

**A Systems Approach to Transportation Infrastructure Management:  
Development of a Highway Management System for the Virginia DOT**

by  
**Wonkyu Kim**

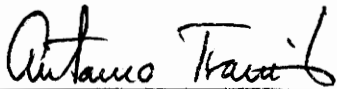
Dissertation submitted to the Faculty of the  
Virginia Polytechnic Institute and State University  
in partial fulfillment of the requirements for the degree of

Doctor of Philosophy  
in  
Civil Engineering

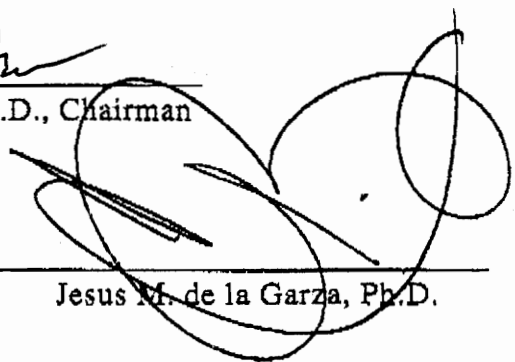
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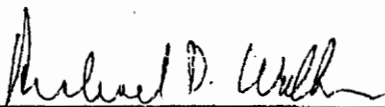
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September, 1996  
Blacksburg, Virginia

Keywords: Transportation Infrastructure Management, System Dynamics, PMS, BMS,  
Planning

c.2

LD  
5655  
V856  
1996  
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c.2

**A SYSTEMS APPROACH TO TRANSPORTATION INFRASTRUCTURE  
MANAGEMENT: DEVELOPMENT OF A HIGHWAY MANAGEMENT SYS-  
TEM FOR THE VIRGINIA DOT**

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**(ABSTRACT)**

Although there have been warnings about the decline in the U.S. transportation infrastructure for the last two decades, the infrastructure's service condition remains barely above current requirements, and is insufficient to meet future demands of growth and economic development. This deterioration and obsolescence primarily derives from a lack of investment, inappropriate management, and growing travel demands.

The objective of this research is to develop a model, using a system dynamics methodology, that serves as an instrumentality for generating scenarios for facilitating highway infrastructure management-- policy-making, planning, budgeting, and programming for the Virginia highway system.

The Highway Management System (HMS) model, developed in this research, is a system dynamics model equipped with capabilities for analyzing and solving the meta-problems related to highway infrastructure planning and management. The HMS consists of five subsystems: 1) Physical Subsystem (Pavement Management System, and Bridge Management System), 2) Evaluation Subsystem, 3) Functional Subsystem, 4) Financial Subsystem, and 5) Administration Subsystem.

Through steady state analysis, an understanding of the relationship between state variables and decision variables can be obtained. The nomographs corresponding to

the steady state solutions of the HMS are the analytically-based, manual means of gaining understanding by tracing paths from decision variables to state variables.

Simulations were performed using the HMS, based on various budget-size and allocation scenarios for the I-81 corridor. The results indicate that the service condition of the highway will be diminished and will return to its pre-expansion condition in several years, if the maintenance budget is not increased according to the expansion.

The HMS is a useful tool for decision-makers and engineers attempting to analyze and solve meta-problems related to transportation infrastructure management. The HMS presents a whole picture of the highway system according to various policy options. This systems approach to highway management also can be applied to the management of other infrastructure, and eventually it should be possible to achieve an integrated infrastructure management system.

*To my lovely wife*

## **Acknowledgements**

From the bottom of my heart, I would like to thank Dr. Drew, my advisor, for his patience, encouragement and strong support for this dissertation. His advice and guidance greatly helped me throughout the time of my research.

I would also like to thank my committee members, Dr. Antonio Trani, Dr. Jesus M. de la Garza, Dr. Richard D. Walker, and Dean Benjamin S. Blanchard, for their consistent advice and assistance for this work.

Additionally, I would like to send my warm gratitude to Dr. Wann Yu, my former advisor and to the professors during my undergraduate studies in Yonsei University.

I would like to express special thanks to Mr. A. Williams, and Virginia Department of Transportation for their support.

My greatest thanks go to my lovely wife, Eunryoung, for her love and sacrifice, which made it possible for me to complete this degree. Her prayers and encouragement gave me strength in my times of greatest need. I am greatly thankful to my parents, my brother and sister, and parents-in-law for their prayers and support. Most of all, I sincerely thank God for blessing me in this achievement.

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# **I Introduction**

## ***I-1. Background***

Infrastructure is a basic physical framework which supports all social and economic activities and the movement of people and goods. Transportation infrastructure is especially important for the nation's economic health (McNeil et. al., 1992). Production of goods and services requires a desired level of service for freight movement and passenger trips using the existing transportation infrastructure. All economic activities inevitably incur transportation related cost, which is determined by the service level of the transportation infrastructure.

If the transportation infrastructure is in physically and functionally good condition, goods can be delivered on time, without delay and additional operating costs. In some cases, the deterioration of transportation facilities restricts industrial location. The state DOT has had to restrict the location of heavy industry, because the access roadways were in bad condition, and facilities could not accommodate heavy truck traffic. Maintaining and managing efforts for highway systems will beneficially influence the economy, as the efforts can hold down the unnecessary increase of transportation costs.

A significantly large part of the transportation infrastructure of the United States is deteriorating and becoming obsolete, and no longer functions as it was originally designed. For example, there are about 0.6 million highway bridges in the United States, and almost one-half of them were built before 1940 (Hudson et. al., 1987). Most of their designs were for less traffic, lower speeds, smaller vehicles, and lighter loads (Hudson et. al., 1987). Due to deferred maintenance and deteriorated service

conditions, the bridges that had been built after 1940 do not provide efficient service, and are in need of rehabilitation and replacement (Hudson et. al., 1987). In simply maintaining current highway conditions and performance, the FHWA estimates that over 100,000 miles of highways and 11,000 bridges require some degree of capital investment. (BTS, 1995)

The deterioration in the transportation infrastructure comes primarily from deferred maintenance and functional obsolescence due to lack of investment, inappropriate management, and growing travel demands. 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 highway investment and management process has a dynamic structure with cause and effect. 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. This systems approach will be useful in support-

ing decision-making about highway infrastructure management, including investment and allocation.

## ***I-2. Motivation for the Research***

Efficient and optimal investments in highway management are needed to improve highway conditions and to provide better transportation services. In the transportation infrastructure management process, planners and policy makers often encounter critical decisions regarding the allocation of maintenance budgets. "What if?" type questions relating to the highway management policy can be addressed. However, these questions are related to complex meta-problems and it is more effective to build a systems approach than to use other existing approaches.

A comprehensive Highway Management System (HMS) is designed using the systems approach to provide a tool for analyzing and solving the addressed problems. The HMS can help decision-makers by providing an instrument for evaluating planning-level alternatives with different funding levels, spending policies, and other scenarios which will incur unique consequences. There have been some efforts to utilize systems approaches for highway planning and management problems to some extent. (Huang, et. al. (1983), and Chasey, et. al. (1995)). However, because they are somewhat fragmented, there is a need for a complete and comprehensive systems modeling of the HMS.

This dissertation represents a portion of a research contract submitted to the Virginia Department of Transportation by a research team from Virginia Tech and Arizona State Universities (VDOT, 1996 and de la Garza, et. al., 1995). Specific work to be accomplished under this contract is the development of a simulation model for

determining the impact of deferred maintenance of the Interstate System, based on, and calibrated for, the Salem District.

### ***I-3. Objectives of the Research***

The purpose of this research is to develop a model using the system dynamics methodology that serves as an instrumentality for generating scenarios to facilitate the management- policy-making, planning, budgeting, and programming- of the Virginia highway system. Specific objectives of this research are to conceptualize, model, analyze and synthesize the various submodels that define the highway system of the Virginia Department of Transportation (VDOT). Emphasis of this research is on organization, not calibration, of the model. A Management Information System (MIS) was also developed under the VDOT research project to calibrate this model.

### ***I-4. Scope of the Research***

The system dynamics model for the Highway Management System (HMS) includes all the necessary aspects of highway and bridge management actions, traffic engineering, transportation planning, highway engineering and related socio-economic forecasting and estimation. HMS is conceived as consisting of the following subsystems:

- The Physical Subsystem
  - . The Pavement Management System (PMS)
  - . The Bridge Management System (BMS)
- The Functional Subsystem
- The Administration Subsystem
- The Financial Subsystem



## - The Evaluation Subsystem

The physical subsystem consists of The Pavement Management System (PMS) and The Bridge Management System (BMS). The PMS includes the prediction of the physical condition of highways according to the deterioration rate and the improvement rate. The BMS shows the physical and functional condition of the highway bridges.

The evaluation subsystem functions as an evaluation routine for the entire HMS system, and gives us an objective index which helps show the feasibility of the alternatives. The evaluation subsystem estimates measures of effectiveness (MOEs) such as the user-benefit, non-user benefit, benefit/cost ratio, etc.. The functional subsystem includes routines which estimate the life-cycle costs according to the specifications of various design, construction and maintenance strategies.

The financial subsystem includes routines concerning revenue generation, budget allocation, and the estimation routines for socio-economic factors with various budgeting options. The highway system can be categorized as Interstate Highways, Primary Highways, Secondary Highways, and Urban Highways. Each of these highways is planned, operated, and maintained by different procedures and standards, and might have different maintenance and construction costs. The administration subsystem helps the HMS produce simulation results for these different kinds of highway system.

The HMS model is developed with a concentration on physical, evaluation, functional, and financial subsystems. Extension of the model through an administration subsystem is discussed and suggested. Simulations are done for the scenarios of ex-

pansion of the Salem section of the Interstate Highway I-81, with various financial options.

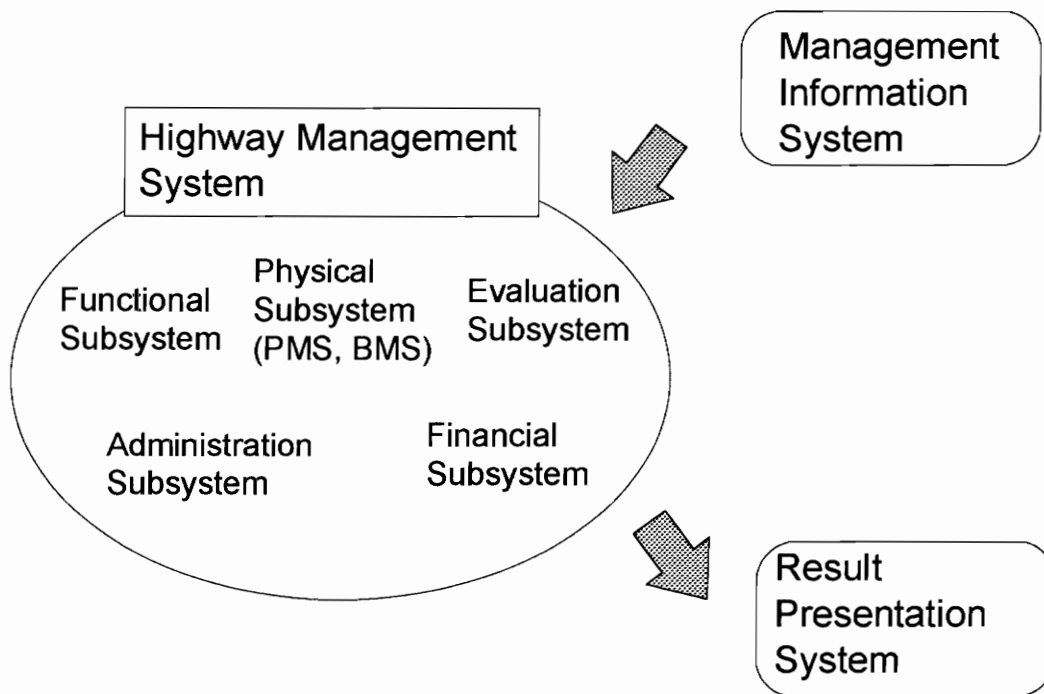


Figure I-1 Highway Management Decision Support System (HMDSS)

A Management Information System (MIS), a Result Presentation System (RPS) and HMS construct the Highway Management Decision Support System (HMDSS). Figure I-1 illustrates the Highway Management Decision Support System (HMDSS) architecture. The MIS on line can be used to systematically and continuously update parameter values. The RPS is used to display the simulation of the results from the HMS. The parallel independent research for MIS and RPS has been done for the VDOT research contract. Further detail descriptions about MIS and RPS are documented in VDOT (1996).

### ***I-5. Contribution to the Body of Knowledge***

The highway management activities, including planning, construction, and maintenance for highways and bridges are funded from the budget-pool from the state DOT budget allocation practice. There exist different levels for budget allocation decisions, which might be on the federal, state, and district level. Each of these decisions affects and constrains the next level budgeting decision and management activities. The deterioration process and improvement actions take place simultaneously with this decision-making process. A highway management system, therefore, should have a systematic and dynamic structure to accommodate the entire process. The systems approach is useful for modeling this kind of systematic and dynamic decision-making process.

Quantification of the impact of deferred maintenance due to the reduction of the investments for the highway system will be facilitated by a comprehensive decision support system for highway management. Many PMS and BMS have been developed separately, and little attention has been paid to a comprehensive management system. Furthermore, existing systems are dealing with the project level and the network level, which are not connected to a higher level decision-making process.

Current highway management can be portrayed as "maintaining highways by looking through a small windowpane." Field engineers' interests are a narrow perspective of highway management and do not include the whole picture of the highway infrastructure under consideration. Managers and engineers have some communication problems. This may be due to bottlenecks or sometimes disconnection of the information flow. A 'Planning-Level' management model is needed to link information

flow between the manager level and the engineer level and to support highway management with more macroscopic perspectives.

This research may be the first attempt to develop a comprehensive, planning-level decision-support, systems model for highway management, integrating PMS and BMS and concentrating on traffic engineering, and transportation planning factors. The HMS model is the system dynamics model equipped with capabilities for analyzing and solving the meta-problems related to highway infrastructure management.

## **II Transportation Infrastructure Management**

### ***II-1 Overview of Transportation Infrastructure***

Infrastructure is defined as "the basic facilities and installations that serve social purposes of health, safety, economics, employment, and recreation" (Rainer 1990; Chasey, 1995). Transportation infrastructure is a critical part of infrastructure, which includes facilities related to the movement of freight and people, such as roadways, mass transit facilities, railroads, airports, seaports, waterways, etc. The deterioration of infrastructure can negatively affect economic activities and quality of life. Restricted accessibility hinders efficient mobility, and thus the transfer of people, and the movement of industrial products, while a well-maintained transportation system helps to attain an efficient distribution of population and industrial activities (Queiroz et. al., 1994).

It is possible to derive proper strategies for solving transportation infrastructure problems caused by deferred maintenance, given an understanding of the current status of the infrastructure. In Section II-2, the status of the transportation infrastructure of the United States, and the possible reasons for the deterioration of the infrastructure, is discussed. Economic productivity of the transportation infrastructure is also illustrated in Section II-3.

### ***II-2 The Status of the Transportation Infrastructure of the United States***

A recently released surface transportation condition and performance study, done by the U.S. Department of Transportation, claims that in 20 years, given the current

funding situation, the portion of “poor” highway pavement will increase to 50% from 15% in 1993, and 40% of the nation's bridges will be rated as "deficient", up from 28% in 1994 (Drew, et al. 1996; ENR, 1995). Almost half of 0.6 million highway bridges in the United States were built before 1940, and are functionally out-of-date or structurally deteriorated. Due to deferred maintenance and deteriorated service conditions, the bridges that were built later also do not provide efficient service, and are in need of rehabilitation and replacement. (Hudson et. al., 1987). Simply to maintain current highway conditions and performance, the FHWA estimates that over 100,000 miles of highway, and 11,000 bridges, require some degree of capital investment. (BTS, 1995)

Obviously, a lack of funding can be the major reason for deferred maintenance and deterioration of transportation facilities. Furthermore, operation of funds under budget constraints can also affect situations in transportation infrastructure management. In other words, infrastructure conditions could have been better had there been well planned and properly directed management of the transportation infrastructure.

Institutional, and political constraints can also be contributors to the degradation of transportation infrastructure. Barker (1984) stated that some federal funding policies to aid state and local transportation policies encourage deferring actions by state and local officials. 75% to 90% of new construction of bridges and highways can be paid by Federal grants (Barker, 1984). Consequently, state and local officials are tempted to promote new construction in order to obtain more federal funding, instead of maintaining existing deteriorated infrastructure. Some political factors influence situations concerning transportation infrastructure. Elected officials tend to pay attention to those policies having greater political returns, such as salary increases for

teachers, or additional police manpower, rather than the unnoticeable effects of the maintenance of infrastructure (Vaughn et. al., 1984; Chasey, 1995). Existing infrastructure problems are neglected, and new infrastructure problems are added. Hence, greatly increased funding will be needed to retain serviceable conditions of infrastructures.

### ***II-3 Economic Productivity of the Transportation Infrastructure***

It is obvious that better industrial productivity can be obtained by having a more efficient transportation infrastructure. It is not surprising that developed countries such as the United States, Canada, and Australia have announced stimulus packages with significant components related to reconstruction and repair of their road networks in order to revitalize their economies (Queiroz et. al., 1994). Several research projects concerning the productivity of infrastructure have been done since early 1980. The initial research was done by Ratner (1983), who found an output elasticity of non-military public capital using aggregate national data from 1949 to 1973 (BTS, 1995). After that, research by Costa, Ellison, and Martin (Costa, Ellison, and Martin, 1987), and by Aschauer (Aschauer, 1989) shows how public fixed capital favorably affects industrial production. Although the connections between productivity and investment in infrastructure are not necessarily obvious, living standards, health, and safety of society are partially dependent on mobility, and consequently, on the condition of transportation infrastructure (McNeil et. al., 1992)

More conclusive empirical research has been done recently by Queiroz et. al. (1994). They established regression models to investigate the relationship between the Gross National Product and roadway infrastructure. Three models were built with

data sets from different countries. They established a cross-sectional model with data sets from 98 developed and undeveloped countries. For the United States and Canada, time series regression models were built. Figure II-1 illustrates a comparison between those three models.

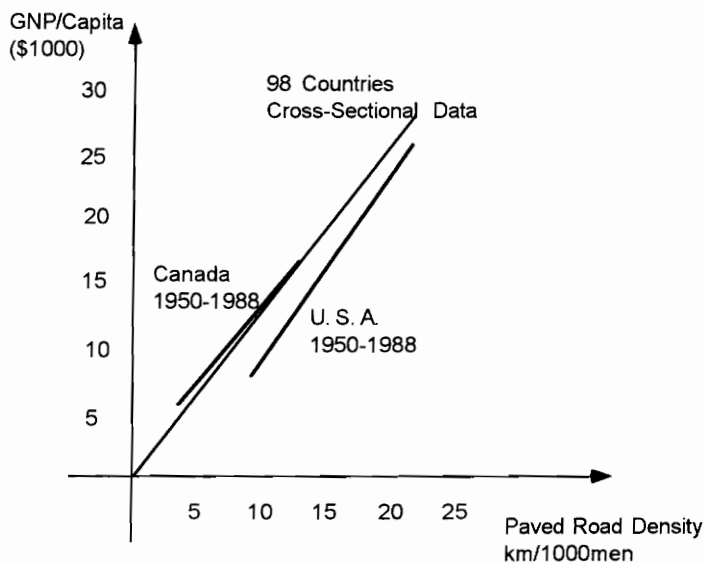


Figure II-1 Comparison of Efficiency of Roadway Infrastructure (Reproduction of Figure in Queiroz et. al., 1994)

Assuming that roadway infrastructure affects industrial production, the gradients of the lines in Figure II-1 might imply the marginal productivity of roadway infrastructure. As shown in the Figure, the efficiency of Canada's roadway infrastructure is similar to that of 98 countries, and there is some offset in its relationship to that of the United States. In other words, for any given GNP per capita value for the U.S., there is a 13% greater roadway infrastructure than the world average (Queiroz et. al., 1994). However, the direction of casualty is not clear in this relationship, because one might claim that the growing GNP can also stimulate investment in infrastructure.



Nevertheless, one may conclude with the consensus that roads themselves 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 (Queiroz et. al., 1994).

#### ***II-4 Review of Transportation Infrastructure Management***

There have been various computer-based tools developed for transportation facilities management during last two decades. The development of the Pavement Management System (PMS) has been dominant in this area. Many state and local agencies developed their own pavement management systems (PMS), and are supported by many research studies. Major concerns for the PMS have been decisions regarding timely and suitable Maintenance, Replacement, and Rehabilitation (MRR), and the priorities among various projects.

Although transportation infrastructure management systems dealing with bridges and pavement have been developed separately, there also have been several efforts to integrate BMS and PMS. Application of new technologies to transportation infrastructure management systems, such as Expert Systems, Decision Support Systems, and Geographical Information Systems, is another noticeable research trend in the infrastructure management area. However, some research points out that more discussion is required in order to apply already available technology, such as the Geographic Information System (GIS), because of some difficulties in the cost-effectiveness of its applications (O'Neil et. al. 1993, Chen, et. al. 1993)

McNeil et. al. (1992) viewed transportation infrastructure management as monitoring, maintenance, and repair of facilities on a regular basis to assure the efficient use of existing and future resources. They claimed that decisions should consider condi-

tion and traffic criteria, budget constraints, and other tangible and intangible factors which affect the decision-making process. This process is also claimed to be systematic and scientific, rather than empirical or intuitive in evaluating the MRR programs properly. Karaa (1989) suggested five major components of the decision-making process for transportation infrastructure management: (1) Data collection and monitoring; (2) impacts modeling and application of impacts models; (3) strategy selection; (4) strategy implementation; and (5) objective specification and re-evaluation.

McNeil et. al., (1992) categorized models included in the transportation infrastructure management process as deterioration models, benefit estimation routines, and optimization models. They grouped deterioration models as empirical or mechanistic, aggregate or desegregate, network-level or project-level. Deterioration models include regression models, Markov models, survivor curves, latent variables models, two-phases models, and mechanistic models (McNeil et. al., 1992). Schwartz (1993) also suggested the usefulness of neural network applications in infrastructure deterioration models. The states of the art of PMS and BMS, and integrated systems are discussed in detail in the following sections.

### ***II-5 The State of The Art of The Pavement Management System (PMS)***

In 1989, FHWA set a policy requiring that each state highway agency have a PMS by 1993 (Irrgang et al, 1993). Each state PMS should follow the concept of PMS in AASHTO's "Guidelines on Pavement Management" described as "a systematic approach to providing highway administrators and engineers with the types of information needed to effectively and efficiently manage their highway pavements" (Irrgang, et al, 1993). Haas, et. al, (1978) also pointed out that a PMS includes a

comprehensive, coordinated set of activities associated with the planning, design, construction maintenance, evaluation, and research of pavements.

Many research projects 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 and methodologies. The Advisory Circular from U.S. DOT (U.S. DOT, 1988) clearly defined PMS with an outline of how it can be used in making cost-effective decisions regarding pavement maintenance and rehabilitation. In this circular, the objective of PMS is described as follows: "A PMS provides consistent objectives and systematic procedures for setting priorities and schedules, allocating resources, and budgeting for pavement maintenance and rehabilitation. It can also 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." (U.S. DOT, 1988). For these objectives, PMS evaluates the current pavement condition, predicts its future condition, and provides cost-effective solutions for various management levels. PMS includes data inventory or a management information system, as historic data on the pavement is crucial for prediction of pavement condition.

PMS can be divided into two categories, network-level PMS, and project-level PMS, according to their management level. Network-level PMS concentrates on decisions dealing with groupings of projects throughout the entire network. Cook et. al. (1987) divided the network-level PMS into program planning and financial planning. The former concentrates on determining which projects should be carried out, when they should be done, and what treatment should be used (Cook et. al., 1987). Finan-

cial planning generally is concerned with decisions on the level of funding needed to achieve the desired level of the physical condition of the highway (Cook et. al., 1987).

Project-level PMS handles individual projects. Decisions here are made according to the cost-effectiveness of the individual project. Gaspar claimed that the network-level PMS usually has to be done prior to the project-level PMS, for several reasons. First, financial decisions at the regional or local levels precede decisions about optimal ranking of individual projects. Second, network-level PMS is less confined by the deficiencies and limited reliabilities of historic data sets than is project-level PMS. Third, network-level PMS is easier for an agency to initiate, because many methodologies are already available (Gaspar, 1994).

Network-level PMS has been evolving along with the advancement of new technologies in computer science and mathematical modeling (Wang et. al. 1994). The methodologies primarily used for network-level PMS are the prioritization of projects and network-level optimization (Irrgang, et al, 1993). In the project prioritization method, the individual projects are evaluated and ranked by a certain overall pavement index or score, and then pavement maintenance resources are allocated according to this priority. Factors used for prioritization of projects are pavement distress, pavement roughness, traffic, economic factors (Life-Cycle Cost), functional class, accidents, skid resistance, geometric deficiencies, structural capacity, engineering judgment, age, strategic location, etc. (Irrgang, et al, 1993). Fwa et. al. (1993) also proposed the neural networks method for project priority rating.

A network-level optimization model identifies the network MRR strategies that maximize the total network benefit (or performance), or minimize costs subject to

budget constraints and desired performance standards (Irrgang, et al, 1993). Mathematical programs used for network-level optimization include linear programming, integer programming, dynamic programming, optimal control theory, nonlinear programming, incremental benefit/cost, and marginal cost-effectiveness (Irrgang, et al, 1993, Fwa et. al., 1994).

PAVER, developed by the U.S. Army Construction Engineering Research Laboratory, is a PMS designed for use in military installations, cities, and counties (Shahin et. al. 1982). PAVER, developed and tested since the 1970's, provides the engineer with various capabilities for practical decision-making, as in the following: data storage and retrieval, definition of the pavement networks, pavement condition rating, project prioritization, inspection scheduling, determination of present and future network condition, determination of MRR needs, performance of economic analysis, and budget planning (Shahin et. al. 1982).

Gaspar (1994) used the Markovian process and linear programming technique for developing the first Hungarian network-level PMS. He obtained the necessary funding to retain a certain level of serviceability through trial and error runs. A cost-minimizing routine was used for optimization of fund distribution between pavement type, condition variants, and amount of traffic (Gaspar, 1994).

Chua et. al. (1993) proposed a dynamic decision model combined with a mechanistic pavement performance model. They applied a cost minimization objective function for the proposed dynamic programming model (Chua et. al., 1993). They also formulated a mechanistic pavement performance model within a stochastic

framework, so that the assumption of time-invariant transition probabilities in the Markovian model is not necessarily needed in their model (Chua et. al., 1993).

Wisconsin DOT's (WisDOT) GIS-based comprehensive PMS consists of a data inventory system and a decision support system (De Cabooter et. al., 1994). The objectives of WisDOT PMS are as follows: 1) to provide an analytical tool for evaluating the impacts of treatment strategies, 2) to support upper level decisions about pavement management strategies, 3) to assist in acquisition of basic pavement condition and cross-sectional data, 4) to assist staffs in developing pavement performance models, and, 5) to assist DOT engineers in developing treatment strategies based on field pavement performance.

Hall et. al. (1994) found rehabilitation needs in the Illinois interstate highway system by using the ILLINET program. ILLINET has data connection with the Illinois Pavement Feedback System (IPFS), performance prediction models, and various project-level and network-level management routines used to generate feasible rehabilitation strategies (Hall et. al., 1994).

MDOT PMS is a PMS for Mississippi DOT with the following subsystems: 1) a pavement system inventory and monitoring database, 2) a condition data analysis/interface program, 3) a maintenance planning and budgeting (MPB) program, and 4) a priority ranking and an annual work program (George et. al. 1994). The MPB program is effective for selection of alternative strategies and calculation of agency costs and vehicle operating costs. MDOT PMS is good example of a project-level PMS.

The Delaware Department of Transportation PMS is well documented in Smith, et. al. (1993). DelDOT PMS features: unique and unambiguous milepost referencing, dynamic segmentation, a decision-tree process for prioritizing capital improvement and rehabilitation projects for annual programs, interim pavement performance models based on currently available data, multi-year planning capabilities to forecast conditions and needs, and color graphics and mapping capabilities to illustrate current pavement conditions and projected conditions for various program scenarios (Smith, et. al., 1993).

The Arizona Network Optimization System (AZNOS) is a pavement network optimization system for Arizona DOT, which is capable of extensive sensitive analysis, testing and steady state run, and includes a cost-minimization linear programming routine (Wang et. al., 1994). AZNOS, updated from NOS (Network Optimization system), which has been applied to Alaska DOT, Kansas DOT, Finland, and Saudi Arabia, uses the Markov chain to predict pavement transition (Wang et. al., 1994).

Khedr et. al. (1994) established priority factors, including not only road conditions, but also socio-economic and transportation planning factors such as population distribution, regional development, economic development, traffic growth, and tourism attraction. Khedr's approach to PMS seems theoretically solid, because its factors are strongly connected and affect each other. The inclusion of UTPP (Urban Transportation Planning Process) can also be considered for a comprehensive transportation infrastructure management system.

Fwa et. al. (1994) applied Genetic Algorithm (GA) for pavement management optimization. GA is similar to integer programming in that it has objective functions and

constraints. However, GA works with a coding of parameters instead of the parameter itself. First of all, the initial parent-pool of solutions is randomly generated, and then GA finds its optimal solution through repeated GA operations: 1) generation of offspring, 2) formation of a new parent-pool, and 3) performance evaluation and convergence assessment of the parent-pool solutions (Fwa et. al., 1994). Better results, with a better objective function value and faster convergence, could be obtained with GA than with integer programming (Fwa et. al., 1994).

Another example of PMS for small communities can be found in Tavakoli et. al. (1992). Their Pavement Management System for Small Communities (PMSC) consists of seven modules: 1) inventory, 2) distress survey, 3) maintenance / rehabilitation, 4) unit cost, 5) deterioration rates, 6) priority ratings and goals, and 7) backups (Tavakoli et. al., 1992). PMSC provides maintenance rehabilitation strategies based on the surveyed Pavement Condition Index (PCI), and a priority rating based on the PCI, the traffic factor, the functional classification factor, the transit or bus route factor, and the maintenance rating factor (Tavakoli et. al., 1992).

An interesting categorization of PMS methods was done by Novak et. al. (1993). They pointed out that two categories of PMS analysis methods exist: reactive, and generative (Novak, et. al., 1993). Reactive methods refer to an event-centered analysis that is proper for project-level pavement management analysis (Novak, et. al., 1993). Generative methods are systematic and structured approaches that make network-level management analysis possible, e.g. long-term funding analysis, network condition evaluation, program evaluation, and etc. (Novak, et. al., 1993).



Abkowitz et. al. (1990) discussed the advantage of "GIS-T" (GIS implemented for the transportation field) for highway management, including pavement management, traffic engineering, transportation planning, and bridge maintenance. The most noticeable merit of PMS based on GIS-T is its capability to convey information about geographical location along with data about physical condition (Abkowitz, et. al., 1990). This kind of capability will aid in the understanding of the geographical distribution of investments. A PMS based on GIS-T would allow for a more equitable distribution of funds and a more visual medium for policy decision-making (Abkowitz, et. al., 1990).

Chen et. al. (1993) proposed a graphic-based PMS for small sized and medium sized cities, rather than using available GIS software. They claimed that stand-alone graphic-based PMS had advantages over the utilization of GIS software because of the following reasons: 1) high cost, time, and effort in implementing GIS for pavement management, 2) applicability may be restricted because GIS is not stand-alone software, 3) GIS-based systems are difficult to implement in other agencies without major modification, and this modification often turns out not to be cost-effective (Chen, et. al. 1993a). Their PMS includes both project-level (Chen et. al. 1994) and network-level models (Chen et. al. 1993b).

Grivas et. al. (1993a) developed a computerized PMS of the New York State Thruway Authority, by integrating individual programs into a prototype window-based system, WinPMS. WinPMS features a graphical user-interface which provides a logical, consistent command structure that flows seamlessly between programs, and allows further development of other components of PMS models (Grivas et. al.

1993a). Their optimization model in the network-level PMS is well documented in Grivas et al. (1993b).

### ***II-6 The State of The Art of The Bridge Management System (BMS)***

The history of the development of BMS is comparatively shorter than that of PMS. A BMS has similar functions to a PMS, which includes a deterioration model, a prioritization model, an optimization model, etc. Hudson et. al. (1987) defined BMS as "a rational and systematic approach to organizing and carrying out all the activities related to providing programs for bridges vital to the transportation infrastructure". They suggested that BMS should include data inventory for bridges, prioritization functions, and network-level policy solution functions (Hudson et. al., 1987). The activities concerning bridge management that should be considered in BMS, can be summarized as: 1) predicting bridge needs, 2) defining bridge conditions, 3) allocating funds for construction, replacement, rehabilitation, and maintenance actions, 4) identifying and prioritizing bridges for MRR actions, 5) identifying bridges for posting, 6) discovering cost effective alternatives for each bridge, 7) recommending MRR actions, 8) the accounting of MRR actions involving the scheduling and performance of minor maintenance, 9) monitoring and rating bridges, 10) maintaining an appropriate database of information (Hudson et. al., 1987).

Wells et. al. (1993) described the use of a bridge management system as a means of prioritizing and optimizing tools used to identify and schedule the most critical needs of bridge management. Hudson et. al. (1987) summarized the objectives of the network-level BMS as follows:

- a) engineering methods to assess present and future needs of existing bridges

- b) guidelines for determining cost-effective alternatives both with and without financial constraints.
- c) priority treatment of needs through the use of generalized work activities
- d) flexibility in accommodating a variety of policy approaches
- e) flexibility in accommodating future expansions at the project-level
- f) methods for ascertaining standards of data reliability.

They also listed the necessary components of BMS, as follows (Hudson et. al., 1987): a) BMS should contain the assessment procedures of the costs incurred by gradual functional deterioration and functional obsolescence and costs, and the benefits of routine maintenance, interim repairs, partial rehabilitation, and/or major reconstruction for each structure. b) The BMS also should have the ability to evaluate alternatives with different funding levels, different spending policies, different project options, different timing alternatives, and different scenarios incurring different consequences.

There are many problems that restrict the development of a BMS, and the development process should include suggestions or solutions for these problems, described as follows (Hudson et. al., 1987):

- a) data deficiencies related to effective bridge maintenance management
- b) inadequate bridge maintenance data (Insufficient code for bridge activities; Cost breakdowns are not available; Data are lumped, and can not be reported for individual bridges; Performance standards and unit cost data for various bridge maintenance activities are generally not available)
- c) lack of cost-effective data and Life-Cycle Cost analyses
- d) lack of prioritization methods

e) unanswered Network-Level policy questions

The intermodal Surface Transportation Efficiency Act (ISTEA) of 1991 mandates implementation of BMS for all states by 1997. The Federal Highway Administration (FHWA) responded to this legislation in advance, with the commission of a BMS called PONTIS (Latin for bridge) (Wells et. al., 1993). PONTIS is comprehensive network-level bridge management system capable of managing all of the activities related to the bridge network (Wells et. al., 1993). PONTIS was designed to generate bridge optimization and priority scheduling from inspection and inventory data. It uses minimizing Life-Cycle Costing for identifying economically efficient actions. Although, there are several objections to Life-Cycle Costing because of its inaccuracy, PONTIS has tried to solve this problem by combining expert opinion and providing a data manager (Wells et. al., 1993). Deterioration prediction is done by the Markov process using four different environmental classes. Benefit/cost analysis is used for the prioritization of projects (Wells et. al., 1993).

The Indiana Bridge Management System (IBMS), by the Indiana Department of Transportation (INDOT) is well documented in Gion et. al. (1993). IBMS includes a decision tree program, an economic analysis program, a project-ranking program, and an optimization program. For the successful implementation of IBMS, some suggestions were made (Gion et. al., 1993). First, a close working relationship is needed between the development team and the implementing agencies. Second, it must be ensured that the package can be learned quickly, and can be easily adapted to the needs of agencies. Third, the models and database must be updated periodically to improve the accuracy of the IBMS.

Hudson et. al. (1993) developed a computerized BMS executable in micro-computer, in order to meet the needs of small to medium-sized states and large counties and cities. This software includes a database module, a level of service module, a maintenance module, a system upkeep module, and a help module (Hudson et. al., 1993). This BMS analyzes and organizes bridge inventory, inspection, and appraisal data to assist decision-making in bridge management based on benefit maximization criteria (Hudson et. al., 1993).

Cesare et. al. (1993) proposed a bridge management model using the reliability method and optimization procedures. The overall system reliability of the bridge was calculated by combining the individual reliability of the components in a series system. An optimization model was formulated in order to obtain the risk minimization solution (Cesare et. al., 1993). The optimal set of repairs is defined as that which minimizes the total network risk in the planning horizon (Cesare et. al., 1993).

Sobanjo (1993) summarized deterioration models for highway bridges as statistical regression-based models, stochastic deterioration models, and models based on the concept of the Markov Process. He pointed out that the stochastic models and high-order Markovian models are more realistic alternatives (Sobanjo, 1993). Abkowitz et. al. (1990) pointed out the advantage of GIS-T applications to bridge maintenance. Because the functions in BMS are similar to those of PMS, the same merits of PMS can be obtained from the adaptation of the GIS-T (Abkowitz, et. al., 1990). The most noticeable merit would be in the preparation of bridge maps, and automatic updates of the geographical data, which currently are performed manually (Abkowitz, et. al., 1990).

## ***II-7 Integrating PMS and BMS***

Little has been done to provide state-level, comprehensive transportation infrastructure management systems capable of covering all the management decision processes and activities of an agency, although some research projects have tried to integrate their PMS and BMS. The Infrastructure Management System (IMS) of the Finnish National Road Administration (FINRA) attempted to integrate a pavement management system and a bridge management system (Männistö et. al. 1994). FINRA IMS integrated existing Highway Investment Programming (HIPS), which is the Finnish network-level PMS, and the Finnish Bridge Management System (Männistö et. al. 1994). FINRA IMS uses the Markov model to predict the physical status of bridges and pavement, and benefit/cost procedures for the selection of cost-effective alternatives. The objectives of FINRA IMS are to decide and support: 1) optimal levels of expenditures on rehabilitation, 2) optimal allocations of funding among sub-networks, 3) cost-effectiveness means, 4) the proper scale of budgets, and 5) the importance to society of user-costs, relative to agency costs (Männistö et. al. 1994). The FINRA model seems to be a collection of separate models, but does not have a completely integrated structure, in that analysis is done separately, using each independent model within the system.

Harper et. al. (1993) have tried to design an integrated optimization model that deals with pavement and bridges. They used fuzzy set theory to categorize the physical level of bridges and pavement, and to express the uncertainty and the continuity of the physical level (Harper et. al. 1993). They ran optimization models for benefit maximization and cost minimization to obtain the optimum proportion of units in each physical level (Harper et. al. 1993).

Ravirala et. al. (1995) integrated bridge and pavement programs using the Goal-Programming methodology. Goal-Programming involves the following five steps (Ravirala, et. al., 1995): 1) Identification of multiple objectives, 2) Development of policies which can establish specific goals for each objective, 3) Assessment of penalty weights based on fulfillment of each goal, 4) Construction of a mathematical model for abstracting the annual program development process, 5) Formulation of a goal program for constrained optimization. The Goal-Programming methodology has the advantage of capturing economies of scale and scope, and determines an optimal program that best achieves its goals (Ravirala, et. al., 1995).

The city of Cornwell, Ontario, Canada, developed a GIS-based IMS with graphical mapping capability (Lee and Deighton, 1995). Although this IMS doesn't have the capability to examine trade-offs between expenditures on, for instance, solid waste vs. pavement rehabilitation, the model leads to an intelligent pavement program that considers other infrastructure components (Lee and Deighton, 1995). Another hi-tech display approach for infrastructure management is the hyper-media based infrastructure management system, which can enhance already available GIS technology (Aley et. al., 1993).

### ***II-8 Research Directions in Transportation Infrastructure Management System***

Most research in transportation infrastructure management has been done within the boundary of highway systems-- pavement and bridges. Figure II-2 summarizes the current research trends of each of the components of the Transportation Infrastructure Management System (TIMS) and suggests new directions in the develop-

ment of the system, for each of the interacting three bases - the model base, the data base, and the display base.

Most of the research at the model base level concentrates on the development of separate PMS and BMS at the project-level and the network-level. Project-level models concentrate on the individual project, and are concerned with the timing of treatment, and the type of treatment that should be applied. Network-level models mainly concentrate on the prioritization or ranking of projects throughout the network, and optimization of resource allocations among projects or different classes of pavement sections.

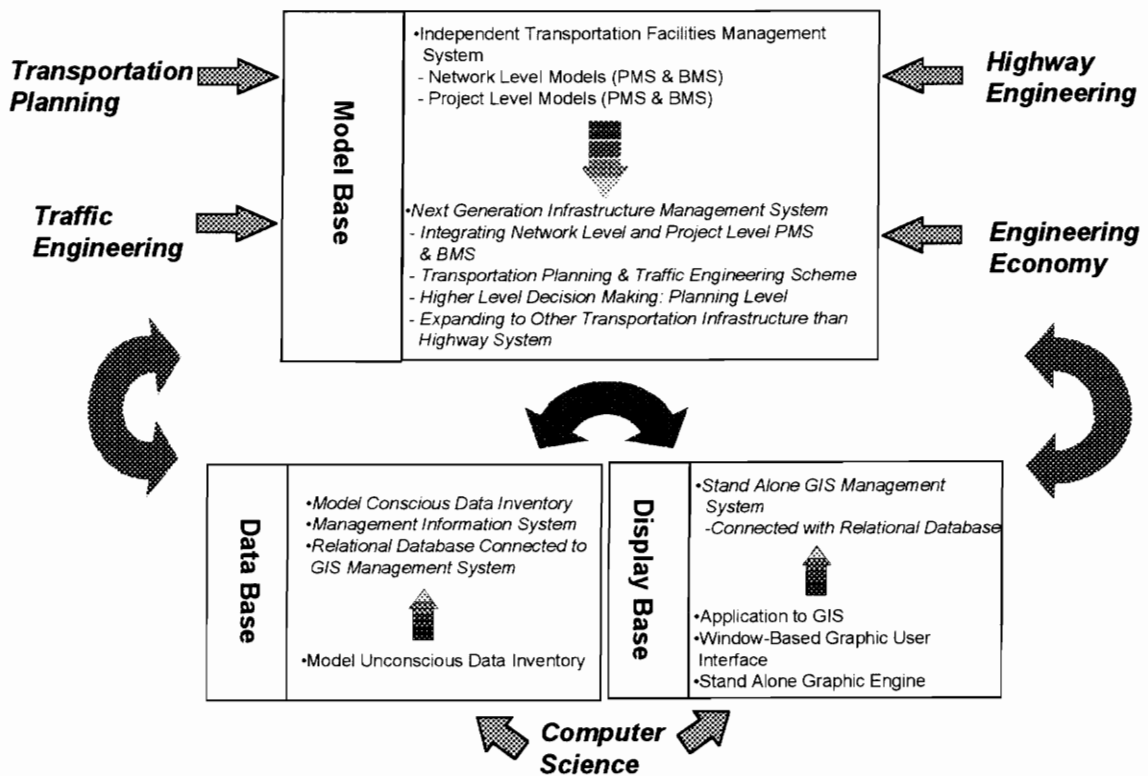


Figure II-2 Development of the Transportation Infrastructure Management System



Markow (1993) has made an interesting suggestion for a new generation model for transportation infrastructure management. He suggested a new concept for an integrated maintenance management system featuring a higher level of integration among maintenance functions, and between maintenance systems and other systems, than those presently existing (Markow, 1993). His concept about the next generation of management system includes the capabilities of various new modes of analysis, including tradeoffs between maintenance options, and optimal resource allocation (Markow, 1993). The integration of infrastructure management components will also make it easier to accomplish the various sensitivity analyses between different infrastructure components.

Research emphases on transportation infrastructure management systems concentrate primarily on highway engineering, such as deterioration modeling, and on engineering economy, such as Life-Cycle Cost analysis. More consideration about transportation planning and traffic engineering aspects, such as travel demand, level of service, etc., is needed in transportation infrastructure management systems. This change will make it easier to connect current decision-making levels in the PMS or BMS model to higher decision-making levels related to highway planning and traffic management.

Another important enhancement in the model-base may be a representation of the higher level decision-making process. Most of the PMS and the BMS mainly deal with decisions on a project, or a group of projects, or optimized resource allocations among sections or classes of pavement or bridges. There are many different levels of decision-making for state highway agencies, e.g. decisions on allocation between construction and maintenance, between bridges and pavement, or decisions on in-

crease of maintenance budgets owing to the new construction of highways, etc.. The Highway Management System (HMS) developed in this research includes higher level decision-making processes than those of network-level and project-level models, such as investment plan evaluation, policy evaluation, etc.. Therefore, this HMS would be called the "Planning Level Highway Management System", which focuses on policy and strategy level highway management analysis. With this planning level management model, the information flow structure from field data to policy and planning can be completed. Information flow structure in highway management is depicted in Figure II-3.

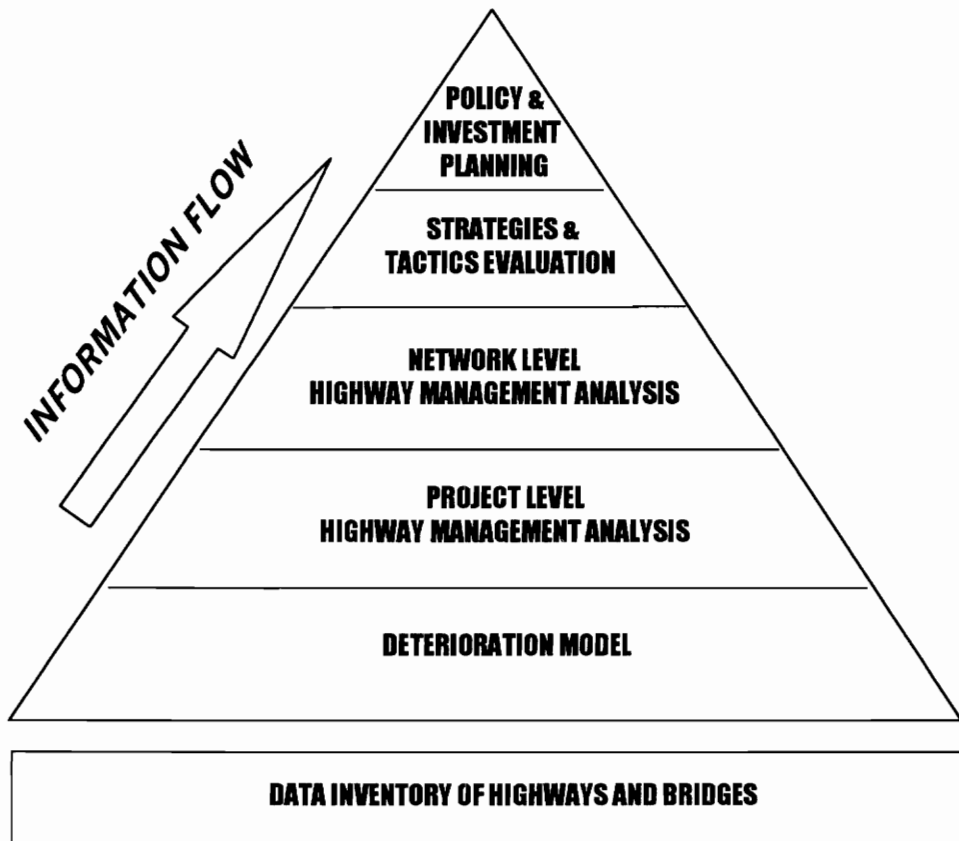


Figure II-3 Information Flow Structure in the Highway Management Decision Process (created based on Navak et. al., 1993)

A single objective function is not sufficient to accommodate these multiple layers of decisions. A systematic modeling methodology which can handle multiple level decisions is desirable for the next generation of transportation infrastructure management models. Multiple-level decisions also dynamically affect highway management. Evaluation models or optimization models, which provide a snap-shot of the results of the decision-making process cannot depict these dynamic and multiple decision processes.

The data inventory must be redesigned, based on the requirements of the new model. The existing transportation data inventory was established before the model requirements. It is not surprising that the constraint on modeling transportation infrastructure management is sometimes the unavailability of the required data and the irrelevance of existing data. The modeling process should precede database building.

The database also should be built using state of the art computer science database technologies. The database structure ought to be designed based on consideration of GIS application. Properly collected data concerning transportation infrastructure management represents the experience and knowledge of agencies. Therefore, the database itself can also be a tool for decision-making. The Management Information System can be a tool for this kind of use, and also for the convenience of data updating for the model base.

The management system should be easy for local or state personnel to learn, and if possible, easy for them to understand. The user-friendly interface and well prepared help-system in the software, facilitates implementation of the management system. GIS or stand-alone software developed for transportation infrastructure management

systems using the state of the art computer science mapping technologies will help display the results and data management.

### **III Highway Infrastructure Performance Evaluation**

Measurement of performance is critical to infrastructure management systems, because it aids in the classification of highway infrastructure status and the presentation of the service level. The term "highway" used in this research refers to roadways, including not only Interstate and Urban highway systems, but also primary and secondary systems. Highway Infrastructure performance can be evaluated by using three criteria: 1) physical performance, 2) traffic performance, and 3) economic performance.

Physical performance is measured for each of the highway infrastructure components, i.e. pavements, and bridges. Traffic performance is measured in the context of the measurement of congestion, using the Level of Service concept. Economic performance cannot be measured as a snapshot of the service level. This measurement should be done over a considerable amount of time, because the economic impacts of a system cannot be realized immediately. In this chapter, user and non-user benefits, and benefit/cost ratios of highway infrastructure systems are discussed concerning the economic performance of highway infrastructure. Highway user satisfaction seems to be a somewhat subjective measurement; nevertheless it also can be an important measurement of highway service. Consumer satisfaction survey results on highway management service is discussed in this chapter.

#### ***III-1 Pavement Performance Evaluation***

There are several different pavement condition indexes that indicate the physical status of a pavement. The Virginia Department of Transportation (VDOT) is currently changing the measurement unit used for data inventory, from the old Present

Serviceability Index (PSI) to the Pavement Condition Index (PCI). This PCI index is used for the physical classification of highways in the PMS of the Highway Management System, which is discussed in Chapter VI. PCI was initially used in order to record vital airport pavement performance data, and is well documented in the Federal Aviation Authority (FAA)'s Advisory Circular, "Guidelines and Procedures for Maintenance of Airport Pavements" (U.S. DOT, 1982).

Although all the procedures of the PCI calculation in the Advisory Circular concentrate on airport pavement, these procedures can also be applied to PCI calculations of highway systems. The steps for performing the condition survey and determining the PCI of airport pavement are described below (U.S. DOT, 1982);

1. Mark off the pavement in 100-ft increments. This marking should be done semi-permanently in order to obtain sure and proper positioning for the condition survey. First, the overall pavement should be divided into features based on pavement design, construction history, and traffic data. By this division, the homogeneous features of the pavement, which have consistent structural thickness and materials, and the same opening date, can be obtained. After dividing the features of the pavement, a preliminary survey, which requires a brief yet complete visual survey of pavement, will follow. The feature can be subdivided based on degrees of distress.
2. Divide the pavement feature into sample units. A sample unit for jointed rigid pavement is approximately 20 slabs; a sample unit for flexible pavement is an area of about 5,000 sq.-ft.

3. Inspect sample units, and record distress types, their severity levels, and densities. The surveying of distress types and severity levels should be done based on certain criteria for accurate PCI.
4. A deduct-value for each distress type, severity level, and density in the sample unit is determined from the appropriate charts provided in the FAA's Advisory Circular.
5. The total deduct value (TDV) is determined by a summation of all deduct values for each distress condition inspected.
6. A corrected deduct value (CDV) is determined using the procedures for each pavement type.
7. PCI is calculated using the following formula:

$$PCI = 100 - CDV \text{ -----(Eq III-1)}$$

If the CDV of a sample unit is less than the highest individual deduct value, the highest value should be used instead of CDV in the above formula.

8. The PCI of the entire feature can be obtained by calculating the average of the PCI's from all sample units inspected.

Although inspection of an entire feature is desirable, the entire inspection may require tremendous effort and time, especially if the flexible pavement contains much distress. Therefore, FAA guidelines suggest a statistical sampling scheme for PCI estimation, and this optional sampling plan may considerably reduce the costs of inspection (U.S. DOT, 1982).

The minimum number of sample units ( $n$ ) that should be surveyed, can be obtained using the chart which the FAA provided (U.S. DOT, 1982). The spacing interval of units to be sampled ( $i$ ) is then expressed as:

$$i = \frac{N}{\eta} \text{-----(Eq III-2)}$$

where N = total number of sample units in the featured group

By this sampling scheme, the mean PCI of the pavement feature is expressed as:

$$PCI_f = \frac{(N - A)}{N} \overline{PCI}_1 + \frac{A}{N} \overline{PCI}_2 \text{-----(Eq III-3)}$$

where  $PCI_f$  = mean PCI of feature

A = number of additional sample units

$\overline{PCI}_1$  = mean PCI for  $\eta$  number of statistically selected units

$\overline{PCI}_2$  = mean PCI for all additional sample units

VDOT has constructed a new pavement data inventory using the PCI unit through videolog inspection. Table II-1 shows an example of a pavement distress matrix of bituminous concrete for the calculation of PCI. In Table II-1, five types of distress, the multiplier, and deduction values, based on densities and severities of distress, were defined. Pavement inspection is done by VDOT's inspectors, with monitoring of pavement surfaces recorded in videotapes.

Table III-1 Pavement Distress Matrix- Deduct Points for Bituminous Concrete

Distress Type (Multiplier)	Videolog Condition Rating Scores								
	0-10% Low Severity	0-10% Med Severity	0-10% High Severity	10-40% Low Severity	10-40% Med Severity	10-40% High Severity	< 40% Low Severity	< 40% Med Severity	< 40% High Severity
Alligator Cracking (3)	3.0	6.0	9.0	6.0	12.0	18.0	9.0	18.0	27.0



Longitudinal & Transverse Cracking (1)	1.0	2.0	3.0	2.0	4.0	6.0	3.0	6.0	9.0
Rutting (2)	2.0	4.0	6.0	4.0	8.0	12.0	6.0	12.0	18.0
Raveling (1)	1.0	2.0	3.0	2.0	4.0	6.0	3.0	6.0	9.0
Patching (3)		6.0			12.0				

(Proposed by VDOT, Data from VDOT Salem District Office)

### ***III-2 Bridge Condition Evaluation***

A physical classification of bridges in the BMS of the Highway Management System is done using a condition rating system of the Federal Highway Administration (FHWA). FHWA defined condition ratings for bridge components in the "Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges". FHWA's bridge condition rating system is as follows (FHWA, 1988) :

- a) N- Not Applicable
- b) 9- Excellent Condition
- c) 8- Very Good Condition: no problem indicated.
- d) 7- Good Condition: some minor problems.
- e) 6- Satisfactory Condition: structural elements show some minor deterioration, no loss of carrying capacity, isolated problems.
- f) 5- Fair Condition: all primary structural elements are sound but may have minor section loss, cracking, spalling, scour, possible loss of carrying capacity, more widespread problems.

- g) 4- Poor Condition: advanced section loss, deterioration, spalling or scour, definite loss of carrying capacity, measurable section loss
- h) 3- Serious Condition: loss of section, deterioration, spalling or scour have seriously affected primary structural components, local failures are possible, fatigue cracks in steel or shear cracks in concrete may be present
- i) 2- Critical Condition: advanced deterioration of primary structural elements, fatigue cracks in steel or shear cracks in concrete may be present or scour may have removed substructure support. Unless closely monitored it may be necessary to close the bridge until corrective action is taken
- j) 1- Imminent Failure Condition: major deterioration or section loss present in critical structural components or obvious vertical or horizontal movement affecting structural stability. Bridge is closed to traffic but corrective action may put back in light service.

Evaluation is undertaken separately for each of the bridge elements, such as deck, superstructure, and substructure. The critical rating among them usually represents an entire bridge's rating.

### ***III-3 Traffic Condition Evaluation***

Traffic volume-capacity ratio ( $\frac{q}{Q}$ ) has been a popular measurement for the presentation of traffic congestion. Traffic volume - capacity ratio is used in travel time estimations in the continuous flow approach, or in the stochastic queuing approach, and is also utilized in the level of service concept using the total energy momentum analogy. The generalized volume (q) and speed (u) equation using the continuous flow concept is as follows (Drew, 1968):

$$q = ku = ku_f \left[ 1 - \left( \frac{k}{k_j} \right)^{\frac{n+1}{2}} \right], n > -1 \text{-----(Eq III-4)}$$

where k= density

k<sub>j</sub>= jammed density

u<sub>f</sub>= free flow speed

Using Hydrodynamic notation, Kinetic energy (E) in traffic systems is expressed as (Drew, 1968):

$$E = \alpha k u_f^2 \left[ 1 - 2 \left( \frac{k}{k_j} \right)^{\frac{n+1}{2}} + \left( \frac{k}{k_j} \right)^{n+1} \right], n > -1 \text{-----(Eq III-5)}$$

where  $\alpha$  = kinetic energy correction factor (constant)

For the special case, n=1, if normalized and expressed in terms of speed only, (Eq III-4), and (Eq III-5) become (Eq III-6), and (Eq III-7) respectively:

$$\frac{q}{q_m} = 4 \left[ \frac{u}{u_f} - \left( \frac{u}{u_f} \right)^2 \right] \text{-----(Eq III-6)}$$

$$\frac{E}{T} = \frac{27}{4} \left[ \left( \frac{u}{u_f} \right)^2 - \left( \frac{u}{u_f} \right)^3 \right] \text{-----(Eq III-7)}$$

where T= total energy

$q_m$ = maximum traffic volume, i.e. capacity (Q)

Since  $T=E+I$  (where I= internal energy of the traffic stream), (Eq III-7) is also expressed as:

$$\frac{I}{T} = 1 - \frac{27}{4} \left[ \left( \frac{u}{u_f} \right)^2 - \left( \frac{u}{u_f} \right)^3 \right] \text{-----(Eq III-8)}$$

(Eq III-6), (Eq III-7), and (Eq III-7) are plotted in Figure III-1. The abscissa of Figure III-1 is the volume-capacity ratio, and the ordinate is the speed-free speed ratio. Equating (Eq III-7), and (Eq III-7) yields two speed parameters,  $u=0.33u_f$  and  $u=0.91u_f$ , for which kinetic and internal energy are equal. Maximizing kinetic energy and minimizing internal energy yields  $u'_m=(2/3)u_f$ , which is optimum speed. Proceeding to right side of the graph also yields  $q'_m=(8/9)q_m$  and  $q=0.35q_m$ . These speed and volume-capacity parameters establish four levels of service zones, illustrated in Table III-2.

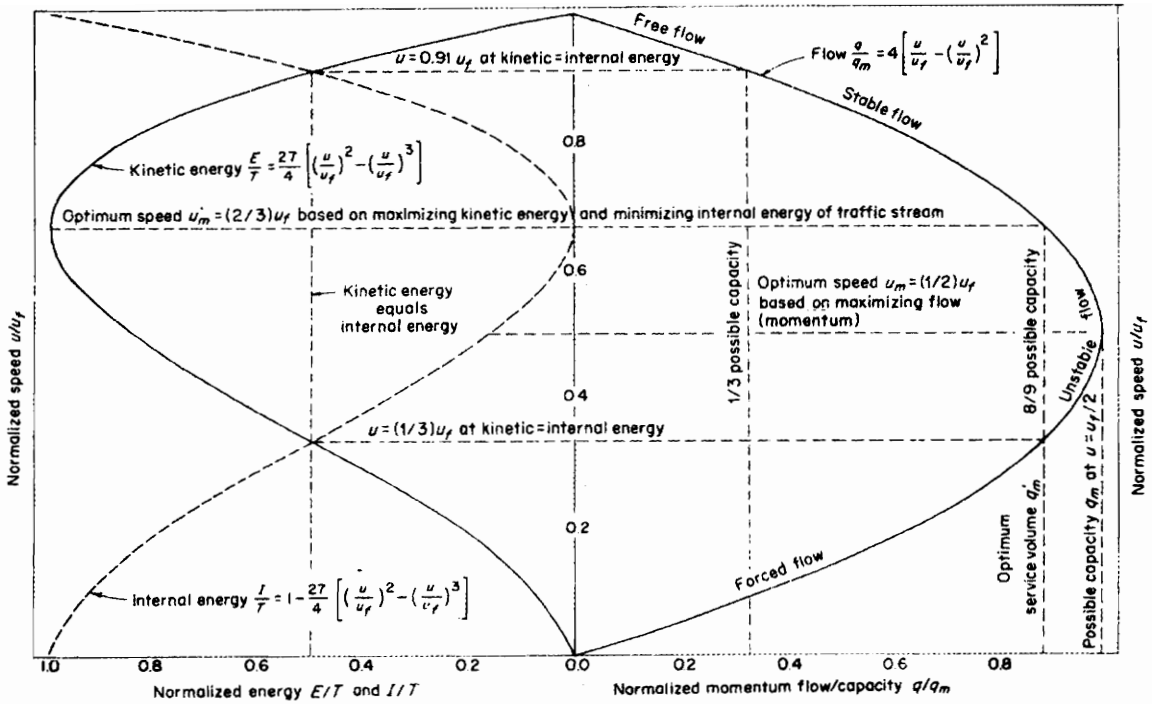


Figure III-1 Quantitative Approach to Level of Service Using the Total Energy-momentum Analogy (Drew, 1968)

Table III-2 Level of Service as Established by the Energy-Momentum Concept (Drew, 1968)

Level of Service Zone	Zone Limits		Description
	Upper	Lower	
Free Flow A	$u_f$	$0.91u_f, 0.35q_m$	Speeds controlled by driver desires and physical roadway conditions. This is the type of service expected in rural locations.
	B	$0.91u_f, 0.35q_m$ $0.83u_f, 0.55q_m$	
Stable Flow C	$0.83u_f, 0.55q_m$	$0.75u_f, 0.75q_m$	The conditions in this zone are acceptable for freeways in suburban locations
	D	$0.75u_f, 0.75q_m$ $u'_m, q'_m$	The conditions in this zone are acceptable for

			urban design practice. The lower limit $u'_m, q'_m$ represents the critical level of service.
Unstable Flow $E_1$  $E_2$	$u'_m, q'_m$	$u_m, q_m$	A small increase in demand (flow) is accompanied by a large decrease in speed leading to high densities and internal friction.
	$u_m, q_m$	$0.33u_f, q'_m$	This type of high-density operation can not persist and leads inevitably to congestion.
Forced Flow F	$0.33u_f, q'_m$	0	Flows are below capacity and storage areas consisting of queues of vehicles form. Normal operation is not achieved until the storage queue is dissipated.

### III-4 Economic Appraisal of Highway System

Economic evaluation can be utilized as a measure of effectiveness resulting from highway management policy. User-benefit of the highway system can be estimated using the consumer surplus concept. Consumer surplus is estimated based on the quantification of "willingness to pay" for travel cost. Figure III-2 shows the supply functions and demand functions in the cases of facility expansion, or construction of new facilities. Both new construction or expansion of new facilities may cause the reduction of travel costs. Meanwhile, the increased capacity of highways attracts trips from other modes of transportation (diverted trips), and creates new demands (induced trip). Increased demand also increases the travel cost due to an increase in travel time.

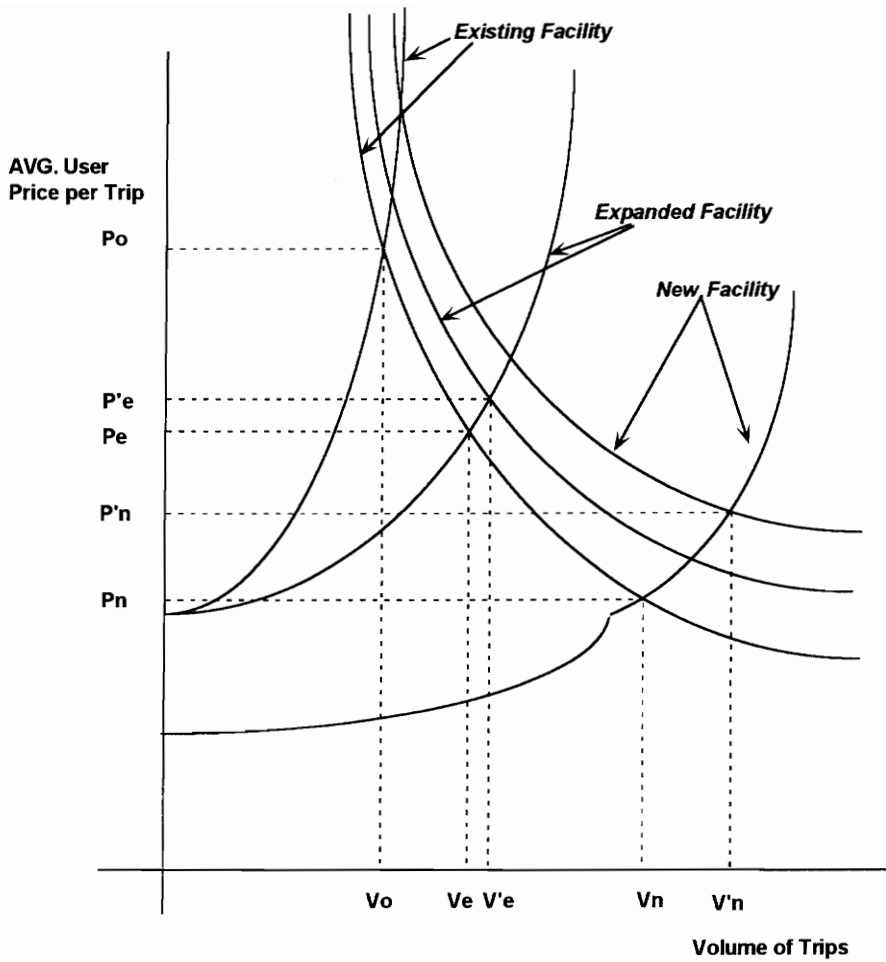


Figure III-2 Highway User-Cost and Benefit Relationship (Drew, 1994)

The user-benefits due to the expansion of the existing facility ( $B_e$ ), or the construction of a new facility ( $B_n$ ) is expressed as follows;

$$B_e = \frac{(P_o - P_e)(V_o + V_e)}{2} \text{-----(Eq III-9)}$$

$$B_n = \frac{(P_o - P_n)(V_o + V_n)}{2} \text{-----(Eq III-10)}$$

where  $P_o$ = the user-cost per trip without the improvement

$P_e, P_n$ = the user-cost per trip with the improvement, due to expansion and new construction, respectively

$V_o$ = the level of traffic without the improvement

$V_e, V_n$ = the level of traffic with the new improvement for the expansion and new construction cases, respectively

The user-benefits for all traffic, including induced and diverted traffic, as well as for present traffic for each of the expansion cases and new construction cases, are as follows:

$$B'_e = \frac{(P_o - P'_e)(V_o + V'_e)}{2} \text{-----(Eq III-11)}$$

$$B'_n = \frac{(P_o - P'_n)(V_o + V'_n)}{2} \text{-----(Eq III-12)}$$

where  $P'_e, P'_n$ = the user-cost per trip with the improvement due to expansion and new construction respectively, including induced and diverted traffic

$V_e, V_n$ = the level of traffic with the new improvement for the expansion and new construction cases respectively, including induced and diverted traffic

If it is assumed that user-benefits come primarily from travel time savings, user travel cost can be derived from the value of time and travel time. However, there is no universally accepted delay-flow formula for estimating travel time in a finite length of highway (Drew, 1994). There has been a commonly practiced continuous flow approach, which claims that the reciprocal of the speed variable is proportional to the travel time per unit distance. However, this is not realistic, because delay in this



context may arise from the disturbance in speed distribution resulting from faster vehicles catching up with slower ones, or being required to wait until passing or lane-changing occurs, or in the case of single-lane or crowded lane conditions, passing may not be possible (Drew, 1994). Drew (1994) claimed that a queuing mechanism works in this case.

Using the average delay in a single channel queue, the travel time term from classical stochastic queuing notation is expressed as (Eq III-13), and is plotted in Figure III-3.

$$T = T_f \frac{1 - (1 - j)\rho}{1 - \rho} \text{-----(Eq III-13)}$$

where T= travel time

$T_f$ = travel time at free flow

$j$ = service parameter ( $j = \frac{Q^{-1}}{T_f}, 0 \leq j \leq 1$ )

$\rho = \frac{q}{Q}$  (q=travel volume, Q= capacity)

Non-User Benefits are much more difficult to determine and are sometimes handled subjectively, or neglected (Drew, 1994). Perera (1990) described possible non-user impacts of transportation for the various economic categories, such as construction activities, business activities, land-use and land-values, general industry, agriculture, mining and forestry, energy consumption, etc.. Drew (1991) proposed a non-user benefit determination scheme using a highway transportation economic development relationship. Detailed formulation of non-user benefits based on Drew (1991) are illustrated in Chapter VI.

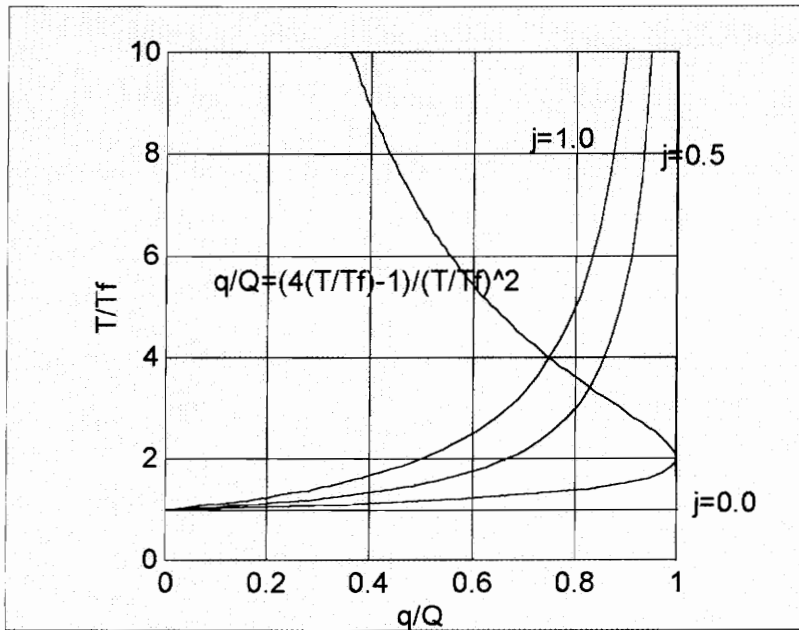


Figure III-3 Plot of  $\frac{T}{T_f} = \frac{1 - (1 - j)\rho}{1 - \rho}$  (reproduction from Drew (1994))

The costs for highway management include project costs for construction or expansion, and operation and maintenance costs, etc.. Finally, the benefit/cost ratio, the measure of effectiveness for highway management policy, can be estimated by using user and non-user benefits and costs describe above. Based on the assumption of continuous compounding of interest, the benefit/cost ratio can be computed using a simplified form, as follows (Drew, 1994):

$$BCR = \frac{R - E}{C \times r} (1 - e^{-n}) \text{-----(Eq III-14)}$$

where BCR= benefit / cost ratio

R= annual revenues

E= annual expenses

C=capital costs

r= interest rate

t= life-span of the project

### ***III-5 Consumer Satisfaction with Highway Management***

Passengers experience highway service daily, and encounter any existing problems first. Clearly, the purpose of public service is to give tax payers the maximum satisfaction, given the budget constraints. Therefore, consumer satisfaction with highway management can provide criteria for investment priorities. Without a doubt, there may be more important and fundamental highway management activities, and consumers may not feel their effects in a short period of time. However, consumers' satisfaction with highway service remains an important factor for investment decisions.

Barker et. al. (1995) performed a consumer satisfaction survey on VDOT's highway management services. Over 1200 consumers participated through telephone interviews about VDOT's highway management service. Table III-3 and Table III-4 show consumers' priorities about the highway management service. As shown in Table III-3, consumers put the highest priority on snow removal service (36.44%), with street and surface repair (30.58) as a second priority. This result indicated that consumers are sensitive to travel time reduction factors. Delay in snow removal in winter affects travel time negatively, and sometimes stops traffic altogether. Deferred repair actions for street and surfaces also negatively affect travel speed and safety.

Bridge inspection (14.37), Roadside Maintenance (8.38), Signs and Signals (7.83) followed in the priority ranking. These three factors are primarily related to traffic safety service. Table III-4 shows consumers' low priority rankings of highway management services. The low priority order of highway management services is the reverse of the high priority order, except for bridge inspection and roadside service.

Table III-3 High Priority VDOT Services (Barker et. al., 1995)

VDOT Services	Percent
Snow Removal	36.44
Street and Surface Repair	30.58
Bridge Inspection	14.37
Roadside Maintenance	8.38
Signs and Signals	7.83
Dead Animal Removal	2.40
Total	100

Table III-4 Low Priority VDOT Services (Barker et. al., 1995)

VDOT Services	Percent
Dead Animal Removal	52.20
Roadside Maintenance	23.25
Bridge Inspection	10.59

Signs and Signals	8.12
Street and Surface Repair	3.16
Snow Removal	2.68
Total	100

## **IV Life-Cycle Cost Analysis**

During the course of the lifetime of a highway system, many relevant construction and maintenance activities are needed to sustain a required service level and a proper operational condition. The amount of incurred expenses according to the costs of these activities is one of the important evaluation criteria for selection among investment alternatives. The Life-Cycle Cost (LCC) of a highway system can be defined as the total cost incurred throughout the lifetime of the highway system according to the specifications of various design, construction and maintenance strategies. Life-Cycle Cost Analysis (LCCA) is a method used to appraise the competitive alternatives with reference to the total cost at the end of the life-cycle of the product (i.e., LCC). In this chapter, the basic principles concerning LCCA and its application to the highway management system are discussed.

### ***IV-1 The Principles of Life-Cycle Cost Analysis***

The LCC was conceived of and first used by the Department of Defense in the early 1960s (Seldon, 1979). Since then, LCCA has been adopted primarily by the manufacturing field in evaluating design alternatives with different design specifications, maintenance requirements, and operating costs. LCCA has several primary application fields. The following is the reproduction from Seldon (1979), explaining the application fields of LCCA. Although his illustration of LCCA is primarily about government procurement, it aids in the understanding of the objectives of LCCA. The six fields are:

1. Long-range planning and budgeting: LCC provides estimates to help choose a feasible alternative by providing a quantitative measure of alternatives. LCC pro-

vides a quantitative basis for a total budget, and also provides details for planning purposes.

2. Comparison of competing programs: LCCA produces a cost comparison scheme among a number of alternative programs for meeting operational requirements.
3. Comparison of logistics concepts: Diversified logistic support approaches must be evaluated through the entire life-cycle of the system, not only for a specific operation. LCCA is the proper way to appraise those approaches in monetary terms.
4. Decisions about the replacement of aging equipment.
5. Control over an ongoing program: LCC must be used as a criterion for various decisions in the process of a program. The decisions should be involved in more than one phase, rather than being limited to just one period of operation.
6. Selection among competing contractors: The most frequent use of LCCA is as a criterion to select a contractor for developing and producing military equipment from the standpoint of a government agency.

Several principles also should be remembered for structuring a suitable LCC framework. First, proper rules and assumptions are necessary for every LCCA scheme in order to arrive at the best cost estimates, and should be revised whenever needed. Second, the system should be thoroughly examined and mastered in order to prepare appropriate estimating routines for more accurate costs. Reliable awareness of the system leads to an appropriate cost breakdown structure of the system, which can produce acceptable cost estimates. Third, estimating procedures must be prepared in a very cautious manner. Once the required accuracy is determined, the degree of detail, the complexity of the estimating procedure, and the size of the required database can be correspondingly fixed.

## *IV-2 Life-Cycle Cost Analysis for Highway Management Systems*

For the sake of convenience, the life-cycle of the system is divided into several phases. There are four generally accepted phases of the system life-cycle: the research and development phase, the production phase, the operating and support phase, and the disposal phase (Seldon, 1979). The highway system also follows this four step life phase, although the length of the period for each phase is longer than that of manufacturing goods.

It should be noted that the highway system consists of groups of highways and bridges having different open dates and different physical conditions, which means that there are subgroups, each of which is in a distinct phase of physical life. This overlapped phase, characteristic of the highway and bridge system, is a justification of the benefit of the system dynamics approach for highway system management, because the dynamically changing physical state of the system can be estimated using this approach.

The LCC of highway systems consists of the costs for maintenance, construction, and operation of highways. All of the LCC cost-items for managing highway systems depend on the physical state of the highway system, because different maintenance and construction activities are needed for different physical conditions of highways and bridges. The Life-Cycle Cost of highway and bridge systems in this research does not represent that of a bridge or a pavement section. Since the Highway Management System in this research deals with planning-level decision-making, the aggregated concept Life-Cycle Cost is used. This aggregated concept of Life-Cycle Cost represents the total amount of cost occurring throughout the lifetime of highways and bridges, which are viewed as a system, not as an independent bridge or highway sec-



tions. Therefore, the Cost Break-Down structure of highways discussed in the following section will deal with this aggregated and averaged cost of the system.

### ***IV-3 Generic Cost Break-Down Structure of Life-Cycle Cost Analysis***

Several basic characteristics should be fulfilled in a Cost Break-Down structure. The following five basic characteristics of a Cost Break-Down structure are quoted from Blanchard (1992);

1. All system cost elements must be considered.
2. Cost categories must be well defined.
3. The cost structure and categories should be coded in such a manner as to allow for the analysis of certain specific areas of interest.
4. When related to a specific program, the cost structure should be compatible with the program work break-down structure (e.g. task list) and with the management accounting procedures used in collecting costs.
5. For programs where subcontracting is prevalent, it is often desirable and necessary to separate supplier costs (i.e., initial bid price and follow-on program costs) from other costs. Cost structure should allow for the identification of specific work packages that require close monitoring and control.

Blanchard et. al. (1990) suggest a Cost Break-Down structure that can be generally accepted for the LCC of manufactured goods. The outline of this Cost Break-Down structure can also be applied to the highway system, but the detail cost items of the highway system can be different. Table IV-1 would be the generic Cost Break-Down structure for a highway system. It should be noted that the Cost Break-Down

structure of the highway system should follow detail cost items according to the highway management task list.

Table IV-1 Generic Cost Break-Down Structure for a Highway System (created based on Blanchard et. al. (1990))

Total System Cost			
Research and Development cost	Construction Cost	Operation and Maintenance Cost	Disposal Cost
<ul style="list-style-type: none"> <li>• Highway Planning Management</li> <li>• Highway Planning               <ul style="list-style-type: none"> <li>⇒ travel demand analysis</li> <li>⇒ transportation feasibility studies</li> <li>⇒ programming planning for highway planning</li> </ul> </li> <li>• Research for Construction of highway system               <ul style="list-style-type: none"> <li>⇒ applied research</li> <li>⇒ research facilities</li> <li>⇒ geometric and structural design</li> <li>⇒ system engineering</li> <li>⇒ conceptual design</li> <li>⇒ preliminary design</li> <li>⇒ detailed design</li> <li>⇒ design support</li> <li>⇒ design review</li> </ul> </li> <li>• Highway Design Documentation</li> <li>• Transportation Planning and Software</li> <li>• Geometric Design Software</li> <li>• Transportation Planning Software</li> <li>• Simulation for transportation Planning and Engineering Design               <ul style="list-style-type: none"> <li>⇒ simulation models</li> <li>⇒ evaluation</li> <li>⇒ simulation data/reports</li> </ul> </li> </ul>	<ul style="list-style-type: none"> <li>• Highway Construction Management</li> <li>• Highway Construction               <ul style="list-style-type: none"> <li>⇒ structure</li> <li>⇒ tunnel</li> <li>⇒ pavement</li> <li>⇒ bridges</li> <li>⇒ roadsides, shoulders</li> <li>⇒ drainage and ditches</li> <li>⇒ median</li> <li>⇒ road marking</li> <li>⇒ signs</li> <li>⇒ traffic control device</li> <li>⇒ traffic management system</li> <li>⇒ weigh station</li> </ul> </li> <li>• Highway Construction Quality Control</li> <li>• Initial Logistics Support</li> </ul>	<ul style="list-style-type: none"> <li>• Highway life-cycle management</li> <li>• Highway operations               <ul style="list-style-type: none"> <li>⇒ traffic operations</li> <li>⇒ operational facilities</li> <li>⇒ operating personnel</li> <li>⇒ energy / utilities / fuel</li> </ul> </li> <li>• Distribution of resources for operation and maintenance of highway system               <ul style="list-style-type: none"> <li>⇒ maintenance personnel</li> <li>⇒ maintenance resources</li> </ul> </li> <li>• highway and bridge maintenance               <ul style="list-style-type: none"> <li>⇒ bridge preventive maintenance, repair, rehabilitation, widening and replacement</li> <li>⇒ road surface repair or replacement</li> <li>⇒ vegetation</li> <li>⇒ snow and ice control</li> <li>⇒ road marking maintenance</li> <li>⇒ sign maintenance</li> <li>⇒ traffic control device maintenance</li> <li>⇒ tunnel maintenance</li> <li>⇒ emergency work</li> <li>⇒ repair and replacement of weigh station</li> </ul> </li> <li>• Operator and maintenance training               <ul style="list-style-type: none"> <li>⇒ operator training</li> <li>⇒ maintenance training</li> <li>⇒ training facilities (upkeep)</li> <li>⇒ training data</li> </ul> </li> <li>• Technical data</li> </ul>	<ul style="list-style-type: none"> <li>• Disposal of non repairable system and system element</li> <li>• System retirement               <ul style="list-style-type: none"> <li>⇒ destruction of facilities</li> <li>⇒ personnel</li> <li>⇒ support equipment</li> </ul> </li> <li>• Documentation</li> </ul>

#### ***IV-4 Cost Break-Down Structure of Life-Cycle Cost for the VDOT Bridge System***

The Cost Break-Down structure discussed in this section covers the life-cycle (or physical phase) of bridges. The estimated cost for each management action with the number of bridges in corresponding physical levels estimated by the system dynamics approach, constitutes the LCC of bridges. Maintenance activities for bridges are not well defined in VDOT's maintenance task list. The following cost items representing each bridge maintenance activity were collected from an interview with Dean Hackett, a Senior Structural Engineer for VDOT's Salem District. Detailed bridge maintenance tasks for VDOT is described in Appendix B.

##### **a. Preventive maintenance Cost of Bridges**

- Average Cost of Scour
- Average Cost of Sealing Deck Cracks
- Average Cost of Expansion Joint Maintenance
- Average Cost of Parapets/Guard Rail Maintenance
- Average Cost of Spot Painting

##### **b. Minor Repair Cost of Bridges**

- Average Cost of Deck Overlay
- Average Cost of Cathodic Protection
- Average Cost of Patching
- Average Cost of Expansion Joint Reconstruction
- Average Cost of Repainting
- Average Cost of Bearing and Anchor Bolt Replacement
- Average Cost of Drainage System Replacement and Repair
- Average Cost of Structure Steel Secondary Member Replacement and Repair

- Average Cost of Concrete Diaphragm Repair
- Average Cost of Deck Edge Repair
- c. Major Repair Cost of Bridges
  - Average Cost of Deck Replacement
  - Average Cost of Superstructure Replacement
  - Average Cost of Concrete Beam End Repair
- d. Rehabilitation Cost of Bridges
  - Average Cost of Repair of Abutment
  - Average Cost of Repair of Piers
  - Average Cost of Replacement of Piers
  - Average Cost of Replacement of Abutment
  - Average Cost of Repair of Collision Damage
- e. Replacement Cost of Bridges
- f. Bridge Widening Cost

***IV-5 Cost Break-Down Structure of Life-Cycle Cost for the VDOT Highway Systems***

The Cost Break-Down structure discussed in this section covers the life-cycle (or physical phase) of highways. The cost item for each management action is based on the highway maintenance task list for VDOT, described in Appendix A.

- a. Ordinary Maintenance Cost of Highway
  - Average Cost of General Expenses for Ordinary Maintenance
  - Average Cost of Bituminous Surface Repair

- Average Cost of Concrete Surface Repair
- Average Cost of Non-Hard Surface Work
- Average Cost of Shoulder Maintenance
- Average Cost of Ditches and Drainage Maintenance
- Average Cost of Roadside Maintenance
- Average Cost of Vegetation Control
- Average Cost of Signs and Traffic Control Device Maintenance
- Average Cost of Traffic Service and Operation
- Average Cost of Snow and Ice Control
- Average Cost of Tunnel Maintenance
- Average Cost of Non-Roadway Related Maintenance
- Average Cost of Traffic System Management, System Maintenance
- Average Cost of Supervision for Ordinary Maintenance

b. Maintenance Replacement Cost of Highway

- Average Cost of General Expenses for Maintenance Replacement
- Average Cost of Surface Replacement
- Average Cost of Major Repair of Shoulders, Turnouts, and Drainage
- Average Cost of Major Repair of Roadside
- Average Cost of Replacement of Signs
- Average Cost of Major Repair or Replacement of Tunnels
- Average Cost of Replacement of Weigh Station
- Average Cost of Emergency Work
- Average Cost of Supervision for Maintenance Replacement

VDOT's categorized maintenance groups of activities, such as Ordinary Maintenance and Maintenance Replacement are so ambiguous that they do not address the

physical upgrades of highway sections. Therefore, the HMS does follow the Cost Break-Down structure described above. Instead, new conceptual maintenance activities groups and their average costs were used in the actual HMS model. The details are described in Chapter VI.

#### ***IV-6 Cost Estimating Method***

Cost estimating methods are the next consideration, after building the Cost Break-Down structure. Dependable data inventory is very useful for estimating costs. Some statistical relationships can be derived from historical data by using the database inventory of highway systems. When the data are not sufficient, opinions from experts or field workers can be considered instead. Blanchard (1992) suggests three basic methods for estimating costs, as follows;

1. From recognized factors or known rates
2. Using parametric models and / or analogous relationships
3. Expert opinion

Cost estimations for the Highway Management System for the District agency, or for the State DOT, can be done by research using the existing database system. Unfortunately, VDOT's database systems are fragmented and don't provide the necessary information for the HMS model. Although VDOT has no global database system to provide all the information needed for HMS, it is currently operating database systems such as the Financial Management System (FMS) and the Highway Traffic Records Inventory System (HTRIS). Cost estimation for the simulation has been done by querying VDOT's database and obtaining estimates from key personnel of VDOT.

#### ***IV-7 Life-Cycle Cost Equivalence***

In a Life-Cycle Cost Analysis, competitive alternatives are compared by using the sum of incurred costs throughout their lifetimes. However, costs are related to different activities at different points in time. For instance, a cost item can occur during the initial year, and another cost item can occur after five years. However, these items do not have the same effect on the total Life-Cycle Cost. This discrepancy of cost-occurrence points over time can occur among competitive alternatives. In other words, some alternatives can have same amount of total Life-Cycle Cost; however, we can't really say that these alternatives have same Life-Cycle Costs, if these cost items occurred at different points in time. The economic equivalence of Life-Cycle Cost is a good measurement using common reference points in time.

Three factors are involved in the equivalence of the total Life-Cycle Cost: 1) the amount the of the total Life-Cycle Cost, 2) the times of occurrence of the sums, and 3) the interest rate (Fabrycky, et. al., 1991). The following mathematical depiction of present amount ( $P$ ) and amount at period  $n$  ( $F$ ) of the Life-Cycle Cost are reproduced from Fabrycky, et. al. (1991).

The most common assumption concerning interest formulas is the annual compounding of interest. In this case, interest is compounded for each year discretely. The single-payment present-amount formula is expressed as:

$$P = F \left[ \frac{1}{(1+i)^n} \right] \text{-----} \text{(Eq IV-1)}$$

where  $i$ = annual rate of interest

$n$ = amount of interest period, by year in this formula

P= amount at a time assumed to be the present

F= amount at n interest period, e.g. at year n

Assumption of continuous compounding of interest more closely represents reality than does annual compounding (Fabrycky, et. al., 1991). The single-payment compound amount formula is expressed as:

$$P = F \left[ \frac{1}{e^{rn}} \right] \text{-----(Eq IV-4)}$$

where r=continuous interest rate

#### ***IV-8 Implications of Life-Cycle Cost Analysis***

The basic premise of LCCA is that alternatives are assumed to have the same benefits. Using this assumption, a selection of the best alternative can be possible. If LCCA is used to select the alternative having the least cost, but without the proper assumption, the result will not be valid. For example, LCCA cannot be used for alternatives having different funding levels. In this case, the best alternative will be the one with the least investment. Therefore a cost minimization scheme should be very carefully applied to the analysis.

However, LCCA can be utilized in another way in the HMS model. The Cost-Break-Down structure is useful in estimating the cost for each of the maintenance activities for highway and bridge management. The total system management cost can be obtained, and although this cost cannot be used to select the best alternatives, it will be useful in providing an overall idea of the expenditure of the highway system.



## **V Systems Approach and System Dynamics**

### ***V-1 Overview of the Systems Approach***

Although there has been rapid progress in technologies and fundamental knowledge, solving contemporary problems has not become any easier (Drew, 1995). This is primarily because: 1) problems are meta-problems, 2) contemporary approaches are over-specialized, and 3) meta-problems tend to be devoid of formal treatment because of conceit, arrogance, and apprehension on the part of some researchers, government officials, and others.

The systems approach solves and analyze meta-problems in consistent, logical, objective and quantitative way (Drew, 1995). The systems approach is defined as "an amalgam of scientific approaches to conceptualizing problems and solving them through research, design (or synthesis), and analysis" (Drew, 1995). A systems approach uses a system philosophy concerning problems and knowledge, considers the characteristics of a system, and employs a methodology comprised of procedures, tools, and techniques (Drew, 1995).

The systems approach aids in the selection of the best alternative, and in the prediction of the future performance of a system (Drew, 1995). Ferrari (1978) simply defined the "system" as a collection of associated elements sharing a common purpose or function. Therefore, we can say that a systems approach to highway management should include all of the associated elements for analyzing and solving the meta-problems related to highway management, and should facilitate future predictions of highway system performance and selection of alternatives based on various scenarios concerning highway management policy.

The systems approach has been applied to various disciplines over the past 50 years. Table V-1 shows the foci and examples in the systems approaches for last five decades.

Table V-1 Evolution of the systems approach (Drew, 1995)

EVOLUTION OF THE SYSTEMS APPROACH		
Decade	Focus	Example
1940's	World War II	Blackett's Circus
1950's	Security Planning	Polaris Project
1960's	Space Exploration	Apollo Program
1970's	Environment	World Models
1980's	Development	Regional Models
1990's	Sustainable Development	Reconcile Development and Environments

### *V-2 System Dynamics Methodology*

System dynamics is a methodology which utilizes control theory and feedback structure for a systems approach to analyze meta-problems in social, technological, economic, and political systems. The system dynamics model is a simulation model that deals with deterministic, dynamic, non-linear, and closed boundary systems (Drew, 1995).

System dynamics was initiated in 1956 by J. W. Forrester. He applied the principles of feedback control to socio-economic systems, and later to the problems of managing a corporation, resulting in the publication in 1961 of *Industrial Dynamics* (System Dynamics Society, 1995). Over the past three decades, system dynamics has

been applied broadly in such areas as environmental change, economic development, social unrest, urban decay, psychology and physiology (System Dynamics Society, 1995). There followed development and application of tools such as causal loop diagramming, chaos theory, statistical analysis, and interactive learning environments.

The system dynamics model aids in analyzing the behavior of complex, dynamic S-T-E-P (Social, Technological, Economic, and Political) systems to show how system structure and the policies used in decision-making govern the behavior of the system (Drew 1995). The system dynamics modeling procedure can be simplified, as shown below (Drew, 1995);

- a) Step 1: The formulation of a mental model in the form of a verbal description:  
Verbal Model
- b) Step 2: The expression of this verbal model in the form of a flow diagram: Causal Diagram or Visual Model
- c) Step 3: The conversion of this flow diagram in a set of simultaneous difference equations: Dynamo or digital computer language program, Mathematical Model
- d) Step 4: Analytical solutions and computer simulations

These modeling steps are sequential and iterative, and are exposed to criticism at each step (Drew, 1995). A different form of the model for each step (step 1 to step 3, shown above) aids in understanding for those who are not fluent in the other forms (Drew, 1995).

A system dynamics model is a simulation model. The model simulates the status of the system and constantly updates all the information and physical flow links inside the system. Drew (1995) defined the simulation model as "a special case of mathematical model, which involve changes in the state of the system through time, except

in rare instances. In some cases, it is possible to obtain analytical transient solutions and steady state solutions. These analytical solutions aid in comprehending the idea concerning the relationship between variables, even when they are indirectly connected.

### ***V-3 Causal Diagramming: A Tool for Visual Modeling***

Causal diagramming is a method of structural modeling commonly employed in the application of the system dynamics methodology. A verbally described model statement is transformed into a visually illustrated model. A causal diagram represents cause and effect clearly, and shows whether the effects are positive or negative. The causal diagram uses the variable acronym, full name, and the units of the variable, which correspond with the mathematical equations. The following Figure V-1 shows a causal relationship between a level variable (LV) and rate variables (RV1, RV2) with a first-order negative feedback.

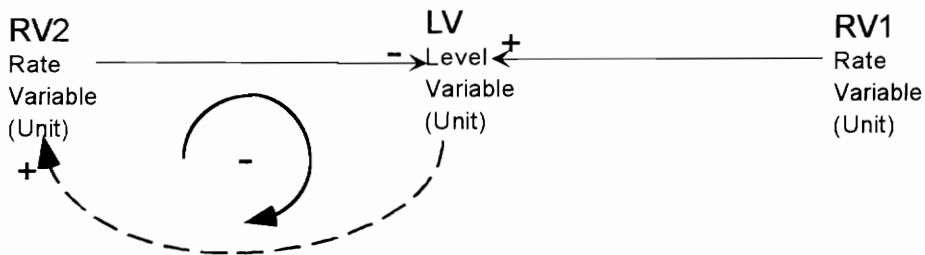


Figure V-1 Causal Diagram for a Level Variable and Rate Variables with a First-Order Negative Feedback Loop

As shown in Figure V-1, a level variable and a rate variable are connected by a solid arrow which transfers physical amount. Rate variables are located at the tails of the solid arrows and the level variable is positioned at the terminal point of the solid arrow. Signs on the arrow represents negative or positive causal relationship. Causal

relationships for non-physical or information flows are represented as dashed arrows in the causal diagram. As shown in Figure V-2, the level variable has a positive effect on a rate variable and this feedback stream is shown by the dashed arrow with a plus sign on the arrow. The next example illustrates cause and effects among constants and auxiliary variables (Figure V-2):

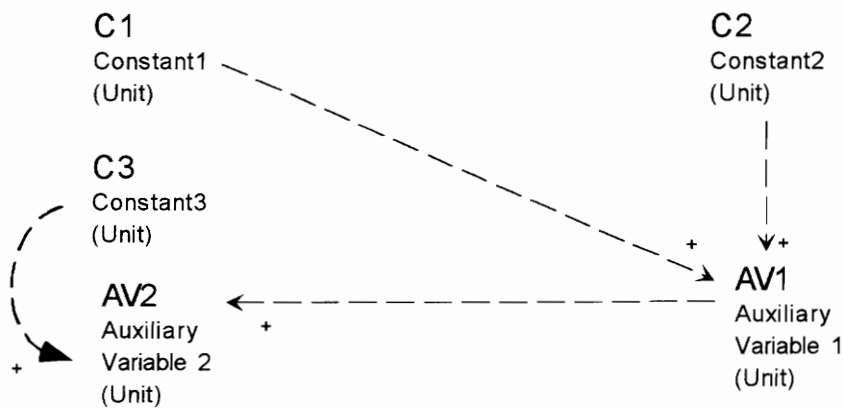


Figure V-2 Causal Diagram for Auxiliary Variables and Constants

The constants (C1, C2, and C3) in the Figure V-2 above cannot be located at a terminal point of an arrow, because they are not influenced by anything. The auxiliary variables (AV1 and AV2) can be at the head or at the tail of a dashed arrow in a feedback loop from a level to a rate. Eliminating auxiliary variables by repeated substitution in the model increases the complexity of the equation for rate variables, and obscures the causal relationships in the model (Drew, 1995).

#### ***V-4 Model Structure and Feedback Loops***

A system dynamics model consists of the associated system elements which are interconnected with each other, with causality. There are four types of major variables defined in a system dynamics model: level variables, rate variables, auxiliary variables, and constants.

Level variables represent the state of the system elements. Rate variables represent the rate of change for the related level variables. The quantity of level variable is altered by the amount of the rate variable. In other words, physical flow occurs between level variables and rate variables.

Auxiliary variables receive information from level variables, auxiliary variables, and constants, and then transfer information to other auxiliary variables or rate variables. In other words, auxiliary variables appear at the information stream and the feedback stream. Constants represent information given externally. Constants transfer information to auxiliary variables or rate variables.

A system can be classified as an open system, or a feedback system, based on information and physical flow structure (Forrester, 1968). In an open system, outputs are isolated from inputs and do not affect inputs, while in a feedback or a closed system, outputs are influenced by their past behaviors (Forrester, 1968).

Feedback can be applied in two cases: 1) from one time period to the next time period; 2) changes in exogenous variables. Figure V-3 shows three different cases for positive and negative feedback. Odd numbers of negative relationships in the loop determine feedback loop polarity as negative, while even numbers of negative signs in the loop determine feedback loop polarity as positive. The number of level variables in the loop determines the order of the feedback loop

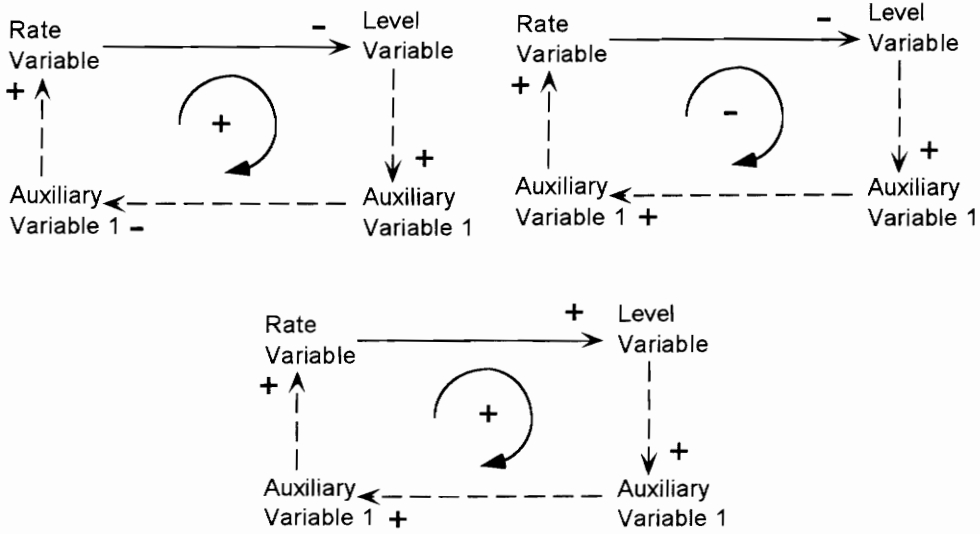


Figure V-3 Feedback Loops

**V-5 Mathematical Presentation of the System Dynamics Model**

System dynamics models are presented as DYNAMO equations in the final stage of the system dynamics modeling methodology. The relationship of rate variables and a level variable depicted in Figure V-1, can be indicated mathematically in the following two ways: integral equations, and differential equations:

$$LV_t = LV_{t-1} + \int_{t-1}^t (RV1 - RV2)dt \text{ -----(Eq VI-1)}$$

$$LV.K = LV.J + (DT)(RV1.JK - RV2.JK) \text{ -----(Eq VI-2)}$$

where t, K= present time

t-1, J= past time

t+1, L= future time

The DYNAMO equation uses a differential equation type of mathematical expression along with time subscripts. The following example shows the DYNAMO equations for a level variable, its initial value designation, and the numerical value of the initial value parameter:

$$L LV.K=LV.J+(DT)(RV1.JK+RV2.JK -RV3.JK) \text{-----}(Eq VI-3)$$

$$N LV=LVN \text{-----}(Eq VI-4)$$

$$C LVN=\text{initial value of LV} \text{-----}(Eq VI-5)$$

where LV= level variable

RV1, RV2, RV3= rate variables

LVN= constant representing initial value of LV

An indicator must appear in the first column of a DYNAMO equation. Table V-2 shows the first column indicator used in the DYNAMO equation. The letter 'L' is used for a level variable, 'N' for an initial value, 'R' for a rate variable, 'A' for an auxiliary variable, 'C' for a constant, '\*' for a title, and 'NOTE' for a comment or variable name. 'DT' is the simulation solution interval normally presented as  $\Delta t$  in differential calculus. The postscript '.K' indicates the value of present time, and '.J' means the last value of the variable. A constant has no postscript. A rate variable has a double postscript such as '.KL', or '.JK', because it represents the rate of change over a time period. A level equation should be followed by an initial value equation. The symbol '^' should be used at the end of the continued equation line.



Table V-2 Equation Indicator in DYNAMO (Pugh-Roberts, 1994)

First Column Indicator (Equation Type)	
A (Auxiliary)	L (Level)
B (Boolean)	N (computed iNitial value)
C (Constant)	P (Parameter)
D (Decision)	R (Rate)
E (Exogenous)	S (Supplementary)
I (given Initial value)	SPEC (run SPECification)
K (re-initial value)	T (Table)

The following is an example showing a rate variable, a constant, and an auxiliary variable.

$$R \text{ RV1} = \text{MAX}(\text{LV}/\text{CONST1}, 0) \text{ ----- (Eq VI-6)}$$

$$C \text{ CONST1} = \text{constant value} \text{ ----- (Eq VI-7)}$$

$$A \text{ AV1.K} = \text{AV2.K} * \text{CONST2} \text{ ----- (Eq VI-8)}$$

where RV1= rate variable

CONST1, CONST2= constants

AV1, AV2= auxiliary variables

As shown in the (Eq VI-6), the 'MAX' function is a special function in DYNAMO, used to select the maximum value between the two values in the parenthesis (LV/CONST1 and 0). There are several more DYNAMO special functions used in the High Management System model. 'MIN' function selects a minimum value be-

tween values in the parenthesis. The 'CLIP' or 'FIFGE' function selects the first value, if the third value is greater than or equal to the fourth value, and selects the second value if the third value is smaller than the fourth value. Examples for MIN and CLIP functions are given below:

$$A \text{ AV1.K}=\text{MIN}(\text{AV2.K}/\text{AV3.K},1) \text{ -----(Eq VI-9)}$$

$$A \text{ AV2.K}=\text{CLIP}(\text{CLIP}(\text{AV3.K},\text{AV4.K},5),\text{CONST}, \text{TIME.K},0) \text{ -----(Eq VI-10)}$$

where CONST= constant

AV3, AV4= auxiliary variables

TIME= auxiliary variables represent simulation time

A table function is used for a non-linear relationship between two variables. The following is an example of a table function.

$$A \text{ AV1.K}=\text{TABLE}(\text{TBL},\text{AV2.K},1,6,1) \text{ -----(Eq VI-11)}$$

$$T \text{ TBL}=0.1/0.2/0.3/0.4/0.6/1 \text{ -----(Eq VI-12)}$$

where TBL= name of the table function

AV1.K in (Eq VI-11) can be thought of as the dependent variable, and AV2.K as the independent variable in this causal relationship. The four commas in the table function define five spaces. The first space is the name of the table function; the second space identifies the independent variable; the third space is the minimum value of the independent variable; the fourth space is the maximum value of the independent variable; and the fifth space defines the increment in the abscissa of the graph. The ordinate value corresponding to the six abscissa values are given in the second equation.

### *V-6 Computer Implementation of the System Dynamics Model*

The Highway Management System is developed using the simulation language, DYNAMO (for DYNAMIC Models). Dynamo is a computer simulation language designed for system dynamics simulation modeling. DYNAMO provide a time-dependent simulation package for solving complex systems models.

Coding system dynamics models using ordinary high level computer languages such as C or FORTRAN is impractical and inefficient, because system dynamics modeling requires special definitions of the variables and the capability of handling subscripts. DYNAMO is equipped with these capabilities, and also other functions which are necessary and convenient for system dynamics modeling. DYNAMO is the oldest, and the industry-standard language for system dynamics modeling, so that the DYNAMO equations themselves represent system dynamics models for some cases. There are three more commercial system dynamics modeling programs currently used in the market: IThink/Stella, PowerSim and VENSIM.

DYNAMO was the first simulation language for system dynamics modeling (Eberine, 1996). DYNAMO was developed initially by Jack Pugh at MIT, and Pugh-Roberts made it commercially available in the early 1960s (Eberine, 1996). 'DYNAMO' is considered to be an equivalent term to system dynamics. The current version of DYNAMO runs on PC compatibles under DOS or Windows. It provides an integrated development environment which has an equation oriented front-end. Stella was introduced in 1984 (Eberine, 1996). Because it was originally developed for the Macintosh computer environment, it has a good graphical front end for the development of system dynamics models (Eberine, 1996).

PowerSim was initiated in the mid 1980s by Norwegian government-sponsored research aimed at the high school education quality using system dynamics models (Eberine, 1996). PowerSim was developed based on the outcome of this research as a Windows based environment for the system dynamics models development (Eberine, 1996).

VENSIM was developed originally in the mid 1980's for use in consulting projects, and has been commercially available since 1992 (Eberine, R., 1996). It also has an integrated environment for the development and analysis of system dynamics models (Eberine, 1996). VENSIM is available on Windows, Windows NT and Macintosh (Eberine, 1996).

Stella is the second-oldest system dynamics modeling tool, and is widely used in education and in the simulation of simple models. Stella facilitates model-building, even for those without solid knowledge of system dynamics. However, there is the possibility that this could lead to improper modeling applications for users without modeling experience. Although Stella has an outstanding graphic environment for model development, its lack of array capability makes large-scale modeling nearly impossible.

VENSIM has a good graphic environment and array capability. However, it has a short application history in system dynamics modeling, such as PowerSim. Therefore, VENSIM is relatively inappropriate and somewhat risky for use in practical application.

DYNAMO, which has a mathematical equation-based modeling environment, also has array capability, which is important for large-scale modeling and expansion of the model. DYNAMO is comparatively difficult to use in developing models, and lacks graphical modeling environment. However, these disadvantages are merely for the

inexperienced users, and there might be some advantages for experienced users. Since DYNAMO is considered as a standard modeling language for system dynamics, other system dynamics programs usually provide tools for translating the DYNAMO equations to their languages. This means that the models created by DYNAMO will be able to be used in other system dynamics programs, while other programs will not.

The HMS model requires future expandability, and a large-scale model size. Because of the factors described above, DYNAMO is a more appropriate modeling language for the development of the HMS model.

## **VI Development of The Highway Management System**

### **Model**

#### *VI-1 Organization of the Model*

The HMS, organized as shown in Figure VI-1, consists of five subsystems: Functional, Physical, Administrative, Financial, and Evaluation. The Physical Subsystem consists of the Pavement Management System (PMS) and the Bridge Management System (BMS). These two system models estimate the physical condition of highways and bridges.

The Functional Subsystem includes Life-Cycle Cost routines, along with various cost estimation routines for individual cost items. The Evaluation Subsystem includes routines for user and non-user benefits and other measures of effectiveness. The Financial Subsystem includes the budget allocation and revenue generation processes which support the other subsystems. The Administrative Subsystem consists of the sets of four subsystems described above for each of the different highway categories such as, Interstate, Primary, Secondary, and Urban Highways.

The model includes more than 250 variables. Development of the model was initiated from the recognition of the causal relationship between basic elements within the subsystems of the HMS, as shown in Figure VI-1. As can be seen from the diagram, travel demands and revenues are positively effected by an increase in socio-economic factors. This increase in revenues will lead to an increase in the available budget for highway management. An increased budget will improve the physical condition of the highway system, while an increase in travel demand and the resulting maintenance and construction costs will have a negative affect. These cost increases also increase the life-cycle cost of the highway system. The Measures of Effective-

ness (MOE) such as the benefit/cost ratio, are affected positively by the improvement of the physical condition of the highway system and negatively by the increased life-cycle costs of the highway system. The improvement of the MOEs impacts the socio-economic environment favorably, thus, closing the loop. The detailed causal diagram for the various sectors of the model are presented in Appendix C.

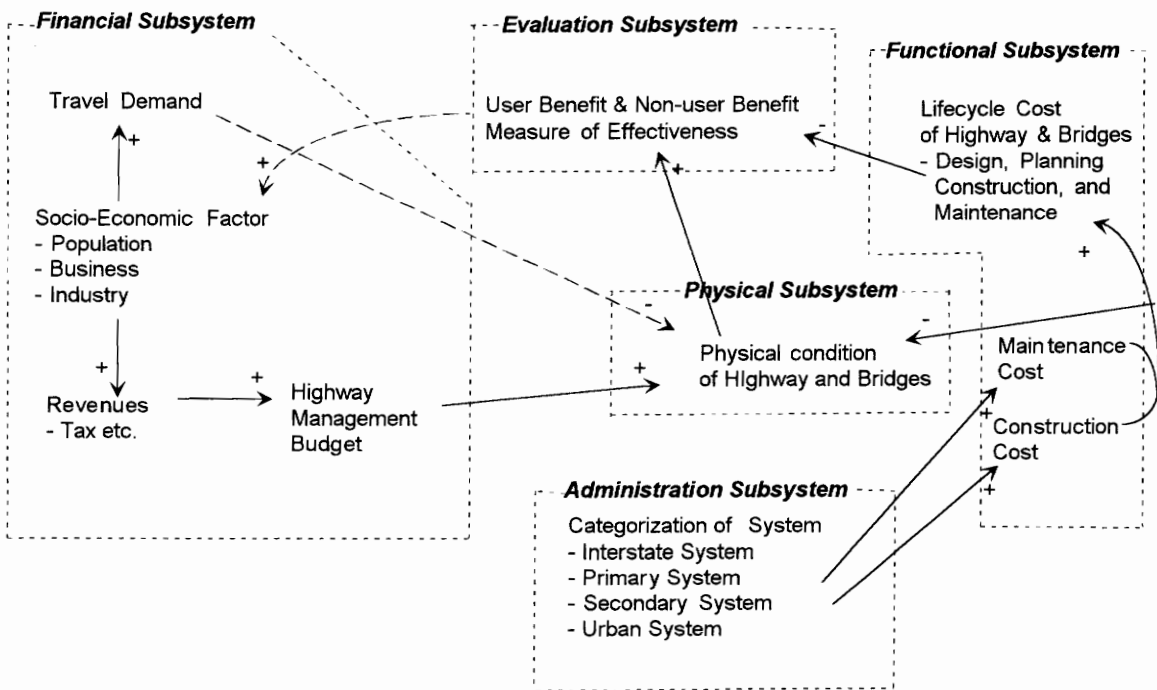


Figure VI-1 Simplified Causal Relationships Between HMS Subsystems

### VI-2 Physical Subsystem

From a maintenance perspective, it is convenient to divide the physical highway into a pavement component and a bridge component. Thus the physical aspects of the highway management system are categorized as the Pavement Management System (PMS), and the Bridge Management System (BMS).

### **VI-2-1 Pavement Management System (PMS).**

The physical condition of the highway system is divided into three physical levels: sufficient, deficient, and deteriorated. These three physical levels are classified in relation to the pavement maintenance activities of the Virginia Department of Transportation. In other words, highways in a deficient condition need some maintenance activities to recover their original physical condition. Also, highways in a deteriorated condition are in need of more intensive maintenance activities in order to be returned to the sufficient condition classification. A complete description of maintenance tasks is given in Appendix A.

In developing this portion of the model for the PMS, it is useful to refer to the causal diagram in Appendix C. The lane-mileage of highways in sufficient condition (HSFPC) will be increased by performing maintenance on the sections of highway in a deficient condition and in a deteriorated condition. Adding a new lane to an existing highway system or constructing new facilities also increases the lane-mileage of highways in sufficient condition. Sufficient condition highways fall to the deficient condition over time. DYNAMO presentations for highways in sufficient pavement condition are shown below:

$$L \text{ HSFPC.K} = \text{HSFPC.J} + (\text{DT})(\text{MRDTH.JK} + \text{ERH.JK} + \text{MRDFH.JK} - \text{ARH.JK})$$

$$N \text{ HSFPC} = \text{HSFPCN}$$

NOTE HSFPC - Highway in Sufficient Pavement Condition (LANE-MI)

NOTE MRDFH - Maintenance Rate for Deficient Highway (LANE-MI/YR)

NOTE MRDTH - Maintenance Rate for Deteriorated Highway (LANE-MI/YR)

NOTE ERH - Expansion Rate of Highway (LANE-MI/YR)

NOTE ARH - Aging Rate of Highway (LANE-MI/YR)



An increase in the highway maintenance budget, with a corresponding increase in the fraction of the budget allocated to maintenance for deficient highways (FMBDFH), will result in an increase of the maintenance rate for deficient highways (MRDFH). An increase in maintenance costs for deficient highways (MCDFH) leads to a decrease in the maintenance rate for deficient highways. DYNAMO expressions for the maintenance rate for deficient highways is as follows:

$$R \text{ MRDFH.KL} = \text{HMB.K} * \text{FMBDFH} / \text{MCDFH.K}$$

NOTE HMB - Highway Maintenance Budget (\$/YR)

NOTE MCDFH- Maintenance Cost for Deficient Highway (\$/LANE-MI)

NOTE FMBDFH - Fraction Maintenance Budget to Deficient Highway (DIM)

The lane-mileage of highways which are in deficient condition (HDFPC) will be increased by the aging rate of highways (ARH) that reflects the effects of weather and loads on highways that were “sufficient,” and will be decreased by the maintenance rate for deficient highways. Deficient condition highways will drop to deteriorated condition highways by the deterioration rate of highways (DRH). In other words, the highway deterioration rate defines how quickly they will progress from a deficient to a deteriorated condition. DYNAMO equations for deficient condition highways, the aging rate of highways, and the deterioration rate of highways are shown below:

$$L \text{ HDFPC.K} = \text{HDFPC.J} + (\text{DT})(\text{ARH.JK} - \text{MRDFH.JK} - \text{DRH.JK})$$

$$N \text{ HDFPC} = \text{HDFPCN}$$

NOTE HDFPC - Highway in Deficient Pavement Condition (LANE-MI)

$$R \text{ ARH.KL} = \text{HSFPC.K} / \text{ATH}$$

NOTE ARH - Aging Rate of Highway (LANE-MI/YR)

NOTE ATH - Aging Time of Highway (YR)

$$R \text{ DRH.KL} = \text{HDFPC.K/DTH}$$

NOTE DRH - Deteriorating Rate of Highway (LANE-MI/YR)

NOTE DTH - Deteriorating Time of Highway (YR)

Highways in the deteriorated condition (HDTPC) will be increased by the deterioration rate of the highway, and will be decreased by the maintenance rate for deteriorated highways (MRDTH). Maintenance for deteriorated highways is defined as those actions which bring the lane-mileage of highways in the deteriorated condition up to the level of sufficient condition. With an increase in the highway maintenance budget and in the fraction of the maintenance budget allocated to deteriorated highways, maintenance activities for deteriorated highways will increase. DYNAMO equations for highways in the deteriorated condition and the maintenance rate for deteriorated highways are shown below:

$$L \text{ HDTPC.K} = \text{HDTPC.J} + (\text{DT})(\text{DRH.JK} - \text{MRDTH.JK})$$

$$N \text{ HDTPC} = \text{HDTPCN}$$

NOTE HDTPC - Highway in Deteriorated Pavement Condition (LANE-MI)

$$R \text{ MRDTH.KL} = \text{HMB.K} * \text{FMBDTH.K/MCDTH.K}$$

NOTE MRDTH - Maintenance Rate for Deteriorated Highway (LANE-MI/YR)

$$A \text{ FMBDTH.K} = 1 - \text{FMBDFH}$$

NOTE FMBDTH - Fraction Maintenance Budget to Deteriorated Highway (DIM)

NOTE MCDTH - Maintenance Cost for Deteriorated Highway (\$/LANE-MI)

Through these deterioration and improvement processes, the lane-miles of highway in each of the three categories can be determined. The highway physical adequacy index (HPAI) reflects the performance of the highway system. The more lane-miles of the highway in sufficient condition, the closer this index will be to 1.0; the

more lane-miles in the deficient and deteriorated condition, the closer this index will be to zero. The DYNAMO equation for highway physical adequacy index is given below:

$$A \text{ HPAI.K} = \frac{(\text{HSFPC.K} + \text{HDFPC.K} * \text{WFDFCH} + \text{HDTPC.K} * \text{WFDTCH})}{(\text{HSFPC.K} + \text{HDFPC.K} + \text{HDTPC.K})}$$

NOTE HPAI - Highway Physical Adequacy Index (DIM)

NOTE WFDFCH - Weighting Factor for Deficient Condition of Highway (DIM)

NOTE WFDTCH - Weighting Factor for Deteriorated Condition of Highway (DIM)

### **VI-2-2 Bridge Management System (BMS).**

Bridges are categorized by two criteria: functional adequacy, and physical condition. A bridge is considered functionally inadequate if it cannot accommodate the current traffic flows, and functionally adequate when it can accommodate the current traffic flow. A complete description of bridge maintenance tasks is given in Appendix B.

In developing this portion of the model for the BMS, it is useful to refer to the causal diagram in Appendix C. The five physical bridge conditions defined in the BMS model are:

- a) preferred condition - needs no maintenance
- b) good condition - needs preventive maintenance
- c) fair condition - needs minor repair
- d) poor condition - needs major repair
- e) critical condition - needs bridge replacement or rehabilitation

The number of good bridges will be increased by the deterioration of bridges that were in the preferred condition. Similarly, good bridges will decline to fair bridges, fair bridges to poor bridges, and poor bridges to critical bridges by further deterioration.

Preventive maintenance is defined as the actions which bring good condition bridges up to the level of preferred condition bridges. Fair condition bridges will be brought up to the level of preferred condition bridges by performing minor repairs. Major repair is performed for poor condition bridges to be upgraded to preferred condition bridges. Critical condition bridges need to be rehabilitated or replaced, to be upgraded to preferred condition bridges.

Bridge widening is performed for functionally inadequate bridges to be upgraded to functionally adequate bridges. This subsystem will provide the numbers for each of the preferred, good, fair, poor, and critical bridges in accordance with the deterioration and improvement processes.

The number of bridges in the functionally adequate preferred condition (BFAPFC) increases as the functionally adequate preventive maintenance of bridges (FAPMB) increases, and with increases in the functionally adequate minor repairs of bridges (FAMNRB), the functionally adequate major repairs of bridges (FAMJRB), rehabilitation of bridges (RHRB) in functionally adequate critical condition, replacement of bridges (RPRB) in functionally inadequate critical conditions, and widening of bridges (BW) in functionally inadequate preferred conditions increase. The number of bridges in functionally adequate preferred condition decreases with an increase in the obsolescence rate of bridges (ORB) and the functionally adequate exposure rate of bridges

(FAERB). The Dynamo equations for bridges in functionally adequate preferred condition is as shown below:

$$L \text{ BFAPFC.K} = \text{BFAPFC.J} + (\text{DT})(\text{FAPMB.JK} + \text{FAMNRB.JK} + \text{FAMJRB.JK} + \text{RHRB.JK} + \text{RPRB.JK} + \text{BW.JK} - \text{ORB.JK} - \text{FAERB.JK})$$

$$N \text{ BFAPFC} = \text{BFAPFCN}$$

NOTE FAPFC - Bridges in Functionally Adequate Preferred Condition (BRIDGES)

The functionally adequate exposure rate of bridges (FAERB) is the rate of change of bridges in functionally adequate preferred condition to bridges in functionally adequate good condition. The functionally adequate exposure rate of bridges increases with an increase of bridges in functionally adequate preferred condition, and decreases with an increase in the exposure time of bridges. DYNAMO equations for the variables described in this paragraph are as shown below:

$$R \text{ FAERB.KL} = \text{BFAPFC.K} / \text{ETB}$$

NOTE FAERB - Functionally Adequate Exposure Rate of Bridges (BRIDGES/YR)

NOTE ETB - Exposure Time of Bridges (YR)

Functionally adequate preventive maintenance of bridges (FAPMB) can be described as the number of bridges which can be maintained through the functionally adequate preventive maintenance budget of bridges (FAPMBB). Therefore, functionally adequate preventive maintenance of bridges increases with an increase in the functionally adequate preventive maintenance budget of bridges (FAPMBB) and a decrease in the preventive maintenance cost of bridge (PMCB). The functionally adequate preventive maintenance budget of bridges is equal to the bridge budget (BB) multiplied by the fraction of budget for functionally adequate preventive maintenance

of bridges (FBFAPMB). DYNAMO equations for the variables described in this paragraph are as follows.

$$R \text{ FAPMB.KL} = \text{FAPMBB} / \text{PMCB}$$

NOTE FAPMB - Functionally Adequate Preventive Maintenance of Bridges

NOTE (BRIDGES/YR)

NOTE PMCB - Preventive Maintenance Cost of Bridge (\$/BRIDGE)

$$A \text{ FAPMBB.K} = \text{BB} * \text{FBFAPMB.K}$$

NOTE FAPMBB - Functionally Adequate Preventive Maintenance Budget of

NOTE Bridges (\$/YR)

NOTE FBFAPMB - Fraction Budget to Functionally Adequate Preventive

NOTE Maintenance of Bridges (DIM)

NOTE BB - Bridge Budget (\$/YR)

The number of bridges in functionally adequate good condition (BFAGC) increases with an increase in the functionally adequate exposure rate of bridges, and decreases with an increase in the functionally adequate preventive maintenance of bridges and the functionally adequate deterioration rate of bridges (FADRB). The equation for the number of bridges in functionally adequate good condition is as shown below.

$$L \text{ BFAGC.K} = \text{BFAGC.J} + (\text{DT})(\text{FAERB.JK} - \text{FAPMB.JK} - \text{FADRB.JK})$$

$$N \text{ BFAGC} = \text{BFAGCN}$$

NOTE FAGC - Functionally Adequate Good Condition (BRIDGES)

The functionally adequate deterioration rate of bridges (FADRB) is the rate of change by which bridges in functionally adequate good condition become bridges in

functionally adequate fair condition. The functionally adequate deterioration rate of bridges decreases with an increase in the deterioration time of bridges (DTTB). The DYNAMO expression of the functionally adequate deterioration rate of bridges is as shown below:

$$R \text{ FADR.B.KL} = \text{BFAGC.K} / \text{DTTB}$$

NOTE FADR.B - Functionally Adequate Deterioration Rate of Bridges (BRIDGES /YR)

NOTE DTTB - Deterioration Time of Bridges (YR)

The functionally adequate minor repairs of bridges (FAMNRB) is derived by dividing the amount of the functionally adequate minor repair budget of bridges (FAMNRBB) with minor repair cost of bridges (MNRCB). The equation for the functionally adequate minor repairs of bridges is as shown below:

$$R \text{ FAMNR.B.KL} = \text{FAMNRBB} / \text{MNRCB}$$

NOTE FAMNR.B - Functionally Adequate Minor Repairs of Bridges (Bridges/YR)

NOTE MNRCB - Minor Repair Cost of Bridges (\$/BRIDGE)

The functionally adequate minor repair budget of bridges (FAMNRBB) is derived by multiplying the bridge budget with the fraction of the budget to the functionally adequate minor repairs of bridges (FBFANRB). The equation for the functionally adequate minor repair budget of bridges is as shown below:

$$A \text{ FAMNRBB.K} = \text{BB} * \text{FBFANRB.K}$$

NOTE FAMNRBB - Functionally Adequate Minor Repair Budget of Bridges

NOTE (\$/YR)

NOTE FBFANRB - Fraction Budget to Functionally Adequate Minor Repairs of

**NOTE Bridges (DIM)**

The number of bridges in functionally adequate fair condition (BFAFC) increases with an increase in the functionally adequate deterioration rate of bridges, and decreases with an increase in the functionally adequate minor repairs of bridges and the functionally adequate accelerated deterioration rate of bridges (FAADR). The equation for the number of bridges in functionally adequate fair condition is as shown below:

$$L \text{ BFAFC.K} = \text{BFAFC.J} + (\text{DT})(\text{FADR.B.K} - \text{FAMNR.B.K} - \text{FAADR.B.K})$$

$$N \text{ BFAFC} = \text{BFAFC.N}$$

**NOTE BFAFC - Bridges in Functionally Adequate Fair Condition (BRIDGES)**

The functionally adequate accelerated deterioration rate of bridges is the rate of change of bridges in functionally adequate fair condition becoming bridges in functionally adequate poor condition (BFAPC). The functionally adequate accelerated deterioration rate of bridges decreases with an increase in the accelerated deterioration time of bridges (ADTB). The DYNAMO equation for the functionally adequate accelerated deterioration rate is shown as follows:

$$R \text{ FAADR.B.KL} = \text{BFAFC.K} / \text{ADTB}$$

**NOTE FAADR - Functionally Adequate Accelerated Deterioration Rate of**

**NOTE Bridges (BRIDGES/YR)**

**NOTE ADTB - Accelerated Deterioration Time of Bridges (YR)**

The functionally adequate major repair of bridges (FAMJRB) is determined by dividing the functionally adequate major repair budget of bridges (FAMJRBB) with the



major repair cost of a bridge (MJRCB). The equation for the functionally adequate major repair of bridges is as shown below:

$$R \text{ FAMJRB.KL} = \text{FAMJRBB} / \text{MJRCB}$$

NOTE FAMJRB - Functionally Adequate Major Repairs of Bridges (Bridges/YR)

NOTE MJRCB - Major Repair Cost of a Bridge (\$/Bridge)

The functionally adequate major repair budget of bridges is derived by multiplying the bridge budget by the fraction of the budget to the functionally adequate major repairs of bridges (FBFAJRB). The DYNAMO equation is given below:

$$A \text{ FAMJRBB.K} = \text{BB} * \text{FBFAJRB.K}$$

NOTE FAMJRBB - Functionally Adequate Major Repair Budget of Bridges (\$/YR)

NOTE FBFAJRB - Fraction of Budget to Functionally Adequate Major Repair of

NOTE Bridges (DIM)

The number of bridges in functionally adequate poor condition (BFAPC) increases with an increase of the functionally adequate accelerated deterioration rate of bridges and decreases with an increase in the functionally adequate major repairs of bridges and functionally adequate serious deterioration rate of bridges (FASDRB). The equation for bridges in functionally adequate poor condition is as shown below:

$$L \text{ BFAPC.K} = \text{BFAPC.J} + (\text{DT})(\text{FAADR.B.JK} - \text{FAMJRB.JK} - \text{FASDRB.JK})$$

$$N \text{ BFAPC} = \text{BFAPCN}$$

NOTE BFAPC - Bridges in Functionally Adequate Poor Condition (BRIDGES)

The functionally adequate serious deterioration rate of bridges is the rate that bridges in functionally adequate poor condition become bridges in functionally ade-

quate critical condition (BFACC). The functionally adequate serious deterioration rate of bridges decreases with an increase in the serious deterioration time of bridges (SDTB).

$$R \text{ FASDRB.KL} = \text{BFAPC.K} / \text{SDTB}$$

NOTE FASDRB - Functionally Adequate Serious Deterioration Rate of Bridges

NOTE (Bridges/YR)

NOTE SDTB - Serious Deterioration Time of Bridges (YR)

The rehabilitation rate of bridges (RHRB) is derived by dividing the budget for rehabilitation of bridges (RHBB) by the rehabilitation cost of a bridge (RHCB). The equation for the rehabilitation rate of bridges is as shown below.

$$R \text{ RHRB.KL} = \text{RHBB} / \text{RHCB}$$

NOTE RHRB - Rehabilitation of Bridges (Bridges /YR)

NOTE RHCB - Rehabilitation Cost of a Bridge (\$/Bridge)

The budget for rehabilitation of bridges is derived by multiplying the bridge budget by the fraction of the budget for rehabilitation of bridges (FBRHB). The DYNAMO equation is as follows:

$$A \text{ RHBB.K} = \text{BB} * \text{FBRHB.K}$$

NOTE RHBB - Rehabilitation Budget of Bridges (\$/YR)

NOTE FBRHB - Fraction of the Budget for Rehabilitation of Bridges (DIM)

The number of bridges in critical condition increases with an increase in the functionally adequate serious deterioration rate of bridges, and decreases with an increase

in rehabilitation of bridges . The equation for bridges in functionally adequate critical condition is as shown below:

$$L \text{ BFACC.K} = \text{BFACC.J} + (\text{DT})(\text{FASDRB.JK} - \text{RHRB.JK})$$

$$N \text{ BFACC} = \text{BFACCN}$$

NOTE BFACC - Bridges in Functionally Adequate Critical Condition (BRIDGES)

The obsolescence rate of bridges is the rate of change of bridges in functionally adequate preferred condition to bridges in functionally inadequate preferred condition (BFIPFC). The obsolescence rate of bridges decreases with an increase in the obsolescence time of bridges (OTB).

$$R \text{ ORB.KL} = \text{BFAPFC.K} / \text{OTB}$$

NOTE ORB - Obsolescence Rate of Bridges (Bridges/YR)

NOTE OTB - Obsolescence Time of Bridges (YR)

The widening of bridges (BW) is determined by dividing the budget for widening of bridges (BWB) by the bridge widening cost (BWC). The equation for widening of bridges is as shown below:

$$R \text{ BW.KL} = \text{BWB} / \text{BWC}$$

NOTE BW - Widening of Bridges (Bridges/YR)

NOTE BWC - Bridge Widening Cost (\$/Bridge)

The bridge widening budget is derived by multiplying the bridge budget by the fraction of the budget for bridge widening (FBBW). The DYNAMO equation for the bridge widening budget is as follows:

$$A \text{ BWB.K} = \text{BB} * \text{FBBW}$$

NOTE BWB - Bridge Widening Budget (\$/YR)

NOTE FBBW - Fraction Budget to Bridge Widening (DIM)

The number of bridges in functionally inadequate preferred condition increases (BFIPFC) with increases in functionally inadequate preventive maintenance of bridges (FIPMB), the functionally inadequate minor repairs of bridges (FIMNRB), the functionally inadequate major repairs of bridges (FIMJRB), and obsolescence rate of bridges (ORB). The number of bridges in functionally inadequate preferred condition decreases with an increase in the widening of bridges and the functionally inadequate exposure rate of bridges (FIERB). The Dynamo equation for bridges in functionally inadequate preferred condition is as shown below:

L BFIPFC.K=BFIPFC.J+(DT)(FIPMB.JK+FIMNRB.JK+FIMJRB.JK

+ORB.JK-BW.JK-FIERB.JK)

N BFIPFC=BFIPFCN

The other four level variables in this subsystem represent four physical levels (good, fair, poor, and critical) of functionally inadequate bridges. This part of the bridge management system model is nearly the same as shown above, with the same level variables of functionally adequate bridges. The DYNAMO equations for these three variables and related rate variables are as follows:

L BFIGC.K=BFIGC.J+(DT)(FIERB.JK-FIPMB.JK-FIDRB.JK)

N BFIGC=BFIGCN

NOTE BFIGC - Bridges in Functionally Inadequate Good Condition (BRIDGES)

R FIERB.KL=BFIPFC.K/ETB

NOTE FIERB - Functionally Inadequate Exposure Rate of Bridges (BRIDGES/YR)

R  $FIPMB.KL = FIPMBB.K / PMCB.K$

NOTE FIPMB - Functionally Inadequate Preventive Maintenance of Bridges

NOTE (BRIDGES/YR)

A  $FIPMBB.K = BB.K * FBFIPMB$

NOTE FIPMBB - Functionally Inadequate Preventive Maintenance Budget of

NOTE Bridges(\$/yr.)

R  $FIDRB.KL = BFIGC.K / DTTB$

NOTE FIDRB - Functionally Inadequate Deterioration Rate of Bridges

NOTE (BRIDGES/YR)

R  $FIMNRB.KL = FIMNRBB.K / MNRCB.K$

NOTE FIMNRB - Functionally Inadequate Minor Repair of Bridges

NOTE (BRIDGES/YR)

A  $FIMNRBB.K = BB.K * FBFINRB$

NOTE FIMNRBB - Functionally Inadequate Minor Repair Budget of Bridges

NOTE (\$/Yr)

L  $BFIFC.K = BFIFC.J + (DT)(FIDRB.JK - FIMNRB.JK - FIADRB.JK)$

N  $BFIFC = BFIFCN$

NOTE BFIFC - Bridges in Functionally Inadequate Fair Condition (BRIDGES)

R  $FIADRB.KL = BFIFC.K / ADTB$

NOTE FIADRB - Functionally Inadequate Accelerated Deterioration Rate of

NOTE Bridges (BRIDGES/YR)

R  $FIMJRB.KL = FIMJRBB.K / MJRCB.K$

NOTE FIMJRB - Functionally Inadequate Major Repair of Bridges (BRIDGES/YR)

A  $FIMJRBB.K = BB.K * FBFIJRB$

NOTE FIMJRBB - Functionally Inadequate Major Repair Budget of Bridges (\$/Yr)

$$L \text{ BFIPC.K} = \text{BFIPC.J} + (\text{DT})(\text{FIADR.B.JK} - \text{FIMJRB.JK} - \text{FISDRB.JK})$$

$$N \text{ BFIPC} = \text{BFIPCN}$$

NOTE BFIPC - Bridges in Functionally Inadequate Poor Condition (BRIDGES)

$$L \text{ BFICC.K} = \text{BFICC.J} + (\text{DT})(\text{FISDRB.JK} - \text{RPRB})$$

$$N \text{ BFICC} = \text{BFICCN}$$

NOTE BFICC - Bridges in Functionally Inadequate Critical Condition (BRIDGES)

$$R \text{ FISDRB.KL} = \text{BFIPC.K} / \text{SDTB}$$

NOTE FISDRB - Functionally Inadequate Serious Deterioration Rate of Bridges

NOTE (BRIDGES/YR)

$$R \text{ RPRB.KL} = \text{RPBB.K} / \text{RPCB.K}$$

NOTE RPRB - Replacement Rate of Bridges (BRIDGES/YR)

$$A \text{ RPBB.K} = \text{BB.K} * \text{FBRPB}$$

NOTE RPBB - Replacement Budget of Bridges (\$/YR)

The bridge physical adequacy index (BPAI) reflects the performance or physical condition of the bridge system. This index will have a value of 1 if all of the bridges are in preferred condition, and will have a value of 0 if all of the bridges are in critical condition. The DYNAMO equation for the bridge physical adequacy index is as shown below:

$$A \text{ BPAI.K} = (\text{BPFC.K} * \text{WFPFB} + \text{BGC.K} * \text{WFGB} + \text{BFC.K} * \text{WFFB} + \text{BPC.K} * \text{WFPB} + \text{BCC.K} * \text{WFCB}) / (\text{BPFC.K} + \text{BGC.K} + \text{BFC.K} + \text{BPC.K} + \text{BCC.K})$$

NOTE BPFC, BGC, BFC, BPC, BCC - The number of bridges in Preferred, Good,

NOTE Fair, Poor, Critical Condition.

NOTE BPAI - Bridge Physical Adequacy Index (DIM)

NOTE WFPFB - Weighting factor for Preferred Condition Bridges (DIM)

NOTE WFGB - Weighting factor for Good Condition Bridges (DIM)

NOTE WFFB - Weighting factor for Fair Condition Bridges (DIM)

NOTE WFPB - Weighting factor for Poor Condition Bridges (DIM)

NOTE WFCB - Weighting factor for Critical Condition Bridges (DIM)

### ***VI-3 Functional Subsystem***

The Functional Subsystem consists of routines for estimating the Life-Cycle Cost of Virginia's highway system. Life-Cycle Cost is a useful measure of effectiveness when the same amount of benefit is expected. For instance, when comparing between different design configurations for highway pavement, each of which has a different maintenance cost and construction cost, and a different deterioration time, Life-Cycle Cost can indicate the best alternative under the cost minimization criteria. However, a misapplication of Life-Cycle Cost analysis can lead to an unreasonable interpretation of the problem. For example, when evaluating the effects of increasing highway management budgets, misuse of a cost minimization approach using Life-Cycle Cost will lead to the conclusion that the "*do nothing policy*" is the best policy, which may not be reasonable.

The Life-Cycle Cost of a bridge system is estimated based on the various maintenance costs, such as preventive maintenance, major and minor repair, replacement, rehabilitation, and bridge widening costs. The DYNAMO equations for the discounted and undiscounted Life-Cycle Cost of a bridge system are as follows:

$$L \text{ BLCCD.K} = \text{BLCCD.J} + (\text{DT})(\text{TBED.JK})$$

NOTE BLCCD - Bridge Life Cycle Cost Discounted (\$)

$$R \text{ TBED.KL} = (\text{INFLF.K} * \text{TBEXPD.K}) / (1 + \text{DISR})^{**} \text{TIME.K}$$

NOTE TBED - Total Bridge Expenditure Discounted (\$/YR)

$$A \text{ INFLF.K} = (\text{INFLR} + 1) ** \text{TIME.K}$$

NOTE INFLF - Inflation Factor (DIM)

NOTE INFLR - Inflation Rate (DIM)

NOTE DISR - Interest Rate (DIM)

$$L \text{ BLCCUD.K} = \text{BLCCUD.J} + (\text{DT})(\text{TBEUD.JK})$$

NOTE BLCCUD - Bridge Life Cycle Cost Undiscounted (\$)

$$R \text{ TBEUD.KL} = (\text{INFLF.K} * \text{TBEXPD.K})$$

NOTE TBEUD - Total Bridge Expenditure Undiscounted (\$/YR)

The Life-Cycle Cost of a highway system includes the costs of highway expansion, maintenance for deficient highways, and maintenance for deteriorated highways. DYNAMO equations for highway Life-Cycle Cost are as shown below:

$$L \text{ HLCCUD.K} = \text{HLCCUD.J} + (\text{DT})(\text{THEUD.JK})$$

NOTE HLCCUD - Highway Life Cycle Cost Undiscounted (\$)

$$R \text{ THEUD.KL} = \text{INFLF.K} * (\text{THCE.K} + \text{THME.K})$$

NOTE THEUD - Total Highway Expenditure Undiscounted (\$/YR)

$$A \text{ THCE.K} = \text{ERH.KL} * \text{ECH.K}$$

NOTE THCE - Total Highway Construction Expenditure (\$/YR)

$$A \text{ THME.K} = \text{MRDFH.KL} * \text{MCDFH.K} + \text{MRDTH.KL} * \text{MCDTH.K}$$

NOTE THME - Total Highway Maintenance Expenditure (\$/YR)

$$L \text{ HLCCD.K} = \text{HLCCD.J} + (\text{DT})(\text{THED.JK})$$

NOTE HLCCD - Highway Life-Cycle Cost Discounted (\$)

$$R \text{ THED.KL} = (\text{INFLF.K} * (\text{THCE.K} + \text{THME.K})) / (1 + \text{DISR}) ** \text{TIME.K}$$

NOTE THED - Total Highway Expenditure Discounted (\$/YR)



The highway total maintenance expenditure consists of bridge maintenance expenditures and highway (pavement) maintenance expenditures. DYNAMO equations for discounted and undiscounted highway total maintenance expenditures are as shown below.

$$L \text{ HTMED.K} = \text{HTMED.J} + (\text{DT})(\text{TMED.JK})$$

NOTE HTMED - Highway Total Maintenance Expenditure Discounted (\$)

$$L \text{ HMEUD.K} = \text{HMEUD.J} + (\text{DT})(\text{TMEUD.JK})$$

NOTE HMEUD - Highway Total Maintenance Expenditure Undiscounted (\$)

$$R \text{ TMED.KL} = (\text{INFLF.K} * (\text{TBEXPD.K} + \text{THME.K})) / (1 + \text{DISR}) ** \text{TIME.K}$$

NOTE THED - Total Highway & Bridge Maintenance Expenditure Discounted  
NOTE (\$/YR)

$$R \text{ TMEUD.KL} = \text{INFLF.K} * (\text{TBEXPD.K} + \text{THME.K})$$

NOTE TMEUD - Total Highway & Bridge Maintenance Expenditure Undiscounted  
NOTE (\$/YR)

The highway total construction expenditure is the integration of annual construction expenditures for expanding highway lane-miles. DYNAMO equations for discounted and undiscounted highway total construction expenditures are as follows:

$$L \text{ HCEUD.K} = \text{HCEUD.J} + (\text{DT})(\text{TCEUD.JK})$$

NOTE HCEUD - Highway Total Construction Expenditure Undiscounted (\$)

$$R \text{ TCEUD.KL} = \text{INFLF.K} * \text{THCE.K}$$

NOTE TCEUD - Total Construction Expenditure Undiscounted (\$/YR)

#### ***VI-4 Evaluation Subsystem***

The Evaluation Subsystem will function as an evaluation routine for the entire HMS system, providing objective indices which will communicate the feasibility of the alternatives. The evaluation subsystem estimates user and non-user benefits together with other measures of effectiveness, such as the level of service, vehicle operating cost, net present value, benefit cost ratio, and the gasoline tax revenue maintenance budget ratio.

The weighted level of service factor (WLOSF) reflects the performance of the highway system and has a value between  $\alpha$  and  $\beta$ . When all of the highways and bridges are in sufficient and preferred condition, the weighted level of service factor has a value of 1. If all of the highway and bridges are in deteriorated and critical condition, the weighted level of service factor has a value of 6. The level of service factor (LOSF) is the normalization of the weighted level of service, and has a value between 0 and 1. The DYNAMO expression for weighted level of service factor and the level of service factor are as shown below:

$$A \text{ WLOSF.K} = ((\text{WHL} * (\text{WSFHL} * \text{HSFPC.K} + \text{WDFHL} * \text{HDFPC.K} + \text{WDTHL} * \text{HDTPC.K})) / \text{TOTALH.K}) + (\text{WBL} * (\text{WPFBL} * \text{BPFC.K} + \text{WGBL} * \text{BGC.K} + \text{WFBL} * \text{BFC.K} + \text{WPBL} * \text{BPC.K} + \text{WCBL} * \text{BCC.K}) / \text{TOTALB.K})$$

NOTE WLOSF - Weighted Level of Service Factor (DIM)

$$A \text{ LOSF.K} = \text{TABLE}(\text{LOSFT}, \text{WLOSF.K}, \alpha, \beta, \chi)$$

$$T \text{ LOSFT} = 0.1/0.2/0.3/0.4/0.6/1$$

NOTE WHL - Weighting Factor of Highway for LOSF (DIM)

NOTE WSFHL - Weighting Factor of Sufficient Highway for LOSF (DIM)

NOTE WDFHL - Weighting Factor of Deficient Highway for LOSF (DIM)

NOTE WDTHL - Weighting Factor of Deteriorated Highway for LOSF (DIM)

NOTE WBL - Weighting Factor of Bridge for LOSF (DIM)

NOTE WPFBL - Weighting Factor of Preferred Bridge for LOSF (DIM)

NOTE WGBL - Weighting Factor of Good Bridge for LOSF (DIM)

NOTE WFBL - Weighting Factor of Fair Bridge for LOSF (DIM)

NOTE WPBL - Weighting Factor of Poor Bridge for LOSF (DIM)

NOTE WCBL - Weighting Factor of Critical Bridge for LOSF (DIM)

NOTE LOSF-Level of Service Factor (DIM) ( $\alpha$  :MIN. Value of WLOSF,  $\beta$  :

NOTE MAX. Value of WLOSF,  $\chi$  :Interval of WLOSF)

The physical level service (PLS) is derived from the highway physical adequacy index (HPAI) multiplied by the bridge physical adequacy index (BPAI). This index reflects the combined physical condition of the entire highway and bridge system. The DYNAMO equation for the physical level of service is as shown below:

$$A \text{ PLS.K} = \text{HPAI.K} * \text{BPAI.K}$$

NOTE PLS - Physical Level Of Service (DIM)

The vehicle operating cost (VOPC) is a function of the physical level of service of the highway system. The bigger the value of the physical level of service, the smaller the vehicle operating cost. The DYNAMO equation for vehicle operating costs are as follows:

$$A \text{ VOPC.K} = (\text{TABLE}(\text{VOPCT}, \text{PLS.K}, 0, 1, 0.2)) * \text{TVOL.K} * \text{TOTMILG}$$

$$T \text{ VOPCT} = 0.4/0.3/0.22/0.18/0.16/0.15$$

NOTE VOPC - Vehicle Operating Cost (\$/MI)

NOTE TVOL - Annual Traffic Volume (VEH/YR)

NOTE TOTMILG-Average Travel Mileage (MILE)

The travel time of the entire highway network in the Salem District (TTL) is calculated using the well-known travel time formula based on the stochastic queuing concept. Travel time is a function of free flow travel time, the level of service factor, and the average volume-capacity ratio. The DYNAMO equation is as shown below:

$$A \text{ TTL.K} = \text{FFTTL.K} * (1 - (1 - \text{LOS.F.K}) * (\text{AVBC.K})) / (1 - \text{AVBC.K})$$

NOTE TTL - Travel Time (MIN)

NOTE FFTTL-Free Flow Travel Time (MIN)

NOTE AVBC-Average Vehicle by Capacity Ratio (DIM)

The user-benefit is derived from travel time savings. "User" means the direct highway users who travel on the network, while "non-user" means non-highway users who obtain indirect benefits from the highway. User-benefits are a function of traffic volume and travel time. Non-user benefits are derived from the savings of transportation cost by industries served by the network. Non-user benefit is also a function of travel time savings. The DYNAMO equation for user-benefit and non-user benefit is as follows:

$$L \text{ UUBEN.K} = \text{UUBEN.J} + (\text{DT})(\text{UAUBEN.JK})$$

NOTE UBEN - Undiscounted User-Benefit (\$)

$$R \text{ UAUBEN.KL} = ((\text{TTLN} - \text{TTL.K}) * \text{VOT} * \text{INFLF.K}) * ((\text{TVOL.K} + \text{TVOLN}) / 2)$$

NOTE UAUBEN- Undiscounted Annual User-Benefit (\$/YR)

$$L \text{ UNUBEN.K} = \text{UNUBEN.J} + (\text{DT})(\text{UANUBEN.JK})$$

NOTE UNUBEN - Undiscounted Non-User Benefit (\$)

R ANUBEN.KL=(PS.K\*PCIV.K\*DFIOI.K)

NOTE PCIV - Per Capita Income of Virginia (\$/MAN-YR)

NOTE ANUBEN - Annual Non-User Benefit (\$/YR)

A DFIOI.K=TABLE(DFIOIT,DFTT.K,-.5,.5,.1)

T DFIOIT=-.01/-.008/-.006/-.004/-.002/0/.002/.004/.006/.008/.01

NOTE DFIOI- Difference in Fraction Industry Output to Input (DIM)

A DFTT.K=(TTLN-TTL.K)/TTL.K

NOTE DFTT- Difference Fraction of Travel Time (DIM)

One of the important measures of effectiveness in evaluating highway management policy is the benefit/cost ratio, or B/C ratio (BCR). B/C ratio will increase with increases in user-benefits and non-user benefits, and will decrease with increases in maintenance expenditures and construction expenditures. The DYNAMO equation for the B/C ratio is as follows:

A BCR.K=CLIP(BCRN+((UAUBEN.KL+UANUBEN.KL-DFEXPD.K)/

(HCEUDE.K\*DISR)),BCRN,TIME.K,5.25)

N BCR=BCRN

C BCRN=1

NOTE BCR - Benefit Cost Ratio (DIM)

A DFEXPD.K=(HMB.K+BB.K)-(HMBN+BBN)

NOTE DFEXPD - DIFFERENCE IN MAINT. EXPENDITURE (\$)

NOTE HCEUDE-Highway Total Construction Expenditure (\$)

NOTE DISR-Discounted Rate(DIM)

NOTE N - Project Life (YR)

The gasoline tax revenue maintenance budget ratio (GTRMBR) is a measure of the self-sufficiency of a maintenance policy. In other words, it provides a measure of effectiveness that reflects how much of the maintenance budget is covered by the fuel tax. The DYNAMO equation for the gasoline tax revenue maintenance budget ratio is as follows.

$$A \text{ GTRMBR.K} = (\text{TVOL.K} * \text{TOTMILG} * \text{RMFT.K}) / ((\text{HMB.K} + \text{BB.K}) * \text{ADTPG.K})$$

NOTE GTRMBR - Gasoline Tax Revenue Maintenance Budget Ratio (DIM)

NOTE RMFT-Rate for Motor Fuel Tax (\$/Gal)

NOTE ADTPG-Average Distance Traveled per Gallon of Gasoline (Mi./Gal)

### ***VI-5 Financial Subsystem***

The Financial Subsystem includes routines concerning socio-economic factors, revenue generation, and budget allocation. Increased birth rates and in-migration rates contribute to Virginia's population growth; it is decreased by the death and out-migration rates. The number of vehicles registered and the state sales in Virginia are estimated using their own growth rates, based on historic data. Motor vehicle sales and use taxes in Virginia are proportional to the total value of vehicles registered in Virginia. The motor vehicle license fees are a function of the number of vehicles in Virginia. The motor fuel tax is estimated by using the average distance traveled per gallon of fuel, and the average vehicle mileage traveled. This again, is proportional to the number of vehicles in Virginia. The state sales tax is calculated with the state sales of the goods sold in the state and the rate for state sales tax.

Revenues predominantly come from the Transportation Trust Fund (TTF), and the Highway Management and Operation Fund (HMO). The motor vehicle license fees, motor vehicle sales and use taxes, motor fuel tax, and state sales tax, all contribute to

the TTF and HMO. The DYNAMO equations for TTF and HMO are as shown below:

$$A \text{ TTF.K} = \text{FMVLFT.K} * \text{MVLF.K} + \text{FMVSTT.K} * \text{MVSUT.K} + \text{FMFTT.K} * \text{MFT.K} + \text{FSST.K} * \text{SST.K}$$

NOTE TTF - Transportation Trust Fund (\$/YR)

NOTE MVLF - Motor Vehicle License Fee (\$/YR)

NOTE FMVLFT - Fraction Motor Vehicle License Fee to TTF (DIM)

NOTE MVSUT - Motor Vehicle Sales and Use Tax (\$/YR)

NOTE FMVSTT- Fraction Motor Vehicle Sales and Use Tax to TTF (DIM)

NOTE MFT - Motor Fuel Tax (\$/YR)

NOTE FMFTT - Fraction Motor Fuel Tax to TTF (DIM)

NOTE SST - State Sales Tax (\$/YR)

NOTE FSST - Fraction State Sales Tax to TTF (DIM)

$$A \text{ HMO.K} = \text{FMVLFH.K} * \text{MVLF.K} + \text{FMVSTH.K} * \text{MVSUT.K} + \text{FMFTH.K} * \text{MFT.K} + \text{FSSH.K} * \text{SST.K}$$

NOTE HMO - Highway Management and Operation Fund (\$/YR)

NOTE FMVLFH - Fraction Motor Vehicle License Fee to HMO (DIM)

NOTE FMVSTH- Fraction Motor Vehicle Sales and Use Tax to HMO (DIM)

NOTE FMFTH - Fraction Motor Fuel Tax to HMO (DIM)

NOTE FSSH - Fraction State Sales Tax to HMO (DIM)

An increase in the TTF, HMO, and in federal aid to Virginia enhances total transportation revenues. This increase in total transportation revenues leads to an increase in the bridge, and the highway maintenance, construction, and expansion budgets. The DYNAMO equation for total revenue is as shown below:

$$A \text{ TTRV.K} = \text{TTF.K} + \text{HMO.K} + \text{FAV.K}$$

NOTE TTRV - Total Transportation Revenue in Virginia (\$/YR)

NOTE FAV - Federal Aids for Virginia (\$/YR)

Various fraction variables for budget allocation, such as the fraction of budget for highway maintenance and the fraction of budget for highway construction, which represent policy and programming alternatives, are included in this subsystem.

This subsystem also allows for the evaluation of policies with the planned or unplanned budget alternatives. For planned cases, bridge budget and highway maintenance budgets become the fixed value, and for unplanned cases, both budgets come from revenue generation routines. The equations for bridge budgets and highway maintenance budgets provide two possible ways of evaluating budget alternatives using the DYNAMO clip function. DYNAMO equations for bridge budget and highway maintenance budgets are as follows:

$$A \text{ BB.K} = \text{CLIP}(\text{CLIP}(1.33\text{e}6 * \text{K}, 1.33\text{e}6, \text{TIME.K}, 5), \text{FCBB} * \text{HCBS.K} + \text{FMBB} * \text{HMBS.K}, \text{TIME.K}, 0)$$

NOTE BB - Bridge Budget (\$/YR)

$$A \text{ HMB.K} = \text{CLIP}(\text{CLIP}(6.2\text{E}6 * \text{K}, 6.2\text{E}6, \text{TIME.K}, 5), \text{FMBP.K} * \text{HMBS.K}, \text{TIME.K}, 0)$$

NOTE HMB - Highway Maintenance Budget for Pavement Management Only

NOTE(\$/YR)

NOTE K - Budget Multiplier (DIM)

$$A \text{ HCBS.K} = \text{FCBSD} * \text{HCBV.K}$$

NOTE HCB - Highway Construction Budget in Salem District (\$/YR)

NOTE FCBSD - Fraction Construction Budget to Salem District (DIM)

$$A \text{ HCBV.K} = \text{FBHC.K} * \text{ABH.K}$$



NOTE HCBV - Highway Construction Budget in Virginia (\$/YR)

$$A \text{ HMBS.K} = \text{FMBSD} * \text{HMBV.K}$$

NOTE HMBS - Highway Maintenance Budget in Salem District (\$/YR)

NOTE FMBSD - Fraction Maintenance Budget to Salem District (DIM)

$$A \text{ HMBV.K} = \text{FBHM} * \text{ABH.K}$$

NOTE HMBV - Highway Maintenance Budget in Virginia (\$/YR)

$$A \text{ ABH.K} = \text{FRHWY} * \text{TTRV.K}$$

NOTE ABH - Available Budget For Highway (\$/YR)

NOTE FRHWY - Fraction Revenue To Highway (DIM)

### ***VI-6 Administration Subsystem***

The highway system can be categorized as Interstate, Primary, Secondary and Urban systems. Each are planned, operated, and maintained by different means and standards. The Administration Subsystem affords the opportunity to produce the simulation result for the different categories of the highway system. This would represent an expansion of the model. The expansion of the model is discussed further in Chapter IX.

### ***VI-7 Refinement of the HMS Model***

The prototype HMS model which has been described thus far is based on fixed values of pavement and bridge maintenance costs, and budget allocation. This section describes the HMS model refined with continuous maintenance costs and variable fractions of the budget, which are dependent on the system state as measured by the level variables.

### VI-7-1 Continuous Maintenance Costs

The physical conditions of highways and bridges are distributed continuously although there exists an arbitrary border-line between each category, based on some measure of the physical conditions. Instead of using an average cost for each category of the physical state, continuous maintenance costs are employed in this refinement of the model. In other words, some pavements and bridges can remain in one physical state longer than can other pavements and bridges in the same category depending on the size of the relevant level variables. The average upgrade costs for bridges and highways which remain in one state longer, is higher than the other bridges or highways in the same group. Therefore, an application of continuous cost is more logical than a single cost figure.

A MCDFH.K(J)=TABLE(MCDFHT,HDFPC.K(J),0,600,150)\*INFLF.K

T MCDFHT=1500/5440/11842/21200/43000

NOTE MCDFH--Ordinary Maintenance Cost Of Highway (\$/LANE-MI)

A MCDTH.K(J)=TABLE(MCDTHT,HDTPC.K(J),0,600,150)\*INFLF.K

T MCDTHT=43000/76852/90150/95567/100000

NOTE MCDTH-- Maintenance Replacement Cost Of Highway (\$/LANE-MI)

A PMCB.K(I)=EP.K\*TABLE(PMCBT,BFAGC.K(I),0,200,50)\*INFLF.K

T PMCBT=3000/8610/14220/22635/31050

NOTE PMCB.K - Preventive Maintenance Cost Of Bridges (\$/BRIDGE)

A MNRCB.K(I)=EP.K\*TABLE(MNRCBT,BFAFC.K(I),0,200,50)\*INFLF.K

T MNRCBT=31050/47880/68450/95565/118005

NOTE MNRCB - Minor Repair Cost Of Bridges (\$/BRIDGE)

A MJRCB.K(I)=EP.K\*TABLE(MJRCBT,BFAPC.K(I),0,200,50)\*INFLF.K

T MJRCBT=118005/143250/157275/165690/171350

NOTE MJRCB - Major Repair Cost Of Bridge (\$/BRIDGE)

A RHCB.K(I)=EP.K\*TABLE(RHCBT,BFACC.K(I),0,200,50)\*INFLF.K

T RHCBT=171350/174990/178630/181360/185000

NOTE RHCB - Rehabilitation Cost Of Bridge (\$/BRIDGE)

NOTE EP - Expansion Parameter (DIM)

where I= 0.1 to 0.9, Fraction Budget to Preventive Maintenance of Bridge

J= 0.1 to 0.9, Fraction Maintenance Budget to Deficient Highway

### **VIII-7-2 Variable Budget Allocations**

In some cases, the level variable can reach zero during the simulation of the model, based on a fixed budget allocation. If the level variable is zero for a certain category, no budget should be allocated to that category. Furthermore, the savings of the budget from that category can be used for another category of highways and bridges. To make the model reflect this automatic adjustment in budget allocation, the fraction of the budget for each category of highways and bridges is varied, based on the level variables. If a level variable is zero at some point in time, which means that there is no need for this category of maintenance, the fraction for that category also becomes zero and the maintenance budget for that category is re-distributed to other categories. This refinement is done by changing the rate variables in the prototype HMS model using special functions, such as CLIP, MIN, MAX functions.

R FAPMB.KL(I)=MIN(FAPMBB.K(I)/PMCB.K(I),ABFAGC.K(I))

NOTE FAPMB-Functionally Adequate Preventive Maintenance Of Bridges

NOTE (BRIDGES/YR)

$$A \text{ FAPMBB.K(I)} = \text{BB.K} * \text{FBFAPMB.K(I)}$$

NOTE FAPMBB - Functionally Adequate Preventive Maintenance Budget Of  
NOTE Bridges (\$/YR)

$$A \text{ FBFAPMB.K(I)} = \text{AFBAPMB.K(I)} / \text{TFBBM.K(I)}$$

NOTE FBFAPMB - Fract. Budget To Functionally Adequate Preventive  
NOTE Maintenance Of Bridges (DIM)

$$A \text{ AFBAPMB.K(I)} = \text{CLIP}(\text{OFBAPMB.K(I)}, 0, \text{BFAGC.K(I)}, 0.999)$$

NOTE AFBAPMB - Adjusted Fract. Budget To Functionally Adequate  
NOTE Preventive Maintenance Of Bridges (DIM)

$$A \text{ TFBBM.K(I)} = \text{MAX}((\text{AFBAPMB.K(I)} + \text{AFBANRB.K(I)} + \text{AFBAJRB.K(I)} + \\ \text{AFBRHB.K(I)} + \text{AFBBW.K(I)} + \text{AFBIPMB.K(I)} + \text{AFBINRB.K(I)} + \text{AFBIJRB.K(I)} + \\ \text{AFBRPB.K(I)}), 0.000001)$$

NOTE TFBBM -- Total Fraction Of Budget To Bridge Maintenance (DIM)

$$A \text{ OFBAPMB.K(I)} = 0.1/0.3/0.5/0.7/0.9$$

NOTE OFBANRB -- Original Fract. Budget To Func Adequate Preventive  
NOTE Maintenance Of Bridges (DIM)

The complete listings of the DYNAMO equations for the prototype and refined version of the HMS model are presented in Appendices D and E.

## VII Steady State Analysis

### VII-1 Conserved System

The Physical Subsystem in the HMS can be conceptualized as consisting of two conserved systems. A conserved system means that the total physical amount in the model is always constant. In other words, the total number of bridges and the total lane-mileage is constant, unless new construction adds to the physical amount of the level variables in the PMS and the BMS. The sum of rate variables in the conserved system must be zero. These characteristics can be expressed as follows:

$$\sum_{i=1}^N SRV_i = 0 \text{ -----(Eq VII-1)}$$

where  $SRV_i$  = sum of rate variable in level variable  $i$

$i=1, \dots, N$  the number of level variables

A transient analytical solution is not always possible to obtain in a conserved system. A steady state solution is used for understanding the relationship and system state at equilibrium state. A transient solution can be obtained by solving a differential equation. A steady state solution can be obtained by substituting variables repeatedly after equating the sum of rate variables to zero. Detailed methods to obtain analytical solutions in various system dynamics models are well documented by Drew (1995).

**VII-2 Steady State Solution of the PMS model**

Steady State analysis of the level variables in each condition can be obtained by equalizing the improvement rate for highway pavement with its deterioration rate. In other words, rates of change for the level variables should be zero at the steady state or equilibrium state. The sum of the rates of change for the lane-mileage of highway pavement in sufficient condition should be zero at the equilibrium, or steady state as shown in (Eq VII-2)

$$MRDFHe + MRDThe + ERHe - ARHe = 0 \text{ -----(Eq VII-2)}$$

where MRDFHe is the steady state solution of the Maintenance Rate for Deficient Highways

MRDThe is the steady state solution of the Maintenance Rate for Deteriorated Highways

ERHe is the steady state solution of the Expansion Rate of Highways (assumed to be zero)

ARHe is the steady state solution of the Aging Rate of Highways

The steady state solution for lane-mileage in a sufficient pavement condition is obtained by replacing each rate variable with equations from the Pavement Management System (PMS) model and solving for the lane-mileage of highway pavement. (Eq VII-3).

$$HSFPCe = \frac{ATH * HMB * (FMBDFH * MCDTH + FMBDTH * MCDFH)}{MCDFH * MCDTH} \text{ -(Eq VII-3)}$$

where HSFPC<sub>e</sub> is the steady state solution of Highway in Sufficient Pavement Condition

ATH - Aging Time of Highway (YR)

HMB - Highway Maintenance Budget (\$/YR)

MCDFH- Maintenance Cost for Deficient Highway (\$/LANE-MI)

FMBDFH - Fraction Maintenance Budget to Deficient Highway (DIM)

FMBDTH - Fraction Maintenance Budget to Deteriorated Highway (DIM)

MCDTH - Maintenance Cost for Deteriorated Highway (\$/LANE-MI)

Similarly, the steady state solution for the lane-mileage of deficient pavement conditions can be obtained by making the sum of the related rate variables equal to zero, as shown in (Eq VII-4) below:

$$HDFPC_e = DTH \left( \frac{HSFPC_e}{ATH} - MRDFHe \right) \text{-----(Eq VII-4)}$$

where HDFPC<sub>e</sub> is the steady state solution of Highways in Deficient Pavement Condition

DTH - Deteriorating Time of Highway (YR)

By replacing HSFPC<sub>e</sub> in (Eq VII-4) with (Eq VII-3), (Eq VII-5) is obtained below:

$$HDFPC_e = DHT * \frac{HMB * FMBDTH}{MCDTH} \text{-----(Eq VII-5)}$$

The Pavement Management System is a conserved system if no expansion is assumed. Therefore, the total lane-mileage of highways (TOTALH) at any time will be the same as the initial total lane-mileage. The steady state solution of the critical condition of pavement (HDTPCe) can be obtained by subtracting the summation of the other level variables from the total highway lane-mileage which is the same as the initial value of the total highway lane-mileage (Eq VII-6). If the expansion increases, the total lane-mileage will increase, and so will the steady state solution of highways in deteriorated pavement condition.

$$HDTPCe = TOTALHN - (HSFPCe + HDFPCe) \text{ -----(Eq VII-6)}$$

where HDTPCe is the steady state solution of Highways in Deteriorated Pavement Condition

### ***VII-3 Steady State Nomograph Solution for the PMS***

The steady state solution can be presented in a more illustrative way in the nomograph, as shown in Figure VII-1, than in the mathematical form. The six diagrams in the nomograph chart are created based on the mathematical relationship between variables in the PMS model. This nomograph chart can be a useful aid for anyone who wants to know the steady state solution with various alternative values of maintenance costs and fractions of a budget.

An understanding of the mathematical steady state solution of the PMS is helpful for the utilization of the PMS nomograph chart. There are four diagrams in the PMS nomograph chart. Using Figure VII-1, one starts from one of the two diagrams with



maintenance costs and fraction variables, located at the bottom of the chart. Moving toward the two top charts with connections to values acquired in the diagrams below them leads to the steady state solutions of level variables.

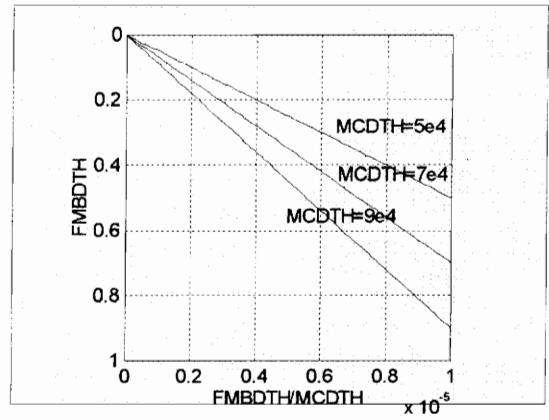
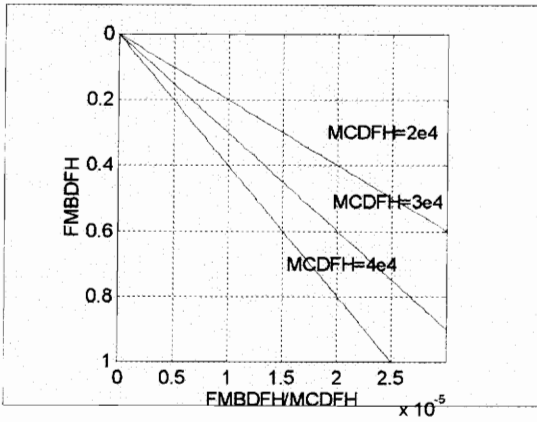
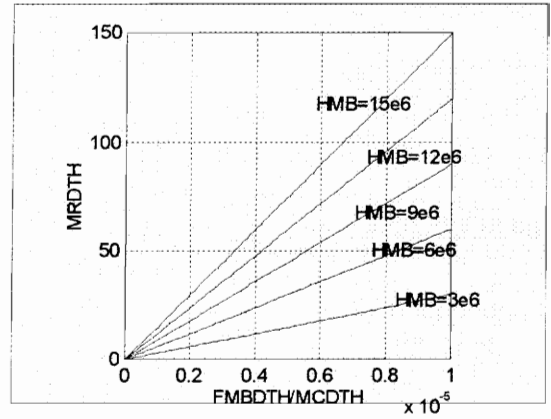
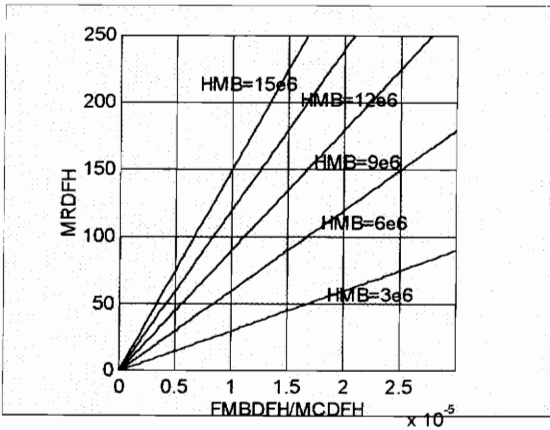
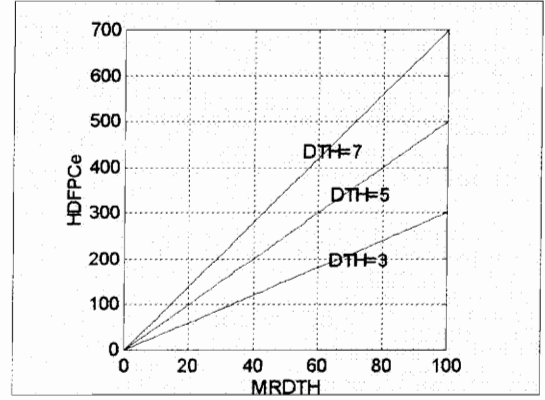
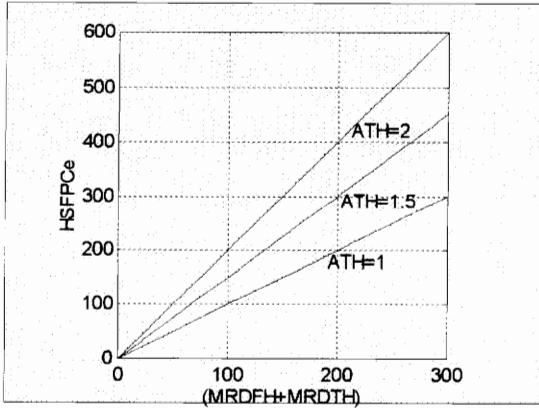


Figure VII-1 Nomograph Steady State Solution of the PMS

#### ***VII-4 Steady State Solution of the BMS model***

The steady state analysis of the Bridge Management System model is similar to that of the Pavement Management System, although it is more complicated owing to the large number of level variables which represent the physical and functional condition of bridges. As shown in the section VII-2.1, the summation of the rates of change for bridges in any condition must be zero at the steady state. Equalizing the summation of the rates of change for the number of preferred condition bridges to zero are presented in (Eq VII-7).

$$FAPMB_e + FAMNRB_e + FAMJRB_e + RHRB_e + RPRB_e + BWe - ORB_e - FAERB_e = 0$$

-----(Eq VII-7)

where FAPMB<sub>e</sub>: The Steady State Value of FAPMB (Functionally Adequate Preventive Maintenance of Bridges) (Bridges/Yr)

FAMNRB<sub>e</sub>: The Steady State Value of FAMNRB (Functionally Adequate Minor Repair of Bridges) (Bridges/Yr)

FAMJRB<sub>e</sub>: The Steady State Value of FAMJRB (Functionally Adequate Major Repair of Bridges) (Bridges/Yr)

RHRB<sub>e</sub>: The Steady State Value of RHRB (Rehabilitation of Bridges) (Bridges/Yr)

RPRB<sub>e</sub>: The Steady State Value of RPRB (Replacement of Bridges) (Bridges/Yr)

BWe: The Steady State Value of BW (Bridge Widening) (Bridges/Yr)

ORB<sub>e</sub>: The Steady State Value of ORB (Obsolescence Rate of Bridges) (Bridges/Yr)

FAERBe: The Steady State Value of FAERB (Functionally Adequate Exposure Rate of Bridges) (Bridges/Yr)

FAPMBe, FAMNRBe, FAMJRBe, RHRBe ≠ 0,

RPre, BWe=0 (The case when RPre, BWe ≠ 0 is illustrated in Appendix F.)

By substituting each rate variable into the model equations and solving for the number of bridges in the preferred condition, the steady state solution is obtained (Eq VII-8).

$$BFAPFC_e = \frac{BB \times ETB \times OTB \times (FBFAPMB \times RHCb \times MJRCb \times MNRCb + FBFAJRB \times RHCb \times MNRCb \times PMCB + FBRHB \times MJRCb \times MNRCb \times PMCB + FBFANRB \times RHCb \times MJRCb \times PMCB)}{(ETB + OTB) \times RHCb \times MJRCb \times MNRCb \times PMCB} \text{ -----(Eq VII-8)}$$

where BFAPFCe is the steady state solution of BFAPFC (Bridges in Functionally Adequate Preferred Condition)

ETB - Exposure Time of Bridges (YR)

OTB - Obsolescence Time of Bridges (YR)

BB - Bridge Budget (\$/YR)

PMCB - Preventive Maintenance Cost of Bridge (\$/Bridge)

MNRCB - Minor Repair Cost of Bridges (\$/Bridge)

MJRCB - Major Repair Cost of a Bridge (\$/Bridge)

RHCb - Rehabilitation Cost of a Bridge (\$/Bridge)

FBFAPMB - Fraction Budget to Functionally Adequate Preventive Maintenance of Bridges (DIM)

FBFANRB - Fraction Budget to Functionally Adequate Minor Repairs of Bridges (DIM)

FBFAJRB - Fraction Budget to Functionally Adequate Major Repair of Bridges (DIM)

FBRHB - Fraction Budget to Rehabilitation of Bridges (DIM)

Similarly, the steady state solution for the rest of the level variables can be obtained by making the summation of the related rate variables zero as shown in (Eq VII-9) through (Eq VII-15) below.

$$BFAGC_e = DTTB \times BB \times \frac{OTB \times (FBFAPMB \times RHC B \times MJRCB \times MNRCB + FBFAJRB \times RHC B \times MNRCB \times PMCB + FBRHB \times MJRCB \times MNRCB \times PMCB + FBFANRB \times RHC B \times MJRCB \times PMCB) - (ETB + OTB) \times (FBFAPMB \times RHC B \times MNRCB \times MJRCB)}{(ETB + OTB) \times RHC B \times MJRCB \times MNRCB \times PMCB} \text{-----(Eq VII-9)}$$

where BFAGCe is the steady state solution of BFAGC (Bridges in Functionally Adequate Good Condition)

DTTB - Deterioration Time of Bridges (YR)

$$BFAFC_e = ADTB \times BB \times \frac{OTB \times (FBFAPMB \times RHC B \times MJRCB \times MNRCB + FBFAJRB \times RHC B \times MNRCB \times PMCB + FBRHB \times MJRCB \times MNRCB \times PMCB + FBFANRB \times RHC B \times MJRCB \times PMCB) - (ETB + OTB) \times (FBFAPMB \times RHC B \times MNRCB \times MJRCB + FBFANRB \times RHC B \times PMCB \times MJRCB)}{(ETB + OTB) \times RHC B \times MJRCB \times MNRCB \times PMCB} \text{-----(Eq VII-10)}$$

where BFAFCe is the steady state solution of BFAFC (Bridges in Functionally Adequate Fair Condition)

ADTB - Accelerated Deterioration Time of Bridges (YR)

$$BFAPC_e = SDTB \times BB \times \frac{OTB \times (FBFAPMB \times RHC B \times MJRC B \times MNRC B + FBFAJRB \times RHC B \times MNRC B \times PMCB + FBRHB \times MJRC B \times MNRC B \times PMCB + FBFANRB \times RHC B \times MJRC B \times PMCB) - (ETB + OTB) \times (FBFAPMB \times RHC B \times MNRC B \times MJRC B + FBFAJRB \times RHC B \times PMCB \times MNRC B)}{(ETB + OTB) \times RHC B \times MJRC B \times MNRC B \times PMCB} \text{-----(Eq VII-11)}$$

where BFAPCe is the steady state solution of BFAPC (Bridges in Functionally Adequate Poor Condition)

SDTB - Serious Deterioration Time of Bridges (YR)

$$BFIPFC_e = ETB \times BB \times \frac{ETB \times (FBFAPMB \times RHC B \times MJRC B \times MNRC B + FBFAJRB \times RHC B \times MNRC B \times PMCB + FBRHB \times MJRC B \times MNRC B \times PMCB + FBFANRB \times RHC B \times MJRC B \times PMCB) + (ETB + OTB) \times (FBFIPMB \times RHC B \times MNRC B \times MJRC B + FBFINRB \times RHC B \times PMCB \times MJRC B + FBFLJRB \times RHC B \times PMCB \times MNRC B)}{(ETB + OTB) \times RHC B \times MJRC B \times MNRC B \times PMCB} \text{-----(Eq VII-12)}$$

where BFIPFCe is the steady state solution of BFIPFC (Bridges in Functionally Inadequate Preferred Condition)

FBFIPMB - Fraction Budget to Functionally Adequate Preventive Maintenance of Bridges (DIM)

FBFINRB - Fraction Budget to Functionally Adequate Minor Repairs of Bridges (DIM)

FBFIJRB - Fraction Budget to Functionally Adequate Major Repair of Bridges (DIM)

FIPMBe, FIMNRBe, FIMJRBe ≠ 0

$$\begin{aligned}
 BFIGC_e = DTTB \times BB \frac{ETB \times (FBFAPMB \times RHC B \times MJRCB \times MNRCB + FBFAJRB \times RHC B \times MNRCB \times PMCB + \\
 FBRHB \times MJRCB \times MNRCB \times PMCB + FBANRB \times RHC B \times MJRCB \times PMCB) + (ETB + OTB) \times (FBFINRB \times RHC B \times \\
 RHC B \times MJRCB \times \\
 MNRCB \times PMCB + FBFIJRB \times RHC B \times PMCB \times MNRCB)}{(ETB + OTB) \times \\
 MNRCB \times PMCB} \text{-----} (Eq VII-13)
 \end{aligned}$$

where BFIGCe is the steady state solution of BFIGC (Bridges in Functionally Inadequate Good Condition)

$$\begin{aligned}
 BFIFC_e = ADTB \times BB \frac{ETB \times (FBFAPMB \times RHC B \times MJRCB \times MNRCB + FBFAJRB \times RHC B \times MNRCB \times PMCB + \\
 FBRHB \times MJRCB \times MNRCB \times PMCB + FBANRB \times RHC B \times MJRCB \times PMCB) + (ETB + OTB) \times (FBFIJRB \times RHC B \times \\
 RHC B \times MJRCB \times \\
 MNRCB \times PMCB)}{(ETB + OTB) \times \\
 MNRCB \times PMCB} \text{-----} (Eq VII-14)
 \end{aligned}$$

where BFIFCe is the steady state solution of BFIFC (Bridges in Functionally Inadequate Fair Condition)

$$BFIPC_e = SDTB \times BB \frac{ETB \times (FBFAPMB \times RHCb \times MJRCb \times MNRCb + FBFAJRB \times RHCb \times MNRCb \times PMCB + FBRHB \times MJRCb \times MNRCb \times PMCB + FBFANRB \times RHCb \times MJRCb \times PMCB)}{(ETB + OTB) \times RHCb \times MJRCb \times MNRCb \times PMCB} \text{-----}(\text{Eq VII-15})$$

where BFIPCe is the steady state solution of BFIPC (Bridges in Functionally Inadequate Poor Condition)

The Bridge Management System is a conserved system if no new bridge construction is considered. Therefore, the total number of bridge (TOTALB) at any time will be the same as the initial total number of bridges. The steady state solution of the number of critical condition bridges can be obtained by subtracting the summation of the other level variables from total number of bridges which is identical to the initial value of the total number of bridges (Eq VII-16).

$$BCCe = TOTALBN - (BFAPFCe + BFAGCe + BFAFCe + BFAPCe + BFIPFCe + BFIGCe + BFIFCe + BFIPCe) \text{-----}(\text{Eq VII-16})$$

where TOTALBN is the initial value of total number of bridges (Bridges)



**VII-5 Steady State Nomograph Solution for the BMS**

The steady state solution of bridges in functionally adequate good condition (BFAGCe) can be described as a function of functionally adequate preferred condition (BFAPFCe) as follows:

$$BFAGC_e = DTTB \left( \frac{BFAPFC_e}{ETB} - \frac{BB \times FBFAPMB}{PMCB} \right) \text{-----} \text{(Eq VII-17)}$$

The relationship between BFAGCe and the steady state solution of bridges in functionally adequate fair condition (BFAFCe) can be formulated as follows:

$$BFAFC_e = ADTB \left( \frac{BFAGC_e}{DTTB} - \frac{BB \times FBFANRB}{MNRCB} \right) \text{-----} \text{(Eq VII-18)}$$

By replacing BFAGCe in (Eq VII-18) with (Eq VII-17)

$$BFAFC_e = ADTB \left( \frac{BFAPFC_e}{ETB} - \frac{BB \times FBFAPMB}{PMCB} - \frac{BB \times FBFANRB}{MNRCB} \right) \text{-----} \text{(Eq VII-19)}$$

The relationship between BFAFCe and the steady state solution of bridges in functionally adequate poor condition (BFAPCe) is as follows:

$$BFAPC_e = SDTB \left( \frac{BFAFC_e}{ADTB} - \frac{BB \times FBF AJRB}{MJRCB} \right) \text{-----} \text{(Eq VII-20)}$$

By replacing BFAGCe in (Eq VII-20) with (Eq VII-19)

$$BFAPC_e = SDTB \left( \frac{BFAPFC_e}{ETB} - \frac{BB \times FBFAPMB}{PMCB} - \frac{BB \times FBFANRB}{MNRCB} - \frac{BB \times FBF AJRB}{MJRCB} \right) \text{-----} \text{(Eq VII-21)}$$

These relationships between steady state solutions for bridge level variables can be depicted as nomographs as shown in Figures VII-2 and VII-3.

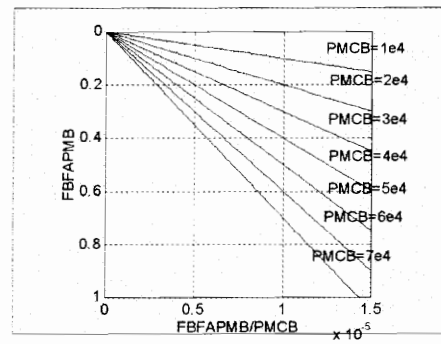
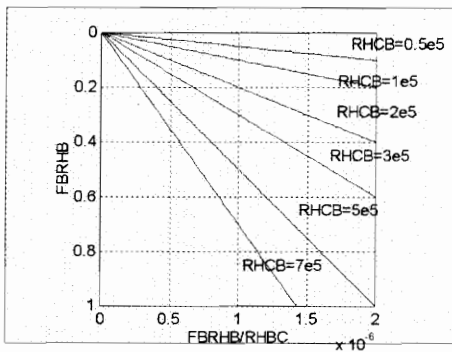
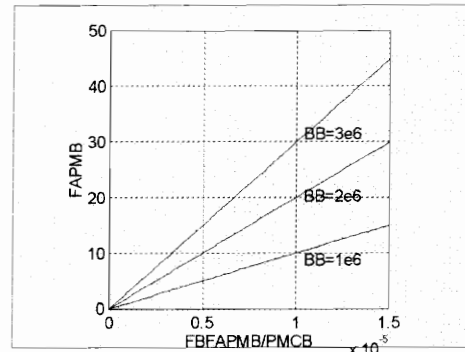
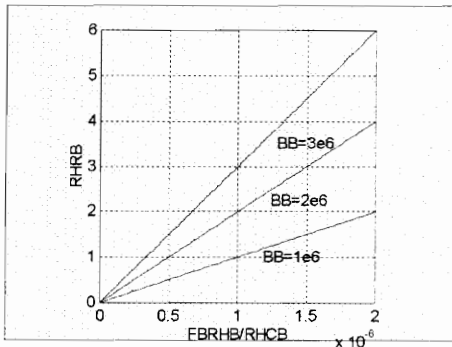
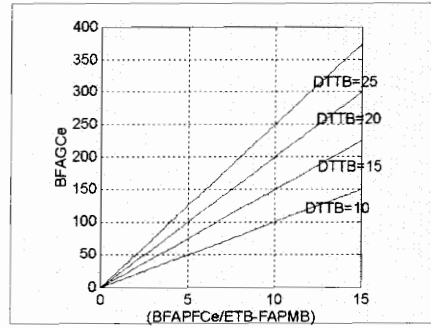
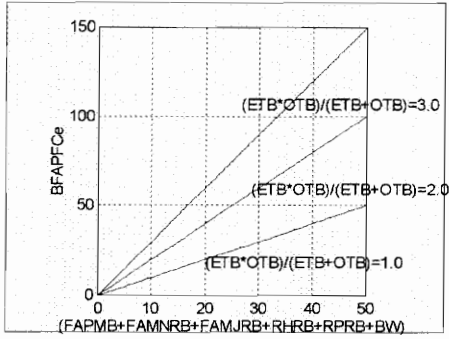
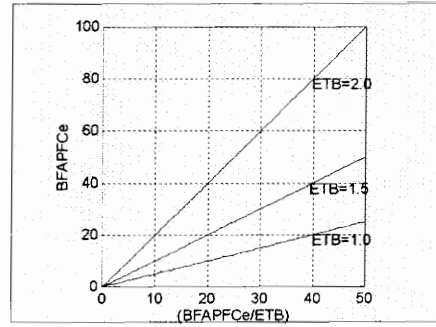
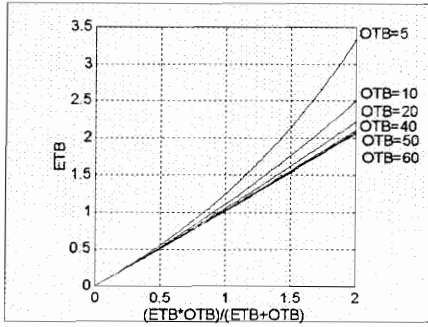


Figure VII-2 Nomograph Steady State Solution of the BMS (1)

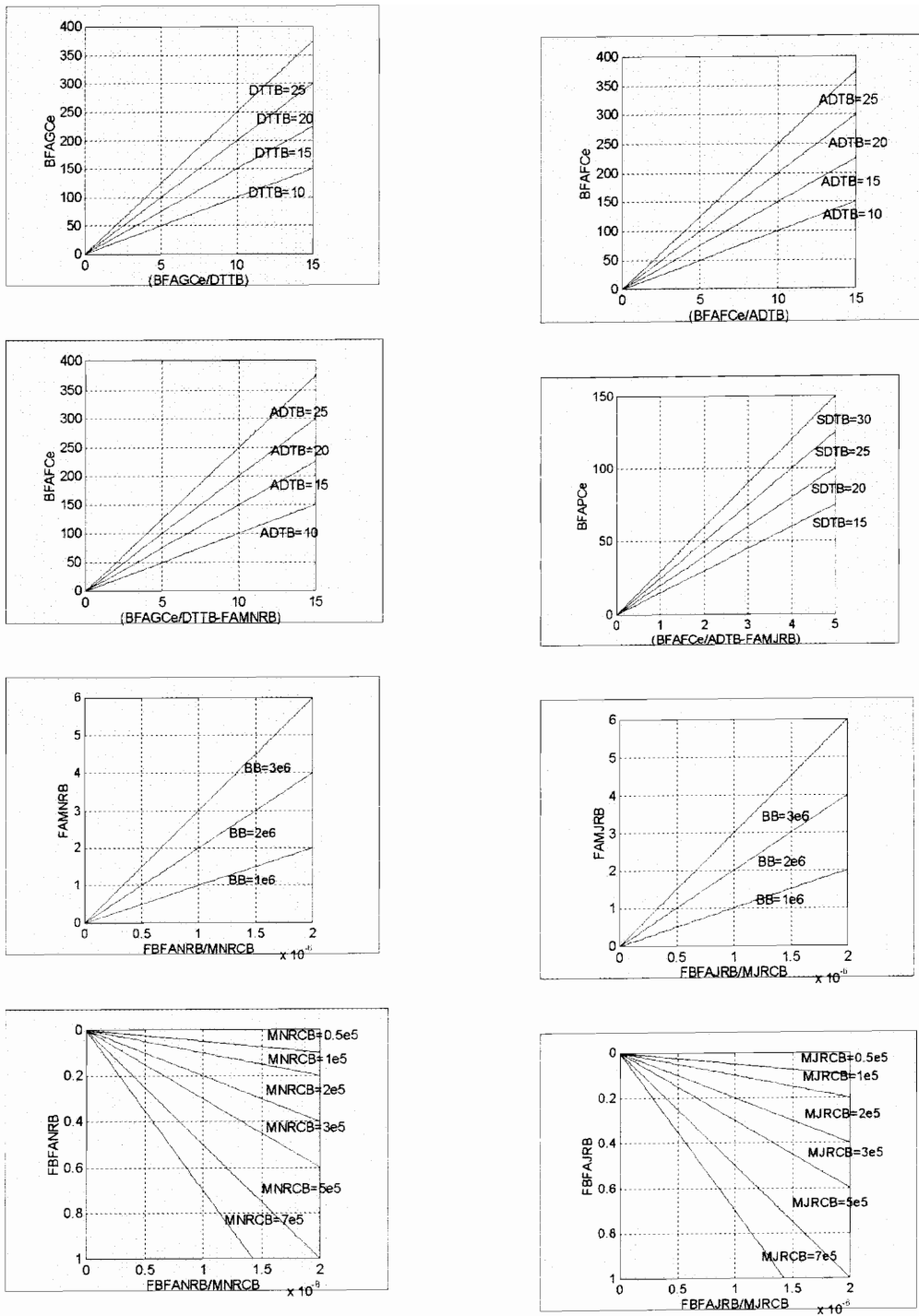


Figure VII-2 Nomograph Steady State Solution of the BMS (2)

## **VIII Simulation Results and Implications**

### ***VIII-1 Basic Simulation***

This section illustrates basic simulation results of the prototype HMS model, showing the behaviors of the PMS and BMS state variables over time, under the base case budget and budget allocation. The base year for the simulation is assumed to be the year 2000. Expansion of the Salem section of I-81 is assumed for the simulation using the prototype HMS and the refined HMS. The addition of a lane to I-81 is assumed to commence at the year 2000 and to be completed in five years.

Figure VIII-1 shows the behavior of the level variables representing pavement condition. The final values of the level variables correspond to the analytical steady state solutions, which are plotted in Appendix G. The highway expansion of I-81 causes an increases in pavement level variables during first five years.

After expansion, the level variables representing sufficient pavement and deficient pavement condition highways decrease, and remain at steady state values. The level variable for deteriorated condition highways increases, and approaches the higher steady state value after the expansion period. This shows that the service level of the highway will be diminished after the expansion of I-81, if the maintenance budget is not increased.

Figure VIII-2 shows the behavior of the level variables representing bridge conditions. Although overall maintenance costs are increased about 50% at year five by the expansion of I-81, bridge conditions show much stability over time.

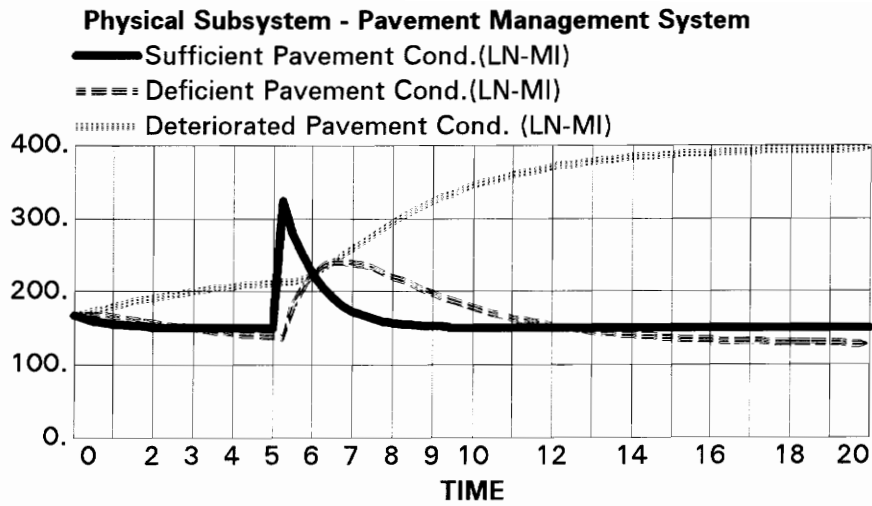


Figure VIII-1 Simulation Result of Highway Pavement Condition

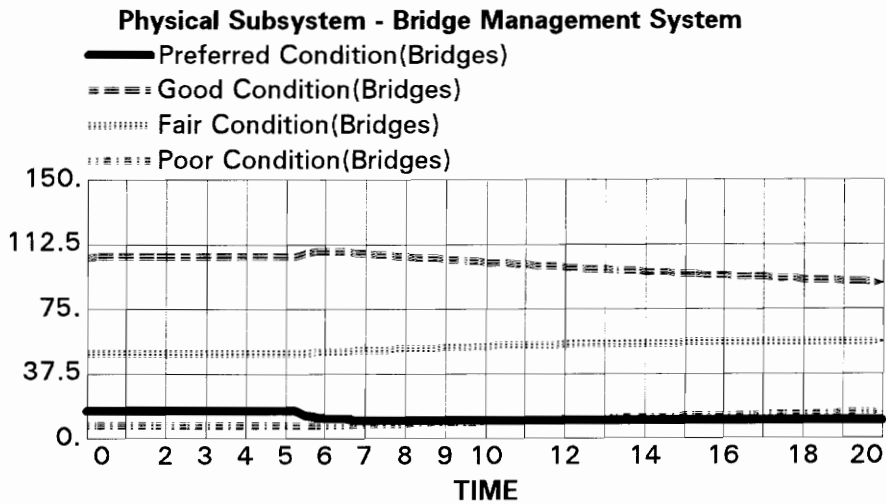


Figure VIII-2 Simulation Result of Highway Bridge Condition

## ***VIII-2 Simulation Results of the Refined Model***

In this section, various simulations of the refined version of the HMS model are done with variable budget allocations and budget size. To illustrate the effect of the refinement of the model, behaviors of allocations in the refined version of the HMS model are described in the following section. In the following sections, the MOEs, such as travel time, travel speed, Life-Cycle-Cost, user and non-user benefits, benefit/cost ratio, and gasoline tax revenue maintenance budget ratio, are illustrated in various graphical forms based on various budget size and allocation options.

### **VIII-2-1 Behavior of Adjusted Allocation Variables**

The fluctuations in the fractional allocations of the maintenance budgets to deficient highways in response to physical system states are shown in Figure VIII-3. In Figure VIII-3, the behavior of the fractional allocations of the PMS are so stable that there is no adjustment of allocation variables due to a zero level variable. The fluctuations in the fractional allocations of the bridge budget for preventive maintenance of the bridge in response to physical system states are also depicted in Figure VIII-4. In Figure VIII-4, the behavior of the allocation variables show significant fluctuations. These fluctuations primarily come from the complexity of the system. The BMS has eleven level variables; some of the variables have an initial value of zero. These fluctuations are the inevitable result of higher order feedback systems and demonstrate vividly the difficulty in implementing a variable budget allocation policy.

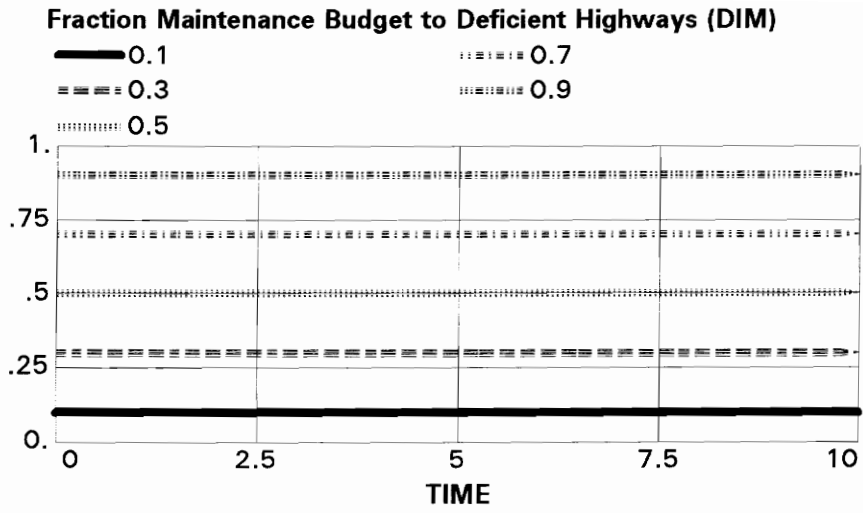


Figure VIII-3 Adjusted Budget Allocation: FMBDFH (Normalized MBPILM=1)

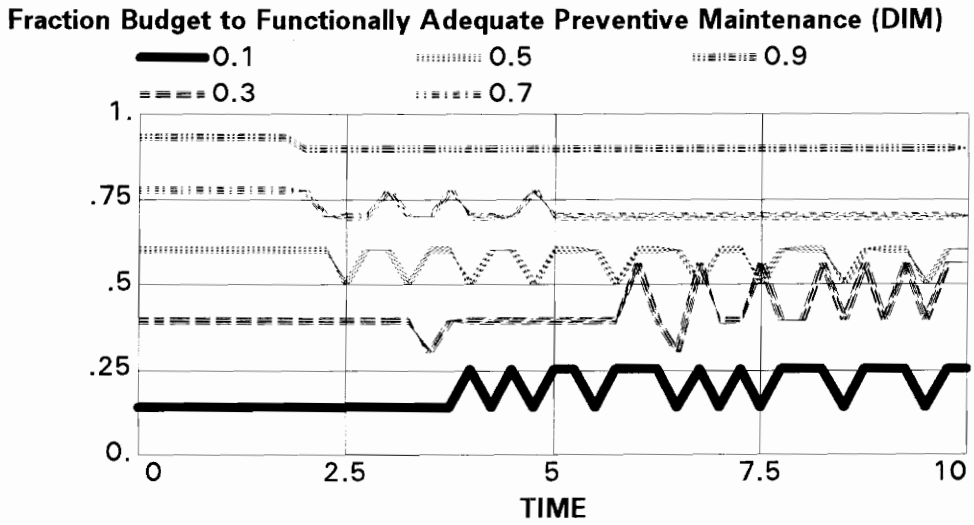


Figure VIII-4 Adjusted Budget Allocation: FBFAPMB (Normalized MBPILM=1)



## **VIII-2-2 Travel Time and Travel Speed**

Travel time and speed are critical MOEs which can tell us traffic conditions and which affect other measures of effectiveness, such as user-benefits or non-user benefits. Travel speed, combined with free flow speed, can be used as the level of service index, which is discussed in Chapter III. Figure VIII-5 and Figure VIII-6 indicate behaviors of travel time and travel speed versus simulation time based on budget size. The normalized maintenance budget per interstate lane mile (MBPILM; K in the DYNAMO program) represents the ratio of the maintenance budget after expansion to the maintenance budget before expansion.

In Figure VIII-5, travel time increases for the first 5 years, which indicate that an increase in travel volume aggravates the traffic condition. The increase in capacity, owing to the expansion of the I-81, brings a sudden fall in travel time at year 5, and then travel time increases again due to a travel volume increase and physical deterioration. In Figure VIII-6, travel speed behaves in the opposite way, because speed is proportional to the reciprocal of travel time. The interesting thing is that without an increase in the maintenance budget, service conditions will be back to the pre-expansion conditions about at year 9.5, and an increase in the maintenance budget will extend this period.

Figure VIII-7 and VIII-8 show relationships of travel time and travel speed to budget size. These figures indicate that an increase in budget size affects travel time and travel speed favorably. Figure VIII-9 and VIII-10 are contours, indicating travel time and speed versus two allocation variables, such as the fraction of the maintenance budget to deficient highways (FMBDFH) and the fraction of the budget to functionally adequate preventive maintenance of bridges (FBFAPMB). These charts aid in decision-making in budget allocations in maintenance of pavements and bridges

based on the criteria of travel time and travel speed. It is interesting that the optimum decision point occurs where FMBDFH is 0.3, as shown in Figure VIII-9 and VIII-10,

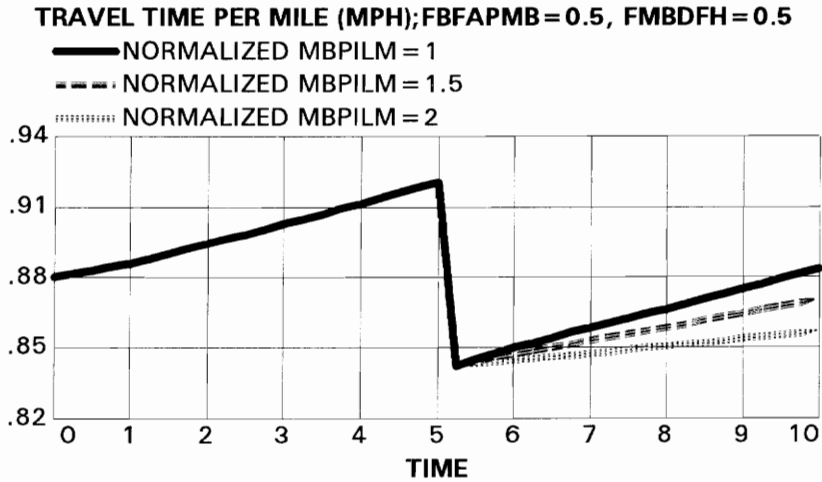


Figure VIII-5 Avg. Travel Time Per Mile During Peak Hour-- Time Plot FBFAPMB=0.5, FMBDFH=0.5; at year 7 (Min./Mi.)

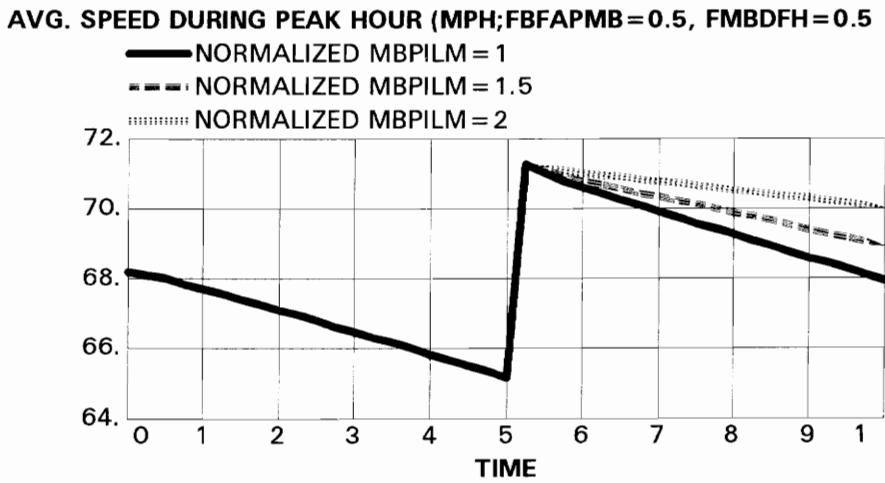


Figure VIII-6 Avg. Speed During Peak Hour-- Time Plot FBFAPMB=0.5, FMBDFH=0.5; at year 7 (mile/hr)

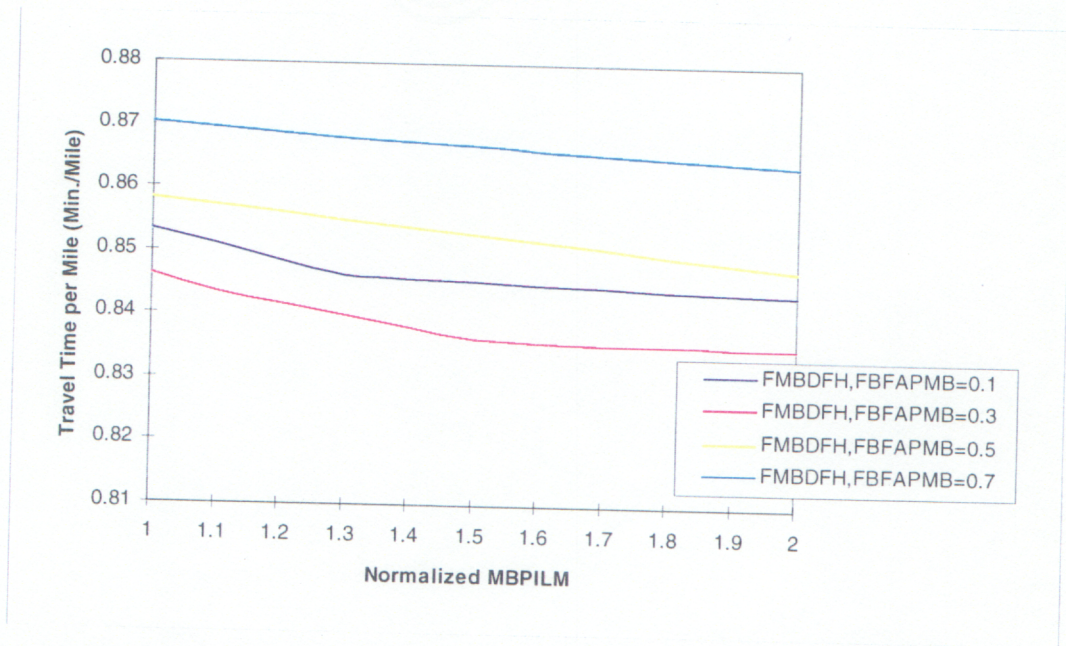


Figure VIII-7 Travel Time per Mile-- Simple Graph Vs. Normalized Maintenance Budget; at year 7 (Min./mile)

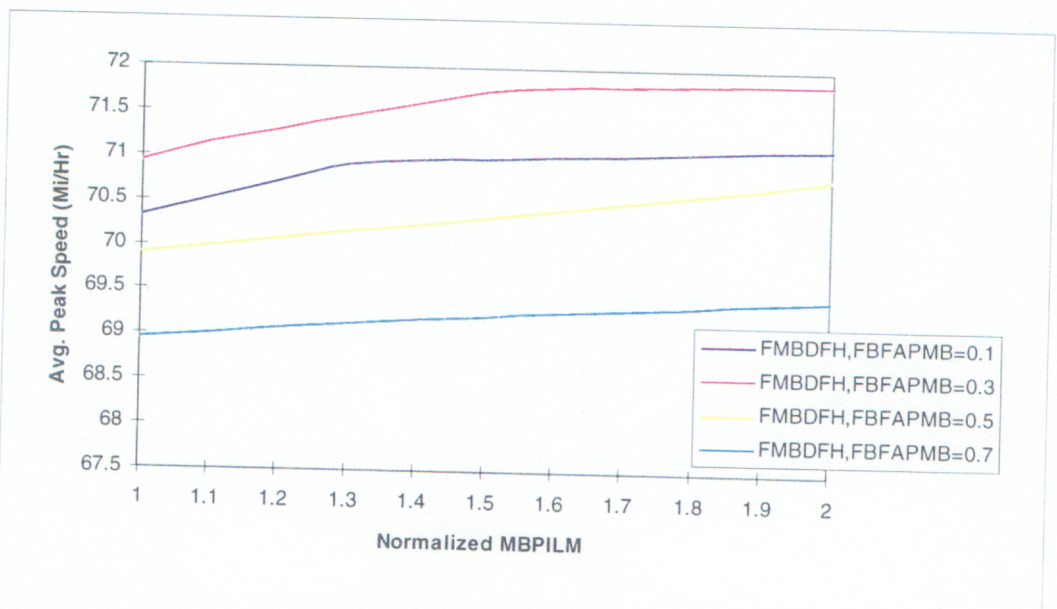


Figure VIII-8 Peak Hour Avg. Speed-- Simple Graph Vs. Normalized Maintenance Budget; at year 7 (mile/hr)

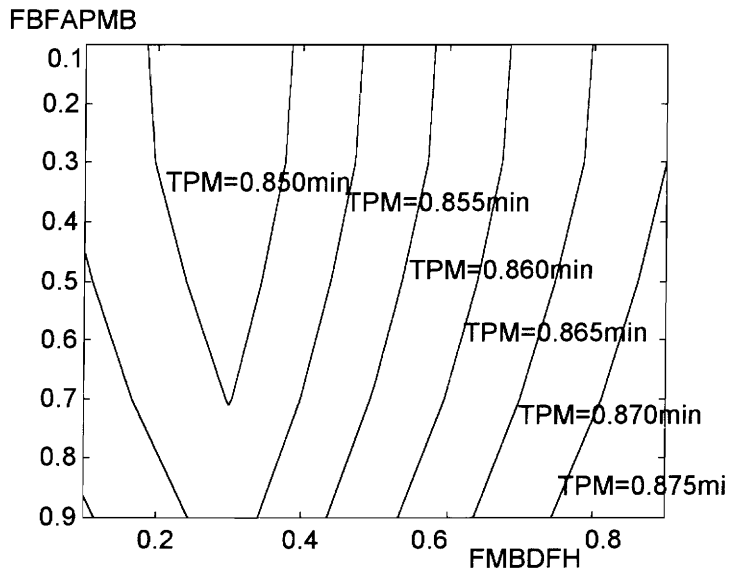


Figure VIII-9 Travel Time per Mile--Contour (Normalized MBPILM=1) at year 7

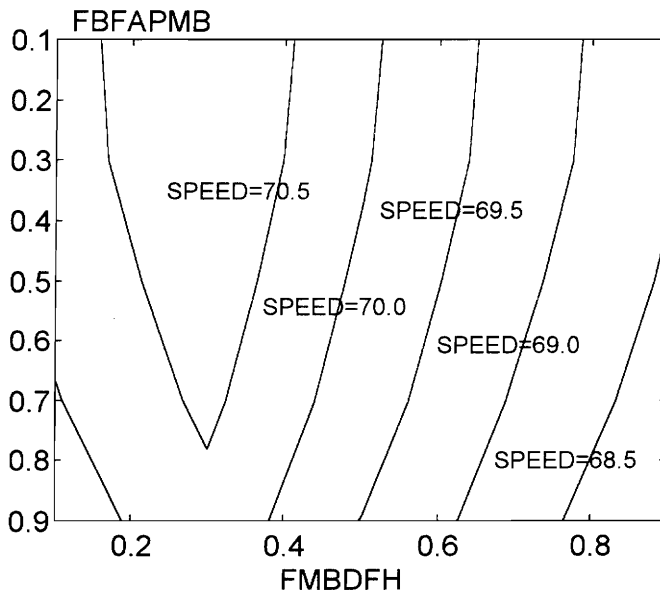


Figure VIII-10 Avg. Speed During Peak Hour--Contour (Normalized MBPILM=1) at year 7

### VIII-2-3 Life-Cycle Cost (LCC)

Figure VIII-11 indicates the total LCC of the highway and bridge systems. As shown in the figure, the total LCC is proportional to the increase in the budget. In other words, an increased investment gives us a higher total LCC. However, this does not mean less investment gives us a better result. As discussed in Section IV-8, a cost minimization scheme necessarily requires assumptions that the alternatives should have the same amount of benefits, which is not the case in the HMS model.

Figure VIII-12 shows contours indicating LCC versus two allocation variables, FMBDFH and FBFAPMB. This result also cannot be used for the selection of the best alternative, because the pairs of decision variables give us different levels of user and non-user benefits. However, this can be used in combination with other MOE contours. For example, LCC contours can be used for determination of a cost minimization point among the points on a contour line which indicate equal MOE levels.

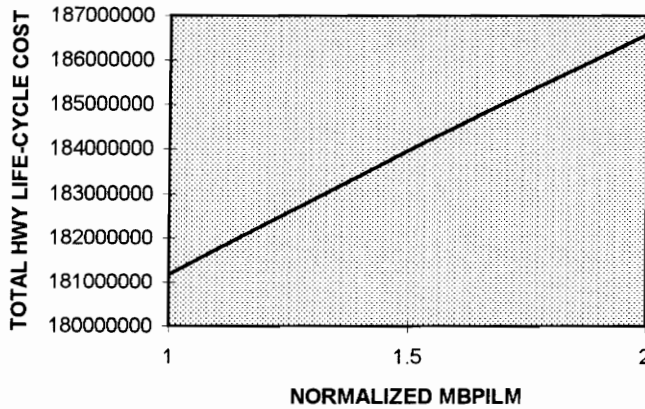


Figure VIII-11 Total Life-Cycle Cost--  
Simple Graph Vs. Normalized Maintenance Budget (\$) at year 7

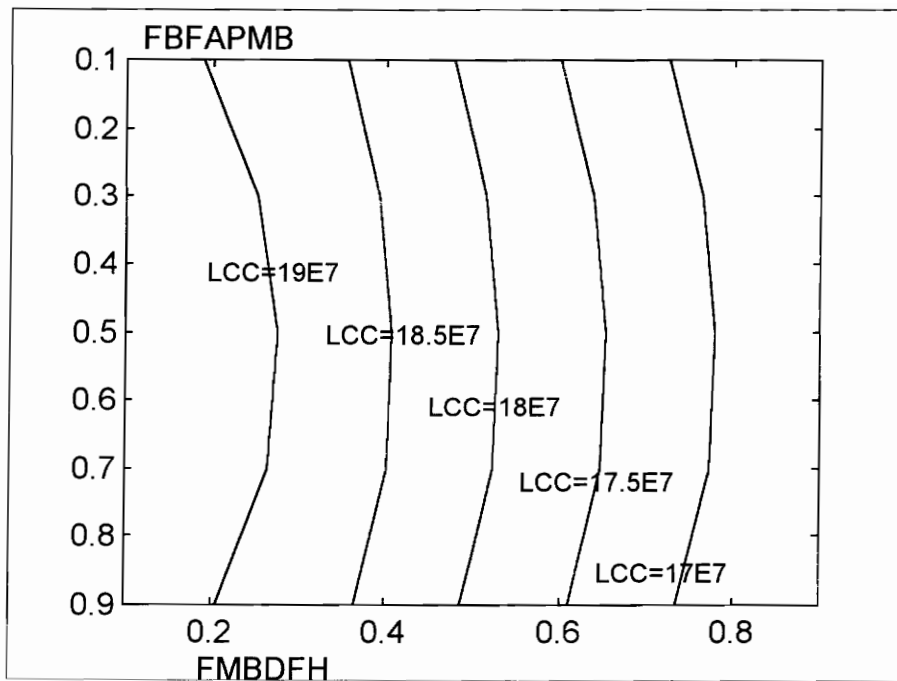


Figure VIII-12 Total Life-Cycle Cost-- Contour Normalized MBPILM=1; year 7 (\$)

#### VIII-2-4 User and Non-User Benefits

The dynamic behaviors of user-benefits and non-user benefits are depicted in Figure VIII-13 and VIII-14. User-benefits and non-user benefits are functions of travel times, and behave similarly to average speed in the previous section. Figures VIII-15 and VIII-16 indicate relationships of user-benefits and non-user benefits to budget size. An increased budget also affects user-benefits and non-user benefits positively.

Contours, indicating user-benefits and non-user benefits against two allocation variables, FMBDFH and FBFAPMB, are represented in Figures VIII-17 and VIII-18. These contours show that the optimum decision occurs where FMBDFH is 0.3, based on user-benefits and non-user benefits.

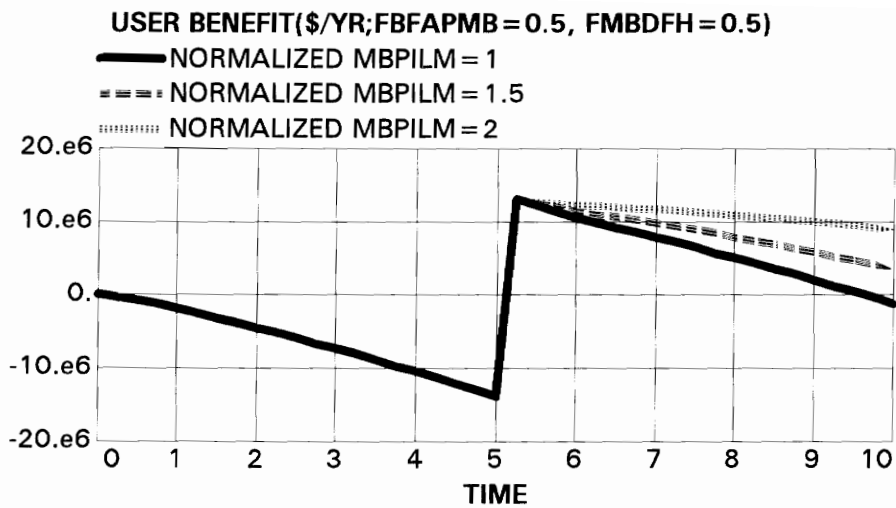


Figure VIII-13 Annual User-Benefit-- Time Plot (\$/yr.) at year 7

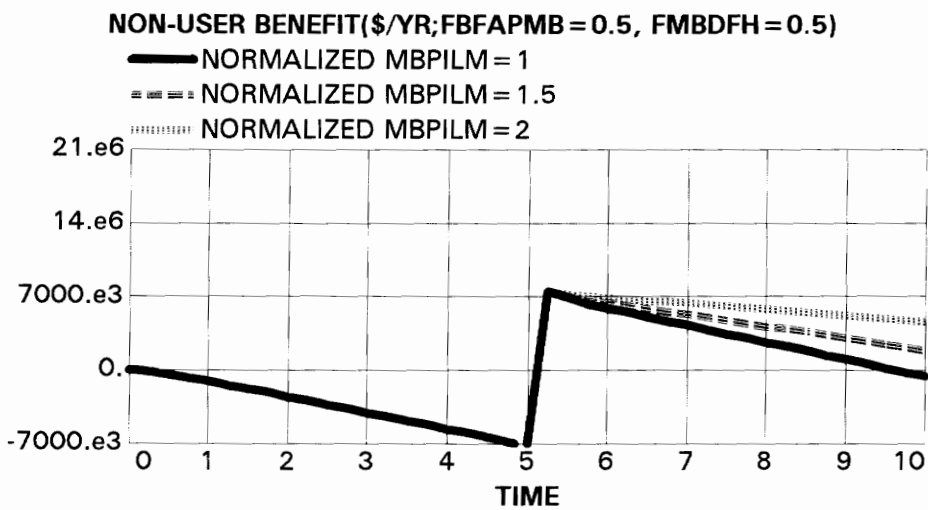


Figure VIII-14 Annual Non-User Benefit-- Time Plot (\$/yr.)

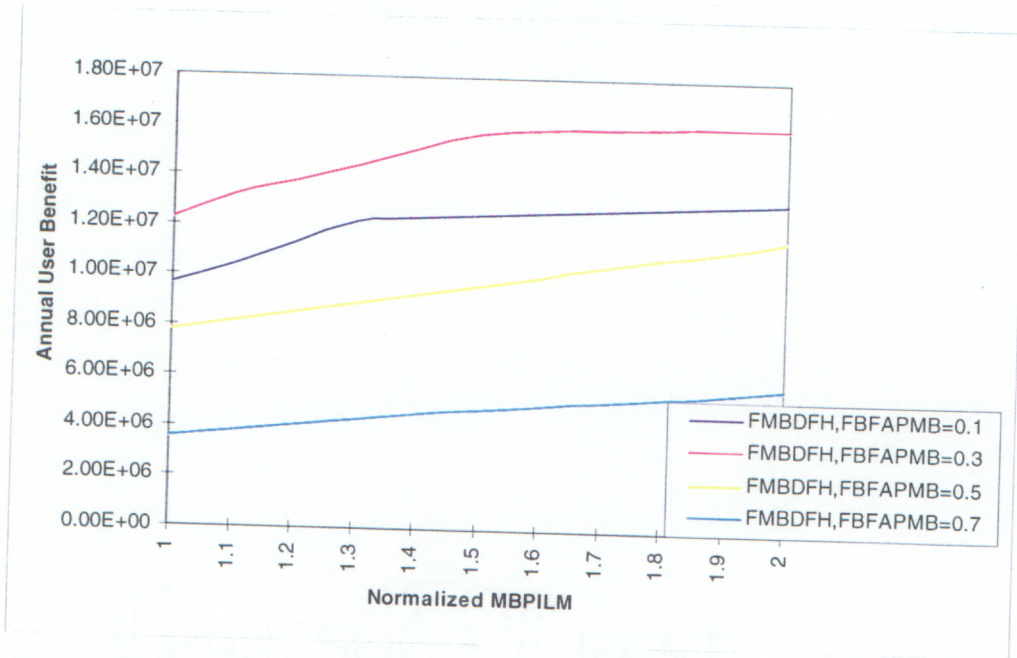


Figure VIII-15 Annual User-Benefit-- Simple Graph Vs. Normalized Maintenance Budget (\$/yr.) at year 7

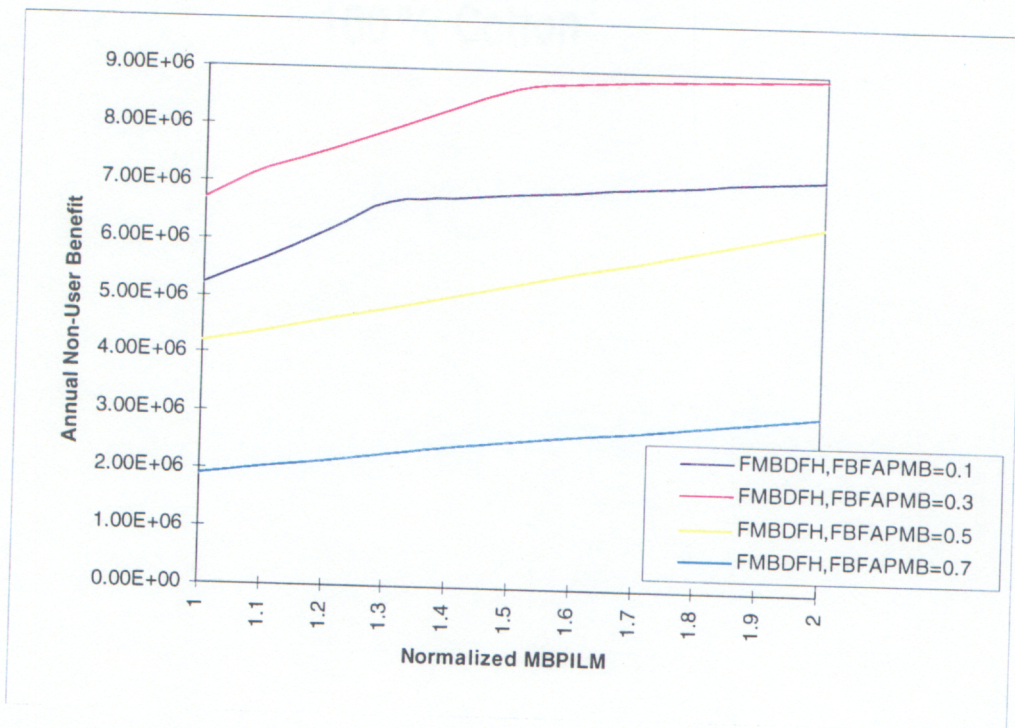


Figure VIII-16 Annual Non-User Benefit-- Simple Graph Vs. Normalized Maintenance Budget (\$/yr.) at year 7



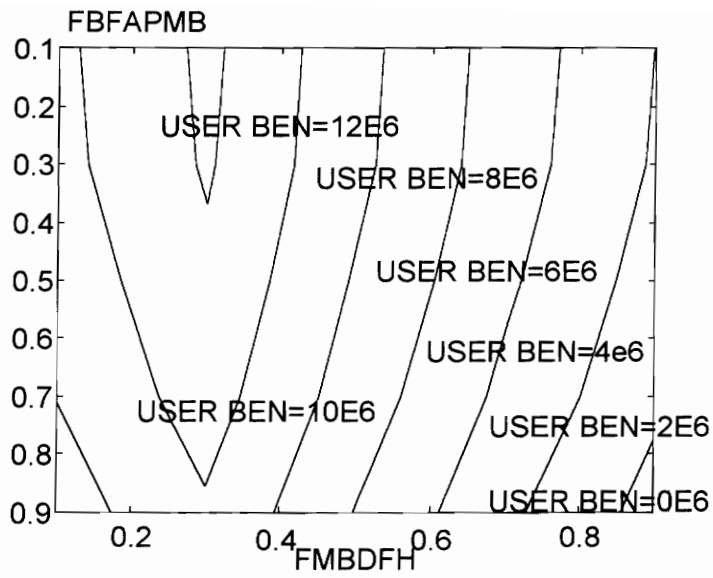


Figure VIII-17 Annual User-Benefit-- Contour Normalized MBPILM=1 at year 7 (\$/yr.)

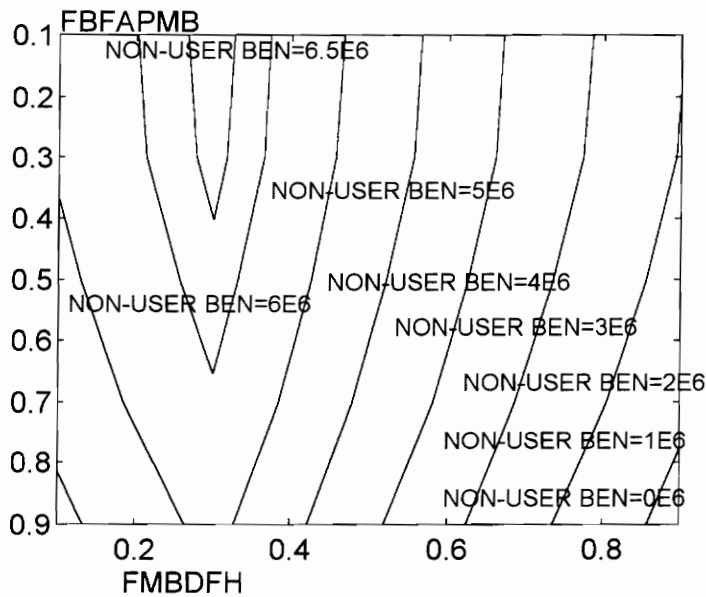


Figure VIII-18 Annual Non-User Benefit-- Contour Normalized MBPILM=1; year 7 (\$/yr.)

### VIII-2-5 Benefit/Cost Ratio

Benefit/cost ratio (B/C Ratio) is one of the popular measures of effectiveness that is frequently used in transportation investment policy evaluation. This measure can tell which is the most efficient among feasible investment alternatives. Figure VIII-19 shows the simulation result of the B/C Ratio. Referring to Figure VIII-19, the B/C ratio, which shows the economic feasibility, arrives at the point where B/C ratio is equal to one, which means the pre-expansion condition, in about 9.5 years after increasing at the expansion point at year five.

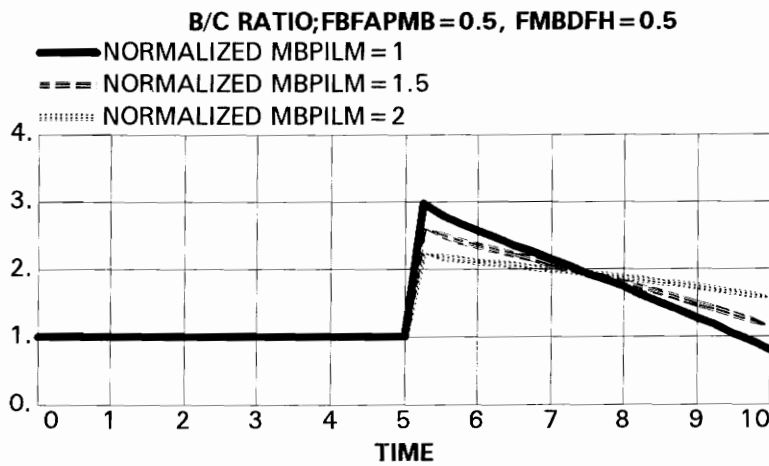


Figure VIII-19 Simulation Result of Benefit Cost Ratio

In a highway management operation, there can be many decision points concerning budget size and allocation. In Figure VIII-20, the B/C ratios are plotted against the normalized maintenance budget size. The result shows how the budget increase affects the B/C ratio and the point at which the B/C ratio starts to decrease. The B/C ratio increases when increases in benefits exceed increases in costs. The increases in benefits can be expected when a new capacity is added to the current system or the

average physical condition is improved. An increase in the annual maintenance budget will improve the physical condition of highways and bridges, and thus will increase the B/C ratio.

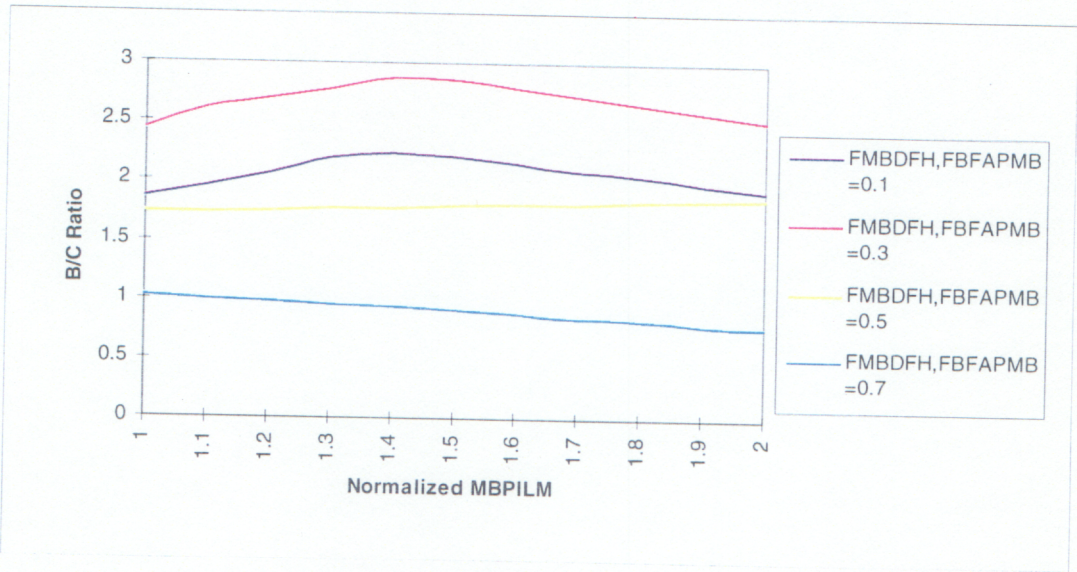


Figure VIII-20 B/C Ratio with Normalized MBPILM, at year 8

The B/C ratio will start to decrease when the marginal increases in the benefits are smaller than the marginal increases in the maintenance budgets, in other words, when the increases in benefits become weakened and cannot cover the increases in expenditures. Furthermore, if the current annual budget is sizable enough to maintain all the pavements and bridges in the best condition, an increase in the maintenance budget won't guarantee increases in benefits, and thus B/C ratio will decrease more sharply. Figure VIII-20 clearly shows these trends based on various budget allocation options. Initially, increases in maintenance budgets affect the B/C ratio positively until the normalized budgets approach about 1.4, except for the case when FMBDFH and FBFAPMB are equal to 1.7. However, in some cases concerning budget allocations (FMBDFH, FBFAPMB=1.1 and 1.3), the B/C ratios decrease after 1.4. For the case

of inefficient budget allocation (FMBDFH, FBFAPMB=1.7), the increase in the maintenance budget exceeds the increase in the benefit, and thus the B/C ratio decreases with the increase of the maintenance budget.

In Figure VIII-21 and Figure VIII-22, the B/C ratios are plotted against two decision variables, FMBDFH and FBFAPMB, for a Normalized MBPILM=1. In Figure VIII-21, the contour format is depicted; in Figure VIII-22, the three dimensional surface format is shown. Both are identical, with each having a certain advantage. The contours provide precision; the surfaces favor context and conceptualization. What is interesting is that the optimal value of the B/C ratio occurs at about FMBDFH=0.3, and the values of the B/C ratio are less on both sides of this decision variable.

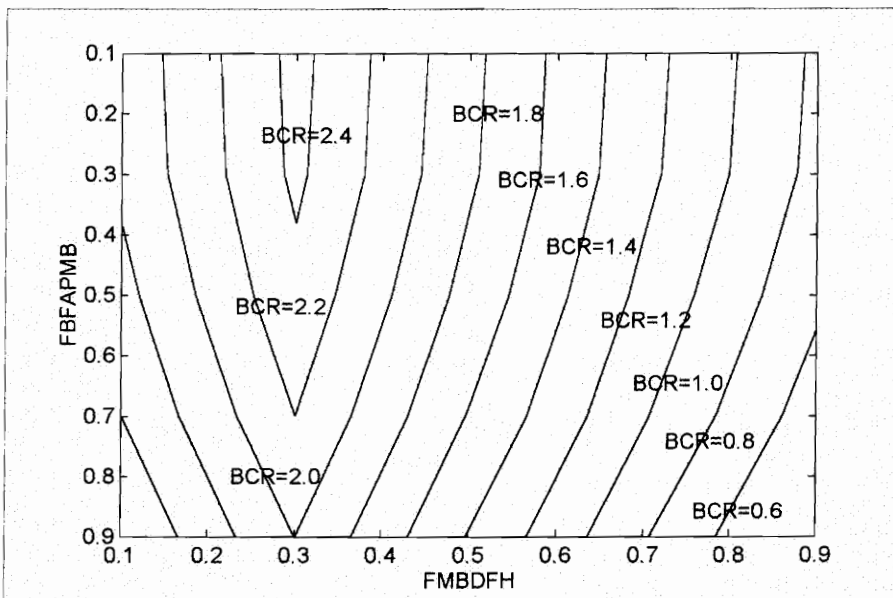


Figure VIII-21 B/C Ratio,2D Format (Normalized MBPILM=1); at Year 8

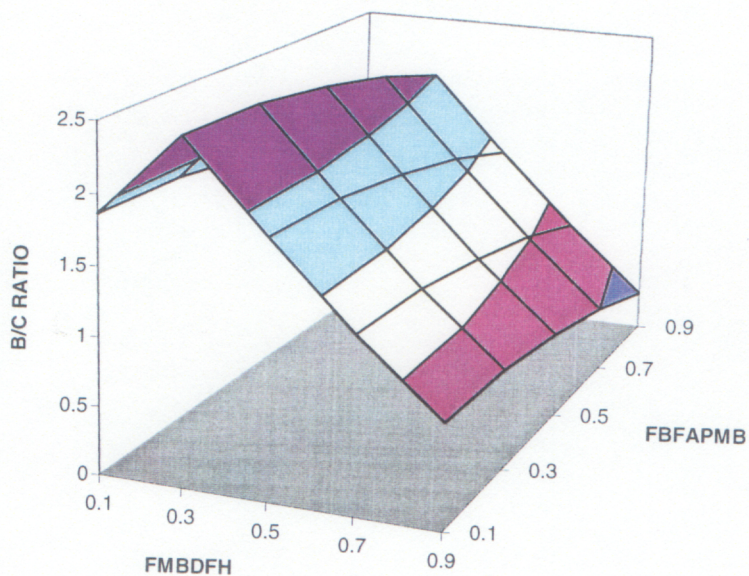


Figure VIII-22 B/C Ratio;3D Format (Normalized MBPILM=1); at Year 8

### VIII-2-6 Gasoline Tax Revenue Maintenance Budget Ratio

The Gasoline tax revenue maintenance budget ratio (GTRMBR) is an index of the self-sufficiency of maintenance policies. By increasing the maintenance budget, the average travel speed may be increased, owing to better service conditions. An increase in travel speed will decrease the average distance traveled per gallon of gasoline in the speed zone of the Interstate system. A decrease in the average distance traveled per gallon of gasoline will lead to more consumption of gasoline and thus more gasoline tax revenue.

The relationships concerning GTRMBR are depicted in Figure VIII-23 through Figure VIII-26 in four forms -- dynamic behaviors over time, a two dimensional plot against the increase in budget size, two dimensional contours, and a three dimensional surface against budget allocations, respectively.

In Figure VIII-23, the GTRMBR with the current budget level shows a moderate increase over time after rapid increase at the expansion point. However, increases in maintenance budgets affect the GTRMBR negatively. This trend becomes obvious in Figure VIII-24, where the GTRMBR is plotted over the normalized MBPILM. This means that the increase in revenue does not pay off the increase in the maintenance budget in this case.

In Figure VIII-25 and Figure VIII-26, the GTRMBR are plotted against two decision variables, FMBDFH and FBFAPMB, for a Normalized MBPILM=1, in contour format and three dimensional surface format respectively. The trend of the relationship seems similar to that of the B/C ratio, although the shapes of the contours are slightly different.

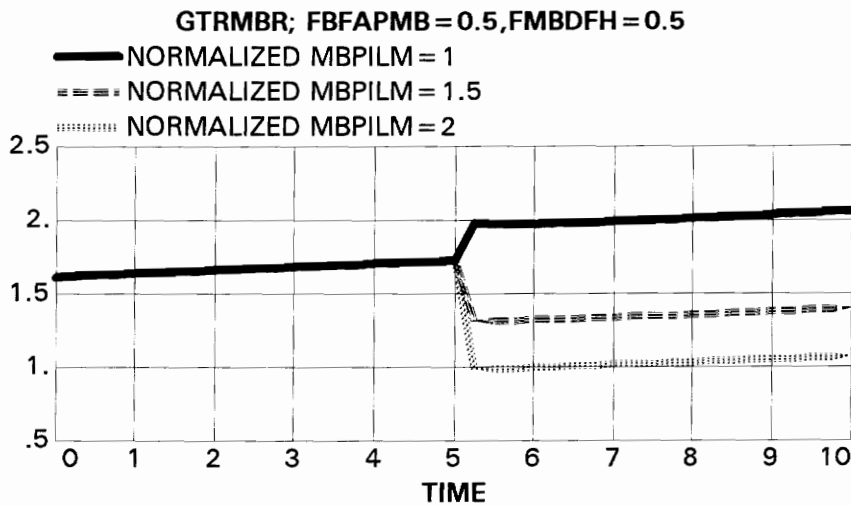


Figure VIII-23 Simulation Result of GTRMBR

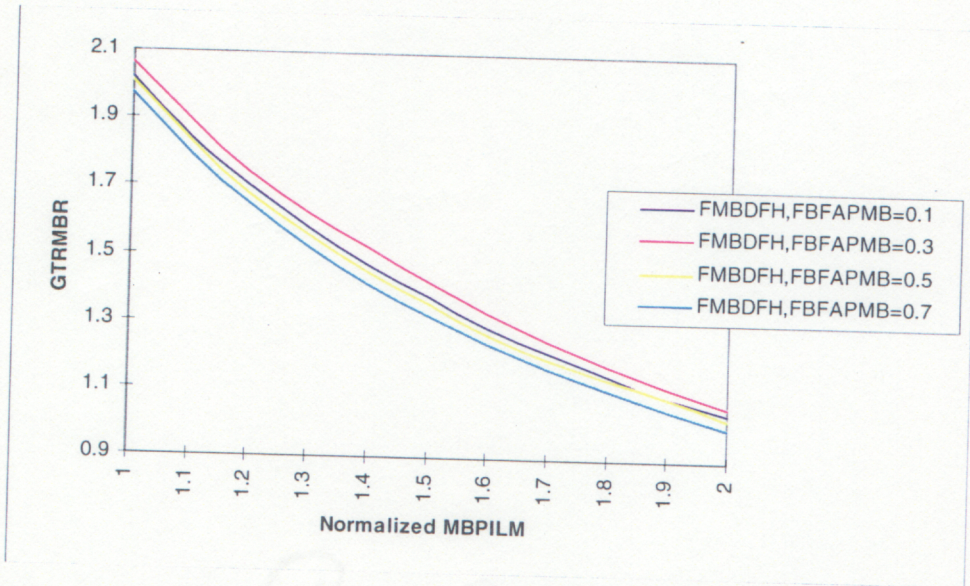


Figure VIII-24 GTRMBR with Normalized MBPILM; at year 8

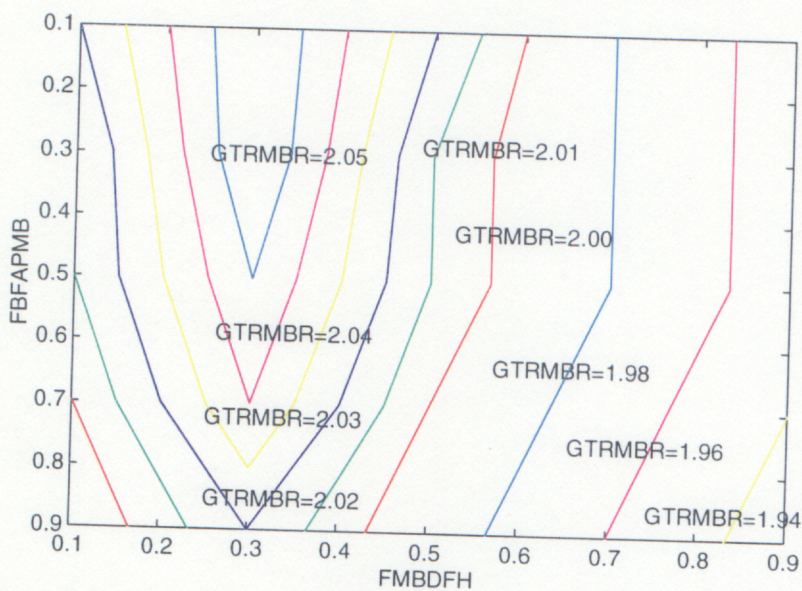


Figure VIII-25 Gasoline Tax Revenue Maintenance Budget Ratio (Normalized MBPILM=1); 2-D Format; at year 8

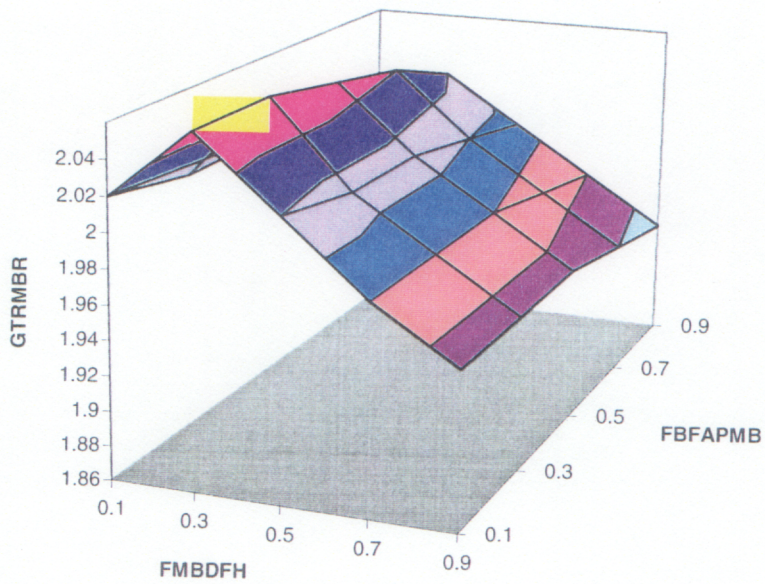


Figure VIII-26 Gasoline Tax Revenue Maintenance Budget Ratio (Normalized MBPILM=1); 3-D Format; at year 8



## **IX Conclusion and Further Studies**

### ***IX-1 Research Summary and Conclusion***

Many research studies have pointed out that the transportation infrastructure of the United States has been deteriorating or is obsolete due to a lack of investment, growing travel demands, and inappropriate operation and management. Efficient and optimal investments in highway management are critical, given an environment of shrinking budgets and a critical public.

The objective of this research is the development of a model using a system dynamics methodology that serves as an instrumentality for generating scenarios to facilitate highway infrastructure management -- policy-making, planning, budgeting, and programming of the Virginia highway system.

Recent trends in transportation infrastructure management primarily consists of the development of separate pavement or bridge management systems at the project and network levels. These levels of transportation infrastructure management systems lack connections to planning, policy and strategy levels.

Several evaluation schemes are discussed in this research, concerning: 1) physical performance, 2) traffic performance, and 3) economic performance of highway infrastructures. Life-Cycle Costing is an important aspect of highway management systems, and gives us a total system management cost, based on the system condition.

A comprehensive "Planning-Level" transportation infrastructure management system, which includes all the aspects of transportation facilities management, with consideration given to transportation planning, traffic engineering, highway engineering,

and engineering economy, is needed to provide a tool for solving and analyzing meta-problems related to transportation infrastructure management.

The Highway Management System (HMS) is developed using a systems approach. The systems approach solves and analyzes meta-problems in consistent, logical, objective and quantitative way. The HMS is a system dynamics model equipped with capabilities for analyzing and solving the meta-problems related to highway infrastructure planning and management. The HMS is conceived as consisting of five subsystems: 1) Physical Subsystem -- Pavement Management System, and Bridge Management System, 2) Evaluation Subsystem, 3) Functional Subsystem, 4) Financial Subsystem, and 5) Administration Subsystem

A steady state analysis of the HMS is performed. Steady state solutions are useful for understanding the relationship between state variables and decision variables. Nomographs corresponding to steady state solutions are analytically-based manual means of gaining understanding by tracing paths from decision variables to state variables.

The expansion of the Interstate I-81, involving an addition of one lane in each direction, is assumed for the simulations. The simulations are executed based on a base case budget and budget allocations, and on scenarios with variable budget-sizes and budget allocations. Results show that the service condition of the highway will be diminished, and will return to its pre-expansion condition in several years following the expansion of I-81, if the maintenance budget is not increased according to the expansion.

## *IX-2 Further Studies*

### **IX-2-1 Expansion of the Model**

The Highway Management System can be extended in three directions. One of these directions is geographic expansion corresponding to VDOT's nine Districts; a second direction is administrative expansion corresponding to VDOT's highway classification into Interstate, Primary, Secondary and Urban; and the third corresponds to the highway life-cycle, consisting of the Financial Subsystem, Physical Subsystem, Functional Subsystem, and Evaluation Subsystem. The number of total subsystems, representing the VDOT highway system, would be 144, if these three directional expansions are accomplished. This research concentrates primarily on the three subsystems-- Physical Subsystem, Functional Subsystem and Evaluation Subsystem, for the Interstate system in the Salem District. However, it would be wrong to interpret this research as only contributing to a mere two percent (3/144) of the understanding of VDOT's total problem, because the model is easily extended along all three directions to encompass the entire VDOT's highway system.

**Incorporation of the Financial Subsystem;** While the Financial Subsystem is modeled in this research, its outputs, which provide the inputs to the Physical Subsystem, are data-generated rather than model-generated. Thus, the highway budget for Interstate Highways in the Salem District is obtained from the Data Base, rather than being generated from revenues based on taxes as part of the Commonwealth's budgeting process. All the socio-economic factors necessary for generating these revenues are included in the model, but the parameter estimation of these relationships for the whole Commonwealth is clearly beyond the scope of the research.

**Expansion of the Administration Subsystem;** The second expandable dimension of the model is the application of the administration subsystem. In this research, the concentration is on the impact of deferred maintenance of the Interstate System of the Salem District. Expansion through the Administration Subsystem would enable the HMS model to operate throughout the rest of the highway system - Primary, Secondary, and Urban highways.

In DYNAMO programming, this expansion can be done using the array capabilities of DYNAMO III, which is similar to the array notation in other high level-languages such as C or FORTRAN. For example, the level variable which represents highway lane-mileage in sufficient condition can be modified using an array for highways under different administrations as follows:

```
FOR ADMIN=INTERST,PRIMARY,SECONDRY,URBAN
```

```
L HSFPC.K(ADMIN)=HSFPC.J(ADMIN)+(DT)(MRDTH.JK(ADMIN)+ERH.JK  
(ADMIN)+MRDFH.JK(ADMIN)-ARH.JK(ADMIN))
```

Other related rate, auxiliary, and constant variables can easily be changed into array form.

**Geographical Expansion of the Model;** There are nine separate districts under the Virginia Department of Transportation. This geographical expansion of the HMS model can be done simply by adding another array dimension to the model which represents districts as follows:

```
FOR ADMIN=INTERST,PRIMARY,SECONDRY,URBAN
```

FOR DISTRCT=SALEM,BRISTOL,STAUNTON,LYNCHBRG,CULPEPER,  
FRDKSBRG,RICHMOND,SUFFORK,NORTHVA  
L HSFPC.K(ADMIN, DISTRCT)=HSFPC.J(ADMIN, DISTRCT)+(DT)  
(MRDTH.JK(ADMIN, DISTRCT)+ERH.JK(ADMIN, DISTRCT)+  
MRDFH.JK(ADMIN,DISTRCT)-ARH.JK(ADMIN, DISTRCT))

### **IX-2-2 Further Extension of the Model**

The HMS model will be able to integrate the management of other transportation infrastructures, such as railroads, seaports, airports, ITS systems, etc. Also, the concept of the systems approach to infrastructure management can be extended to the management of infrastructures, such as sewage, water supply, power plants, etc., eventually extending to integrated social infrastructure management systems.

Currently, the application of the GIS system to highway management data inventory system is being attempted. Data inventory should be re-designed in consideration of the model requirements. The HMS model can be easily integrated with new data inventory systems using GIS technology as a management system module.

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## **Appendixes**

**A. Pavement Maintenance Tasks**

**B. Bridge Maintenance Tasks**

**C. Detailed Causal Diagrams for HMS**

**D. Complete Listing of DYNAMO Program (Prototype Version)**

**E. Complete Listing of DYNAMO Program (Refined Version)**

**F. Steady State Analysis of BMS ( $RPR_e$ ,  $Bwe \neq 0$ )**

**G. Example of Using Nomograph**



## **Appendix A Pavement Maintenance Tasks**

Understanding highway maintenance activities is important because it helps establish the Life-Cycle Cost breakdown structure, and thus the Highway Management System. This Appendix describes the maintenance tasks for pavement. Pavement maintenance tasks are listed based on the maintenance activities in the VDOT data inventory system, the HTRIS.

Pavement maintenance tasks can be divided into ordinary maintenance activities and maintenance replacement activities. The following ordinary maintenance and maintenance replacement task lists are mainly reproductions from the Activity Code Manual of VDOT Maintenance Division.

### ***A.1 Ordinary Maintenance Activities***

Ordinary maintenance includes all the activities done to preserve the roadway as nearly as possible to its original physical condition (VDOT, 1991). Ordinary maintenance includes lighter and cheaper maintenance activities, and is applied to less deteriorated physical condition, in comparison to maintenance replacement.

#### **Bituminous Surface Repair**

- Spot Sealing or Skin Patching on Road Surface
- Premix Patching: Patching using commercial or shop prepared mixes are used.
- Spot Reconditioning
- Seal Cracks on Bituminous Surfaces
- Treat Bleeding Pavement
- Slurry Patching with Slurry Machine

- Heavy Mechanized Patching: Application of hot or cold bituminous mixes with heavy equipment.
- Other Bituminous Surface Maintenance: Planning/milling and smoothing bituminous surfaces, emergency patching with non-bituminous materials, and cleaning intersections, etc.

### **Concrete Surface Repair**

- Patching with Concrete: Patching holes and blow-ups etc. with removal of existing concrete.
- Concrete Joints: Removal and replacement of joint filler, pouring joints, trimming joints, and maintenance of other concrete joints
- Grouting, Under Sealing or Pavement Jacking: Pumping bituminous material, filling voids by grouting and pavement jacking.
- Other Repairs to Concrete Pavement: Emergency repair such as blow-up, epoxy patching, patching concrete with bituminous material, and pouring or trimming cracks.

### **Non-Hard Surface Work**

- Patching Non-hard Surface Roads: Adding spot surfacing material
- Machining Non-hard Surface Roads: Dragging, blading, and other work to pick up debris or rocks. Minor shaping of ditches
- Applying Dust Palliatives: Dust Palliatives such as calcium chloride and sodium chloride.
- Other Non-Hard Surface Maintenance

### **Shoulder Maintenance**

- Machining Non-Hard Shoulder
- Repair Non-Hard Surface Shoulder with Soil or Aggregate
- Wedging Non-Hard Surface Shoulder with Bituminous Mixes
- Repair of Hard Surfaced Shoulder
- Seal Cracks on Bituminous Shoulders and Sealing Joint Between Shoulder and Pavement Edge
- Machining High Shoulders: Surplus material must be loaded and hauled.
- Other Shoulder Care: Application of dust palliatives to shoulders

### **Ditches and Drainage Maintenance**

- Cleaning and Reshaping Ditches by Machine: Cleaning ditch spoil
- Hand Cleaning of Ditches
- Cleaning and Repair Minor Drainage Structure: Drainage structures that have an opening of less than 36 ft<sup>2</sup>
- Other Drainage Care

### **Roadside Maintenance**

- Erosion Repair, Minor Storm Related Work, and Removal of Minor Slides
- Cleaning Right of Way
- Dead Animal and Litter Patrol
- Reseeding, Mulching, Sodding, and Resoiling
- Picnic Areas, Waysides and Rest Areas
- Repair of Roadside Structures such as Sidewalks, Rip Rap, Curb etc.
- Maintenance of Fences

- Routine Street Sweeping with Mechanical Devices (except snow removal, surface treatment, etc.)
- Maintenance of Bike Path

### **Vegetation Control**

- Tractor Mowing
- Hand Mowing
- Brush Cutting
- Spray Weeds or Grass: Using growth inhibitor or soil sterilants on grass.
- Trimming and Removing of Trees
- Spray Brush: Using herbicides or soil sterilants

### **Signs and Traffic Control Device Maintenance**

- Replacing, Cleaning, Repairing Clear Coating, Repainting or Resetting of Signs
- Maintenance of Traffic Signals
- Maintenance and Operation of Railroad Protection Devices such as Grade Crossing, Flashing Light Signals and Gate
- Maintenance of Reversible Lanes
- Repair or Replacement of Vandalized Signs

### **Traffic Service and Operation**

- Repair or Reset Guard Rail
- Cleaning or Painting Guard Rail
- Installation and Maintenance of Historical Markers
- Traffic Counts (that are not part of routine counts)
- Maintenance of Highway Lighting

- Holiday Service Patrol: Service for traveling public
- Maintenance and Operation of Fog Warning and Lighting System
- Maintenance of Impact Attenuators and Glarefoils
- Maintenance and Operation of Highway Advisory Radio System

### **Snow and Ice Control**

- Repair or Replacement of Facilities Damaged by Run-Off from Deicing Chemicals
- Installation and Maintenance of Setting Ponds and Piping to Prevent Chemical Contamination of Adjacent Private Property
- Snow Removal
- Standby and Patrol for Snow and Ice Control
- Installation and Removal of Snow Fence

### **Tunnel Maintenance**

- Operation of Tunnels' Traffic Equipment and Emergency Equipment
- Inspection of Tunnels
- Cleaning of Tunnels
- Maintenance of Tunnel Roadway Lighting System
- Maintenance of Tunnel Discharge and Drainage System

### **Non-Roadway Related Maintenance**

- Maintenance and Repair of Bus Shelter

### **Traffic Management System Maintenance**

- Maintenance of CC-TV, Electronic Gate, Communication System, Loop, Ramp Metering System, Utilities and Lighting

## ***A.2 Maintenance Replacement Activities***

Maintenance replacement is applied to more deteriorated roadway. VDOT defines these activities as maintenance items involving continuous portions of roadway of 1,000 feet or more or the renovation of specific portions of roadway requiring extensive or unusual work (VDOT, 1991).

### **Surface Replacement**

- Reconditioning Roads: Restoring and rehabilitating of base and/or surface to original condition including milling, scarifying, and rejuvenating the existing pavement
- Light Bituminous Retreatments: Applying seal coat to existing bituminous surfaces except for slurry seal
- Heavy Bituminous Retreatments: Applying straight and penetrating treatment to existing bituminous surfaces
- Application of Plant Mix to Existing Paved Surface
- Repair and Replacement of Portland Cement Concrete Pavement Joints: Repair of spalls at joints, and/or replacement of joint filler.
- Repair of Portland Cement Concrete Pavement Slab: Including concrete overlays and grooving

### **Major Repair of Shoulders, Turnouts, and Drainage**

- Reconditioning of Shoulders, Turnouts to Proper Width and Elevation
- Bituminous Treatment for Existing Hard Surfaced Shoulders
- Repair or Replacement of Minor Drainage Structures (that have an opening of less than 36 ft<sup>2</sup>)
- Special Cleaning of Major Outfall Ditches and Channels

### **Major Repair of Roadside**

- Replacement of Major Cut and Fill Slopes, and Removal of Major Slides
- Replacement of Roadside Structures: Including sidewalks, retaining walls, rip raps, curb and gutter, drop inlets, slope pavement, right-of-way markers, and etc.
- Repair or Replacement of Major Rest Area and Waysides
- Replacement of Right-of-Way Fences, Guard Rail, Existing Shrubs and Trees, etc.
- Reseeding Areas without Vegetation, and Major Replacement of Mulch, Sod, and Soil
- Spray Weeds, Grass, Brush: Applying growth inhibitor on grass, and herbicide for control of brush and weeds.

### **Replacement of Signs**

- Replacement of Major Signs, Signs' Trusses, and Light Fixtures on Replaced Trusses
- Replacement of Traffic Signals: Including traffic controllers, treadies, poles, conduits, wiring, etc.
- Replacement of Highway Lighting
- Painting or Repainting Center Lines, Edge Lines, Pavement Messages, Raised Pavement Markers: Including thermo-plastic material marking
- Replacement of Loop Detectors

### **Tunnels**

- Major Repairs or Replacements to Tunnels

### **Weigh Station**

- Replacement of Major Facilities of Weigh Station

## **Emergency Work**

- Removal of Harzadous Materials and/or Waste
- Removal of Debris



## **Appendix B Bridge Maintenance Tasks**

A more detailed bridge maintenance task list than that of the HTRIS is suggested in this Appendix. The purpose of this section is to provide definitions for each category of maintenance activities for bridges. Bridge maintenance tasks described in this appendix are from the literature, and are arranged based on the responses from bridge maintenance personnel of the Virginia Department of Transportation.

### ***B.1 Preventive Maintenance Tasks***

#### **Sealing Voids**

Voids within the concrete which came from the manufacturing process can cause damage to the structure because of corrosive materials. Sealing is conducted to fill the top layer of these voids by applying sealant with sprayer, or brush roller. Choosing sealant and the frequency of application depends upon the environment where it is applied.

#### **Sealing Deck Cracks**

Hair-line cracks allow corrosive agents to erode the concrete and to attack steel inside the concrete. They should be sealed by sealant, which can treat the interior of the cracks thoroughly.

#### **Expansion Joint Replacement**

Reinstallation of a new joint is conducted by removing the existing joint, treating attach areas with special resin, and reinstalling a new joint.

## **Spot Painting**

Spot painting is important for preventing the structure elements from further corrosion.

### ***B.2 Minor Repair Tasks***

#### **Deck Overlay**

The deck overlay process includes drying the concrete, impregnating the concrete with monomer to a sufficient depth for protection of the top layer of steel, and polymerizing the monomer. The purpose of this activity is to prevent further deterioration by preventing corrosion of the steel and sealing the surrounding concrete. Any existing chloride should be immobilized and the concrete should be sealed so that the reinforcing steel would not be exposed to chloride.

#### **Patching**

It includes partial or full depth repairs to deck, superstructure, or substructure. After cleaning the loose or flaking concrete and drying the area, the area should be re-creted.

#### **Repainting**

Repainting the whole structure to protect the surface of the structure.

#### **Cathodic Protection**

The purpose of cathodic protection is to prevent chloride, which mostly comes from pollution, salt water, deicing material, from attacking steel. This action is focused on

the protection of the steel inside the concrete by placing electrically charged anodes throughout the structure. Charged anodes cause more chloride to attach to sacrificial zinc.

### **Other Minor Repair Activities**

- Expansion Joint Reconstruction
- Replacement of Bearing and Anchor Bolt
- Replacement and Repair of Drainage System
- Replacement and Repair of Structure Steel Secondary Member
- Repair of Concrete Diaphragm
- Repair of Deck Edge

### ***B.3 Major Repair***

#### **Deck Replacement**

The important consideration here is to reduce the installation time and the dead load.

#### **Superstructure Replacement**

- Bearing Replacement: The superstructure should be raised temporarily for access to the bearing and its attach points. After that, the bearing should be removed vertically to avoid damage to other parts of the structure, and replaced.
- Parapets/Guard Rail Replacement: Parapets and guard rails should be replaced when the deck is replaced, and accident and environmental effects cause the damage.
- Drainage Replacement: Before the drainage system is replaced, inspection for corrosion of the contact surface should be done. The existing drainage system should

be replaced when the deck or superstructure is replaced and the corrosion hinders proper drainage.

### **Other Major Repair Activities**

- Replacement and Repair of Structure Steel Primary Member
- Repair of Concrete Beam End

## ***B.4 Rehabilitation***

### **Repair of Abutments or Piers**

This is mainly to increase the load-carrying capacity of the substructure component.

- Bagged Concrete: The woven bags filled with a dry concrete ingredient are placed adjacent to the damaged pier or abutment. These bags can be hardened and anchored to the substructure component when exposed to water. The bag itself will allow saturation at a predicted hydration rate.
- Prepacked Aggregated Concrete: Aggregated concrete is injected into the concrete using pipe starting from the bottom of the abutment or pier. The injection pressure should be kept constant to prevent water from entering during the process.
- Rip Rap: This activity involves flexible ground-covering dumped or hand placed as a protective layer. This covering is composed of material such as a mixture of rock, broken concrete and rubble, which can adjust to the changes in the sub-base.

### **Replacement of Abutments or Piers**

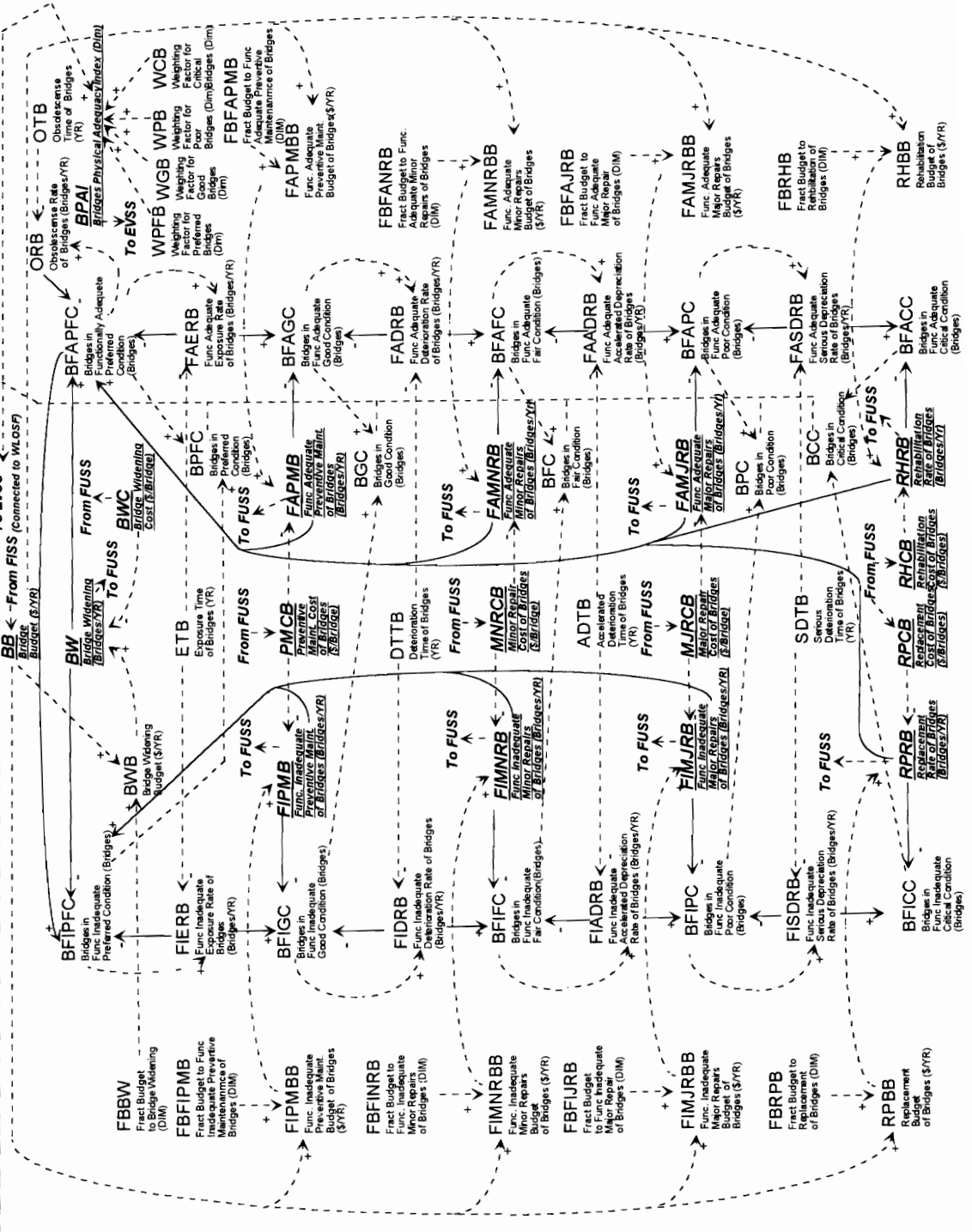
The damaged part is left in place and then the new component is attached to the bridge. The deck of the damaged part of the pier or abutment needs to be removed for replacement of the new substructure component.

### **Repair of Collision Damage**

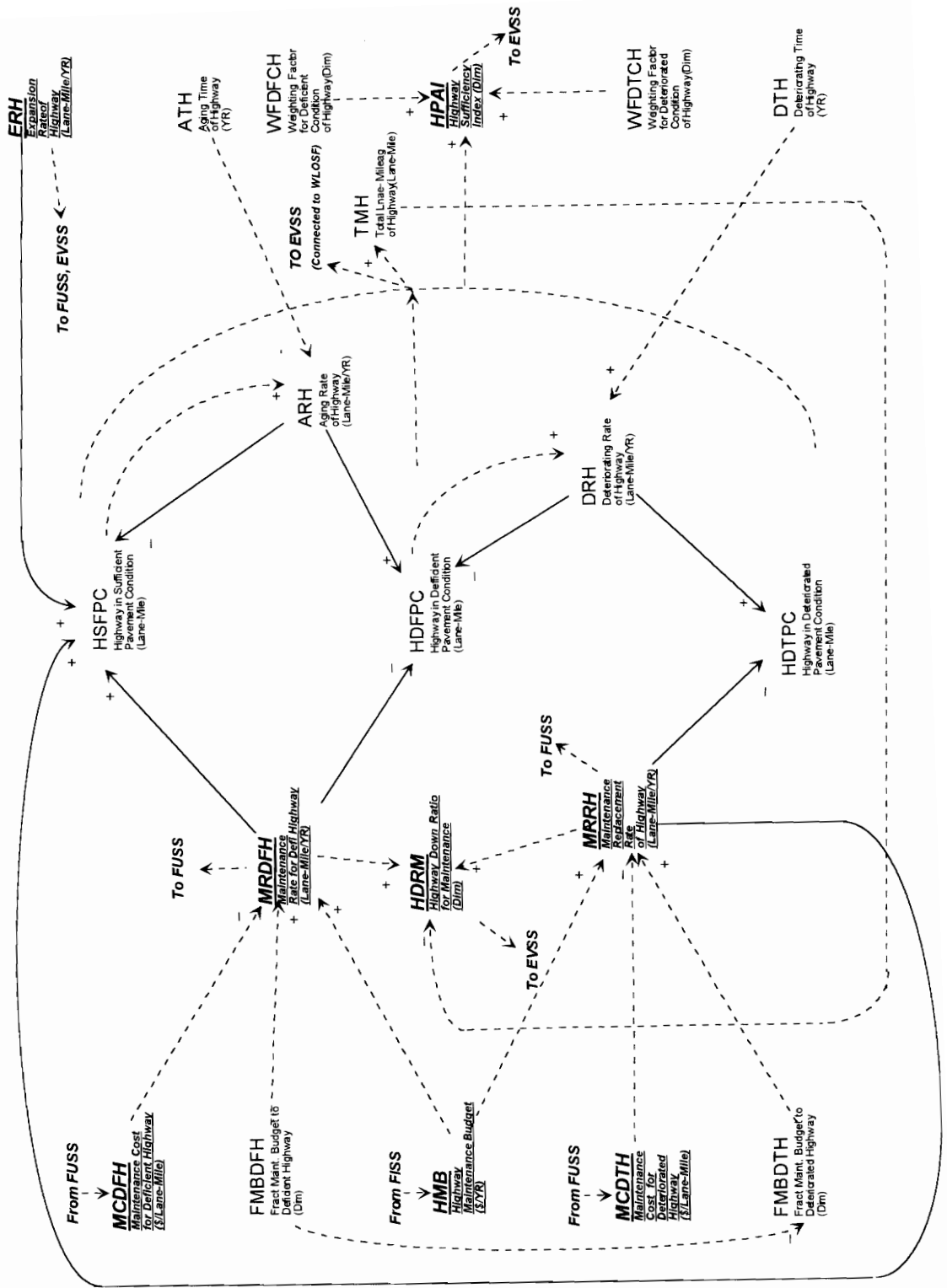
- Repairing of broken Tensioning Strands
- Heating and straightening the steel beams
- Gouging and welding tears and cracks

**Appendix C Detailed Causal Diagrams of the Highway  
Management System Model**

**Physical Subsystem: Bridge Management System (PHSS-BMS)**



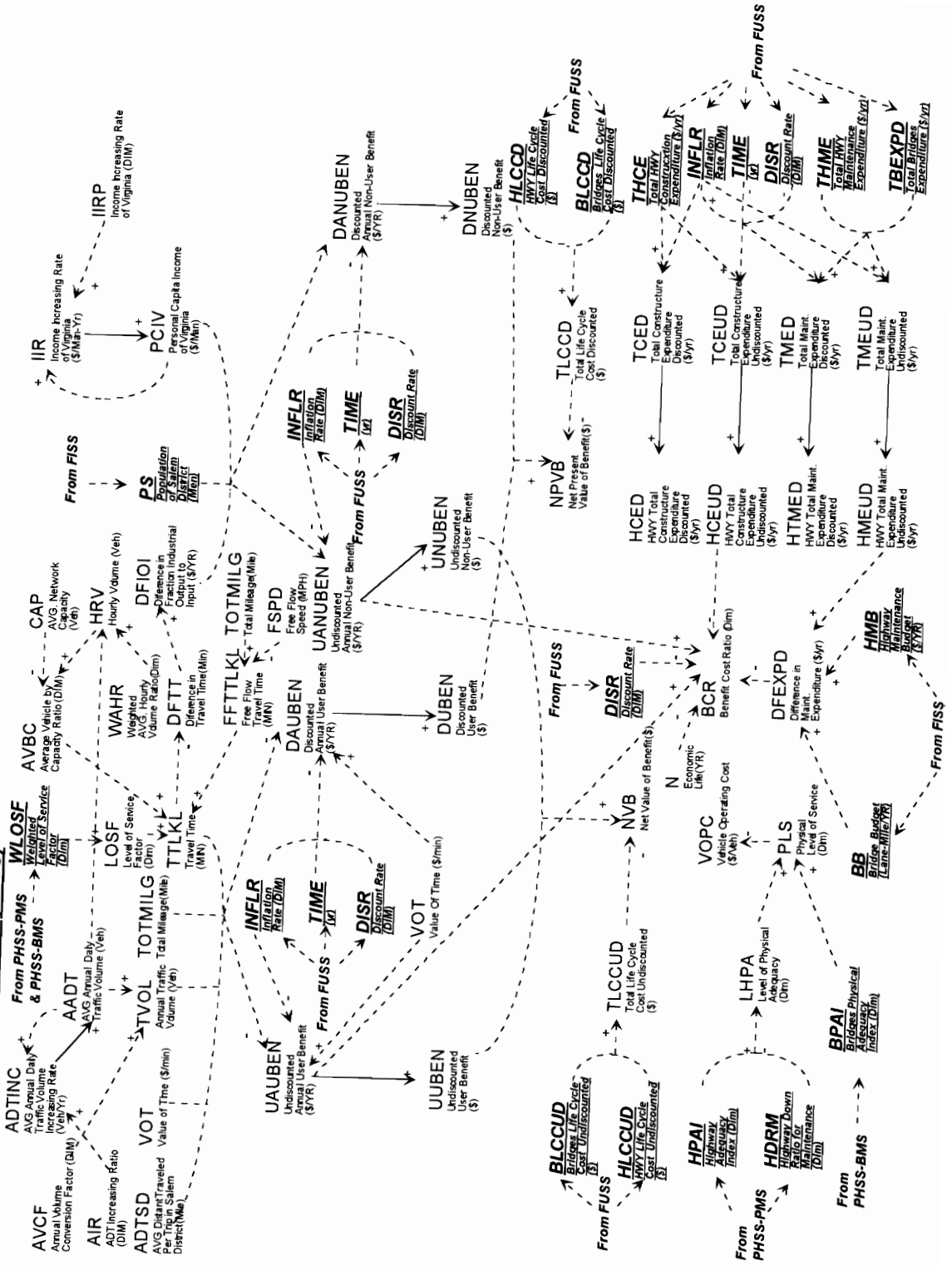
**Physical Subsystem: Pavement Management System (PHSS-PMS)**



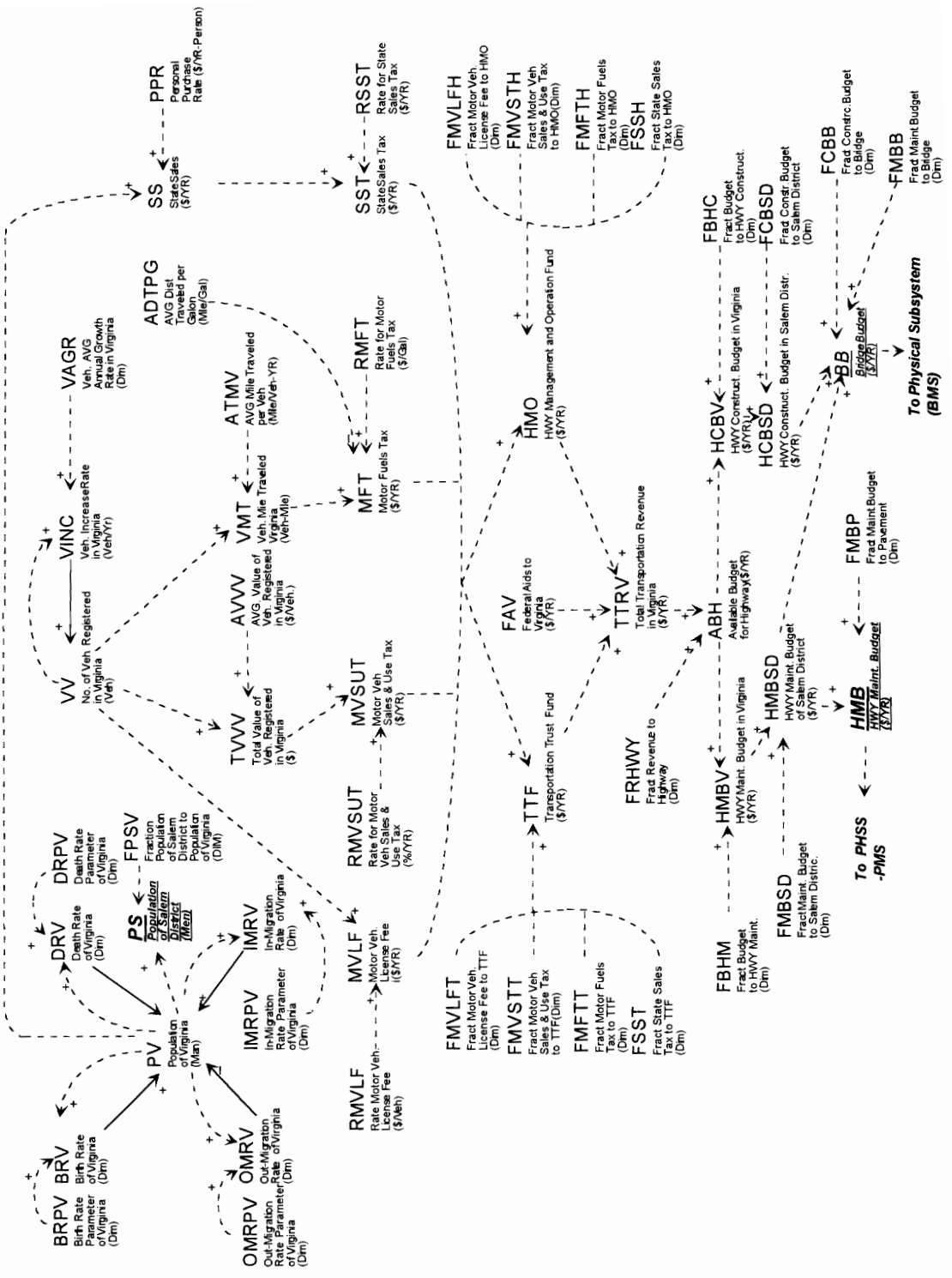




# Evaluation Subsystem (EVSS)



# Financial Subsystem (FISS)



**Appendix D Complete Listing of DYNAMO Program  
(HMS - Prototype Version)**

\* HIGHWAY MANAGEMENT SYSTEM

INSERT PHSBMS1

INSERT PHSPMS1

INSERT FISS1

INSERT FUSS1

INSERT EVSS1

A TOTALB.K=BFAPFC.K+BFAFC.K+BFAGC.K+  
BFAPC.K+BFIPFC.K+BFIFC.K+BFIFC.K+BFIFC.K+BFIFC.K+BCC.K

N TOTALB=TOTALBN

A TOTALBN.K=224

A TOTALH.K=HSFPC.K+HDFPC.K+HDTPC.K

N TOTALH=TOTALHN

C TOTALHN=499.49

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

\* PHYSICAL SUBSYSTEM-BRIDGE MANAGEMENT SYSTEM(BMS) MODELS

C FBFAPMB=0.5  
 A FBFANRB.K=(1-FBFAPMB)/3  
 A FBFAJRB.K=(1-FBFAPMB)/3  
 C FBBW=0.0  
 A FBRHB.K=(1-FBFAPMB)/3  
 C FBFIPMB=0.0  
 C FBFINRB=0.0  
 C FBFIJRB=0.0  
 C FBRPB=0.0  
 A ABFAPFC.K=MAX(BFAPFC.K,0)  
 A ABFAGC.K=MAX(BFAGC.K,0)  
 A ABFAFC.K=MAX(BFAFC.K,0)  
 A ABFAPC.K=MAX(BFAPC.K,0)  
 A ABFIPFC.K=MAX(BFIPFC.K,0)  
 A ABFIGC.K=MAX(BFIGC.K,0)  
 A ABFIFC.K=MAX(BFIFC.K,0)  
 A ABFIPC.K=MAX(BFIPC.K,0)  
 A ABFACC.K=MAX(BFACC.K,0)  
 A ABFICC.K=MAX(BFICC.K,0)  
 L BFAPFC.K=BFAPFC.J+(DT)(FAPMB.JK+FAMNRB.JK+FAMJRB.JK+RHRB.JK+RPRB.JK^  
 +BW.JK-ORB.JK-FAERB.JK)  
 N BFAPFC=BFAPFCN  
 C BFAPFCN=16  
 R FAERB.KL=MAX(BFAPFC.K/ETB,0)  
 C ETB=.5  
 R FAPMB.KL=FAPMBB.K/PMCB.K  
 A FAPMBB.K=BB.K\*FBFAPMB  
 L BFAGC.K=BFAGC.J+(DT)(FAERB.JK-FAPMB.JK-FADR.B.JK)  
 N BFAGC=BFAGCN  
 C BFAGCN=105  
 R FADR.B.KL=MAX(BFAGC.K/DTTB,0)  
 C DTTB=21  
 R FAMNRB.KL=FAMNRBB.K/MNRCB.K  
 A FAMNRBB.K=BB.K\*FBFANRB.K  
 L BFAFC.K=BFAFC.J+(DT)(FADR.B.JK-FAMNRB.JK-FAADR.B.JK)  
 N BFAFC=BFAPCN  
 C BFAPCN=49  
 R FAADR.B.KL=MAX(BFAFC.K/ADTB,0)  
 C ADTB=22  
 R FAMJRB.KL=FAMJRBB.K/MJRCB.K  
 A FAMJRBB.K=BB.K\*FBFAJRB.K  
 L BFAPC.K=BFAPC.J+(DT)(FAADR.B.JK-FAMJRB.JK-FASDRB.JK)  
 N BFAPC=BFAPCN  
 C BFAPCN=7  
 R FASDRB.KL=MAX(BFAPC.K/SDTB,0)  
 C SDTB=15  
 L BFACC.K=BFACC.J+(DT)(FASDRB.JK-RHRB.JK)  
 N BFACC=BFACCN  
 C BFACCN=0  
 R RHRB.KL=RHBB.K/RHCB.K  
 A RHBB.K=BB.K\*FBRHB.K  
 R ORB.KL=MAX(BFAPFC.K/OTB,0)  
 C OTB=20  
 R BW.KL=BWB.K/BWC.K

A BWB.K=BB.K\*FBBW  
L BFIPFC.K=BFIPFC.J+(DT)(FIPMB.JK+FIMNRB.JK+FIMJRB.JK+ORB.JK-BW.JK^  
-FIERB.JK)  
N BFIPFC=BFIPFCN  
C BFIPFCN=0  
R FIERB.KL=MAX(BFIPFC.K/ETB,0)  
R FIPMB.KL=FIPMBB.K/PMCB.K  
A FIPMBB.K=BB.K\*FBFIPMB  
L BFIGC.K=BFIGC.J+(DT)(FIERB.JK-FIPMB.JK-FIDRB.JK)  
N BFIGC=BFIGCN  
C BFIGCN=17  
R FIDRB.KL=MAX(BFIGC.K/DTTB,0)  
R FIMNRB.KL=FIMNRBB.K/MNRB.K  
A FIMNRBB.K=BB.K\*FBFINRB  
L BFIFC.K=BFIFC.J+(DT)(FIDRB.JK-FIMNRB.JK-FIADRB.JK)  
N BFIFC=BFIFCN  
C BFIFCN=17  
R FIADRB.KL=MAX(BFIFC.K/ADTB,0)  
R FIMJRB.KL=FIMJRBB.K/MJRBB.K  
A FIMJRBB.K=BB.K\*FBFIJRB  
L BFIPC.K=BFIPC.J+(DT)(FIADRB.JK-FIMJRB.JK-FISDRB.JK)  
N BFIPC=BFIPCN  
C BFIPCN=12  
R FISDRB.KL=MAX(BFIPC.K/SDTB,0)  
R RPRB.KL=RPBB.K/RPCB.K  
A RPBB.K=BB.K\*FBRPB  
L BFICC.K=BFICC.J+(DT)(FISDRB.JK-RPRB.JK)  
N BFICC=BFICCN  
C BFICCN=0  
A TBFAC.K=BFAPFC.K+BFAGC.K+BFAFC.K+BFAPC.K  
N TBFACN=BFAPFCN+BFAGCN+BFAFCN+BFAPCN+BFACCN  
A TBFIC.K=BFIPFC.K+BFIGC.K+BFIFC.K+BFIPC.K+BCC.K  
N TBFICN=BFIPFCN+BFIGCN+BFIFCN+BFIPCN+BFICCN  
A BFAI.K=(TBFAC.K\*WFFAB+TBFIC.K\*WFFIB)/(TBFAC.K+TBFIC.K)  
N BFAIN=(TBFACN\*WFFAB+TBFICN\*WFFIB)/(TBFACN+TBFICN)  
A BPFC.K=BFIPFC.K+BFAPFC.K  
N BPFCN=BFIPFCN+BFAPFCN  
A BGC.K=BFIGC.K+BFAGC.K  
N BGCN=BFIGCN+BFAGCN  
A BFC.K=BFIFC.K+BFAFC.K  
N BFCN=BFIFCN+BFAFCN  
A BPC.K=BFIPC.K+BFAPC.K  
N BPCN=BFIPCN+BFAPCN  
A BCC.K=BFICC.K+BFACC.K  
N BCCN=BFICCN+BFACCN  
A BPAI.K=(BPFC.K\*WFPFB+BGC.K\*WFGB+BFC.K\*WFFB+BPC.K\*WFPB+BCC.K\*WFCB)/^  
(BPFC.K+BGC.K+BFC.K+BPC.K+BCC.K)  
N BPAIN=(BPFCN\*WFPFB+BGCN\*WFGB+BFCN\*WFFB+BPCN\*WFPB+BCCN\*WFCB)/^  
(BPFCN+BGCN+BFCN+BPCN+BCCN)  
C WFFAB=1  
C WFFIB=0.5  
C WFPFB=1  
C WFGB=1  
C WFFB=0.9  
C WFPB=0.7  
C WFCB=0.4

\* PHYSICAL SUBSYSTEM-PAVEMENT MANAGEMENT SYSTEM (PMS) MODEL

C FMBDFH=0.5  
 A FMBDTH.K=1-FMBDFH  
 A AHSFPC.K=MAX(HSFPC.K,0)  
 A AHDFPC.K=MAX(HDFPC.K,0)  
 A AHDTPC.K=MAX(HDTPC.K,0)  
 L HSFPC.K=HSFPC.J+(DT)(MRDTH.JK+ERH.JK+MRDFH.JK-ARH.JK)  
 N HSFPC=HSFPCN  
 C HSFPCN=166.55  
 R MRDFH.KL=MIN(HMB.K\*FMBDFH/MCDFH.K,HDFPC.K)  
 R MRDTH.KL=MIN(HMB.K\*FMBDTH.K/MCDTH.K,HDTPC.K)  
 R ARH.KL=HSFPC.K/ATH  
 C ATH=1  
 L HDFPC.K=HDFPC.J+(DT)(ARH.JK-MRDFH.JK-DRH.JK)  
 N HDFPC=HDFPCN  
 C HDFPCN=166.55  
 L HDTPC.K=HDTPC.J+(DT)(DRH.JK-MRDTH.JK)  
 N HDTPC=HDTPCN  
 C HDTPCN=166.55  
 R DRH.KL=HDFPC.K/DTH  
 C DTH=3  
 A HDRM.K=(MRDFH.KL+MRDTH.KL)/(HSFPC.K+HDFPC.K+HDTPC.K)  
 A HPAI.K=(HSFPC.K+HDFPC.K\*WDFDFCH+HDTPC.K\*WFDTCH)^  
 /((HSFPC.K+HDFPC.K+HDTPC.K)  
 N HPAIN=(HSFPCN+HDFPCN\*WDFDFCH+HDTPCN\*WFDTCH)/TMHN  
 C WDFDFCH=0.5  
 C WFDTCH=0  
 \*\*\*\*\*  
 \* EXPANSION RATE FOR \*  
 \* ADDING LANE ON I-81 \*  
 \*\*\*\*\*  
 \*R ERH.KL=CLIP(0,((86.87)\*2)/5, TIME.K,5)  
 R ERH.KL=CLIP(CLIP(0,(86.87)\*2\*(1/DT), TIME.K,5.25),0, TIME.K,5)  
 \* R ERH.KL=CLIP(CLIP(0,(86.87)\*2, TIME.K,6.25),0, TIME.K,5.25)  
 A ERH1.K=CLIP(0,((86.87)\*2)/5.25, TIME.K,5.25)  
 A TMH.K=HSFPC.K+HDFPC.K+HDTPC.K  
 N TMHN=HSFPCN+HDFPCN+HDTPCN



\* EVALUATION SUBSYSTEM MODEL

L PCIV.K=PCIV.J+(DT)(IIR.JK)  
 N PCIV=PCIN  
 C PCIN=11933  
 R IIR.KL=PCIV.K\*IIRP  
 C IIRP=0.00143  
 L HTMED.K=HTMED.J+(DT)(TMED.JK)  
 N HTMED=0  
 L HMEUD.K=HMEUD.J+(DT)(TMEUD.JK)  
 N HMEUD=0  
 L HCEUD.K=HCEUD.J+(DT)(TCEUD.JK)  
 N HCEUD=0  
 R TCEUD.KL=INFLF.K\*THCE.K  
 L HCED.K=HCED.J+(DT)(TCED.JK)  
 N HCED=0  
 R TCED.KL=(INFLF.K\*THCE.K)/(1+DISR)\*\*TIME.K  
 R TMED.KL=(INFLF.K\*(TBEXPD.K+THME.K))/(1+DISR)\*\*TIME.K  
 R TMEUD.KL=INFLF.K\*(TBEXPD.K+THME.K)  
 A WLOSF.K=((0.8\*(1\*AHSFPC.K+2\*AHDFPC.K+4\*AHDTPC.K)/TOTALH.K)^  
 +(0.2\*(1\*BPFC.K+2\*BGC.K+4\*BFC.K+8\*BPC.K+16\*BCC.K)/TOTALB.K))  
 N WLOSFN=((0.8\*(1\*HSFPCN+2\*HDFPCN+4\*HDTPCN)/TOTALHN)^  
 +(0.2\*(1\*BPFCN+2\*BGCN+4\*BFCN+8\*BPCN+16\*BCCN)/TOTALBN))  
 A LOSF.K=TABLE(LOSFT,WLOSF.K,1,6.4,1.08)  
 T LOSFT=0.1/0.2/0.3/0.4/0.6/1  
 N LOSFN=TABLE(LOSFTN,WLOSFN,1,6.4,1.08)  
 T LOSFTN=0.1/0.2/0.3/0.4/0.6/1  
 A LHPA.K=HPAL.K\*(1-HDRM.K)  
 N LHPAN=HPAIN  
 A PLS.K=LHPA.K\*BPAL.K  
 N PLSN=LHPAN\*BPAIN  
 A VOPC.K=(TABLE(VOPCT,PLS.K,0,1,0.2))\*TVOL.K\*TOTMILG  
 T VOPCT=0.4/0.3/0.22/0.18/0.16/0.15  
 N VOPCN=TABLE(VOPCNT,PLSN,0,1,0.2)  
 T VOPCNT=0.4,0.3,0.22,0.18,0.16,0.15  
 \* \* \* ADDING CAPACITY FOR EXPANSION  
 A CAP.K=TOTALH.K\*2000/(117.91\*2)  
 \* A CAP.K=CLIP(673.38\*2000/(117.91\*2),499.64\*2000/(117.91\*2),TIME.K,5.25)  
 N CAPN=499.64\*2000/(117.91\*2)  
 A AVBC.K=MIN(HRV.K/CAP.K,1)  
 N AVBCN=MIN(HRVN/CAPN,1)  
 L AADT.K=AAADT.J+(DT)(ADTINC.JK)  
 N AADT=AAADTN  
 N AADTN=((60725.\*0.3\*2+60275\*0.7)\*6.75+(25171\*0.3\*2+25171\*0.7)\*24.29^  
 +(33201\*0.3\*2+33201\*0.7)\*86.87)/(117.91)  
 A HRV.K=AAADT.K\*WAHR  
 N HRVN=AAADTN\*WAHR  
 C WAHR=0.0417  
 R ADTINC.KL=AAADT.K\*AIR.K  
 A AIR.K=CLIP(0.025,0.025,TIME.K,5.25)  
 A TVOL.K=(AAADT.K\*AVCF)  
 N TVOLN=AAADTN  
 C AVCF=350  
 A TTLKL.K=FFTTTLKL.K\*(1-(1-LOSF.K)\*(AVBC.K))/(1.0001-AVBC.K)  
 N TTLKLN=FFTTTLKL.K\*(1-(1-LOSFN.K)\*(AVBCN))/(1.0001-AVBCN)  
 A SPD.K=MIN(TOTMILG/(TTLKL.K/60),FSPD)

A FFTTLKL.K=(TOTMILG/FSPD)\*60  
C FSPD=80  
A DFTT.K=(TTLKLN-TTLKL.K)/TTLKL.K  
A DFIOI.K=TABLE(DFIOIT,DFTT.K,-.5,.5,.1)  
T DFIOIT=-.01/-0.008/-0.006/-0.004/-0.002/0/0.002/0.004/0.006/0.008/0.01  
R UAUBEN.KL=(((TTLKLN-TTLKL.K)\*VOT\*INFLF.K)^  
((TVOL.K+TVOLN)/2))\*(ADTSD/TOTMILG)  
C ADTSD=80  
L UUBEN.K=UUBEN.J+(DT)(UAUBEN.JK)  
N UUBEN=0  
R DAUBEN.KL=(((TTLKLN-TTLKL.K)\*VOT\*INFLF.K)^  
((TVOL.K+TVOLN)/2))/(1+DISR)\*\*TIME.K  
C VOT=0.50  
L DUBEN.K=DUBEN.J+(DT)(DAUBEN.JK)  
N DUBEN=0  
R UANUBEN.KL=(PS.K\*PCIV.K\*DFIOI.K)  
L UNUBEN.K=UNUBEN.J+(DT)(UANUBEN.JK)  
N UNUBEN=0  
R DANUBEN.KL=(PS.K\*PCIV.K\*DFIOI.K)/(1+DISR)\*\*TIME.K  
L DNUBEN.K=DNUBEN.J+(DT)(DANUBEN.JK)  
N DNUBEN=0  
A TLCCUD.K=BLCCUD.K+HLCCUD.K  
A NVB.K=UUBEN.K+UNUBEN.K-TLCCUD.K  
A TLCCD.K=CLIP((BLCCD.K+HLCCD.K),1,TIME.K,1)  
A NPVB.K=DUBEN.K+DNUBEN.K-TLCCD.K  
A HCEUDE.K=CLIP(HCEUD.K,1,TIME.K,1)  
L HEXPD.K=HEXPD.J+(DT)(ERH.JK)  
N HEXPD=HEXPDN  
C HEXPDN=0  
A CCBCR.K=((UUBEN.K+UNUBEN.K-DFEXPD.K)/(HCEUDE.K\*DISR))\*(1-EXP(-DISR\*N))  
A MEPEPH.K=(HMEUD.K\*HEXPD.K/TOTALH.K)  
A TUBEN.K=UUBEN.K+UNUBEN.K  
C N=40  
A DRE.K=UUBEN.K+UNUBEN.K-HMEUD.K  
A GTRMBR.K=(TVOL.K\*TOTMILG\*RMFT.K)/((HMB.K+BB.K)\*ADTPG.K)  
C TOTMILG=117.91  
A BCR.K=CLIP(BCRN+((UAUBEN.KL+UANUBEN.KL-DFEXPD.K)/(HCEUDE.K\*DISR)),BCRN,  
TIME.K,5.25)  
N BCR=BCRN  
C BCRN=1  
A DFEXPD.K=(HMB.K+BB.K)-(HMBN+BBN)

\* FUNCTIONAL SUBSYSTEM

A MCDFH.K=29000

A MCDTH.K=73000

A ECH.K=1E6

\*A EP.K=1

A EP.K=CLIP(1.5,1,TIME.K,5.25)

A PMCB.K=25000\*EP.K

\*A PMCB.K=EP.K\*(CS\*WFS.K+CSDC\*WFSDC.K+CEJM\*WFEJM.K+CPGM\*WFPGM.K^

\* +CSP\*WFSP.K)

A MNRCB.K=80000\*EP.K

\*A MNRCB.K=EP.K\*(CDO\*WFDO.K+CCP\*WFCP.K+CPCH\*WFPCH.K+CEJR\*WFEJR.K+CRPT\*

\* WFRPT.K^+CBAR\*WFBAR.K+CDSR\*WFDSR.K+CSMR\*WFSMR.K+CCDR\*WFCDR.K+

\* CDER\*WFDER.K)

A MJRCB.K=126000\*EP.K

\*A MJRCB.K=EP.K\*(CDKR\*WFDKR.K+CSSR\*WFSSR.K+CCBR\*WFCBR.K)

A RHC.B.K=175000\*EP.K

\*A RHC.B.K=EP.K\*(CRA\*WFRA.K+CRP\*WFRP.K+CRLP\*WFRLP.K+CRLA\*WFLA.K+CRCD\*^

\* WFRCD.K) \*1.5

A BWC.K=500000

A RPCB.K=1500000

C CS=511.81

A WFS.K=0.13

C CSDC=36656.28

A WFSDC.K=0.13

C CEJM=1753.49

A WFEJM.K=0.63

C CPGM=2917.43

A WFPGM.K=0.07

C CSP=5000.96

A WFSP.K=0.04

\*

C CDO=87463.41

A WFDO.K=0.17

C CCP=414739.60

A WFCP.K=0.01

C CPCH=40648.67

A WFPCH.K=0.21

C CEJR=3562.90

A WFEJR.K=0.29

C CRPT=19930.68

A WFRPT.K=0.14

C CBAR=7680

A WFBAR.K=0.01

C CDSR=5000

A WFDSR.K=0.07

C CSMR=100000

A WFSMR.K=0.03

C CCDR=310581

A WFCDR.K=0.03

C CDER=389410

A WFDER.K=0.04

\*

\*

C CDKR=116047.52

A WFDKR.K=0.65  
 C CSSR=404771.57  
 A WFSSR.K=0.22  
 C CCBR=12180  
 A WFCBR.K=0.13  
 \*  
 \*  
 C CRA=7668.45  
 A WFRA.K=0.14  
 C CRP=65122.59  
 A WFRP.K=0.7  
 C CRLA=18231.42  
 A WFRLA.K=0.01  
 C CRLP=84987.46  
 A WFRLP.K=0.07  
 C CRCD=100000  
 A WFRCD.K=0.14  
 \*  
 \*  
 A TBEXPD.K=PMCB.K\*BPM.K+MNRCB.K\*BMNR.K+MJRCB.K\*BMJR.K+BWC.K\*BW.KL^  
 +RPCB.K\*RPRB.KL+RHCB.K\*RHRB.KL  
 A BPM.K=FAPMB.KL+FIPMB.KL  
 A BMNR.K=FIMNRB.KL+FAMNRB.KL  
 A BMJR.K=FIMJRB.KL+FAMJRB.KL  
 L BLCCD.K=BLCCD.J+(DT)(TBED.JK)  
 N BLCCD=0  
 R TBED.KL=(INFLF.K\*TBEXPD.K)/(1+DISR)\*\*TIME.K  
 A INFLF.K=(INFLR+1)\*\*TIME.K  
 C INFLR=0.0  
 C DISR=0.06  
 L BLCCUD.K=BLCCUD.J+(DT)(TBEUD.JK)  
 N BLCCUD=0  
 R TBEUD.KL=(INFLF.K\*TBEXPD.K)  
 A THCE.K=ERHI.K\*ECH.K  
 A THME.K=MRDFH.KL\*MCDFH.K+MRDTH.KL\*MCDTH.K  
 L HLCCUD.K=HLCCUD.J+(DT)(THEUD.JK)  
 N HLCCUD=0  
 R THEUD.KL=INFLF.K\*(THCE.K+THME.K)  
 L HLCCD.K=HLCCD.J+(DT)(THED.JK)  
 N HLCCD=0  
 R THED.KL=(INFLF.K\*(THCE.K+THME.K))/(1+DISR)\*\*TIME.K

\*FINANCIAL SUBSYSTEM

\* \*\*\*\*\* DECISION VARIABLES \*\*\*\*\*

C FBHM=0.5  
A FBHC.K=1-FBHM  
C FCBB=0.5  
C FMBB=0.5  
A FMBP.K=1-FMBB  
\* \*\*\*\*\*  
L PV.K=PV.J+(DT)(BRV.JK+IMRV.JK-DRV.JK-OMRV.JK)  
N PV=PVN  
C PVN=6618358  
A PS.K=PV.K\*FPSV  
C FPSV=0.1  
R BRV.KL=BRPV\*PV.K  
C BRPV=0.014591  
R DRV.KL=DRPV\*PV.K  
C DRPV=0.008249  
R IMRV.KL=IMRPV\*PV.K  
C IMRPV=0.001168  
R OMRV.KL=OMRPV\*PV.K  
C OMRPV=0.001737  
L VV.K=VV.J+(DT)(VVINC.JK)  
N VV=0  
R VVINC.KL=VV.K\*VAGR  
C VAGR=0.01  
A VMT.K=ATMV\*VV.K  
C ATMV=12500  
A SS.K=PPR\*PV.K  
C PPR=1000  
A MVLF.K=VV.K\*RMVLF  
C RMVLF=26.5  
A TVVV.K=AVVV\*VV.K  
C AVVV=20000  
A MVSUT.K=RMVSUT\*TVVV.K  
C RMVSUT=0.03  
A MFT.K=RMFT.K\*VMT.K  
A RMFT.K=0.177  
A ADTPG.K=TABLE(ADTPGT,SPD.K,40,80,10)  
T ADTPGT=40/35/30/25/18  
A SST.K=RSST\*SS.K  
C RSST=0.045  
A TTF.K=FMVLFT.K\*MVLF.K+FMVSTT.K\*MVSUT.K+FMFTT.K\*MFT.K+FSST.K\*SST.K  
A FMVLFT.K=3/26.5  
A FMVSTT.K=1/3  
A FMFTT.K=2.5/17.7  
A FSST.K=0.85\*(0.5/4.5)  
A HMO.K=FMVLFH.K\*MVLF.K+FMVSTH.K\*MVSUT.K+FMFTH.K\*MFT.K+FSSH.K\*SST.K  
A FMVLFH.K=16/26.5  
A FMVSTH.K=2/3  
A FMFTH.K=14.85/17.7  
A FSSH.K=0.85\*(0/4.5)  
A TTRV.K=TTF.K+HMO.K+FAV.K  
A FAV.K=500000  
A ABH.K=FRHWY\*TTRV.K  
C FRHWY=0.8

```
A HMBV.K=FBHM*ABH.K
A HMBSD.K=FMBSD*HMBV.K
C FMBSD=0.15
A HCBV.K=FBHC.K*ABH.K
A HCBSD.K=FCBSD*HCBV.K
C FCBSD=0.15
A BB.K=CLIP(CLIP(1.33E6*K,1.33E6,TIME.K,5.25),FCBB*HCBSD.K+FMBB*HMBSD.K,TIME.K,0)
N BBN=1.33E6
A HMB.K=CLIP(CLIP(6.2E6*K,6.2E6,TIME.K,5.25),FMBP.K*HMBSD.K,TIME.K,0)
N HMBN=6.2E6
C K=1
```

**Appendix E Complete Listing of DYNAMO Program  
(HMS - Refined Version)**

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* HIGHWAY MANAGEMENT SYSTEM
FOR I=1,5
FOR J=ONE,TWO,THREE,FOUR,FIVE
INSERT PHSBMS1
INSERT PHSPMS1
INSERT FISS1
INSERT FUSS1
INSERT EVSS1
A TOTALB.K(I)=BFAPFC.K(I)+BFAFC.K(I)+BFAGC.K(I)+^
BFAPC.K(I)+BFIPFC.K(I)+BFIFC.K(I)+BFIGC.K(I)+BFIPC.K(I)+BCC.K(I)
N TOTALB(I)=TOTALBN
A TOTALBN.K=224
A TOTALH.K(J)=HSFPC.K(J)+HDFPC.K(J)+HDTPC.K(J)
N TOTALH(J)=TOTALHN
C TOTALHN=499.64
SPEC DT=0.25/SAVPER=0.25/LENGTH=8

```



\* PHYSICAL SUBSYSTEM-BRIDGE MANAGEMENT SYSTEM (BMS) MODELS

A OFBAPMB.K(I)=TEMP1(I)  
 T TEMP1(I)=0.1/0.3/0.5/0.7/0.9  
 A OFBANRB.K(I)=(1-OFBAPMB.K(I))/3  
 A OFBAJRB.K(I)=(1-OFBAPMB.K(I))/3  
 A OFBBW.K(I)=0.0  
 A OFBRHB.K(I)=(1-OFBAPMB.K(I))/3  
 A OFBIPMB.K(I)=0.0  
 A OFBINRB.K(I)=0.0  
 A OFBIJRB.K(I)=0.0  
 A OFBRPB.K(I)=0.0  
 A TFBBM.K(I)=MAX((AFBAPMB.K(I)+AFBANRB.K(I)+AFBAJRB.K(I)+AFBRHB.K(I)^  
 +AFBBW.K(I)+AFBIPMB.K(I)+AFBINRB.K(I)+AFBIJRB.K(I)+AFBRPB.K(I)),0.000001)  
 A ABFAPFC.K(I)=MAX(BFAPFC.K(I),0)  
 A ABFAGC.K(I)=MAX(BFAGC.K(I),0)  
 A ABFAFC.K(I)=MAX(BFAFC.K(I),0)  
 A ABFAPC.K(I)=MAX(BFAPC.K(I),0)  
 A ABFIPFC.K(I)=MAX(BFIPFC.K(I),0)  
 A ABFIGC.K(I)=MAX(BFIGC.K(I),0)  
 A ABFIFC.K(I)=MAX(BFIFC.K(I),0)  
 A ABFIPC.K(I)=MAX(BFIPC.K(I),0)  
 A ABFACC.K(I)=MAX(BFACC.K(I),0)  
 A ABFICC.K(I)=MAX(BFICC.K(I),0)  
 L BFAPFC.K(I)=BFAPFC.J(I)+(DT)(FAPMB.JK(I)+FAMNRB.JK(I)+FAMJRB.JK(I)^  
 +RHRB.JK(I)+RPRB.JK(I)+BW.JK(I)-ORB.JK(I)-FAERB.JK(I))  
 N BFAPFC(I)=BFAPFCN  
 C BFAPFCN=16  
 R FAERB.KL(I)=MAX(BFAPFC.K(I)/ETB,0)  
 C ETB=.5  
 R FAPMB.KL(I)=MIN(FAPMBB.K(I)/PMCB.K(I),ABFAGC.K(I))  
 A FAPMBB.K(I)=BB.K\*FBFAPMB.K(I)  
 A FBFAPMB.K(I)=AFBAPMB.K(I)/TFBBM.K(I)  
 A AFBAPMB.K(I)=CLIP(OFBAPMB.K(I),0,BFAGC.K(I),0.999)  
 L BFAGC.K(I)=BFAGC.J(I)+(DT)(FAERB.JK(I)-FAPMB.JK(I)-FADR.B.K(I))  
 N BFAGC(I)=BFAGCN  
 C BFAGCN=105  
 R FADR.B.KL(I)=MAX(BFAGC.K(I)/DTTB,0)  
 C DTTB=21  
 R FAMNRB.KL(I)=MIN(FAMNRBB.K(I)/MNRCB.K(I),ABFAFC.K(I))  
 A FAMNRBB.K(I)=BB.K\*FBFANRB.K(I)  
 A FBFANRB.K(I)=AFBANRB.K(I)/TFBBM.K(I)  
 A AFBANRB.K(I)=CLIP(OFBANRB.K(I),0,BFAFC.K(I),0.999)  
 L BFAFC.K(I)=BFAFC.J(I)+(DT)(FADR.B.JK(I)-FAMNRB.JK(I)-FAADR.B.K(I))  
 N BFAFC(I)=BFAFCN  
 C BFAFCN=49  
 R FAADR.B.KL(I)=MAX(BFAFC.K(I)/ADTB,0)  
 C ADTB=22  
 R FAMJRB.KL(I)=MIN(FAMJRBB.K(I)/MJRCB.K(I),ABFAPC.K(I))  
 A FAMJRBB.K(I)=BB.K\*FBFAJRB.K(I)  
 A FBFAJRB.K(I)=AFBAJRB.K(I)/TFBBM.K(I)  
 A AFBAJRB.K(I)=CLIP(OFBAJRB.K(I),0,BFAPC.K(I),0.999)  
 L BFAPC.K(I)=BFAPC.J(I)+(DT)(FAADR.B.JK(I)-FAMJRB.JK(I)-FASDRB.JK(I))  
 N BFAPC(I)=BFAPCN  
 C BFAPCN=7  
 L BFACC.K(I)=BFACC.J(I)+(DT)(FASDRB.JK(I)-RHRB.JK(I))  
 N BFACC(I)=BFACCN

C BFACCN=0  
R FASDRB.KL(I)=MAX(BFAPC.K(I)/SDTB,0)  
C SDTB=15  
R RHRB.KL(I)=MIN(RHBB.K(I)/RHCB.K(I),ABFACC.K(I))  
A RHBB.K(I)=BB.K\*FBRHB.K(I)  
A FBRHB.K(I)=AFBRHB.K(I)/TFBBM.K(I)  
A AFBRHB.K(I)=CLIP(OFBRHB.K(I),0,BFACC.K(I),0.999)  
R ORB.KL(I)=MAX(BFAPFC.K(I)/OTB,0)  
C OTB=20  
R BW.KL(I)=MIN(BWB.K(I)/BWC.K.,ABFIPFC.K(I))  
A BWB.K(I)=BB.K\*FBBW.K(I)  
A FBBW.K(I)=AFBBW.K(I)/TFBBM.K(I)  
A AFBBW.K(I)=CLIP(OFBBW.K(I),0,BFIPFC.K(I),0.999)  
L BFIPFC.K(I)=BFIPFC.J(I)+(DT)(FIPMB.JK(I)+FIMNRB.JK(I)+FIMJRB.JK(I)+ORB.JK(I)-BW.JK(I)^  
-FIERB.JK(I))  
N BFIPFC(I)=BFIPFCN  
C BFIPFCN=0  
R FIERB.KL(I)=MAX(BFIPFC.K(I)/ETB,0)  
R FIPMB.KL(I)=MIN(FIPMBB.K(I)/PMCB.K(I),ABFIGC.K(I))  
A FIPMBB.K(I)=BB.K\*FBFIPMB.K(I)  
A FBFIPMB.K(I)=AFBIPMB.K(I)/TFBBM.K(I)  
A AFBIPMB.K(I)=CLIP(OFBIPMB.K(I),0,BFIGC.K(I),0.999)  
L BFIGC.K(I)=BFIGC.J(I)+(DT)(FIERB.JK(I)-FIPMB.JK(I)-FIDRB.JK(I))  
N BFIGC(I)=BFIGCN  
C BFIGCN=17  
R FIDRB.KL(I)=MAX(BFIGC.K(I)/DTTB,0)  
R FIMNRB.KL(I)=MIN(FIMNRBB.K(I)/MNRCB.K(I),ABFIFC.K(I))  
A FIMNRBB.K(I)=BB.K\*FBFINRB.K(I)  
A FBFINRB.K(I)=AFBINRB.K(I)/TFBBM.K(I)  
A AFBINRB.K(I)=CLIP(OFBINRB.K(I),0,BFIFC.K(I),0.999)  
L BFIFC.K(I)=BFIFC.J(I)+(DT)(FIDRB.JK(I)-FIMNRB.JK(I)-FIADRB.JK(I))  
N BFIFC(I)=BFIFCN  
C BFIFCN=17  
R FIADRB.KL(I)=MAX(BFIFC.K(I)/ADTB,0)  
R FIMJRB.KL(I)=MIN(FIMJRBB.K(I)/MJRCB.K(I),ABFIPC.K(I))  
A FIMJRBB.K(I)=BB.K\*FBFIJRB.K(I)  
A FBFIJRB.K(I)=AFBIJRB.K(I)/TFBBM.K(I)  
A AFBIJRB.K(I)=CLIP(OFBIJRB.K(I),0,BFIPC.K(I),0.999)  
L BFIPC.K(I)=BFIPC.J(I)+(DT)(FIADRB.JK(I)-FIMJRB.JK(I)-FISDRB.JK(I))  
N BFIPC(I)=BFIPCN  
C BFIPCN=12  
R FISDRB.KL(I)=MAX(BFIPC.K(I)/SDTB,0)  
R RPRB.KL(I)=MIN(RPBB.K(I)/RPCB.K.,ABFICC.K(I))  
A RPBB.K(I)=BB.K\*FBRPB.K(I)  
A FBRPB.K(I)=AFBRPB.K(I)/TFBBM.K(I)  
A AFBRPB.K(I)=CLIP(OFBRPB.K(I),0,BFICC.K(I),0.999)  
L BFICC.K(I)=BFICC.J(I)+(DT)(FISDRB.JK(I)-RPRB.JK(I))  
N BFICC(I)=BFICCN  
C BFICCN=0  
A TBFAC.K(I)=BFAPFC.K(I)+BFAGC.K(I)+BFAFC.K(I)+BFAPC.K(I)  
N TBFACN(I)=BFAPFCN+BFAGCN+BFAFCN+BFAPCN+BFACCN  
A TBFIC.K(I)=BFIPFC.K(I)+BFIGC.K(I)+BFIFC.K(I)+BFIPC.K(I)+BCC.K(I)  
N TBFICN(I)=BFIPFCN+BFIGCN+BFIFCN+BFIPCN+BFICCN  
A BFAI.K(I)=(TBFAC.K(I)\*WFFAB+TBFIC.K(I)\*WFFIB)/(TBFAC.K(I)+TBFIC.K(I))  
N BFAIN(I)=(TBFACN(I)\*WFFAB+TBFICN(I)\*WFFIB)/(TBFACN(I)+TBFICN(I))  
A BPFC.K(I)=ABFIPFC.K(I)+ABFAPFC.K(I)

N BPFCN(I)=BFIPFCN+BFAPFCN  
 A BGC.K(I)=ABFIGC.K(I)+ABFAGC.K(I)  
 N BGCN(I)=BFIGCN+BFAGCN  
 A BFC.K(I)=ABFIFC.K(I)+ABFAFC.K(I)  
 N BFCN(I)=BFIFCN+BF AFCN  
 A BPC.K(I)=ABFIPC.K(I)+ABFAPC.K(I)  
 N BPCN(I)=BFIPCN+BFAPCN  
 A BCC.K(I)=ABFICC.K(I)+ABFACC.K(I)  
 N BCCN(I)=BFICCN+BFACCN  
 A BPAI.K(I)=(BPFC.K(I)\*WFPFB+BGC.K(I)\*WFGB+BFC.K(I)\*WFFB+BPC.K(I)\*WFPB+BCC.K(I)^  
 \*WFCB)/(BPFC.K(I)+BGC.K(I)+BFC.K(I)+BPC.K(I)+BCC.K(I))  
 N BPAIN(I)=(BPFCN(I)\*WFPFB+BGCN(I)\*WFGB+BFCN(I)\*WFFB+BPCN(I)\*WFPB+BCCN(I)\*WFCB)/^  
 (BPFCN(I)+BGCN(I)+BFCN(I)+BPCN(I)+BCCN(I))  
 C WFFAB=1  
 C WFFIB=0.5  
 C WFPFB=1  
 C WFGB=1  
 C WFFB=0.9  
 C WFPB=0.7  
 C WFCB=0.4

```

*PHYSICAL SUBSYSTEM-PAVEMENT MANAGEMENT SYSTEM (PMS) MODEL
A OFBDFH.K(J)=TEMP2(J)
T TEMP2(J)=0.1/0.3/0.5/0.7/0.9
A OFBDTH.K(J)=1-OFBDFH.K(J)
A AHSFPC.K(J)=MAX(HSFPC.K(J),0)
A AHDFPC.K(J)=MAX(HDFPC.K(J),0)
A AHDTPC.K(J)=MAX(HDTPC.K(J),0)
A TFHM.K(J)=MAX(AFBMDT.K(J)+AFBMDF.K(J),0.0000000001)
L HSFPC.K(J)=HSFPC.J(J)+(DT)(MRDTH.JK(J)+ERH.JK+MRDFH.JK(J)-ARH.JK(J))
N HSFPC(J)=HSFPCN
C HSFPCN=166.55
R MRDFH.KL(J)=MIN(HMB.K*FMBDFH.K(J)/MCDFH.K(J),HDFPC.K(J))
A FMBDFH.K(J)=AFBMDF.K(J)/TFHM.K(J)
A FMBDTH.K(J)=AFBMDT.K(J)/TFHM.K(J)
A AFBMDF.K(J)=CLIP(OFBDFH.K(J),0,HDFPC.K(J),0)
A AFBMDT.K(J)=CLIP(OFBDTH.K(J),0,HDTPC.K(J),0)
R MRDTH.KL(J)=MIN(HMB.K*FMBDTH.K(J)/MCDTH.K(J),HDTPC.K(J))
R ARH.KL(J)=HSFPC.K(J)/ATH
C ATH=1
L HDFPC.K(J)=HDFPC.J(J)+(DT)(ARH.JK(J)-MRDFH.JK(J)-DRH.JK(J))
N HDFPC(J)=HDFPCN
C HDFPCN=166.55
L HDTPC.K(J)=HDTPC.J(J)+(DT)(DRH.JK(J)-MRDTH.JK(J))
N HDTPC(J)=HDTPCN
C HDTPCN=166.55
R DRH.KL(J)=HDFPC.K(J)/DTH
C DTH=3
A HDRM.K(J)=(MRDFH.KL(J)+MRDTH.KL(J))/(HSFPC.K(J)+HDFPC.K(J)+HDTPC.K(J))
A HPAI.K(J)=(HSFPC.K(J)+HDFPC.K(J)*WDFCH+HDTPC.K(J)*WFDTCH)^
/(HSFPC.K(J)+HDFPC.K(J)+HDTPC.K(J))
N HPAI(J)=(HSFPCN+HDFPCN*WDFCH+HDTPCN*WFDTCH)/TMHN
C WDFCH=0.5
C WFDTCH=0
*****
* EXPANSION RATE FOR *
* ADDING LANE ON I-81 *
*****
NOTE R ERH.KL=CLIP(0,((86.87)*2)/5,TIME.K,5.25)
NOTE ERH-EXPANSION RATE OF HIGHWAY (LANE-MI/YR)
R ERH.KL=CLIP(CLIP(0,(86.87)*2*(1/DT),TIME.K,5.25),0,TIME.K,5)
* R ERH.KL=CLIP(CLIP(0,(86.87)*2,TIME.K,6.25),0,TIME.K,5.25)
A ERH1.K=CLIP(0,((86.87)*2)/5.25,TIME.K,5.25)
A TMH.K(J)=HSFPC.K(J)+HDFPC.K(J)+HDTPC.K(J)
N TMHN=HSFPCN+HDFPCN+HDTPCN

```

```

* EVALUATION SUBSYSTEM MODEL
L PCIV.K=PCIV.J+(DT)(IIR.JK)
N PCIV=PCIN
C PCIN=11933
R IIR.KL=PCIV.K*IIRP
C IIRP=0.00143
L HTMED.K(I,J)=HTMED.J(I,J)+(DT)(TMED.JK(I,J))
N HTMED(I,J)=0
L HMEUD.K(I,J)=HMEUD.J(I,J)+(DT)(TMEUD.JK(I,J))
N HMEUD(I,J)=0
L HCEUD.K=HCEUD.J+(DT)(TCEUD.JK)
N HCEUD=0
R TCEUD.KL=THCE.K
L HCED.K=HCED.J+(DT)(TCED.JK)
N HCED=0
R TCED.KL=(THCE.K)/(1+DISR)**TIME.K
R TMED.KL(I,J)=(TBEXPD.K(I)+THME.K(J))/(1+DISR)**TIME.K
R TMEUD.KL(I,J)=(TBEXPD.K(I)+THME.K(J))
A WLOSF.K(I,J)=((0.8*(1*AHFPC.K(J)+2*AHDFPC.K(J)+4*AHDTPC.K(J))/TOTALH.K(J))^
+(0.2*(1*BPFC.K(I)+2*BGC.K(I)+4*BFC.K(I)+8*BPC.K(I)+16*BCC.K(I))/TOTALB.K(I)))
N WLOSFN(I,J)=((0.8*(1*HSFPCN+2*HDFPCN+4*HDTPCN)/TOTALHN)^
+(0.2*(1*BPFCN(I)+2*BGCN(I)+4*BFCN(I)+8*BPCN(I)+16*BCCN(I))/TOTALBN))
A LOSF.K(I,J)=TABLE(LOSFT,WLOSF.K(I,J),1,6,4,1.08)
T LOSFT=0.1/0.2/0.3/0.4/0.6/1
N LOSFN(I,J)=TABLE(LOSFTN,WLOSFN(I,J),1,6,4,1.08)
T LOSFTN=0.1/0.2/0.3/0.4/0.6/1
A LHPA.K(J)=HPAI.K(J)*(1-HDRM.K(J))
N LHPAN(J)=HPAIN(J)
A PLS.K(I,J)=LHPA.K(J)*BPAI.K(I)
N PLSN(I,J)=LHPAN(J)*BPAIN(I)
A VOPC.K(I,J)=(TABLE(VOPCT,PLS.K(I,J),0,1,0.2))*TVOL.K*TOTMILG
T VOPCT=0.4/0.3/0.22/0.18/0.16/0.15
N VOPCN(I,J)=TABLE(VOPCNT,PLSN(I,J),0,1,0.2)
T VOPCNT=0.4,0.3,0.22,0.18,0.16,0.15
* ** ADDING CAPACITY FOR EXPANSION
A CAP.K(J)=TOTALH.K(J)*2000/(117.91*2)
NOTE A CAP.K=CLIP(673.38*2000/(117.91*2),499.64*2000/(117.91*2),TIME.K,5.25)
N CAPN=499.64*2000/(117.91*2)
A AVBC.K(J)=MIN(HRV.K/CAP.K(J),1)
N AVBCN=MIN(HRVN/CAPN,1)
L AADT.K=AADT.J+(DT)(ADTINC.JK)
N AADT=AADTN
N AADTN=((60725.*0.3*2+60275*0.7)*6.75+(25171*0.3*2+25171*0.7)*24.29^
+(33201*0.3*2+33201*0.7)*86.87)/(117.91)
A HRV.K=AADT.K*WAHR
N HRVN=AADTN*WAHR
C WAHR=0.0417
R ADTINC.KL=AADT.K*AIR.K
A AIR.K=CLIP(0.025,0.025,TIME.K,5.25)
A TVOL.K=(AADT.K*AVCF)
N TVOLN=AADTN
C AVCF=350
A TTLKL.K(I,J)=FFTTLKL.K*(1-(1-LOSF.K(I,J))*(AVBC.K(J)))/(1.0001-AVBC.K(J))
N TTLKLN(I,J)=FFTTLKL.K*(1-(1-LOSFN(I,J))*(AVBCN))/(1.0001-AVBCN)
A SPD.K(I,J)=MIN(TOTMILG/(TTLKL.K(I,J)/60),FSPD)
A FFTLKL.K=(TOTMILG/FSPD)*60

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C FSPD=80  
A DFTT.K(I,J)=(TTLKLN(I,J)-TTLKL.K(I,J))/TTLKL.K(I,J)  
A DFIOI.K(I,J)=TABLE(DFIOIT,DFTT.K(I,J),-.5,.5,.1)  
T DFIOIT=-.01/-0.008/-0.006/-0.004/-0.002/0/0.002/0.004/0.006/0.008/0.01  
R UAUBEN.KL(I,J)=(((TTLKLN(I,J)-TTLKL.K(I,J))\*VOT\*INFLF.K)^  
((TVOL.K+TVOLN)/2))\*(ADTSD/TOTMILG)  
C ADTSD=80  
L UUBEN.K(I,J)=UUBEN.J(I,J)+(DT)(UAUBEN.JK(I,J))  
N UUBEN(I,J)=0  
R DAUBEN.KL(I,J)=(((TTLKLN(I,J)-TTLKL.K(I,J))\*VOT\*INFLF.K)^  
((TVOL.K+TVOLN)/2))/(1+DISR)\*\*TIME.K)\*(ADTSD/TOTMILG)  
C VOT=0.50  
L DUBEN.K(I,J)=DUBEN.J(I,J)+(DT)(DAUBEN.JK(I,J))  
N DUBEN(I,J)=0  
R UANUBEN.KL(I,J)=(PS.K\*PCIV.K\*DFIOI.K(I,J))\*INFLF.K  
L UNUBEN.K(I,J)=UNUBEN.J(I,J)+(DT)(UANUBEN.JK(I,J))  
N UNUBEN(I,J)=0  
R DANUBEN.KL(I,J)=((PS.K\*PCIV.K\*DFIOI.K(I,J))/(1+DISR)\*\*TIME.K)\*INFLF.K  
L DNUBEN.K(I,J)=DNUBEN.J(I,J)+(DT)(DANUBEN.JK(I,J))  
N DNUBEN(I,J)=0  
A TLCCUD.K(I,J)=BLCCUD.K(I)+HLCCUD.K(J)  
A NVB.K(I,J)=UUBEN.K(I,J)+UNUBEN.K(I,J)-TLCCUD.K(I,J)  
A TLCCD.K(I,J)=CLIP((BLCCD.K(I)+HLCCD.K(J)),1,TIME.K,1)  
A NPVB.K(I,J)=DUBEN.K(I,J)+DNUBEN.K(I,J)-TLCCD.K(I,J)  
A HCEUDE.K=CLIP(HCEUD.K,1,TIME.K,1)  
L HEXPD.K=HEXPJ.J+(DT)(ERH.JK)  
N HEXPD=HEXPJN  
C HEXPDN=0  
A CCBCR.K(I,J)=((UUBEN.K(I,J)+UNUBEN.K(I,J)--DFEXPJ.K)^  
/(HCEUDE.K\*DISR))\*(1-EXP(-DISR\*N))  
C N=40  
A DRE.K(I,J)=UUBEN.K(I,J)+UNUBEN.K(I,J)-HMEUD.K(I,J)  
A GTRMBR.K(I,J)=(TVOL.K\*TOTMILG\*RMFT.K\*INFLF.K)/((HMB.K+BB.K)\*ADTPG.K(I,J))  
C TOTMILG=117.91  
A BCR.K(I,J)=CLIP(BCRN+((UAUBEN.KL(I,J)+UANUBEN.KL(I,J)-DFEXPJ.K)/  
(HCEUDE.K\*DISR)),BCRN,TIME.K,5.25)  
N BCR(I,J)=BCRN  
C BCRN=1  
A DFEXPJ.K=(HMB.K+BB.K)-(HMBN+BBN)  
A TPM.K(I,J)=(1/SPD.K(I,J))\*60

\* FUNCTIONAL SUBSYSTEM  
 \* \*\*\*EXPANSION INCREASE BRIDGE COST 50%\*\*\*  
 A ECH.K=1E6\*INFLF.K  
 NOTE ECH - EXPANSION COST OF HIGHWAY (\$/LN-MI)  
 NOTE A EP.K=1  
 A EP.K=CLIP(1.5,1,TIME.K,5)  
 A MCDFH.K(J)=TABLE(MCDFHT,HDFPC.K(J),0,600,150)\*INFLF.K  
 T MCDFH=1500/5440/11842/21200/43000  
 A MCDTH.K(J)=TABLE(MCDTHT,HDTPC.K(J),0,600,150)\*INFLF.K  
 T MCDTHT=43000/76852/90150/95567/100000  
 A PMCB.K(I)=EP.K\*TABLE(PMCBT,BFAGC.K(I),0,200,50)\*INFLF.K  
 T PMCBT=3000/8610/14220/22635/31050  
 A MNRCB.K(I)=EP.K\*TABLE(MNRCBT,BFAFC.K(I),0,200,50)\*INFLF.K  
 T MNRCBT=31050/47880/68450/95565/118005  
 A MJRCB.K(I)=EP.K\*TABLE(MJRCBT,BFAPC.K(I),0,200,50)\*INFLF.K  
 T MJRCBT=118005/143250/157275/165690/171350  
 A RHC.B.K(I)=EP.K\*TABLE(RHC.BT,BFACC.K(I),0,200,50)\*INFLF.K  
 T RHC.BT=171350/174990/178630/181360/185000  
 \*  
 \*  
 A BWC.K=500000\*INFLF.K  
 A RPCB.K=EP.K\*1500000\*INFLF.K  
 \*  
 A TBEXPD.K(I)=PMCB.K(I)\*BPM.K(I)+MNRCB.K(I)\*BMNR.K(I)+MJRCB.K(I)\*BMJR.K(I)^  
 +BWC.K\*BW.KL(I)+RPCB.K\*RPRB.KL(I)+RHC.B.K(I)\*RHRB.KL(I)  
 A BPM.K(I)=FAPMB.KL(I)+FIPMB.KL(I)  
 A BMNR.K(I)=FIMNRB.KL(I)+FAMNRB.KL(I)  
 A BMJR.K(I)=FIMJRB.KL(I)+FAMJRB.KL(I)  
 L BLCCD.K(I)=BLCCD.J(I)+(DT)(TBED.JK(I))  
 N BLCCD(I)=0  
 R TBED.KL(I)=(TBEXPD.K(I))/(1+DISR)\*\*TIME.K  
 C DISR=0.06  
 A INFLF.K=(INFLR+1)\*\*TIME.K  
 C INFLR=0.0  
 L BLCCUD.K(I)=BLCCUD.J(I)+(DT)(TBEUD.JK(I))  
 N BLCCUD(I)=0  
 R TBEUD.KL(I)=(TBEXPD.K(I))  
 A THCE.K=ERH1.K\*ECH.K  
 A THME.K(J)=MRDFH.KL(J)\*MCDFH.K(J)+MRDTH.KL(J)\*MCDTH.K(J)  
 L HLCCUD.K(J)=HLCCUD.J(J)+(DT)(THEUD.JK(J))  
 N HLCCUD(J)=0  
 R THEUD.KL(J)=(THCE.K+THME.K(J))  
 L HLCCD.K(J)=HLCCD.J(J)+(DT)(THED.JK(J))  
 N HLCCD(J)=0  
 R THED.KL(J)=((THCE.K+THME.K(J)))/(1+DISR)\*\*TIME.K

\*FINANCIAL SUBSYSTEM

\* \*\*\*\*\* DECISION VARIABLES \*\*\*\*\*

C FBHM=0.5

A FBHC.K=1-FBHM

C FCBB=0.5

C FMBB=0.5

A FMBP.K=1-FMBB

\* \*\*\*\*\*

L PV.K=P.V.J+(DT)(BRV.JK+IMRV.JK-DRV.JK-OMRV.JK)

N PV=PVN

C PVN=6618358

A PS.K=P.V.K\*FPSV

C FPSV=0.1

R BRV.KL=BRPV\*PV.K

C BRPV=0.014591

R DRV.KL=DRPV\*PV.K

C DRPV=0.008249

R IMRV.KL=IMRPV\*PV.K

C IMRPV=0.001168

R OMRV.KL=OMRPV\*PV.K

C OMRPV=0.001737

L VV.K=V.V.J+(DT)(VVINC.JK)

N VV=0

R VVINC.KL=VV.K\*VAGR

C VAGR=0.01

A VMT.K=ATMV\*VV.K

C ATMV=12500

A SS.K=PPR\*PV.K

C PPR=1000

A MVLF.K=VV.K\*RMVLF

C RMVLF=26.5

A TVVV.K=AVVV\*VV.K

C AVVV=20000

A MVSUT.K=RMVSUT\*TVVV.K

C RMVSUT=0.03

A MFT.K=RMFT.K\*VMT.K

A RMFT.K=0.177

A ADTPG.K(I,J)=TABLE(ADTPGT,SPD.K(I,J),40,80,10)

T ADTPGT=40/35/30/25/18

A SST.K=RSST\*SS.K

C RSST=0.045

A TTF.K=FMVLFT.K\*MVLF.K+FMVSTT.K\*MVSUT.K+FMFTT.K\*MFT.K+FSST.K\*SST.K

A FMVLFT.K=3/26.5

A FMVSTT.K=1/3

A FMFTT.K=2.5/17.7

A FSST.K=0.85\*(0.5/4.5)

A HMO.K=FMVLFH.K\*MVLF.K+FMVSTH.K\*MVSUT.K+FMFTH.K\*MFT.K+FSSH.K\*SST.K

A FMVLFH.K=16/26.5

A FMVSTH.K=2/3

A FMFTH.K=14.85/17.7

A FSSH.K=0.85\*(0/4.5)

A TTRV.K=TTF.K+HMO.K+FAV.K

A FAV.K=500000

A ABH.K=FRHWY\*TTRV.K

C FRHWY=0.8

A HMBV.K=FBHM\*ABH.K



```
A HMBSD.K=FMBSD*HMBV.K
C FMBSD=0.15
A HCBV.K=FBHC.K*ABH.K
A HCBS.K=FCBSD*HCBV.K
C FCBSD=0.15
A BB.K=CLIP(CLIP(1.33E6*K,1.33E6,TIME.K,5.25),FCBB*HCBS.K+FMBB*HMBSD.K,TIME.K,0)^
  *INFLF.K
N BBN=1.33E6
A HMB.K=CLIP(CLIP(6.2E6*K,6.2E6,TIME.K,5.25),FMBP.K*HMBSD.K,TIME.K,0)*INFLF.K
N HMBN=6.2E6
C K=1.5
```

## Appendix F Steady State Analysis of BMS (RPre, Bwe≠0)

Let  $MMC = RHC B \times MJRC B \times MNRC B \times PMCB \times BWC \times RPCB$

$$BFAPFC_e = \frac{BB \times ETB \times OTB \times (FBFAPMB \times \frac{MMC}{PCB} + FBFANRB \times \frac{MMC}{MNRCB} + FBFAJRB \times \frac{MMC}{MJRCB} + FBRHB \times \frac{MMC}{RHC B} + FBRPB \times \frac{MMC}{RPCB} + FBBW \times \frac{MMC}{BWC B})}{(ETB + OTB) \times MMC}$$

$$BFAGC_e = BB \times DITB \times \frac{OTB \times (FBFAPMB \times \frac{MMC}{PCB} + FBFANRB \times \frac{MMC}{MNRCB} + FBFAJRB \times \frac{MMC}{MJRCB} + FBRHB \times \frac{MMC}{RHC B} + FBRPB \times \frac{MMC}{RPCB} + FBBW \times \frac{MMC}{BWC B}) - (ETB + OTB) (FBFAPMB \times \frac{MMC}{PCB})}{MMC}$$

$$BFAPC_e = BB \times ADITB \times \frac{OTB \times (FBFAPMB \times \frac{MMC}{PCB} + FBFANRB \times \frac{MMC}{MNRCB} + FBFAJRB \times \frac{MMC}{MJRCB} + FBRHB \times \frac{MMC}{RHC B} + FBRPB \times \frac{MMC}{RPCB} + FBBW \times \frac{MMC}{BWC B}) - (ETB + OTB) (FBFAPMB \times \frac{MMC}{PCB} + FBFANRB \times \frac{MMC}{MNRCB})}{MMC}$$

$$BFAPC_e = BB \times SDITB \times \frac{OTB \times (FBFAPMB \times \frac{MMC}{PCB} + FBFANRB \times \frac{MMC}{MNRCB} + FBFAJRB \times \frac{MMC}{MJRCB} + FBRHB \times \frac{MMC}{RHC B} + FBRPB \times \frac{MMC}{RPCB} + FBBW \times \frac{MMC}{BWC B}) - (ETB + OTB) (FBFAPMB \times \frac{MMC}{PCB} + FBFANRB \times \frac{MMC}{MNRCB} + FBFAJRB \times \frac{MMC}{MJRCB})}{MMC}$$

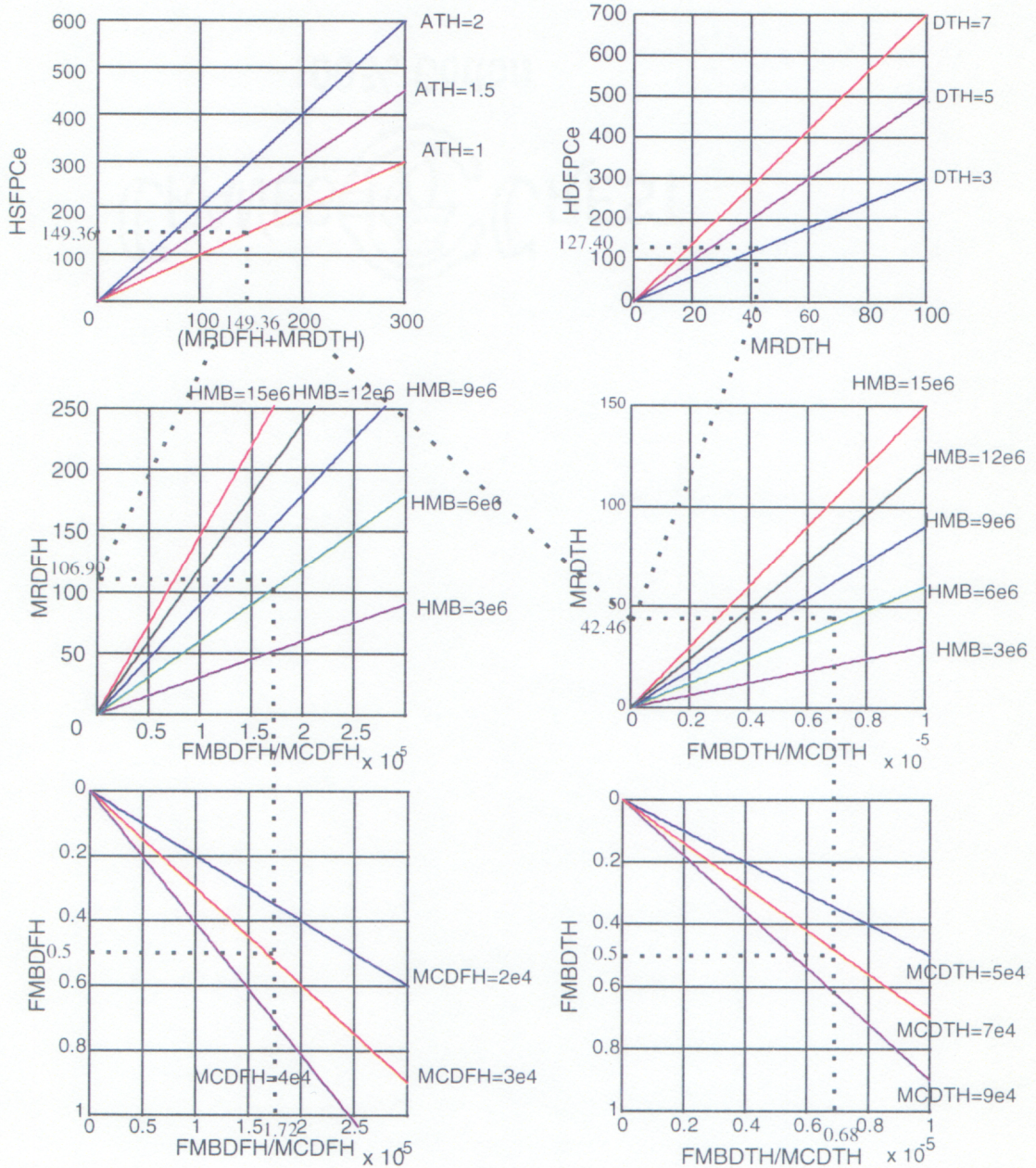
$$BFIPFC_e = BB \times ETB \times \frac{ETB \times (FBFAPMB \times \frac{MMC}{PCB} + FBFANRB \times \frac{MMC}{MNRCB} + FBFAJRB \times \frac{MMC}{MJRCB} + FBRHB \times \frac{MMC}{RHC B} + FBRPB \times \frac{MMC}{RPCB} + FBBW \times \frac{MMC}{BWC B}) + (ETB + OTB) (FBFIPMB \times \frac{MMC}{PCB} + FBFINRB \times \frac{MMC}{MNRCB} + FBFINRB \times \frac{MMC}{MJRCB} - FBBW \times \frac{MMC}{BWC B})}{MMC}$$

$$BFIGC_e = BB \times DITB \times \frac{ETB \times (FBFAPMB \times \frac{MMC}{PMCB} + FBFANRB \times \frac{MMC}{MNRCB} + FBFAJRB \times \frac{MMC}{MJRCB} + FBRHCB \times \frac{MMC}{RHCB})}{(ETB + OTB) \times} \\ + FBRPB \times \frac{MMC}{RPCB} + FBBW \times \frac{MMC}{BWCB} + (ETB + OTB) \left( FBFNRB \times \frac{MMC}{MNRCB} + FBFJRB \times \frac{MMC}{MJRCB} - FBBW \times \frac{MMC}{BWCB} \right) \\ \frac{MMC}{}$$

$$BFIFC_e = BB \times ADTB \times \frac{ETB \times (FBFAPMB \times \frac{MMC}{PMCB} + FBFANRB \times \frac{MMC}{MNRCB} + FBFAJRB \times \frac{MMC}{MJRCB} + FBRHCB \times \frac{MMC}{RHCB})}{(ETB + OTB) \times} \\ + FBRPB \times \frac{MMC}{RPCB} + FBBW \times \frac{MMC}{BWCB} + (ETB + OTB) \left( FBFJRB \times \frac{MMC}{MJRCB} - FBBW \times \frac{MMC}{BWCB} \right) \\ \frac{MMC}{}$$

$$BFIPC_e = BB \times SDTB \times \frac{ETB \times (FBFAPMB \times \frac{MMC}{PMCB} + FBFANRB \times \frac{MMC}{MNRCB} + FBFAJRB \times \frac{MMC}{MJRCB} + FBRHCB \times \frac{MMC}{RHCB})}{(ETB + OTB) \times} \\ + FBRPB \times \frac{MMC}{RPCB} + FBBW \times \frac{MMC}{BWCB} - (ETB + OTB) \left( FBBW \times \frac{MMC}{BWCB} \right) \\ \frac{MMC}{}$$

## Appendix G Example of Using Nomograph



## VITA

Mr. Wonkyu Kim was born in Seoul, Korea in 1964. He achieved his Bachelor of Science degree in Architectural Engineering at Yonsei University in 1988. He majored in Urban and Regional Planning in the graduate school of Yonsei University, and earned a Master of Science degree in Architectural Engineering in 1990. He worked as a research associate in the Korea Transport Institute from 1990 to 1994. He began his Ph.D. study at Virginia Tech in the fall of 1994.

A handwritten signature in black ink, appearing to read 'Wonkyu Kim', written in a cursive style.