10.0/11.5/13.0/14.5/16.0
A CCB.K(H)=CCBN(H)*CCBDM.K(H)*(1+INFL*DT)**TIME.K
NOTE CCB-CONSTRUCTION COST OF BRIDGE ($/BRDG)
A MCDFHM.K(1)=TABLE(INSTF,HDF.K(1),0,6000,600)
T INSTF=1.0/1.5/2.0/2.5/3.0/3.5/4.0/4.5/5.0/5.5/6.0
NOTE MCDFHM-MAINT COST OF DEFICIENT HIGHWAY MULTIPLIER (DIM)
A MCDFH.K(1)=34000*MCDFHM.K(1)*(1+INFL*DT)**TIME.K
NOTE MCDFH-MAINT COST OF DEFICIENT HIGHWAY ($/LN-MI)
A MCDFHM.K(2)=TABLE(PRMYF,HDF.K(2),0,10000,1000)
T PRMYF=1.0/1.1/1.2/1.3/1.4/1.5/1.6/1.7/1.8/1.9/2.0
A MCDFH.K(2)=24460*MCDFHM.K(2)*(1+INFL*DT)**TIME.K
NOTE MCDFH-MAINT COST OF DEFICIENT HIGHWAY ($/LN-MI)
A MCDFHM.K(3)=TABLE(SCDYF,HDF.K(3),0,50000,5000)
T SCDYF=1.0/1.1/1.2/1.3/1.4/1.5/1.6/1.7/1.8/1.9/2.0
A MCDFH.K(3)=12230*MCDFHM.K(3)*(1+INFL*DT)**TIME.K
NOTE MCDFH-MAINT COST OF DEFICIENT HIGHWAY ($/LN-MI)
A MCDFHM.K(4)=TABLE(URBNF,HDF.K(4),0,10000,1000)
T URBNF=1.0/1.1/1.2/1.3/1.4/1.5/1.6/1.7/1.8/1.9/2.0
A MCDFH.K(4)=21845*MCDFHM.K(4)*(1+INFL*DT)**TIME.K
NOTE MCDFH-MAINT COST OF DEFICIENT HIGHWAY ($/LN-MI)
A MCDTHM.K(1)=TABLE(INSTT,HDT.K(1),0,12000,1200)
T INSTT=1.0/1.5/2.0/2.5/3.0/3.5/4.0/4.5/5.0/5.5/6.0
NOTE MCDTHM-MAINT COST OF DETERIORATED HIGHWAY MULTIPLIER (DIM)
A MCDTH.K(1)=85400*MCDTHM.K(1)*(1+INFL*DT)**TIME.K
NOTE MCDTH-MAINT COST OF DETERIORATED HIGHWAY ($/LN-MI)
A MCDTHM.K(2)=TABLE(PRMYT,HDT.K(2),0,25000,2500)
T PRMYT=1.0/1.1/1.2/1.3/1.4/1.5/1.6/1.7/1.8/1.9/2.0
A MCDTH.K(2)=61430*MCDTHM.K(2)*(1+INFL*DT)**TIME.K
NOTE MCDTH-MAINT COST OF DETERIORATED HIGHWAY ($/LN-MI)
A MCDTHM.K(3)=TABLE(SCDYT,HDT.K(3),0,100000,10000)
T SCDYT=1.0/1.1/1.2/1.3/1.4/1.5/1.6/1.7/1.8/1.9/2.0
A MCDTH.K(3)=30715*MCDTHM.K(3)*(1+INFL*DT)**TIME.K
NOTE MCDTH-MAINT COST OF DETERIORATED HIGHWAY ($/LN-MI)
A MCDTHM.K(4)=TABLE(URBNT,HDT.K(4),0,20000,2000)
T URBNT=1.0/1.1/1.2/1.3/1.4/1.5/1.6/1.7/1.8/1.9/2.0
A MCDTH.K(4)=54860*MCDTHM.K(4)*(1+INFL*DT)**TIME.K
NOTE MCDTH-MAINT COST OF DETERIORATED HIGHWAY ($/LN-MI)
A MCH.K(H)=MCDFH.K(H)+MCDTH.K(H)
NOTE MCH-MAINTENANCE COST OF HIGHWAY ($/LN-MI)
T CCHN=1000000/728000/500000/800000
NOTE CCHN-CONSTRUCTION COST OF HIGHWAY NORMAL ($/LN-MI)
A CCH.K(H)=CCHN(H)*(1+INFL*DT)**TIME.K
NOTE CCH-CONSTRUCTION COST OF HIGHWAY ($/LN-MI)
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APPRAISAL SUBSYSTEM

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A TAVMH.K(H)=TVMH.K(H)*360
NOTE TAVMH-TOTAL ANNUAL VEHICLE MILES OF HIGHWAYS (VEH-MI)
A IVOC.K=IVOCN*(1+IVOCG)**TIME.K
NOTE IVOC-INITIAL VEHICLE OPERATING COSTS (CENTS/VEH-MI)
N IVOCN=61.58
C IVOCG=0.040194
NOTE IVOCG-IVOC GROWTH RATE (DIM)
A BVOC.K=IVOC.K-0.00136*(AMTV.K-10000)
NOTE BVOC-BASIC VEHICLE OPERATING COSTS (CENTS/VEH-MI)
A ABVOC.K(H)=BVOC.K*OSF.K(H)*DCRF.K(H)*PVCF.K(H)
NOTE ABVOC-ADJUSTED BVOC (CENTS/VEH-MI)
A OSF.K(1)=TABLE(OSFTI,OPS.K(1),10,80,10)
T OSFTI=1.1/1.0/0.95/0.95/0.98/1.0/1.02/1.04
A OSF.K(2)=TABLE(OSFTP,OPS.K(2),10,80,10)
T OSFTP=1.1/1.0/0.95/0.95/0.98/1.0/1.02/1.04
A OSF.K(3)=TABLE(OSFTS,OPS.K(3),10,80,10)
T OSFTS=1.1/1.0/0.95/0.95/0.98/1.0/1.02/1.04
A OSF.K(4)=TABLE(OSFTU,OPS.K(4),10,80,10)
T OSFTU=1.1/1.0/0.95/0.95/0.98/1.0/1.02/1.04
NOTE OSF-OPERATING SPEED FACTOR (DIM)
A DCRF.K(1)=TABLE(DCRFTI,DCRH.K(1),0.0,1.0,0.1)
T DCRFTI=0.50/0.60/0.70/0.80/0.90/1.00/1.10/1.20/1.30/1.40/1.50
A DCRF.K(2)=TABLE(DCRFTP,DCRH.K(2),0.0,1.0,0.1)
T DCRFTP=0.50/0.60/0.70/0.80/0.90/1.00/1.10/1.20/1.30/1.40/1.50
A DCRF.K(3)=TABLE(DCRFTS,DCRH.K(3),0.0,1.0,0.1)
T DCRFTS=0.90/0.92/0.94/0.96/0.98/1.00/1.02/1.04/1.06/1.08/1.10
A DCRF.K(4)=TABLE(DCRFTU,DCRH.K(4),0.0,1.0,0.1)
T DCRFTU=0.50/0.60/0.70/0.80/0.90/1.00/1.10/1.20/1.30/1.40/1.50
NOTE DCRF-DEMAND CAPACITY RATIO FACTOR (DIM)
A PVCF.K(1)=TABLE(PVCFTI,PSIH.K(1),0.66,0.80,0.02)
T PVCFTI=2.5/2.3/2.1/1.9/1.7/1.5/1.4/1.1
A PVCF.K(2)=TABLE(PVCFTP,PSIH.K(2),0.64,0.76,0.01)
T PVCFTP=5.8/5.6/5.4/5.2/5.0/4.8/4.6/4.4/4.2/4.0/3.6/3.2/2.8
A PVCF.K(3)=TABLE(PVCFS,PSIH.K(3),0.57,0.75,0.02)
T PVCFS=17/15/13/11/8/5/4/3/2/1
A PVCF.K(4)=TABLE(PVCFTU,PSIH.K(4),0.64,0.77,0.01)
T PVCFTU=5.8/5.6/5.4/5.2/5.0/4.8/4.6/4.4/4.2/4.0/3.8/3.5/3.2/2.9
NOTE PVCF-PAVEMENT CONDITION FACTOR (DIM)
A VOC.K(H)=((TAVMH.K(H)*ABVOC.K(H)/100)/(1+DSCR)**TIME.K)
NOTE VOC-VEHICLE OPERATING COSTS OF HIGHWAY ($)
C DSCR=0.06
NOTE DSCR-DISCOUNT RATE (DIM)
C INFL=0.04
NOTE INFL-INFLATION RATE (DIM)
N FAC=371500
NOTE FAC-FATAL ACCIDENT COST ($)
N PIC=3160
NOTE PIC-PERSONAL INJURY COST ($)
N PDC=750
NOTE PDC-PROPERTY DAMAGE COST ($)
C PFA=0.035
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NOTE PFA-PROPORTION OF FATAL ACCIDENTS (DIM)
C PPIA=0.185
NOTE PPIA-PROPORTION OF PERSONAL INJURY ACCIDENTS (DIM)
C PPDA=0.78
NOTE PPDA-PROPORTION OF PROPERTY DAMAGE ACCIDENTS (DIM)
N BFAR=2.0/(10**8)
NOTE BFAR-BASIC FATAL ACCIDENT RATE (ACCIDENTS/VEH-MI)
A ABFAR.K(H)=BFAR*PVCFA.K(H)
NOTE ABFAR-ADJUSTED BFAR (ACCIDENTS/VEH-MI)
A PVCFA.K(1)=TABLE(PVCFATI,PSIH.K(1),0.66,0.80,0.02)
T PVCFATI=2.5/2.3/2.1/1.9/1.7/1.5/1.4/1.1
A PVCFA.K(2)=TABLE(PVCFATP,PSIH.K(2),0.64,0.76,0.01)
T PVCFATP=5.8/5.6/5.4/5.2/5.0/4.8/4.6/4.4/4.2/4.0/3.6/3.2/2.8
A PVCFA.K(3)=TABLE(PVCFAS,PSIH.K(3),0.57,0.75,0.02)
T PVCFAS=17/15/13/11/8/5/4/3/2/1
A PVCFA.K(4)=TABLE(PVCFATU,PSIH.K(4),0.64,0.77,0.01)
T PVCFATU=5.8/5.6/5.4/5.2/5.0/4.8/4.6/4.4/4.2/4.0/3.8/3.5/3.2/2.9
NOTE PVCFA-PAVEMENT CONDITION FACTOR FOR ACCIDENTS (DIM)
N BPIAR=141/(10**8)
NOTE BPIA-BASIC PERSONAL INJURY ACCIDENT RATE (ACCIDENTS/VEH-MI)
A ABPIAR.K(H)=BPIAR*PVCFA.K(H)
NOTE ABPIAR-ADJUSTED BPIAR (ACCIDENTS/VEH-MI)
N BPDAR=278/(10**8)
NOTE BPDAR-BASIC PROPERTY DAMAGE ACCIDENT RATE (ACCIDENTS/VEH-MI)
A ABPDAR.K(H)=BPDAR*PVCFA.K(H)
NOTE ABPDAR-ADJUSTED BPDAR (ACCIDENTS/VEH-MI)
A ACST.K(H)=TAVMH.K(H)*(PFA*ABFAR.K(H)*FAC+PPIA*ABPIAR.K(H)*PIC+PPDA*^
    ABPDAR.K(H)*PDC)*(1+RDSCR)**TIME.K
NOTE ACST-ACCIDENT COSTS ($)
N RDSCR=((1+DSCR)/(1+INFL))-1
NOTE RDSCR-RELATIVE DISCOUNT RATE (DIM)
C VOT=8
NOTE VOT-VALUE OF TIME ($/HR)
A TTC.K(H)=(TTA.K(H)/60)*VOT*AADTH.K(H)*360*(1+RDSCR)**TIME.K
NOTE TTC-TRAVEL TIME COST ($)
A TUC.K(H)=(VOC.K(H)+ACST.K(H)+TTC.K(H))/TVMH.K(H)
NOTE TUC-TOTAL USER COSTS ($)
A BCR.K(H)=((LTRBH.K(H)-AEH.K(H))/(CAPCH.K(H)*DSCR))*(1-EXP(-DSCR*1))
NOTE BCR-BENEFIT COST RATIO (DIM)
R RCAPCH.KL(H)=HCE.K(H)+CEB.K(H)+RPEB.K(H)+WEBPFC.K(H)+^
    WEBGC.K(H)+WEBPC.K(H)+WEBSC.K(H)
NOTE RCAPCH-RATE OF CAPITAL COSTS OF HIGHWAY ($)
L CAPCH.K(H)=CAPCH.J(H)+(DT)(RCAPCH.JK(H))
N CAPCH(H)=CAPCHN(H)
NOTE CAPCH-CAPITAL COSTS OF HIGHWAY ($)
R RAEH.KL(H)=MEDFH.K(H)+MEDTH.K(H)+PMEB.K(H)+RREB.K(H)+RHEB.K(H)
NOTE RAEH-RATE OF ANNUAL EXPENDITURES ON HIGHWAY ($/YR)
L AEH.K(H)=AEH.J(H)+(DT)(RAEH.JK(H))
N AEH(H)=AEHN(H)
NOTE AEH-ACCUMULATED EXPENDITURES ON HIGHWAY ($)
R RTRBH.KL(H)=TRBH.K(H)
NOTE RTRBH-RATE OF TOTAL REVENUE BY HIGHWAYS ($/YR)
L LTRBH.K(H)=LTRBH.J(H)+(DT)(RTRBH.JK(H))
N LTRBH(H)=LTRBHN(H)
NOTE LTRBH-ACCUMULATED TOTAL REVENUE ($)
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APPENDIX C

Data Base of the TPMSHM

SUBSYSTEM	ACRONY	NAME	VALUE	UNIT	TDP	TIDP	TYPE	SOURCE
TRANSPN	AADTH	annual average daily traffic of highway	-	vehs/day	Yes	No	model generation	-
TRANSPN	AATH	average annual traffic on highway	-	vehs/yr	Yes	No	model generation	-
APPRASAL	ABFAR	adjusted BFAR	-	act/veh-mi	Yes	No	model generation	-
APPRASAL	ABPDAR	adjusted BPDAR	-	act/veh-mi	Yes	No	model generation	-
APPRASAL	ABPIAR	adjusted BPIAR	-	act/veh-mi	Yes	No	model generation	-
APPRASAL	ABVOC	adjusted BVOC	-	cnt/veh-mi	Yes	No	model generation	-
APPRASAL	ACST	accident costs	-	$	Yes	No	model generation	-
DMGRPHY	ADMTV	average daily miles traveled per vehicle	-	mi/veh-	Yes	No	model generation	-
DMGRPHY	ADMTVN	average daily miles traveled per vehicle normal	-	mi/veh-	Yes	No	model generation	-
DMGRPHY	ADTG	average distance traveled per gallon	-	mi/gal	Yes	No	model generation	-
DMGRPHY	ADTGGR	ADTG growth rate	0.0162	dim	No	Yes	data research	BTS 1997
DMGRPHY	ADTGN	average distance traveled per gallon normal	18.32	mi/gal	No	Yes	data research	BTS 1997
APPRASAL	AEH	accumulated expenditures on highway	-	$	Yes	No	model generation	-
TDM-B	AET	annual empty trucks	-	trck/yr	Yes	No	model generation	-
DMGRPHY	AHS	average household size	-	prsn/hh	Yes	No	model generation	-
DMGRPHY	AHSGR	average household size growth rate	-0.0075	dim	No	Yes	data research	CPS annual
DMGRPHY	AHSN	average household size normal	2.47	prsn/hh	No	Yes	data research	CPS annual
ECONOMY	ALC	average lifetime of capital	-	yr	Yes	No	model generation	-
ECONOMY	ALCM	average lifetime of capital multiplier	-	yr	Yes	No	model generation	-
ECONOMY	ALCN	average lifetime of capital normal	25	yr	No	Yes	user definition	-
DMGRPHY	AMTV	average miles traveled per vehicle	-	mi/veh-yr	Yes	No	model generation	-
DMGRPHY	AMTVGR	AMTV growth rate	0.0108	dim	No	Yes	data research	BTS 1997
DMGRPHY	AMTVN	average miles traveled per vehicle normal	12704	mi/veh-yr	No	Yes	data research	BTS 1997
TRANSPN	ANLH	average number of lanes of highway	-	lanes	Yes	No	model generation	-
DMGRPHY	ANVP	average new vehicle price	-	$	Yes	No	model generation	-
DMGRPHY	ANVPN	average new vehicle price normal	23777	$	No	Yes	data research	VDMV 1997
FINANCE	APRP	average purchase rate per person	9500	$/yr	No	Yes	user definition	-
BMS	ARB	aging rate of bridge	-	bridges/yr	Yes	No	model generation	-
BMS	ARCDAB	anticipated retirement of CDAB	77	year	No	Yes	data research	Klaiber, et al. 1987
BMS	ARCSB	anticipated retirement of CSB	64	year	No	Yes	data research	Klaiber, et al. 1987
BMS	ARCSTB	anticipated retirement of CSTB	54	year	No	Yes	data research	Klaiber, et al. 1987
BMS	ARCTB	anticipated retirement of CTB	67	year	No	Yes	data research	Klaiber, et al. 1987
PMS	ARH	aging rate of highway	-	lane-mi/yr	Yes	No	model generation	-
BMS	ARSGFB	anticipated retirement of SGFBB	61	year	No	Yes	data research	Klaiber, et al. 1987
BMS	ARSSB	anticipated retirement of SSB	57	year	No	Yes	data research	Klaiber, et al. 1987
BMS	ARSTTB	anticipated retirement of STTB	73	year	No	Yes	data research	Klaiber, et al. 1987
BMS	ARTSB	anticipated retirement of TSB	47	year	No	Yes	user definition	-
TDM-B	AT	annual trucks	-	trck/yr	Yes	No	model generation	-
BMS	ATB	aging time of bridges	-	year	Yes	No	model generation	-

TDM-B	ATDC	average travel distance for commuting	-	mi	Yes	No	model generation	-
TDM-B	ATDCN	average travel distance for commuting normal	14.54	mi	No	Yes	data research	FHWA 1994
TDM-A	ATDGP	average travel distance for general purpose trip	-	mi	Yes	No	model generation	-
TDM-B	ATDGR	average travel distance growth rate	0.0231	dim	No	Yes	data research	FHWA 1994
TDM-B	ATDT	average travel distance for truck	48.18	mi	No	Yes	data research	FHWA 1985-1995
PMS	ATH	aging time of highway	-	yr	Yes	No	model generation	-
PMS	ATHM	aging time of highway multiplier	table	dim	Yes	No	model generation	-
PMS	ATHN	aging time of highway normal	1	yr	No	Yes	user definition	-
TDM-B	ATIO	annual trucks from industrial output	-	trck/yr	Yes	No	model generation	-
TDM-A	ATLHO	average trip length for h.b. other trip	-	mi/trip	Yes	No	model generation	-
TDM-A	ATLHON	average trip length normal for h.b. other trip	6.81	mi/trip	No	Yes	data research	FHWA 1994
TDM-A	ATLHS	average trip length for home-based shopping trip	-	mi/trip	Yes	No	model generation	-
TDM-A	ATLHSN	average trip length normal for h.b. shopping trip	5.25	mi/trip	No	Yes	data research	FHWA 1994
TDM-A	ATLHSR	average trip length for h.b.social and rec. trip	-	mi/trip	Yes	No	model generation	-
TDM-A	ATLHSR	average trip length normal for h.b.social and rec. trip	13.25	mi/trip	No	Yes	data research	FHWA 1994
TDM-A	ATLNH	average trip length for non-home based trip	-	mi/trip	Yes	No	model generation	-
TDM-A	ATLNHN	average trip length normal for non-home based trip	8.55	mi/trip	No	Yes	data research	FHWA 1994
DMGRPHY	AUVP	average used vehicle price	-	$	Yes	No	model generation	-
DMGRPHY	AUVPN	average used vehicle price normal	6333	$	No	Yes	data research	VDMV 1997
TDM-B	AVOCP	average vehicle occupancy in carpool	-	prsn/veh	No	Yes	model generation	-
TDM-B	AVODA	average vehicle occupancy for d.a. traffic	1.0	prsn/veh	No	Yes	user definition	-
TDM-A	AVOHO	average vehicle occupancy for h.b. other trip	1.65	prsn/veh	No	Yes	data research	FHWA 1994
TDM-A	AVOHS	average vehicle occupancy for h.b. shopping trip	1.51	prsn/veh	No	Yes	data research	FHWA 1994
TDM-A	AVOHSR	average vehicle occupancy for h.b.s.r. trip	1.91	prsn/veh	No	Yes	data research	FHWA 1994
TDM-A	AVONH	average vehicle occupancy for non-home based trip	1.32	prsn/veh	No	Yes	data research	FHWA 1994
BMS	BCC	bridges in critical condition	-	bridges	Yes	No	model generation	-
BMS	BCCN(1)	bridges in critical condition normal for interstate hwy	43	bridges	No	Yes	user definition	-
BMS	BCCN(2)	bridges in critical condition normal for primary hwy	308	bridges	No	Yes	user definition	-
BMS	BCCN(3)	bridges in critical condition normal for secondary	1791	bridges	No	Yes	user definition	-
BMS	BCCN(4)	bridges in critical condition normal for urban hwy	380	bridges	No	Yes	user definition	-
APPRASAL	BCR	benefit cost ratio	-	dim	Yes	No	model generation	-
APPRASAL	BFAR	basic fatal accident rate	-	act/veh-mi	No	Yes	data research	BTS 1997
BMS	BGC	bridges in good condition	-	bridges	Yes	No	model generation	-
BMS	BGCN(1)	bridges in good condition normal for interstate	43	bridges	No	Yes	user definition	-
BMS	BGCN(2)	bridges in good condition normal for primary	308	bridges	No	Yes	user definition	-
BMS	BGCN(3)	bridges in good condition normal for secondary	1791	bridges	No	Yes	user definition	-
BMS	BGCN(4)	bridges in good condition normal for urban	380	bridges	No	Yes	user definition	-
DMGRPHY	BGF	birth growth factor	0.0103	dim	No	Yes	data research	CPS annual
FUNCTIONAL	BMC	bridge mr&r cost	-	$/brdg	Yes	No	model generation	-
BMS	BPC	bridges in poor condition	-	bridges	Yes	No	model generation	-

BMS	BPCN(1)	bridges in poor condition normal for interstate hwy	43	bridges	No	Yes	user definition	-
BMS	BPCN(2)	bridges in poor condition normal for primary	308	bridges	No	Yes	user definition	-
BMS	BPCN(3)	bridges in poor condition normal for secondary hwy	1791	bridges	No	Yes	user definition	-
BMS	BPCN(4)	bridges in poor condition normal for urban	380	bridges	No	Yes	user definition	-
APPRASAL	BPDAR	basic property damage accident rate	-	act/veh-mi	No	Yes	data research	BTS 1997
BMS	BPFC	bridges in preferred condition	-	bridges	Yes	No	model generation	-
BMS	BPFCN(1	bridges in preferred condition normal for interstate	43	bridges	No	Yes	user definition	-
BMS	BPFCN(2	bridges in preferred condition normal for primary	308	bridges	No	Yes	user definition	-
BMS	BPFCN(3	bridges in preferred condition normal for secondary	1791	bridges	No	Yes	user definition	-
BMS	BPFCN(4	bridges in preferred condition normal for urban	380	bridges	No	Yes	user definition	-
APPRASAL	BPIAR	basic personal injury accident rate	-	act/veh-mi	No	Yes	data research	BTS 1997
BMS	BRHB	bridges rehabilitated	-	bridges	Yes	No	model generation	-
BMS	BRPL	bridges replaced	-	bridges	Yes	No	model generation	-
DMGRPHY	BRTH	births	-	prsn/yr	Yes	No	model generation	-
BMS	BSC	bridges in serious condition	-	bridges	Yes	No	model generation	-
BMS	BSCN(1)	bridges in serious condition normal for interstate hwy	43	bridges	No	Yes	user definition	-
BMS	BSCN(2)	bridges in serious condition normal for primary hwy	308	bridges	No	Yes	user definition	-
BMS	BSCN(3)	bridges in serious condition normal for secondary	1791	bridges	No	Yes	user definition	-
BMS	BSCN(4)	bridges in serious condition normal for urban hwy	380	bridges	No	Yes	user definition	-
APPRASAL	BVOC	basic vehicle operating costs	-	cnt/veh-mi	Yes	No	model generation	-
TDM-B	C	commuters	-	prsn/prd	Yes	No	model generation	-
APPRASAL	CAPCH	capital costs on highway	-	$	Yes	No	model generation	-
TRANSPN	CAPH	capacity of highway	-	vehs/hr	Yes	No	model generation	-
FUNCTIONAL	CBAR(1)	cost of bearing & anchor bolt rpl for interstate	8984	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CBAR(2)	cost of bearing & anchor bolt rpl for primary	4492	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CBAR(3)	cost of bearing & anchor bolt rpl for secondary	1123	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CBAR(4)	cost of bearing & anchor bolt rpl for urban	2560	$/brdg	No	Yes	user definition	-
FUNCTIONAL	CCB	construction cost of bridge	-	$/brdg	Yes	No	model generation	-
FUNCTIONAL	CCBDM	construction cost of bridge multiplier	-	dim	Yes	No	user definition	-
FUNCTIONAL	CCBN(1)	construction cost of bridge normal for interstate	1.8e6	$/brdg	No	Yes	user definition	-
FUNCTIONAL	CCBN(2)	construction cost of bridge normal for primary	1.31e6	$/brdg	No	Yes	user definition	-
FUNCTIONAL	CCBN(3)	construction cost of bridge normal for secondary	655200	$/brdg	No	Yes	user definition	-
FUNCTIONAL	CCBN(4)	construction cost of bridge normal for urban	749000	$/brdg	No	Yes	user definition	-
FUNCTIONAL	CCBR(1)	cost of concrete beam end repair for interstate	14248	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CCBR(2)	cost of concrete beam end repair for primary	6785	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CCBR(3)	cost of concrete beam end repair for secondary	1357	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CCBR(4)	cost of concrete beam end repair for urban	3867	$/brdg	No	Yes	user definition	-
FUNCTIONAL	CCDR(1)	cost of concrete diaphragm repair for interstate	3633	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CCDR(2)	cost of concrete diaphragm repair for primary	1761	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CCDR(3)	cost of concrete diaphragm repair for secondary	185	$/brdg	No	Yes	data research	de la Garza, et al. 1996

FUNCTIONAL	CCDR(4)	cost of concrete diaphragm repair for urban	1004	$/brdg	No	Yes	user definition	-
FUNCTIONAL	CCH	construction cost of highway	-	$/brdg	Yes	No	model generation	-
FUNCTIONAL	CCHN(1)	construction cost of highway normal for interstate	1e6	$/brdg	No	Yes	data research	-
FUNCTIONAL	CCHN(2)	construction cost of highway normal for primary	728000	$/brdg	No	Yes	user definition	-
FUNCTIONAL	CCHN(3)	construction cost of highway normal for secondary	500000	$/brdg	No	Yes	user definition	-
FUNCTIONAL	CCHN(4)	construction cost of highway normal for urban	800000	$/brdg	No	Yes	user definition	-
FUNCTIONAL	CCP(1)	cost of cathodic protection for interstate	485186	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CCP(2)	cost of cathodic protection for primary	304354	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CCP(3)	cost of cathodic protection for secondary	72804	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CCP(4)	cost of cathodic protection for urban	173481	$/brdg	No	Yes	user definition	-
ECONOMY	CD	capital depreciation	-	$/yr	Yes	No	model generation	-
TDM-B	CDA	commuters driving alone	-	prsn/prd	Yes	No	model generation	-
FUNCTIONAL	CDER(1)	cost of deck edge repair for interstate	4555	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CDER(2)	cost of deck edge repair for primary	3313	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CDER(3)	cost of deck edge repair for secondary	1395	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CDER(4)	cost of deck edge repair for urban	1888	$/brdg	No	Yes	user definition	-
FUNCTIONAL	CDO(1)	cost of deck overlay for interstate	102319	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CDO(2)	cost of deck overlay for primary	64184	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CDO(3)	cost of deck overlay for secondary	15353	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CDO(4)	cost of deck overlay for urban	53685	$/brdg	No	Yes	user definition	-
FUNCTIONAL	CDR(1)	cost of deck replacement for interstate	135759	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CDR(2)	cost of deck replacement for primary	85160	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CDR(3)	cost of deck replacement for secondary	20371	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CDR(4)	cost of deck replacement for urban	48541	$/brdg	No	Yes	user definition	-
FUNCTIONAL	CDRR(1)	cost of drainage system rpl & rpr for interstate	5849	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CDRR(2)	cost of drainage system rpl & rpr for primary	5849	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CDRR(3)	cost of drainage system rpl & rpr for secondary	5849	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CDRR(4)	cost of drainage system rpl & rpr for urban	3334	$/brdg	No	Yes	user definition	-
BMS	CEB	construction expenditure on bridges	-	$/yr	Yes	No	model generation	-
FUNCTIONAL	CEJM(1)	cost of expansion joint maintenance for interstate	2051	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CEJM(2)	cost of expansion joint maintenance for primary	1326	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CEJM(3)	cost of expansion joint maintenance for secondary	502	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CEJM(4)	cost of expansion joint maintenance for urban	736	$/brdg	No	Yes	user definition	-
FUNCTIONAL	CEJR(1)	cost of expansion joint replacement for interstate	4168	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CEJR(2)	cost of expansion joint replacement for primary	2696	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CEJR(3)	cost of expansion joint replacement for secondary	1021	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CEJR(4)	cost of expansion joint replacement for urban	1536	$/brdg	No	Yes	user definition	-
TDM-B	CFDT	conversion factor to daily trucks	360	dim	No	Yes	user definition	-
ECONOMY	CI	capital investment	-	$/yr	Yes	No	model generation	-
FINANCE	CMBD	construction & maintenance budget for each district	-	$	Yes	No	model generation	-

FINANCE	CMBH	construction & maintenance budget for highways	-	$	Yes	No	model generation	-
TDM-B	CMCP	commuters in carpool	-	prsn/prd	Yes	No	model generation	-
TDM-B	COM	commuters using other modes	-	prsn/prd	Yes	No	model generation	-
ECONOMY	COR	capital output ratio	table	yr	No	Yes	user definition	-
FUNCTIONAL	CP(1)	cost of patching for interstate	47553	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CP(2)	cost of patching for primary	29829	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CP(3)	cost of patching for secondary	7135	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CP(4)	cost of patching for urban	17002	$/brdg	No	Yes	user definition	-
TDM-B	CPCD	carpool commuter demand	-	veh/prd	Yes	No	model generation	-
FUNCTIONAL	CPGM(1)	cost of parapet guard rail maintenance for interstate	3412	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CPGM(2)	cost of parapet guard rail maintenance for primary	2482	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CPGM(3)	cost of parapet guard rail maintenance for secondary	1045	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CPGM(4)	cost of parapet guard rail maintenance for urban	1045	$/brdg	No	Yes	user definition	-
FUNCTIONAL	CRA(1)	cost of replacement of abutment for interstate	21328	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CRA(2)	cost of replacement of abutment for primary	18396	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CRA(3)	cost of replacement of abutment for secondary	10451	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CRA(4)	cost of replacement of abutment for urban	10485	$/brdg	No	Yes	user definition	-
FUNCTIONAL	CRAT(1)	cost of repair of abutment for interstate	9204	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CRAT(2)	cost of repair of abutment for primary	7939	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CRAT(3)	cost of repair of abutment for secondary	4510	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CRAT(4)	cost of repair of abutment for urban	4525	$/brdg	No	Yes	user definition	-
BMS	CRB	construction rate of bridge	-	bridges/yr	Yes	No	model generation	-
FUNCTIONAL	CRCD(1)	cost of repair of collision damage for interstate	116985	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CRCD(2)	cost of repair of collision damage for primary	116985	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CRCD(3)	cost of repair of collision damage for secondary	116985	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CRCD(4)	cost of repair of collision damage for urban	116985	$/brdg	No	Yes	user definition	-
PMS	CRH	construction rate of highway	-	lane-mi/yr	Yes	No	model generation	-
FUNCTIONAL	CRP(1)	cost of replacement of pier for interstate	99423	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CRP(2)	cost of replacement of pier for primary	42936	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CRP(3)	cost of replacement of pier for secondary	14312	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CRP(4)	cost of replacement of pier for urban	24473	$/brdg	No	Yes	user definition	-
FUNCTIONAL	CRPT(1)	cost of repainting for interstate	23316	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CRPT(2)	cost of repainting for primary	12112	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CRPT(3)	cost of repainting for secondary	2039	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CRPT(4)	cost of repainting for urban	6903	$/brdg	No	Yes	user definition	-
FUNCTIONAL	CRRP(1)	cost of repair of pier for interstate	76184	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CRRP(2)	cost of repair of pier for primary	33241	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CRRP(3)	cost of repair of pier for secondary	11080	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CRRP(4)	cost of repair of pier for urban	18947	$/brdg	No	Yes	user definition	-
FUNCTIONAL	CSC(1)	cost of scour for interstate	1197	$/brdg	No	Yes	data research	de la Garza, et al. 1996

FUNCTIONAL	CSC(2)	cost of scour for primary	1032	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CSC(3)	cost of scour for secondary	586	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CSC(4)	cost of scour for urban	588	$/brdg	No	Yes	user definition	-
FUNCTIONAL	CSDC(1)	cost of sealing deck/crack for interstate	42882	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CSDC(2)	cost of sealing deck/crack for primary	26899	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CSDC(3)	cost of sealing deck/crack for secondary	6434	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CSDC(4)	cost of sealing deck/crack for urban	6434	$/brdg	No	Yes	user definition	-
FUNCTIONAL	CSP(1)	cost of spot painting for interstate	5850	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CSP(2)	cost of spot painting for primary	3039	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CSP(3)	cost of spot painting for secondary	511	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CSP(4)	cost of spot painting for urban	1732	$/brdg	No	Yes	user definition	-
FUNCTIONAL	CSSR(1)	cost of superstructure replacement for interstate	473525	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CSSR(2)	cost of superstructure replacement for primary	277829	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CSSR(3)	cost of superstructure replacement for secondary	63065	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CSSR(4)	cost of superstructure replacement for urban	158362	$/brdg	No	Yes	user definition	-
FUNCTIONAL	CSSSR(1	cost of structural steel sec member rpl & rpr for intst.	19071	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CSSSR(2	cost of structural steel sec member rpl & rpr for	9246	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CSSSR(3	cost of structural steel sec member rpl & rpr for scnd.	973	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	CSSSR(4	cost of structural steel sec member rpl & rpr for	5270	$/brdg	No	Yes	user definition	-
PMS	CTMT	construction termination time	10	yr	No	Yes	user definition	-
TDM-B	CVDP	commuter vehicle demand per period	-	veh/prd	Yes	No	model generation	-
TDM-B	DACD	driving alone commuter demand	-	veh/prd	Yes	No	model generation	-
APPRASAL	DCRF(1)	demand capacity ratio factor for interstate highway	table	dim	Yes	No	user definition	-
APPRASAL	DCRF(2)	demand capacity ratio factor for primary highway	table	dim	Yes	No	user definition	-
APPRASAL	DCRF(3)	demand capacity ratio factor for secondary highway	table	dim	Yes	No	user definition	-
APPRASAL	DCRF(4)	demand capacity ratio factor for urban highway	table	dim	Yes	No	user definition	-
TRANSPN	DCRH	demand capacity ratio of highway	-	dim	Yes	No	model generation	-
TDM-B	DCVD	daily commuter vehicle demand	-	veh/day	Yes	No	model generation	-
TDM-B	DCVDH	daily commuter vehicle demand of highway	-	veh/day	Yes	No	model generation	-
DMGRPHY	DGF	death growth factor	0.0078	dim	No	Yes	data research	CPS annual
TDM-A	DHOPD	daily home-based other person demand	-	prsn/day	Yes	No	model generation	-
TDM-A	DHOT	daily home-based other trips	-	trips/day	Yes	No	model generation	-
TDM-A	DHOTP	daily home-based other trips per person	1.18	trips/prsn	No	Yes	data research	FHWA 1994
TDM-A	DHOVD	daily home-based other vehicle demand	-	veh/day	Yes	No	model generation	-
TDM-A	DHSPD	daily home-based shopping person demand	-	prsn/day	Yes	No	model generation	-
TDM-A	DHSRPD	daily home-based social and recre. person demand	-	prsn/day	Yes	No	model generation	-
TDM-A	DHSRT	daily home-based social and recreational trips	-	trips/day	Yes	No	model generation	-
TDM-A	DHSRTP	daily home-based social and recre. trips per person	0.63	trips/prsn	No	Yes	data research	FHWA 1994
TDM-A	DHSRVD	daily home-based social and recre. vehicle demand	-	veh/day	Yes	No	model generation	-
TDM-A	DHST	daily home-based shopping trips	-	trips/day	Yes	No	model generation	-

TDM-A	DHSTP	daily home-based shopping trips per person	0.49	trips/prsn	No	Yes	data research	FHWA 1994
TDM-A	DHSVD	daily home-based shopping vehicle demand	-	veh/day	Yes	No	model generation	-
TRANSPN	DHVH	design hour volume on highway	-	vehs/hr	Yes	No	model generation	-
TDM-A	DNHPD	daily non-home based person demand	-	prsn/day	Yes	No	model generation	-
TDM-A	DNHT	daily non-home-based trips	-	trips/day	Yes	No	model generation	-
TDM-A	DNHTP	daily non-home based trips per person	0.97	trips/prsn	No	Yes	data research	FHWA 1994
TDM-A	DNHVD	daily non-home based vehicle demand	-	veh/day	Yes	No	model generation	-
BMS	DRB	deterioration rate of bridge	-	bridges/yr	Yes	No	model generation	-
PMS	DRH	deteriorating rate of highway	-	lane-mi/yr	Yes	No	model generation	-
BMS	DTB	deterioration time of bridges	-	year	Yes	No	model generation	-
TDM-B	DTD	daily truck demand	-	veh/day	Yes	No	model generation	-
TDM-A	DTDGP	daily travel distance for general purpose	-	mi/day	Yes	No	model generation	-
TDM-B	DTDH	daily truck demand on highway	-	veh/day	Yes	No	model generation	-
TDM-A	DTDHO	daily travel distance for h.b. other trip	-	mi/day	Yes	No	model generation	-
TDM-A	DTDHS	daily travel distance for home-based shopping trip	-	mi/day	Yes	No	model generation	-
TDM-A	DTDHSR	daily travel distance for h.b.social and rec. trip	-	mi/day	Yes	No	model generation	-
TDM-A	DTDNH	daily travel distance for non-home based trip	-	mi/day	Yes	No	model generation	-
DMGRPHY	DTH	deaths	-	prsn/yr	Yes	No	model generation	-
TDM-B	DTR	daily trucks	-	trck/day	Yes	No	model generation	-
TDM-A	DVDGP	daily vehicle demand for general purpose	-	vehs/day	Yes	No	model generation	-
TDM-A	DVDGPH	daily vehicle demand for general purpose of highway	-	vehs/day	Yes	No	model generation	-
ECONOMY	E	employment	-	prsns	Yes	No	model generation	-
BMS	ERB	exposure rate of bridge	-	bridges/yr	Yes	No	model generation	-
ECONOMY	ES	employment in each sector	-	prsns	Yes	No	model generation	-
BMS	ETB	exposure time of bridges	-	year	Yes	No	model generation	-
TDM-B	ETF	empty truck factor	0.1	dim	No	Yes	user definition	-
APPRASAL	FAC	fatal accident cost	371500	$	No	Yes	data research	NHTSA 1983
PMS	FAI	functional adequacy index of pavement	-	dim	Yes	No	model generation	-
BMS	FBBC	fraction of BMS budget to construction	-	dim	Yes	No	model generation	-
BMS	FBGCN(1	functionally obsolescent BGC normal for interstate	0	bridges	No	Yes	user definition	-
BMS	FBGCN(2	functionally obsolescent BGC normal for primary	0	bridges	No	Yes	user definition	-
BMS	FBGCN(3	functionally obsolescent BGC normal for secondary	0	bridges	No	Yes	user definition	-
BMS	FBGCN(4	functionally obsolescent BGC normal for urban	0	bridges	No	Yes	user definition	-
BMS	FBPCN(1	functionally obsolescent BPC normal for interstate	0	bridges	No	Yes	user definition	-
BMS	FBPCN(2	functionally obsolescent BPC normal for primary	0	bridges	No	Yes	user definition	-
BMS	FBPCN(3	functionally obsolescent BPC normal for secondary	0	bridges	No	Yes	user definition	-
BMS	FBPCN(4	functionally obsolescent BPC normal for urban	0	bridges	No	Yes	user definition	-
BMS	FBPFCN(	functionally obsolescent BPFC normal for interstate	0	bridges	No	Yes	user definition	-
BMS	FBPFCN(	functionally obsolescent BPFC normal for primary	0	bridges	No	Yes	user definition	-
BMS	FBPFCN(	functionally obsolescent BPFC normal for secondary	0	bridges	No	Yes	user definition	-

BMS	FBPFCN(	functionally obsolescent BPFC normal for urban	0	bridges	No	Yes	user definition	-
BMS	FBPM	fraction of budget to preventive maintenance	-	dim	Yes	No	model generation	-
BMS	FBRH	fraction of budget to rehabilitation	-	dim	Yes	No	model generation	-
BMS	FBRP	fraction of budget to replacement	-	dim	Yes	No	model generation	-
BMS	FBRR	fraction of budget to repairs	-	dim	Yes	No	model generation	-
BMS	FBSCN(1	functionally obsolescent BSC normal for interstate	0	bridges	No	Yes	user definition	-
BMS	FBSCN(2	functionally obsolescent BSC normal for primary	0	bridges	No	Yes	user definition	-
BMS	FBSCN(3	functionally obsolescent BSC normal for secondary	0	bridges	No	Yes	user definition	-
BMS	FBSCN(4	functionally obsolescent BSC normal for urban	0	bridges	No	Yes	user definition	-
TDM-B	FCCP	fraction of commuters in carpool	0.2	dim	No	Yes	user definition	-
TDM-B	FCDA	fraction of commuters driving alone	0.7	dim	No	Yes	user definition	-
FINANCE	FCMBI(1)	fraction of CMBH to interstate highway	0.192	dim	No	Yes	data research	VDOT annual
FINANCE	FCMBI(2)	fraction of CMBH to primary highway	0.270	dim	No	Yes	data research	VDOT annual
FINANCE	FCMBI(3)	fraction of CMBH to secondary highway	0.311	dim	No	Yes	data research	VDOT annual
FINANCE	FCMBI(4)	fraction of CMBH to urban highway	0.227	dim	No	Yes	data research	VDOT annual
TRANSPN	FFS(1)	free flow speed on interstate	80	mi/hr	No	Yes	user definition	-
TRANSPN	FFS(2)	free flow speed on primary	70	mi/hr	No	Yes	user definition	-
TRANSPN	FFS(3)	free flow speed on secondary	50	mi/hr	No	Yes	user definition	-
TRANSPN	FFS(4)	free flow speed on urban	60	mi/hr	No	Yes	user definition	-
TRANSPN	FFT	free flow time	-	min	Yes	No	model generation	-
TRANSPN	FFTA	free flow time annual	-	min	Yes	No	model generation	-
PMS	FHMEDF	fraction of maint expenditure to deficient highway	-	dim	Yes	No	model generation	-
PMS	FHMEDT	fraction of maint expenditure to deteriorated highway	-	dim	Yes	No	model generation	-
FINANCE	FHRACM	fraction of HRA to construction & maintenance	0.737	dim	No	Yes	data research	VDOT annual, VDOT 1995, Miller
ECONOMY	FIOI	fraction of IO to inputs	0.45	dim	No	Yes	user definition	-
BMS	FOBGC	functionally obsolescent BGC	-	bridges	Yes	No	model generation	-
BMS	FOBPC	functionally obsolescent BPC	-	bridges	Yes	No	model generation	-
BMS	FOBPFC	functionally obsolescent BPFC	-	bridges	Yes	No	model generation	-
BMS	FOBSC	functionally obsolescent BSC	-	bridges	Yes	No	model generation	-
BMS	FOFBGC	func obsolescence factor for BGC	-	dim	Yes	No	model generation	-
BMS	FOFBPC	func obsolescence factor for BPC	-	dim	Yes	No	model generation	-
BMS	FOFBPF	func obsolescence factor for BPFC	-	dim	Yes	No	model generation	-
BMS	FOFBSC	func obsolescence factor for BSC	-	dim	Yes	No	model generation	-
BMS	FORB	functionally obsolescent rate of bridges	-	bridges/yr	Yes	No	model generation	-
PMS	FPMSBC	fraction of PMS budget to construction	-	dim	Yes	No	model generation	-
PMS	FPMSBM	fraction of PMS budget to maintenance	-	dim	Yes	No	model generation	-
ECONOMY	FPSCI	fraction of PS to CI	table	dim	No	Yes	user definition	-
FINANCE	FR	federal aid revenue	-	$	Yes	No	model generation	-
FINANCE	FRIF	federal aid revenue increasing factor	0.0475	dim	No	Yes	data research	VDOT annual, VDOT 1995, Miller
FINANCE	FRN	federal aid revenue normal	450e6	$	No	Yes	data research	VDOT annual, VDOT 1995, Miller

FINANCE	FTRH	fraction of total revenue to highways	0.85	dim	No	Yes	data research	VDOT annual, VDOT 1995, Miller
BMS	FWBGC	fraction of BMS budget to BGC widening	-	dim	Yes	No	model generation	-
BMS	FWBPC	fraction of BMS budget to BPC widening	-	dim	Yes	No	model generation	-
BMS	FWBPFC	fraction of BMS budget to BPFC widening	-	dim	Yes	No	model generation	-
BMS	FWBSC	fraction of BMS budget to BSC widening	-	dim	Yes	No	model generation	-
ECONOMY	GSP	gross state product	-	$/yr	Yes	No	model generation	-
TDM-A	HAM	highway attraction multiplier	table	dim	Yes	No	user definition	-
PMS	HCE	highway construction expenditure	-	$/yr	Yes	No	model generation	-
PMS	HDF	highway in deficient condition	-	lane-mi	Yes	No	model generation	-
PMS	HDFN(1)	highway in deficient condition normal for interstate	1854.7	lane-mi	No	Yes	data research	DTS annual
PMS	HDFN(2)	highway in deficient condition normal for primary	7160.4	lane-mi	No	Yes	data research	DTS annual
PMS	HDFN(3)	highway in deficient condition normal for secondary	31677.	lane-mi	No	Yes	data research	DTS annual
PMS	HDFN(4)	highway in deficient condition normal for urban	6396.1	lane-mi	No	Yes	data research	DTS annual
PMS	HDT	highway in deteriorated condition	-	lane-mi	Yes	No	model generation	-
PMS	HDTN(1)	highway in deteriorated condition normal for	1854.7	lane-mi	No	Yes	data research	DTS annual
PMS	HDTN(2)	highway in deteriorated condition normal for primary	7160.4	lane-mi	No	Yes	data research	DTS annual
PMS	HDTN(3)	highway in deteriorated condition normal for	31677.	lane-mi	No	Yes	data research	DTS annual
PMS	HDTN(4)	highway in deteriorated condition normal for urban	6396.1	lane-mi	No	Yes	data research	DTS annual
PMS	HDTT	highway deterioration time	-	yr	Yes	No	model generation	-
PMS	HDTTM	highway deterioration time multiplier	table	dim	Yes	No	model generation	-
PMS	HDTTN	highway deterioration time normal	3	yr	No	Yes	user definition	-
PMS	HME	highway maintenance expenditure	-	$/yr	Yes	No	model generation	-
FINANCE	HMOF	highway maintenance & operating fund	-	$	Yes	No	model generation	-
TDM-B	HMSC(1)	highway modal split for commuting for interstate	0.15	dim	No	Yes	user definition	-
TDM-B	HMSC(2)	highway modal split for commuting for primary	0.15	dim	No	Yes	user definition	-
TDM-B	HMSC(3)	highway modal split for commuting for secondary	0.10	dim	No	Yes	user definition	-
TDM-B	HMSC(4)	highway modal split for commuting for urban	0.60	dim	No	Yes	user definition	-
TDM-A	HMSGP	highway modal split for general purpose trip	0.25	dim	No	Yes	user definition	-
TDM-B	HMST(1)	interstate modal split for truck	0.4	dim	No	Yes	user definition	-
TDM-B	HMST(2)	primary modal split for truck	0.4	dim	No	Yes	user definition	-
TDM-B	HMST(3)	secondary modal split for truck	0.1	dim	No	Yes	user definition	-
TDM-B	HMST(4)	urban modal split for truck	0.1	dim	No	Yes	user definition	-
TDM-A	HOTR	home-based other trip rate	1.84	trips/hh-dy	No	Yes	data research	FHWA 1994
FINANCE	HRA	highway revenue allocated	-	$	Yes	No	model generation	-
PMS	HSF	highway in sufficient condition	-	lane-mi	Yes	No	model generation	-
PMS	HSFN(1)	highway in sufficient condition normal for interstate	1854.7	lane-mi	No	Yes	data research	DTS annual
PMS	HSFN(2)	highway in sufficient condition normal for primary	7160.4	lane-mi	No	Yes	data research	DTS annual
PMS	HSFN(3)	highway in sufficient condition normal for secondary	31677.	lane-mi	No	Yes	data research	DTS annual
PMS	HSFN(4)	highway in sufficient condition normal for urban	6396.1	lane-mi	No	Yes	data research	DTS annual
TDM-A	HSRTR	home-based social and recreational trip rate	0.98	trips/hh-dy	No	Yes	data research	FHWA 1994

TDM-A	HSTR	home-based shopping trip rate	0.76	trips/hh-dy	No	Yes	data research	FHWA 1994
DMGRPHY	HV	households in Virginia	-	household	Yes	No	model generation	-
ECONOMY	IC	industrial capital	-	$	Yes	No	model generation	-
FINANCE	ICMB	construction & maintenance budget for each system	-	$	Yes	No	model generation	-
ECONOMY	ICN	industrial capital normal	table	$	No	Yes	user definition	-
DMGRPHY	INM	in-migrations	-	prsn/yr	Yes	No	model generation	-
DMGRPHY	INMF	in-migration factor	0.0348	dim	No	Yes	data research	CPS annual
ECONOMY	IO	industrial output	-	$/yr	Yes	No	model generation	-
APPRASAL	IVOC	initial vehicle operating costs	-	cnt/veh-mi	Yes	No	model generation	-
APPRASAL	IVOCG	IVOC growth rate	0.0402	dim	No	Yes	data research	AAA annual
APPRASAL	IVOCN	IVOC normal	61.58	cnt/veh-mi	No	Yes	data research	AAA annual
TRANSPN	KF(1)	peak hour factor for interstate	0.08	dim	No	Yes	user definition	-
TRANSPN	KF(2)	peak hour factor for primary	0.15	dim	No	Yes	user definition	-
TRANSPN	KF(3)	peak hour factor for secondary	0.15	dim	No	Yes	user definition	-
TRANSPN	KF(4)	peak hour factor for urban	0.15	dim	No	Yes	user definition	-
TRANSPN	LCH(1)	lane capacity of interstate	2400	vehs/hr-ln	No	Yes	user definition	-
TRANSPN	LCH(2)	lane capacity of primary	2200	vehs/hr-ln	No	Yes	user definition	-
TRANSPN	LCH(3)	lane capacity of secondary	2000	vehs/hr-ln	No	Yes	user definition	-
TRANSPN	LCH(4)	lane capacity of urban	2500	vehs/hr-ln	No	Yes	user definition	-
TRANSPN	LOSF(1)	level of service factor for interstate highway	table	dim	Yes	No	user definition	-
TRANSPN	LOSF(2)	level of service factor for primary highway	table	dim	Yes	No	user definition	-
TRANSPN	LOSF(3)	level of service factor for secondary highway	table	dim	Yes	No	user definition	-
TRANSPN	LOSF(4)	level of service factor for urban highway	table	dim	Yes	No	user definition	-
TRANSPN	LOSP	level of service parameter	-	dim	Yes	No	model generation	-
TRANSPN	LOSPB	level of service parameter for bridges	-	dim	Yes	No	model generation	-
TRANSPN	LOSPH	level of service parameter for highways	-	dim	Yes	No	model generation	-
ECONOMY	LP	labor productivity	table	dim	No	Yes	user definition	-
ECONOMY	LPF	labor productivity factor	-	dim	Yes	No	model generation	-
APPRASAL	LTRBH	accumulated total revenue	-	$	Yes	No	model generation	-
FUNCTIONAL	MCDFH	maint cost of deficient highway	-	$/brdg	Yes	No	model generation	-
FUNCTIONAL	MCDFHM	maint cost of deficient highway multiplier	-	dim	Yes	No	user definition	-
FUNCTIONAL	MCDFHN	maint cost of deficient highway normal for interstate	34000	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	MCDFHN	maint cost of deficient highway normal for primary	24460	$/brdg	No	Yes	user definition	-
FUNCTIONAL	MCDFHN	maint cost of deficient highway normal for secondary	12230	$/brdg	No	Yes	user definition	-
FUNCTIONAL	MCDFHN	maint cost of deficient highway normal for urban	21845	$/brdg	No	Yes	user definition	-
FUNCTIONAL	MCDTH	maint cost of deteriorated highway	-	$/brdg	Yes	No	model generation	-
FUNCTIONAL	MCDTHM	maint cost of deteriorated highway multiplier	-	dim	Yes	No	user definition	-
FUNCTIONAL	MCDTHN	maint cost of deteriorated highway normal for intst.	85400	$/brdg	No	Yes	data research	-
FUNCTIONAL	MCDTHN	maint cost of deteriorated highway normal for	61430	$/brdg	No	Yes	user definition	-
FUNCTIONAL	MCDTHN	maint cost of deteriorated highway normal for scndry	30715	$/brdg	No	Yes	user definition	-

FUNCTIONAL	MCDTHN	maint cost of deteriorated highway normal for urban	54860	$/brdg	No	Yes	user definition	-
FUNCTIONAL	MCH	maintenance cost of highway	-	$/brdg	Yes	No	model generation	-
PMS	MEDFH	maintenance expenditure for deficient highway	-	$/yr	Yes	No	model generation	-
PMS	MEDTH	maintenance expenditure for deteriorated highway	-	$/yr	Yes	No	model generation	-
DMGRPHY	MFTF	motor fuels tax factor	table	dim	No	Yes	user definition	-
FINANCE	MFTH	motor vehicle fuels tax for HMOF	0.1485	$/gal	No	Yes	data research	VDOT 1995, Miller 1995
FINANCE	MFTT	motor vehicle fuels tax for TTF	0.025	$/gal	No	Yes	data research	VDOT 1995, Miller 1995
DMGRPHY	MGR	migration rate	-	prsn/yr	Yes	No	model generation	-
TRANSPN	MH	mileage of highway	-	mi	Yes	No	model generation	-
TRANSPN	MHN(1)	mileage of highway normal for interstate	1155	mi	No	Yes	data research	DTS annual
TRANSPN	MHN(2)	mileage of highway normal for primary	8001	mi	No	Yes	data research	DTS annual
TRANSPN	MHN(3)	mileage of highway normal for secondary	47210	mi	No	Yes	data research	DTS annual
TRANSPN	MHN(4)	mileage of highway normal for urban	10467	mi	No	Yes	data research	DTS annual
FINANCE	MLFH	motor vehicle license fees for HMOF	16	$/veh	No	Yes	data research	VDOT 1995, Miller 1995
FINANCE	MLFT	motor vehicle license fees for TTF	3	$/veh	No	Yes	data research	VDOT 1995, Miller 1995
TRANSPN	MLGR(1)	mileage growth rate for interstate	0.0189	dim	No	Yes	data research	DTS annual
TRANSPN	MLGR(2)	mileage growth rate for primary	0.0006	dim	No	Yes	data research	DTS annual
TRANSPN	MLGR(3)	mileage growth rate for secondary	0.0037	dim	No	Yes	data research	DTS annual
TRANSPN	MLGR(4)	mileage growth rate for urban	0.0125	dim	No	Yes	data research	DTS annual
PMS	MRDFH	maintenance rate for deficient highway	-	lane-mi/yr	Yes	No	model generation	-
PMS	MRDTH	maintenance rate for deteriorated highway	-	lane-mi/yr	Yes	No	model generation	-
FINANCE	MRH	miscellaneous revenue for HMOF	-	$	Yes	No	model generation	-
FINANCE	MRHM	miscellaneous revenue for HMOF multiplier	table	dim	Yes	No	user definition	-
FINANCE	MRHN	miscellaneous revenue for HMOF normal	8e6	$	No	Yes	data research	VDOT annual, VDOT 1995, Miller
FINANCE	MRT	miscellaneous revenue for TTF	-	$	Yes	No	model generation	-
FINANCE	MRTM	miscellaneous revenue for TTF multiplier	table	dim	Yes	No	user definition	-
FINANCE	MRTN	miscellaneous revenue for TTF normal	165e6	$	No	Yes	data research	VDOT annual, VDOT 1995, Miller
FINANCE	MSUTH	motor vehicle sales & use tax for HMOF	0.02	dim	No	Yes	data research	VDOT 1995, Miller 1995
FINANCE	MSUTT	motor vehicle sales & use tax for TTF	0.01	dim	No	Yes	data research	VDOT 1995, Miller 1995
BMS	MTBGC(1	marginal traffic intensity of BGC for interstate	0.43	dim	No	Yes	user definition	-
BMS	MTBGC(2	marginal traffic intensity of BGC for primary	0.24	dim	No	Yes	user definition	-
BMS	MTBGC(3	marginal traffic intensity of BGC for secondary	0.20	dim	No	Yes	user definition	-
BMS	MTBGC(4	marginal traffic intensity of BGC for urban	0.38	dim	No	Yes	user definition	-
BMS	MTBPC(1	marginal traffic intensity of BPC for interstate	0.43	dim	No	Yes	user definition	-
BMS	MTBPC(2	marginal traffic intensity of BPC for primary	0.24	dim	No	Yes	user definition	-
BMS	MTBPC(3	marginal traffic intensity of BPC for secondary	0.20	dim	No	Yes	user definition	-
BMS	MTBPC(4	marginal traffic intensity of BPC for urban	0.38	dim	No	Yes	user definition	-
BMS	MTBPFC(	marginal traffic intensity of BPFC for interstate	0.43	dim	No	Yes	user definition	-
BMS	MTBPFC(	marginal traffic intensity of BPFC for primary	0.24	dim	No	Yes	user definition	-
BMS	MTBPFC(	marginal traffic intensity of BPFC for secondary	0.2	dim	No	Yes	user definition	-

BMS	MTBPFC(	marginal traffic intensity of BPFC for urban	0.38	dim	No	Yes	user definition	-
BMS	MTBSC(1	marginal traffic intensity of BSC for interstate	0.43	dim	No	Yes	user definition	-
BMS	MTBSC(2	marginal traffic intensity of BSC for primary	0.24	dim	No	Yes	user definition	-
BMS	MTBSC(3	marginal traffic intensity of BSC for secondary	0.20	dim	No	Yes	user definition	-
BMS	MTBSC(4	marginal traffic intensity of BSC for urban	0.38	dim	No	Yes	user definition	-
TDM-B	NCP	number of commuting period	2	prd/day	No	Yes	user definition	-
BMS	NFOB	number of functionally obsolescent bridges	-	bridges	Yes	No	model generation	-
DMGRPHY	NGR	natural growth rate	-	prsn/yr	Yes	No	model generation	-
TDM-A	NHTR	non-home-based trip rate	1.52	trips/hh-dy	No	Yes	data research	FHWA 1994
DMGRPHY	NVPG	new vehicle price growth factor	0.0348	dim	No	Yes	data research	VDMV 1997
DMGRPHY	NVT	new vehicles titled	-	vehicles	Yes	No	model generation	-
DMGRPHY	NVTG	new vehicles titled growth factor	-0.0079	dim	No	Yes	data research	VDMV 1997
DMGRPHY	NVTN	new vehicles titled normal	344817	vehicles	No	Yes	data research	VDMV 1997
TRANSPN	OPS	operating speed	-	mi/hr	Yes	No	model generation	
BMS	ORBGC	obsolescence rate of BGC	-	bridges/yr	Yes	No	model generation	-
BMS	ORBPC	obsolescence rate of BPC	-	bridges/yr	Yes	No	model generation	-
BMS	ORBPFC	obsolescence rate of BPFC	-	bridges/yr	Yes	No	model generation	-
BMS	ORBSC	obsolescence rate of BSC	-	bridges/yr	Yes	No	model generation	-
APPRASAL	OSF(1)	operating speed factor for interstate highway	table	dim	Yes	No	user definition	-
APPRASAL	OSF(2)	operating speed factor for primary highway	table	dim	Yes	No	user definition	-
APPRASAL	OSF(3)	operating speed factor for secondary highway	table	dim	Yes	No	user definition	-
APPRASAL	OSF(4)	operating speed factor for urban highway	table	dim	Yes	No	user definition	-
BMS	OTBGC	obsolescence time of BGC	8	year	No	Yes	user definition	-
BMS	OTBPC	obsolescence time of BPC	6	year	No	Yes	user definition	-
BMS	OTBPFC	obsolescence time of BPFC	15	year	No	Yes	user definition	-
BMS	OTBSC	obsolescence time of BSC	4	year	No	Yes	user definition	-
DMGRPHY	OTM	out-migrations	-	prsn/yr	Yes	No	model generation	-
DMGRPHY	OTMF	out-migration factor	0.0296	dim	No	Yes	data research	CPS annual
BMS	PCDAB	proportion of concrete-deck arch bridges	0.013	dim	No	Yes	data research	Klaiber, et al. 1987
TDM-B	PCET	passenger car equivalents for truck	3	veh/trck	No	Yes	user definition	-
BMS	PCSB	proportion of concrete slab bridges	0.088	dim	No	Yes	data research	Klaiber, et al. 1987
BMS	PCSTB	proportion of concrete stringer bridges	0.035	dim	No	Yes	data research	Klaiber, et al. 1987
BMS	PCTB	proportion of concrete tee bridges	0.056	dim	No	Yes	data research	Klaiber, et al. 1987
APPRASAL	PDC	property damage cost	750	$	No	Yes	data research	NHTSA 1983
ECONOMY	PDT	productivity	-	dim	Yes	No	model generation	-
APPRASAL	PFA	proportion of fatal accidents	0.035	dim	No	Yes	user definition	-
APPRASAL	PIC	personal injury cost	3160	$	No	Yes	data research	NHTSA 1983
ECONOMY	PLR	product labor ratio	-	($/yr)/prsn	Yes	No	model generation	-
ECONOMY	PLRN	product labor ratio normal	table	($/yr)/prsn	No	Yes	user definition	-
FUNCTIONAL	PMCB	preventive maint cost for bridge	-	$/brdg	Yes	No	model generation	-

FUNCTIONAL	PMCBM	preventive maint cost for bridge multiplier	-	dim	Yes	No	user definition	-
FUNCTIONAL	PMCBN	preventive maint cost for bridge normal	-	$/brdg	No	Yes	model generation	-
BMS	PMEB	preventive maintenance expenditure on bridges	-	$/yr	Yes	No	model generation	-
FINANCE	PMFT	portion of total revenue to fuels tax revenue	-	%	Yes	No	model generation	-
APPRASAL	PPDA	proportion of property damage accidents	0.78	dim	No	Yes	user definition	-
APPRASAL	PPIA	proportion of personal injury accidents	0.185	dim	No	Yes	user definition	-
ECONOMY	PS	product by each sector	-	$/yr	Yes	No	model generation	-
BMS	PSGFBB	proportion of steel-girder floor beam bridges	0.019	dim	No	Yes	data research	Klaiber, et al. 1987
BMS	PSIB	physical sufficiency index of bridges	-	dim	Yes	No	model generation	-
PMS	PSIH	physical sufficiency index of highway	-	dim	Yes	No	model generation	-
BMS	PSSB	proportion of steel stringer bridges	0.272	dim	No	Yes	data research	Klaiber, et al. 1987
BMS	PSTTB	proportion of steel through-truss bridges	0.065	dim	No	Yes	data research	Klaiber, et al. 1987
BMS	PTSB	proportion of timber stringer bridges	0.12	dim	No	Yes	data research	Klaiber, et al. 1987
DMGRPHY	PV	population of Virginia	-	prsns	Yes	No	model generation	-
APPRASAL	PVCF(1)	pavement condition factor for interstate highway	table	dim	Yes	No	user definition	-
APPRASAL	PVCF(2)	pavement condition factor for primary highway	table	dim	Yes	No	user definition	-
APPRASAL	PVCF(3)	pavement condition factor for secondary highway	table	dim	Yes	No	user definition	-
APPRASAL	PVCF(4)	pavement condition factor for urban highway	table	dim	Yes	No	user definition	-
APPRASAL	PVCFA(1	pavement condition factor for accidents for interstate	table	dim	Yes	No	user definition	-
APPRASAL	PVCFA(2	pavement condition factor for accidents for primary	table	dim	Yes	No	user definition	-
APPRASAL	PVCFA(3	pavement condition factor for accidents for	table	dim	Yes	No	user definition	-
APPRASAL	PVCFA(4	pavement condition factor for accidents for urban	table	dim	Yes	No	user definition	-
BMS	PVMB	preventive maintenance rate of bridge	-	bridges/yr	Yes	No	model generation	-
DMGRPHY	PVN	population of virginia initial	7048e3	prsns	No	Yes	data research	CPS annual
APPRASAL	RAEH	rate of annual expenditures on highway	-	$/yr	Yes	No	model generation	-
APPRASAL	RCAPCH	rate of capital costs on highway	-	$/yr	Yes	No	model generation	-
DMGRPHY	RCVOS	regression coefficient of veh ownership	0.0006	dim	No	Yes	user definition	-
APPRASAL	RDSCR	relative discount rate	-	dim	No	Yes	model generation	-
FUNCTIONAL	RHCB	rehabilitation cost of bridge	-	$/brdg	Yes	No	model generation	-
FUNCTIONAL	RHCBM	rehabilitation cost of bridge multiplier	-	dim	Yes	No	user definition	-
FUNCTIONAL	RHCBN	rehabilitation cost of bridge normal	-	$/brdg	No	Yes	model generation	-
BMS	RHEB	rehabilitation expenditure on bridges	-	$/yr	Yes	No	model generation	-
BMS	RHRB	rehabilitation rate of bridge	-	bridges/yr	Yes	No	model generation	-
DMGRPHY	RIVOS	regression intercept value of veh ownership	0.8989	dim	No	Yes	user definition	-
FINANCE	RMFT	revenue from motor fuels tax	-	$	Yes	No	model generation	-
FINANCE	RMFTH	revenue from motor vehicle fuels tax for HMOF	-	$	Yes	No	model generation	-
FINANCE	RMFTT	revenue from motor vehicle fuels tax for TTF	-	$	Yes	No	model generation	-
FINANCE	RMLFH	revenue from motor vehicle license fees for HMOF	-	$	Yes	No	model generation	-
FINANCE	RMLFT	revenue from motor vehicle fuels tax for TTF	-	$	Yes	No	model generation	-
FINANCE	RMSUTH	revenue from motor vehicle sales & use tax for	-	$	Yes	No	model generation	-

FINANCE	RMSUTT	revenue from motor vehicle sales & use tax for TTF	-	$	Yes	No	model generation	-
FUNCTIONAL	RPCB	replacement cost of bridge	-	$/brdg	Yes	No	model generation	-
FUNCTIONAL	RPCBM	replacement cost of bridge multiplier	-	dim	Yes	No	user definition	-
FUNCTIONAL	RPCBN(1	replacement cost of bridge normal for interstate	1.7e6	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	RPCBN(2	replacement cost of bridge normal for primary	1.23e6	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	RPCBN(3	replacement cost of bridge normal for secondary	618e3	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	RPCBN(4	replacement cost of bridge normal for urban	707e3	$/brdg	No	Yes	user definition	-
BMS	RPEB	replacement expenditure on bridges	-	$/yr	Yes	No	model generation	-
BMS	RPRB	replacement rate of bridge	-	bridges/yr	Yes	No	model generation	-
FUNCTIONAL	RRCB	repair cost of bridge	-	$/brdg	Yes	No	model generation	-
FUNCTIONAL	RRCBM	repair cost of bridge multiplier	-	dim	Yes	No	user definition	-
FUNCTIONAL	RRCBN	repair cost of bridge normal	-	$/brdg	No	Yes	model generation	-
BMS	RREB	repair expenditure on bridges	-	$/yr	Yes	No	model generation	-
BMS	RRRB	repair rate of bridge	-	bridges/yr	Yes	No	model generation	-
BMS	RSLBCC	remaining service life of BCC	-	year	Yes	No	model generation	-
BMS	RSLBGC	remaining service life of BGC	-	year	Yes	No	model generation	-
BMS	RSLBPC	remaining service life of BPC	-	year	Yes	No	model generation	-
BMS	RSLBPF	remaining service life of BPFC	-	year	Yes	No	model generation	-
BMS	RSLBSC	remaining service life of BSC	-	year	Yes	No	model generation	-
FINANCE	RSST	revenue from state sales tax	-	$	Yes	No	model generation	-
BMS	RTBCC	remaining to total service life ratio of BCC	0.01	dim	No	Yes	user definition	-
BMS	RTBGC	remaining to total service life ratio of BGC	0.70	dim	No	Yes	user definition	-
BMS	RTBPC	remaining to total service life ratio of BPC	0.20	dim	No	Yes	user definition	-
BMS	RTBPFC	remaining to total service life ratio of BPFC	1.0	dim	No	Yes	user definition	-
BMS	RTBSC	remaining to total service life ratio of BSC	0.10	dim	No	Yes	user definition	-
APPRASAL	RTRBH	rate of total revenue by highways	-	$/yr	Yes	No	model generation	-
BMS	SDRB	serious deterioration rate of bridge	-	bridges/yr	Yes	No	model generation	-
BMS	SDTB	serious deterioration time of bridges	-	year	Yes	No	model generation	-
ECONOMY	SIC	sum of industrial capital of each sector	-	$	Yes	No	model generation	-
ECONOMY	SICN	initial sum of industrial capital of each sector	-	$	No	Yes	model generation	-
ECONOMY	SIO	sum of industrial output of each sector	-	$	Yes	No	model generation	-
FINANCE	SST	state sales tax	0.005	dim	No	Yes	data research	VDOT 1995, Miller 1995
APPRASAL	TAVMH	total annual vehicle miles of highways	-	veh-mi	Yes	No	model generation	-
ECONOMY	TFIH	transport friction indicator	table	dim	Yes	No	model generation	-
TDM-B	TIO	trucks per industrial output	5E-6	trck/$	No	Yes	user definition	-
PMS	TLMH	total lane-mileage of highway	-	lane-mi	Yes	No	model generation	-
PMS	TLMHN	total lane-mileage of highway initial	-	lane-mi	No	Yes	model generation	-
BMS	TNB	total number of bridges	-	bridges	Yes	No	model generation	-
BMS	TNBN	total number of bridges normal	-	bridges	Yes	No	model generation	-
BMS	TNFOB	total number of func obsolescent bridges	-	bridges	Yes	No	model generation	-

FINANCE	TR	total transportation revenue	-	$	Yes	No	model generation	-
BMS	TSL	total service life of bridges	-	year	Yes	No	model generation	-
BMS	TSLM	total service life multiplier	-	dim	Yes	No	model generation	-
BMS	TSLN	total service life normal	-	year	No	Yes	model generation	-
TRANSPN	TT	travel time	-	min	Yes	No	model generation	-
TRANSPN	TTA	travel time annual	-	min	Yes	No	model generation	-
APPRASAL	TTC	travel time cost	-	$	Yes	No	model generation	-
FINANCE	TTF	transportation trust fund	-	$	Yes	No	model generation	-
TDM-A	TTPH(1)	thru traffic portion on interstate highway	0.10	dim	No	Yes	user definition	-
TDM-A	TTPH(2)	thru traffic portion on primary highway	0.10	dim	No	Yes	user definition	-
TDM-A	TTPH(3)	thru traffic portion on secondary highway	0.06	dim	No	Yes	user definition	-
TDM-A	TTPH(4)	thru traffic portion on urban highway	0.02	dim	No	Yes	user definition	-
TDM-B	TTTPH(1)	truck thru traffic portion on interstate	0.3	dim	No	Yes	user definition	-
TDM-B	TTTPH(2)	truck thru traffic portion on primary	0.2	dim	No	Yes	user definition	-
TDM-B	TTTPH(3)	truck thru traffic portion on secondary	0.1	dim	No	Yes	user definition	-
TDM-B	TTTPH(4)	truck thru traffic portion on urban	0.05	dim	No	Yes	user definition	-
APPRASAL	TUC	total user costs	-	$	Yes	No	model generation	-
TRANSPN	TVMH	total vehicle miles on highway	-	veh-	Yes	No	model generation	-
DMGRPHY	UVPG	used vehicle price growth factor	0.0582	dim	No	Yes	data research	VDMV 1997
DMGRPHY	UVT	used vehicles titled	-	vehicles	Yes	No	model generation	-
DMGRPHY	UVTG	used vehicles titled growth factor	0.0148	dim	No	Yes	data research	VDMV 1997
DMGRPHY	UVTN	used vehicles titled normal	1.07e6	vehicles	No	Yes	data research	VDMV 1997
TDM-B	VMCH	vehicle miles for commuting on a highway	-	veh-	Yes	No	model generation	-
TDM-A	VMGPH	veh miles per day for general purpose trip on	-	veh-	Yes	No	model generation	-
FINANCE	VMT	vehicle miles traveled	-	veh-mi	Yes	No	model generation	-
TDM-B	VMTH	vehicle miles for truck on highway	-	veh-	Yes	No	model generation	-
APPRASAL	VOC	vehicle operating costs of highway	-	$	Yes	No	model generation	-
DMGRPHY	VOS	vehicle ownership in Virginia	-	veh/prsn	Yes	No	model generation	-
APPRASAL	VOT	value of time	8	$/hr	No	Yes	data research	NHTSA 1983
DMGRPHY	VR	vehicle registrations in Virginia	-	vehicles	Yes	No	model generation	-
BMS	WBGC	widening rate of BGC	-	bridges/yr	Yes	No	model generation	-
BMS	WBPC	widening rate of BPC	-	bridges/yr	Yes	No	model generation	-
BMS	WBPFC	widening rate of BPFC	-	bridges/yr	Yes	No	model generation	-
BMS	WBSC	widening rate of BSC	-	bridges/yr	Yes	No	model generation	-
FUNCTIONAL	WCB	widening cost of bridge	-	$/brdg	Yes	No	model generation	-
FUNCTIONAL	WCBN(1)	widening cost of bridge normal for interstate	584929	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	WCBN(2)	widening cost of bridge normal for primary	425828	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	WCBN(3)	widening cost of bridge normal for secondary	243330	$/brdg	No	Yes	data research	de la Garza, et al. 1996
FUNCTIONAL	WCBN(4)	widening cost of bridge normal for urban	242722	$/brdg	No	Yes	user definition	-
BMS	WEBGC	widening expenditure on BGC	-	$/yr	Yes	No	model generation	-

BMS	WEBPC	widening expenditure on BPC	-	$/yr	Yes	No	model generation	-
BMS	WEBPFC	widening expenditure on BPFC	-	$/yr	Yes	No	model generation	-
BMS	WEBSC	widening expenditure on BSC	-	$/yr	Yes	No	model generation	-
BMS	WFBCC	weighting factor for BCC	0.1	dim	No	Yes	user definition	-
BMS	WFBGC	weighting factor for BGC	0.5	dim	No	Yes	user definition	-
BMS	WFBPC	weighting factor for BPC	0.3	dim	No	Yes	user definition	-
BMS	WFBPFC	weighting factor for BPFC	0.8	dim	No	Yes	user definition	-
BMS	WFBSC	weighting factor for BSC	0.2	dim	No	Yes	user definition	-
PMS	WFHDF	weighting factor for HDF	0.7	dim	No	Yes	user definition	-
PMS	WFHDT	weighting factor for HDT	0.5	dim	No	Yes	user definition	-
PMS	WFHSF	weighting factor for HSF	1.0	dim	No	Yes	user definition	-
TDM-B	WRR	workplace report rate	0.9	dim	No	Yes	user definition	-

VITA

Kyeil Kim

Kyeil Kim was born on April 20, 1965, in Seoul, Korea. He graduated from Kyung Hee High School in Seoul in February, 1984. He graduated with a Bachelor of Science degree in Urban Planning in February, 1991 from Hanyang University in Seoul.

Subsequently, he worked as a transportation planner for Yooshin Engineering Corporation in Seoul. He was involved in many national and local projects, and gained considerable experience in transportation planning. In 1993, he resigned the position of Associate in Yooshin Engineering Corporation to follow an enthusiastic interest in higher education.

He began studies towards a Masters' degree at the University of New South Wales in Sydney, Australia, and earned a Master of Engineering Science in Transport Engineering in 1995. Subsequently, he enrolled at Virginia Polytechnic Institute and State University to pursue a Ph.D. degree in Transportation Engineering.