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# The Effects of Dynamic Decision Making on Resource Allocation: The Case of Pavement Management

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**The Effects of Dynamic Decision Making on Resource Allocation:  
The Case of Pavement Management**

Dissertation in Partial Completion of Ph.D. Program  
Department of Social Science and Policy Studies and  
Department of Civil and Environmental Engineering  
Worcester Polytechnic Institute  
Worcester, Massachusetts

Prepared by Sheldon Friedman  
April 2003

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## **Abstract**

Pavement performance is a broad term that tries to describe how changing usage and varying conditions effect changes in pavement conditions. Measures of performance such as the Pavement Serviceability Index (PSI), the Pavement Condition Index (PCI) or Pavement Quality Index are available for use.

Modeling pavement management is an essential activity of a pavement management system. Currently, models are used in the pavement planning and budget development process, as well as in helping to determine pavement life cycle management (George, Rajagopal, and Lim 1989). This process provides a way to plan for both routine maintenance and full rehabilitation of current roads. Maintaining these roads in good order is essential for providing a safe and rapid means of ground transportation in order to support both the current and future economic needs of our communities.

System Dynamics is a simulation modeling process that allows the modeler to capture both the structure and behavior of the system under study. It is based on the concept that real world systems are non-linear in nature and the results of actions taken feed back and effect the system necessitating new actions.

The objective of this study is to use the System Dynamics modeling process to:

- Determine if and how current pavement management practices contribute to problems that pavement managers confront on a day to day basis.
- Develop a set of recommendations to improve those practices that are found to contribute to or create problems.
- Provide a tool that pavement managers can use to test their own proposed changes to their management practices in the form of a gaming environment.

## **Preface and Acknowledgements**

This dissertation and the accompanying system dynamics model examine a public policy issue. More specifically, the economies of small towns and states are dependent upon safe, usable highway systems, yet the maintenance of these systems is, in many respects sub-optimal. The model was developed with the hope of providing engineers with a tool for maintaining highway system at costs that are reasonable today, without sacrificing performance or creating future costs that are too high to support.

This model could not have been developed without the help of:

Dr. Michael J. Radzicki, Committee Chair, Department of Social Systems and Policy Studies, Worcester Polytechnic Institute-whose teaching and guidance made my learning possible.

Dr. Khalid Saeed, Chairman, Department of Social Systems and Policy Studies, Worcester Polytechnic Institute-who made me question myself.

Dr. James Doyle, Department of Social Systems and Policy Studies, Worcester Polytechnic Institute - who made me think about thinking and decisions.

Dr. Rajib Mallick, Department of Civil and Environmental Engineering, Worcester Polytechnic Institute -whose help in learning about road engineering made the research feasible.

Dr. Guillermo Salazar, Department of Civil and Environmental Engineering, Worcester Polytechnic Institute -who taught me the core of project management.

Pavement Managers from the states of Rhode Island, Massachusetts and Connecticut and the State Police, Office of Safety, State of Connecticut- without whose inputs this model could not have been structured.

### **Dedication**

This model could not have been accomplished without the dedication of my wife, Renee. This dissertation is dedicated to her support, patience, tolerance and mostly her love. Without these, the commitment to this work could not have been possible.

**The Effects of Dynamic Decision Making on Resource Allocation:  
The Case of Pavement Management**

# Pavement Management Systems

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Purpose and Summary of Research  
Findings and Recommendations

## **Purpose and Summary of Findings**

### **i.1 Objective of this Dissertation Study**

The objective of this study is to use the System Dynamics modeling process to:

- Determine if and how current pavement management practices contribute to the problem represented in Figure 1.1.
- Develop a set of recommendations to improve those practices that are found to contribute to or create problems.
- Provide a tool that pavement managers can use to test their own proposed changes to their management practices in the form of a gaming environment.

### **i.2 Purpose of Model**

The purposes of this system dynamics model are to:

- Model the conditions of a pavement network system and evaluate how these conditions effect resource utilization.
- Evaluate how the resource allocation process, as perceived and used by management, affects the condition of the system.
- Provide better insights into the effects of the decision making process and the consequences of the current use of that process.
- Provide a tool that pavement managers may use to improve their decision-making.

In order to determine a possible set of policy changes, which could improve the inferred future state of the system, a number of experiments will be attempted using the model as an experimental field. These experiments will be used to evaluate:

- Current processes used to control the allocation of resources (i.e. PSI critical value and residual life)
- Current criteria affecting the controls used (i.e. user satisfaction, accident rates, damage to system, and how these are weighed in the decision process).

- Underlying assumptions affecting the perceived conditions of the system and their effect on criteria development (those assumptions about the system that are being made that create a negative impact on decision making in the system).

To accomplish this task, a set of experiments testing current assumptions and processes in use will be carried out. It is believed that these experiments will reveal several weaknesses in these process and methods as practiced today, and will result in a set of recommendations for changing current practices that will improve the long-term state of the system.

### **i.3 Summary Findings of the Research**

The operating conditions that are in existence, in the current system include:

- Repairs are carried out in the winter.
- Roadway that becomes backlogged for repairs does not change category.
- More money is spent on repairs as accident rates increase.
- The budget that is obtained for the first year is reduced for successive years until a floor of 47% of the original is received (based on manager's best estimations).
- Managers give completed road repairs a better score of quality than is appropriate.
- Long range planning that could include Pavement Manager's inputs is not in place.
- Hiring of labor is accomplished that uses a method that does not account for growth in utilization.

In addition, funding over the past years that is received from the state has become more constrained and appears to have diminished with each year. This finding has lead managers to place more utility on short-term maintenance, in place of longer lasting pavement repairs. Pavement managers increase their allocation of funding for road improvements if there appears to be a greater increase in the risk of accident occurrence.

### **i.4 Results and Recommendations**

What was discovered is the lack of information available to implement the guidelines that have been suggested in GASB 34. Currently, managers make decisions based on

pressures of the system. Pressures include the need to spend down the total allocated yearly budget or lose it, not to allow any deaths, to respond to political pressures, and appear to maintain the road at best quality possible for the budget available. To accomplish, this, decisions are made to repair roads in the winter, categorize roads at better actual quality after repairs, and plan budgets that downplay the damage classification of the roads. In addition, there is a lack of information available to managers for the correct management of the roads they are responsible for. For example, inventories of roads at town levels proved to be unavailable. At the state level there was no record kept of the amount of road repaired by type, and how much was allocated for its maintenance. The lack of such data makes good decision making difficult. In fact benefit to cost analysis is made impossible. Therefore, the allocation of resources based on pressure tends to create the high possibility that resources are wasted. The simulation reveals that improved operational decisions can improve the road without great increases in resources. A system for collecting and using data to standardize performance evaluation needs to be designed.

The results of analysis of the simulation indicate that the behavior of the system can be improved by enacting the following changes in operational and general policies in place that are driving current decision making.

1. The development of a benefit to cost methodology needs to be established, if decision –making and the conservation of resources are to be improved.
2. Winter repairs should not be carried out in the winter season. Performing repairs in winter has two negative consequences. These effects are 1) less road is actually repaired and 2) deterioration rates of these repairs increase the number of times such repairs are performed. [Section 6.10]
3. Road categorization processes need to be evaluated. Incorrect classification or roads distorts current spending and therefore effects future budgetary planning. [Section 6.11]
4. Assigning of incorrect quality to a repair process creates a distortion in the apparent future needs, rates of deterioration and both current and future costs.[Section 6.91]

5. Labor hiring polices may or may not impact total operations depending on the budgets available. The additional teams may improve the initial condition, PSI, of the road, but the effect on the budget is to decrease overall paving capability. [Section 6.14]
6. Funding must catch up with repair needs if collapse of the system is to be prevented. At the same time once available funds are increased, managers need to change their spending patterns to increase the amount of long-term repairs patterns [Section 6.17]. Adding money to the system (what managers claim is necessary) does not work alone. [Section 6.18] However, this needs to be balanced against the implications of road quality on accidents. The response of spending more to improve road quality, intended to reduce accidents, may, in fact be increasing the number of accidents that occur.[Chapter 7]
7. Involvement of pavement managers and the use of data for future planning should be enacted.
8. The development of a record keeping system to move into compliance with GASB 34, and to control budget planning is needed in most small towns.

### **i.5 Assumption and Limitations of the model**

A model is not the real world. The intent is to simulate processes in the real world and interpret the output of the simulation, with an understanding of the model's limitations.

As the quality (PSI) of the road improves, development increases. The design of the simulation includes a process for an increase in spending as accident rates increase. Therefore, as the PSI increases, accident rates and industry output appear to be higher. According to managers, this drives them to spend more on improvements in the hopes of reducing accidents

After repairs are performed in the simulation, it is unlikely that industry will move in because managers assume the road to be of higher quality. Drivers perceive the road as used, not as perceived by managers. Industry attraction and accidents would be based on



the actual road conditions. However, to do so in the model would require a reproduction of the entire PSI process for drivers, separate from that used by management. This was not done because the process would not offer any more insight than those gained. Recognition of the weakness itself allows for understanding of a simulation's limitations.

Conclusions based on the simulated accident rate, while showing conclusions opposite to those recommended in the literature may be premature. There are multiple variables unaccounted for that can also increase the accident rate. Such variables include time of day, drug or alcohol use by drivers, direction of travel as related to solar glare, the geometric design of the road, wetness of pavement, etc.. Before attempting to implement the suggested policy, research is needed to evaluate highway accident rates by classification of cause and the sequence of such accidents (i.e. before or after type of pavement improvement).

Data for development was taken from the towns of Grafton, Massachusetts and Manchester, Connecticut. The data showed expected growth for a period of ten years. This data was used to develop the trends in area development. The model generates rates for a period of 800 months. The range of reliability may be exceeded, but a short-run of 10 years would be less than the expected life span of roadway. In fact, however, finding any accurate predictions of growth for any area, for any period, would be highly questionable.

## **Chapter 1 Introduction**

### **1.1 Pavement Management**

Pavement performance is a broad term that tries to describe how changing usage and varying conditions effect changes in pavement conditions. Measures of performance such as the Pavement Serviceability Index (PSI), the Pavement Condition Index (PCI) or Pavement Quality Index are available for use.

### **1.2 Modeling Pavement Management**

Modeling pavement management is an essential activity of a pavement management system. Currently, models are used in the pavement planning and budget development process, as well as in helping to determine pavement life cycle management (George, Rajagopal, and Lim 1989). This process provides a way to plan for both routine maintenance and full rehabilitation of current roads. Maintaining these roads in good order is essential for providing a safe and rapid means of ground transportation in order to support both the current and future economic needs of our communities.

These models allow for the development of long-range plans and the estimation of the results of pavement management processes. In addition, models take into consideration those factors thought to be responsible for the deterioration of the pavements under study. While current prediction methods are useful, they often leave out impacts other than the direct effects, such as usage and weather on the physical structure of the pavement. Prediction methods used today are not formulated to see pavement management as part of a greater system whose total interactions affect the condition of the pavement.

A review of the methods used for modeling pavement management reveals an inadequacy in their ability to deal with the nonlinear relationships that exist in pavement management systems. Because of these inadequacies, recommendations made by managers for the application of available resources to repairs often do not consider the long-term sustainability of the system.

### **1.3 System Dynamics**

System Dynamics is a simulation modeling process that allows the modeler to capture both the structure and behavior of the system under study. It is based on the concept that real world systems are non-linear in nature and the results of actions taken feed back and effect the system necessitating new actions. A system dynamics model can include structural features such as delay times and political processes that cannot be captured by regression or Monte Carlo methods. Both regression and Monte Carlo techniques assume that past changes will continue into the future, whether or not they actually will. Messy decisions are not based solely on data and in such situations participation by those in the system is helpful in clarifying relationships and choosing key variables. Regression methods often use mathematical processes to determine the usefulness of a variable. The process does not take into account how chosen variables effect decisions made by managers of pavement systems, or why road conditions are changing as a result of those decisions.

### **1.4 Problem Statement and Reference Mode**

In order to develop a system dynamics model, one needs to create a guide. The guide used for development has two parts 1) the reference mode and 2) a dynamic hypothesis. Both will be developed in the next two sections of this dissertation. This process has been reviewed by Saeed (1992, 1998) who states that, “with no problem definition we have no boundary, and with no boundary we have no model” (Saeed class notes). The reference mode (Figure 1.1) helps to establish the boundary of the problem. It is the boundary of the model, which aids in the selection of variables used in creating the model. The reference mode is developed using several sources of information, such as interviews, data from public records and/or research from the area of interest of a problem.

Interviews (Note 1) with pavement managers from the New England region of the country reveal the following visual representation of the problem statement that will be

the focus of this dissertation (Figure 1.1). These interviews were based on the works of Cunningham (1993), Erlandosn, Harris,E.L., Skipper, and Allen,S.D. (1993), Nadler (1977) and Rubin (1995). The process applied in this dissertation was the use of open-ended and topical interviews. Limitations of such a process, where the use of participants is based on their knowledge and their willingness to participate, may however, create a bias in the information used.

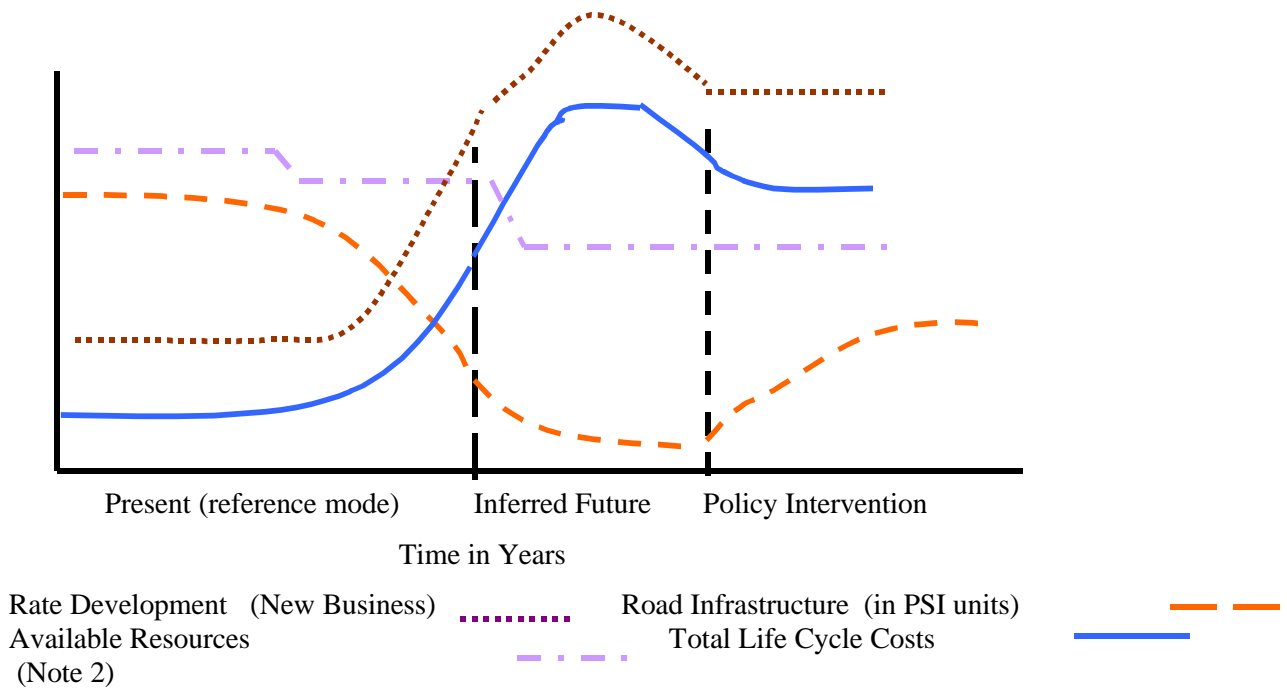


Fig. 1.1 Reference Mode (Behavior Over Time)

Reference Mode: Inputs and Described Behaviors

Each year the states and towns are receiving less aid from the federal government. At the same time, economic development in terms of new construction, both residential and commercial, is increasing and is placing greater strains on already constrained budgets. The constrained budget motivates managers to spend on short-term repairs. The short-term solutions create greater future expenses thus increasing the life cycle costs of pavement systems. The constrained budgets are actually creating a decision making process that is increasing the life cycle costs of pavement systems. The increase in demands on the infrastructure coupled with an inability to meet the demands is causing an increase in decay of the infrastructure, which then creates the demand for

more resources, which are becoming less available. One possible future state of such a situation is shown in Figure 1.1, the Inferred Future. In this inferred future state, a decrease in available funding accompanied with increasing deterioration of the infrastructure leads to higher long-term costs. As the infrastructure deteriorates, the ability to sustain development decreases. This process leads to less resource availability to sustain the infrastructure and a downward spiral has been initiated.

Although the problem, as presented above, seems relevant to New England it is not an isolated issue (Transportation and Regional Growth Study News 2001; Development Spring TRG Workshops 2001). “The inter-city freight hauled by trucks in the U.S. increased by over 29% between 1980 and 1991, and the ton-miles of freight increased by over 36%. In Wisconsin, an estimated 78 million tons of inter-city freight moved over the highways in 1991, over 35% of total inter-city freight movements in the state. There were over 28,000 commercial truck tractors registered in Wisconsin in 1992, 33% more than a decade ago” (Wisconsin).

However, increased truck traffic is the cause of more damage to our highway system (Shahin 1994). With an increase in commercial and residential development, there is an increase in damage to the system’s serviceability, which effects life cycle costs (Fwa and Sinha 1985; Petereson 1987; Shahin 1994). The additional increase in damage due to development occurs for two reasons. These are: 1) half of the new vehicles sold in the United States are SUVs (Hartford Courant 2002), that are classified as small trucks and add to the damage done by larger commercial trucks and 2) smaller roads were never constructed to handle the loads of new larger trucks.

The problem may be stated as an investment question;

Should a pavement manager spend a major share of funds available on one or two projects to achieve acceptable performance over an extended period? Or does he/she distribute the funds over several projects with reduced expectations of the service life for each project, but with an overall raising of the serviceability to the highway system in the short-run (Finn 1998)? What are the long-term budgetary and road condition results of the chosen strategies? In short, does the pavement manager fund smaller projects at less

cost but with a rapid deterioration rate creating long-run higher cost, or spend more for initial projects with longer life and higher initial cost but lower long-term cost?

### **1.5 Objective of this Dissertation Study**

The objective of this study is to use the System Dynamics modeling process to:

- Determine if and how current pavement management practices contribute to the problem represented in Figure 1.1.
- Develop a set of recommendations to improve those practices that are found to contribute to or create problems.
- Provide a tool that pavement managers can use to test their own proposed changes to their management practices in the form of a gaming environment.
- 

### **1.6 Purpose of Model**

The purposes of this system dynamics model are to:

- Model the conditions of a pavement network system and evaluate how these conditions effect resource utilization.
- Evaluate how the resource allocation process, as perceived and used by management, affects the condition of the system.
- Provide better insights into the effects of the decision making process and the consequences of the current use of that process.
- Provide a tool that pavement managers may use to improve their decision-making.

In order to determine a possible set of policy changes, which could improve the inferred future state of the system, a number of experiments will be attempted using the model as an experimental field. These experiments will be used to evaluate:

- Current processes used to control the allocation of resources (i.e. PSI critical value and residual life)
- Current criteria affecting the controls used (i.e. user satisfaction, accident rates, damage to system, and how these are weighed in the decision process).

- Underlying assumptions affecting the perceived conditions of the system and their effect on criteria development (Those assumptions about the system that are being made that create a negative impact on decision making in the system).

To accomplish this task, a set of experiments testing current assumptions and processes in use will be carried out. It is believed that these experiments will reveal several weaknesses in these process and methods as practiced today, and will result in a set of recommendations for changing current practices that will improve the long-term state of the system.

### **1.7 Summary Findings of the Research**

The operating conditions that are in existence, in the current system include::

- Repairs are carried out in the winter.
- Roadway that becomes backlogged for repairs does not change category.
- More money is spent on repairs as accident rates increase
- The budget that is obtained for the first year is reduced for successive years until a floor of 47% of the original is received. (To capture the condition of a reduced budget allocation from state level government).
- Managers give completed road repairs a better score of quality than is appropriate.
- Long range planning that could include Pavement Manager's inputs is not in place.
- Hiring of labor is accomplished that uses a method, which does not account for growth in highway utilization and deterioration.

In addition funding over the past years that is received from the state has become more constrained and appears to have diminished with each year. This finding has lead managers to place more utility on short -term maintenance, in place of longer lasting pavement repairs. Pavement managers tend increase their allocation of funding for road improvements if there appears to be a greater increase in the risk of accident occurrence.

Further, most towns do not maintain adequate records to manage the capacity of their road systems and changes to that capacity. Specifically, information is not collected and kept on the:

- Amount of spending as related to the types of repairs accomplished.
- Longevity of these repairs as related to spending.
- Types of repairs and how these relate to the classification of the road after repair completion.
- Number of complaints, types of complaints and exact costs of complaint management. (In one instance, no one knew who was responsible for managing complaints. On others, there was a person responsible, but no records were kept).

## **1.8 Results and Recommendations**

The results of analysis of the simulation indicate that the state of the system can be improved by enacting the following changes in operational and general policies in place that are driving current decision making.

1. The development of a benefit to cost methodology and the collection of supporting data need to be established by managers responsible for decision-making.
2. Repairs should not be carried out in the winter season. Performing repairs in winter has two negative consequences. These effects are 1) Less road is actually repaired and 2) deterioration rates of these repairs increase the number of times such repairs are performed.
3. Road categorization processes need to be evaluated. Incorrect classification of roads distorts current spending and therefore effects future budgetary planning.
4. Assigning of incorrect quality to a repair process creates a distortion in the apparent future needs, rates of deterioration and both current and future costs.
5. Labor hiring policies may or may not impacts total operations depending on the budgets available.
6. Funding must catch up with repair needs if collapse of the system is to be prevented. At the same time once available funds are increased, managers need to change their spending patterns to increase the amount of long –term repairs patterns. However, this needs to be balanced against the implications of road quality on accidents.



7. The response of spending more to improve road quality, intended to reduce accidents, may, in fact be increasing the number if accidents that occur.
8. Involvement of pavement managers and the use of data for future planning should be enacted.
3. The development of a record keeping system to move into compliance with GASB 34, and to control budget planning is needed in most small towns.

### **1.9 Reference Mode and Implied Future Behavior**

The reference mode represents the story told about the behavior of the system. It captures the core of the problem and helps establish the basic mechanism creating the dynamics of the system (Figure 1.1). The reference mode should not only capture the current state of the system and the defined problem but also allow for a representation of a possible outcome. In the above reference mode graphic one of the desired results could be the creation of a sustainable future for the system (Figure 1.1, Policy Intervention).

While control over the available budget may not be attainable, a policy could be developed that balances development with resource allocations that enable improvement of the infrastructure and allow a lowering of life cycle costs. Development may be constrained by natural resources, but it is hoped that the same consequence does not occur due to poor policy, which effects infrastructure.

### **1.10 Dynamic Hypothesis (Sector Map and Dynamic Hypothesis)**

The next step in the development of a system dynamics model is the development of a dynamic hypothesis. With the reference mode graph and information available from interviews the development of a sector map and dynamic hypothesis can proceed. The sector map is created from the key variables of interest and is guide for the creation of an appropriate simulation of the stated problem. It is a high level view of the problem.

The map allows the modeler to cluster variables into operational groupings. The map helps in defining what effect the variables that have been chosen create within and between sectors, and acts as a guide to the feedback processes that exist between sets of variables within a sector and

feedback that exists between sectors.

Those variables that effect the PSI are listed as either those that improve or those that cause deterioration of the PSI value. The PSI sector is related to the development sector through damages caused by development and to the allocations sector through accidents and the effect of accidents on funding released to allow repairs. The allocations sector affects budget availability through decisions that require the release of funds. The spending sector is linked to rehabilitation as spending provides the resources needed for rehabilitation. Development creates damages that generate complaints that effect spending. ESAL damages due to development effect the performance of the road and the point at which the road requires repair (PSI Critical Value). Budget constraint effects the ability to carry out required repairs. Depending on the decision made, life cycle costs are effected by accident costs, vehicle use and future repair costs.

The cause of the current problem appears to be:

- 1 As development increases more damage is done to the current road system.
2. Increases in damage create demands for spending.
3. Budget constraint cause a decision process that selects short-term repairs over long-term repairs and creates the need for more repairs of a short-term nature.
4. The entire process increases life-cycle costs and greater pressure on future budgets.
5. The problem seems generated by the decision rules used by pavement managers (the rules that are used were created through the experience and education managers have received).

The sector map, Figure 1.3, and dynamic hypothesis, acts as a guide in model formulation. The model formulation process is essentially the process where sets of variables and their relationships are transformed into quantitative expressions

The model formulation process will be covered in Chapter 4, but is essentially the process where sets of variables and their relationships are transformed into quantitative expressions.

The concept of building confidence in a model relates to the trust that the builder and group creating the model have in both the process and model. At the end of one interview (interviewee I3), the interviewee ran a computer projection of road conditions. A forecast that used computer

software that considered, budgets, road-conditions, priorities between projects and cost to benefits was run. A graphics printout of the predicted road conditions was obtained. This graphic is shown in Figure 1.2. When the print out is compared to the inferred reference mode, the similarity in dynamics is evident.

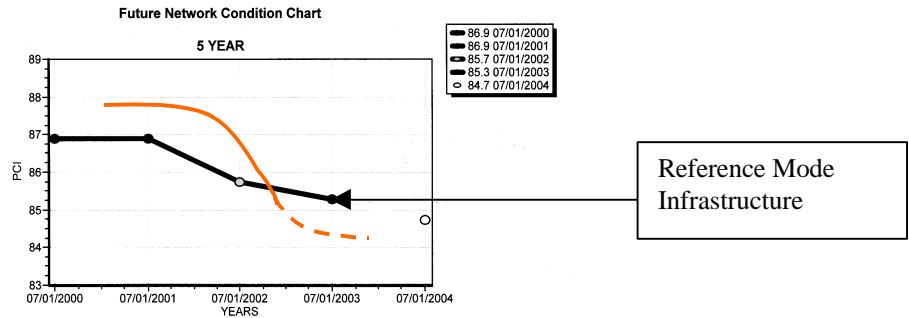


Fig. 1.2 Comparison of Reference Mode to Computer Generated Prediction

The implications for the model seem clear. The data contained in the tacit knowledge of pavement management professionals, although not quantitative, is powerful enough to develop meaningful and useful decision models.

# Sector Map

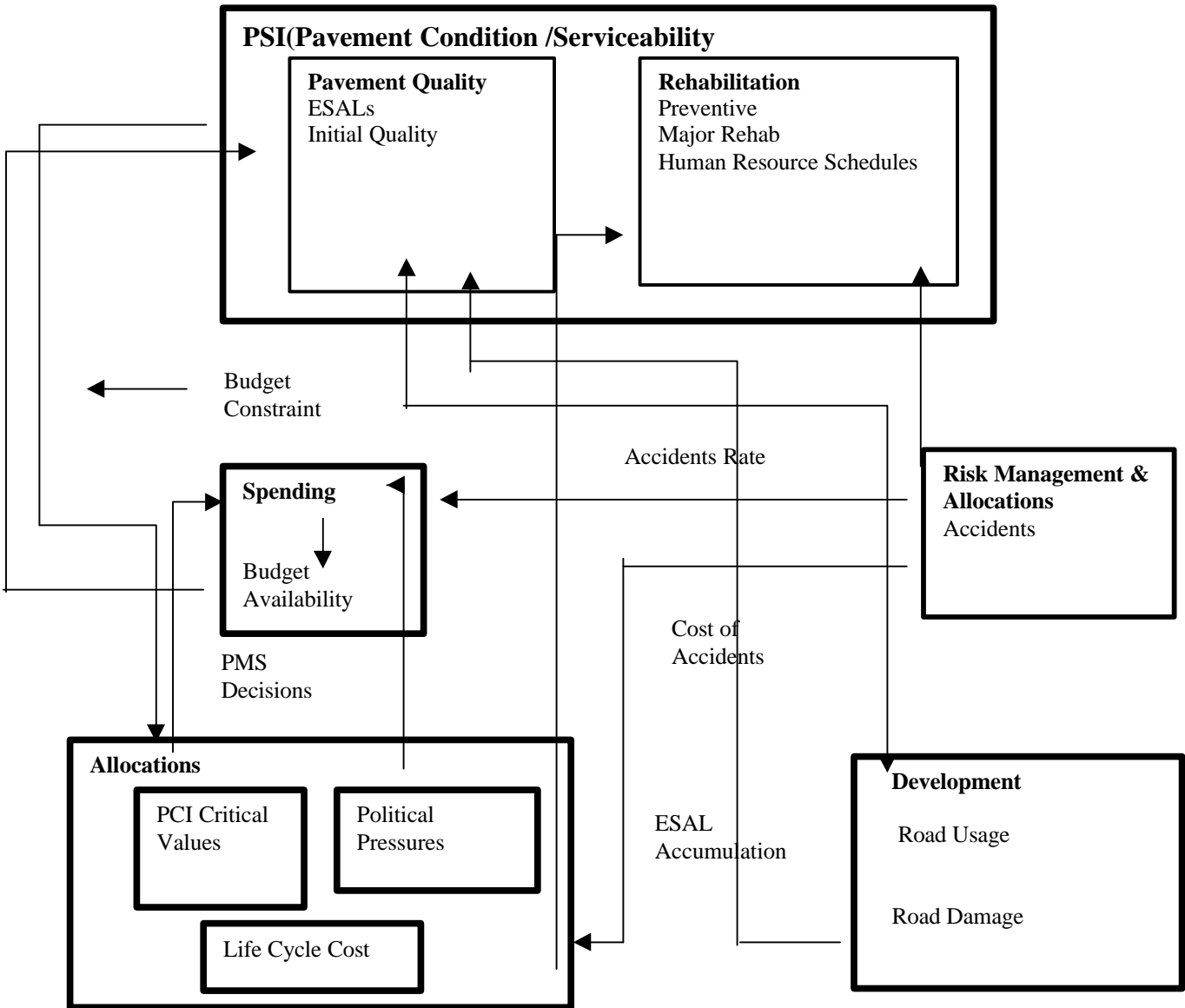


Fig. 1.3

Sector Map

## **Notes to Chapter 1**

1. The methodology of interviews is covered in the Research Methods section of this proposal. Further, a full set of interviews is attached as an appendix to the dissertation.

2. Scale-As the problem statement represents variables of different category types, the vertical axis is dimensionless and consists of different metrics. The PSI is a measure of road quality; available resources and life cycle costs are measured in dollars; development is a measure of business and residential growth), while the horizontal axis is in time.

## Chapter 2

### Problem Background

#### 2.1 Background

The typical performance curve shows that pavements remain in good to excellent condition for several years following construction or rehabilitation. However, after about 7-10 years, the rate of deterioration rapidly increases until the entire pavement system must be replaced at a high cost (Figure 2.1).

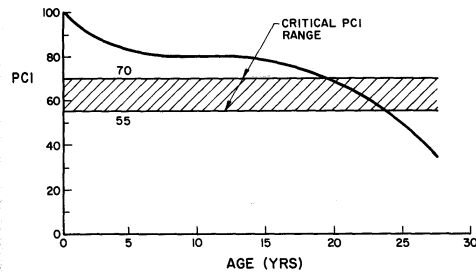


Fig. 2.1  
From (Shahin 1994 :163)

PSI Curve

As studies (Roberts, Kendall, Brown and Kennedy 1991) show that preventive maintenance is usually 20% of the cost of rehabilitation, more emphasis is being placed by managers on maintenance and the application of life cycle management, due to the need of public accountability.

#### 2.2 Performance Evaluation

Three generally accepted measures of pavement performance are safety, functional performance, and structural performance. Safety is generally measured by the change in frictional characteristics between the pavement and tires over time. The most widely known index that is used to measure these three attributes is the serviceability performance concept. There are five general assumptions used in this process.

1. Highways are for the comfort and convenience of the traveling public.
2. Comfort or ride quality is a matter of subjective response.
3. Serviceability can be expressed by the mean of the ratings given by all highway users.
4. A pavement has certain physical characteristics, which can be measured objectively and related to subjective evaluations.
5. Performance can be represented by a pavement's serviceability history.

Structural performance is a measure of a pavement's physical condition in terms of either its ability to carry additional loads or the occurrence of various distresses such as cracking or rutting (Bednar 1989).

Typically, pavement rehabilitation does not take place until some predetermined minimal acceptable level of performance has been reached. Network pavement management would be greatly improved if engineers could predict with some certainty the rate at which pavement conditions are deteriorating.

## **2.21 Issues**

1. Although pavement conditions or serviceability data are commonly used in deriving the values of individual cost items, no consideration is explicitly given to the overall pavement performance in the analysis.
2. Each of the agency and user cost items has a different physical meaning from pavement performance.
3. Most agencies formulate strategies that include a minimum serviceability level as the intervention level. This allows an agency to keep the condition of pavement above this minimum level. This is not equivalent to pavement performance considerations, as many strategies with different overall performances can be formulated to satisfy this requirement.
4. While the time valuation of individual cost components can always be related to pavement performance in some nonlinear fashion, they do not represent pavement performance. The relationship cannot be expressed as a monotonically increasing or decreasing function of time and the rates of change of the costs differ from that of pavement performance. (Fwa and Sinha 1991). However, the time value of money rate change does not necessarily represent the true

value of the pavement condition (Note 1).

5. It is questionable whether regression models can capture the true allocation processes, which are effected by the decision making of others, outside the engineering domain. In many cases budgets are not controlled by those responsible for maintenance decisions and are effected by political processes beyond their control.
6. Techniques such as regression and Monte Carlo simulation assume a linear decomposition or the development of a steady state of decomposition, neither of which may be occurring in the real world.
7. The complexity of the interactions of environment, initial pavement makeup and road usage as described above is difficult to capture, even in a multiple regression model. Such models tend not to include feedback from the effects of interacting variables. For example, user costs change as the PSI (Pavement Serviceability Index) changes, sometimes in the same direction and sometimes in an opposite direction. A regression model would average the change rather than include both of the effects.

### **2.3 Pavement Management Systems**

Pavement maintenance management systems fall into several categories. These have been classified by Berger (Berger, Greenstein and Hoffman (1991) as:

1. Pavement network identification.
2. Pavement condition survey and rating procedures
3. Distress prediction models
4. Maintenance activities and strategies
5. Economic analysis and prioritized maintenance programs.

Category 1 and 2 determine section PCI from type, severity, and density of observed distresses and their corresponding deduct values (Note 2).

In category 3 the distress models are sigmoid regression curves developed from the local network data for each type of distress in two possible categories, load associated distresses, and climate/durability related distresses. The models in this module predict distress extents, not



condition indexes.

In category 4, each distress is assigned a corresponding maintenance activity.

Assumptions are made based on experience and judgment concerning the effectiveness of the maintenance activity for the elimination or reduction of particular distress, and consequently for the predicted PCI. The aim of the strategy in this module is to perform in prioritized order all maintenance activities needed to bring the section up to target PCI during each year of the analysis period. The effectiveness and the prioritized order of the maintenance activities can easily be changed to fit local experience.

In category 5, the PMS incorporates the unit cost of all maintenance activities, so that it reports annual projected costs for all sections analyzed. A cost benefit scheme within the PMS evaluates total costs and benefits with and without the recommended maintenance and lists annual expenditures in hierarchical order. Maximum expenditures cannot be surpassed (Berger et. al. 1991).

In the case of a road PMS (Pavement Management Systems), the control of the process is determined by the pavement condition index, represented by the curve in Figure 2.2.

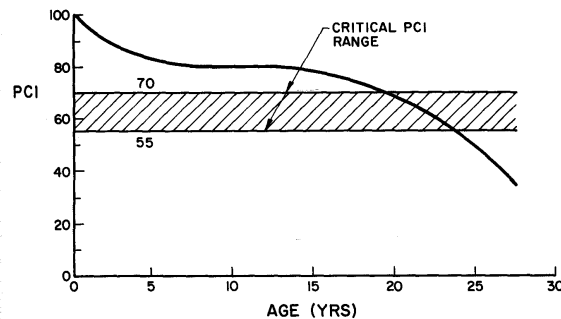


Fig. 2.2  
From (Shahin 1994 :163)

The curve represents the deterioration of the pavement. It assumes that the original condition of the pavement starts with a value of 100 when the PCI is used and 5 when the PSI is used, as a measure of deterioration. Critical PCI is defined as, “the PCI value at which the rate of change of PCI loss increases with time, or the cost of applying localized preventive maintenance

increases significantly (Shahin 1994: 163)”.

The critical value is important, as it is this point which determines the allocation of resources. The allocation of resources is dependent on both the critical PCI value and the amount of funding (budget) available. Managers have pointed out that:

“You need to be careful about the critical value selected. If you pick too high a number you can wind up doing a lot of preventive work that is not necessary. Too low and you are over spending”. (I7) “We use a critical value of 2.5 out of 5.” (I6) (Note 3 )

The critical value determines whether the work will be Patch or an Overlay rehabilitation and therefore effects the total cost of operating the maintenance system, aside from discretionary decisions made by management.

### **2.31 Short-term Repairs**

Under current financial conditions and constraints, the use of the available budget leads to repeat short-term repairs and long term financial losses. Minor repairs often become major and these major repairs then get put off until safety or citizen complaints cause action to be taken. These expenditures are usually greater than necessary. The process drains a given year’s budget, making it more difficult to keep up with the road repairs that are needed.

### **2.32 Budget Allocation**

The budget allocation process appears to be based on several considerations, among which are road condition, user complaints, and the political decision making process. For special projects, the towns can apply for federal grant money. However, restrictions exist for such funding. Backlogs build due to either work being put off due to budget constraints or because of delays in an application process. These backlogs could be of two types: either lower cost short-term repairs or higher cost major rehabilitation.

### **2.34 Other Costs:**

In determining the Life Cycle Cost, VOC (vehicle operating costs) also need to be given consideration. Research (Calffy 1971) has shown that vehicle-operating costs are not linear in nature and may be higher with both poor and good road conditions. Further, where major rehabilitation is undertaken, road travel is often slowed down and waiting costs increase. In addition the costs of accidents need to be included as part of Life Cycle Cost.

#### **2.4 Pavement Management Systems Problems and Limitations**

In actual use, the system sometimes creates its own problems. In one state, an expensive computerized model is used to help determine resource allocation. However:

1. The method used to assign a degree of deterioration and then used to forecast future pavement conditions were incorrect in application. In one case, data was collected and entered which was multi-collinear in nature. The data as entered would create an error in the regression analysis. Management created a one to one measure, therefore the data as entered was perfectly correlated creating a manmade error, that was not part of the normal statistical process.
2. The triggering of allocations is done by scoring, created with subjective inputs, and is based on a low score of 65. This low score was chosen as it represented a failing grade in college classes. This information is then used to negotiate what should be spent.
3. Finally, the information regarding road use (cumulative ESALs) is collected and passed on to designers. However, the designers and maintenance people never discuss the impact of design on actual deterioration and repair.(I2)

In a second state, towns put in designs that tend to yield overbuilding in hopes of getting Federal Highway money. These designs are usually rejected, creating a backlog of work. The minor work becomes major at a greater overall expense (I1).

In another state, after the analysis is accomplished, the information is sent to a finance committee, which determines if the state should fund other projects in preference to road

repairs. This then allows less extensive projects to become major work the following year (13).

In addition, there are several limitations to the current methods used. These include

1. The value of the pavement distress index reflects the pavement condition observed during the survey. The value of the index alone does not reflect the rate of pavement deterioration.
2. Any prioritized list generated on the basis of the values of distress indices without considering the rate of the change can be misleading. (Two sections may have the same indices, but be deteriorating at different speeds, which would determine when rehabilitation would be needed in the future.
3. For newly rehabilitated pavements that show no distress, the values of the various indices are the same. Yet, one section may be designed to last eight years while the other is designed to last fifteen years.
4. The distress indices alone cannot be used to assess the benefits of rehabilitation activities. For example, the improvement in the distress index (short-term benefit) for one or five inch overlay may be the same. The long-term benefits, however, are likely to be different. Hence, the rehabilitation benefits cannot be related to the value of the distress index alone.
5. If rehabilitation benefits are measured only by the improvements in the value of the distress index, then rehabilitation decisions tend to favor a cheap repair. Because the expected service time of the cheaper repair is relatively shorter than a more expensive process the rest of the network is continually deteriorating, and the backlog of pavement sections in need of repair will continuously grow if only short-term design life rehabilitation options are used.
6. The indices are not intended for use in identifying the percentage of damage contributed by each distress attribute. The values indicate the average amount of damage delivered to pavement sections by various distress attributes (Baladi, Noval and Kuo 1992: 71).

With the above background, it was felt that the formulation of a system dynamics model could address the weaknesses present in the current methods of measurement and decision making now in use.

A description of these methods and the use of system dynamics are provided in Chapter 4, Methods. A detailed review of the load and non-load effects on the system may be found in Chapter 3, Literature Review of this dissertation. The details in Chapter 3 combined with interviews are used in the formulation of the model created for this dissertation. The formulation of the model will be the topic of Chapter 5.

## **Notes to Chapter 2**

1. A change in interest rates changes the factors used for the value of the costs, it does not measure the change in the future condition of the pavement. Yet, the change in the discount rate can influence the choice of a strategy.

2. Pavement deducts are calculated based on density of distress per section of road sampled. A full description of the process is found in Shahin (1994).

3. Interview notations

I1-Bostontg

I2-Rhode Island

I3-Auburn MA.

I4-Grafton ,MA.

I5-MA. District No.3

I6 MA. Regional Planning

I7-State CT. DOT

I8-Manchester.CT.

I9 Groton, CT.

## **Chapter 3**

### **Literature Review and Interviews Use In Model Formulation**

#### **3.1 Introduction**

This chapter will provide a review of the literature, which when integrated with information gathered from interviews provide the necessary background for the development of parameters, table functions, feedback and causal relationships formulated in a model. Where appropriate, commentary is included to indicate how this knowledge was incorporated into use in the model. In some cases there may be more information presented than utilized in the formulation of the model. The information, however, was used as background for a better understanding of the dynamics of a pavement management system.

As the central theme of this dissertation is pavement management it was felt that the most appropriate place to start would be with the means by which the conditions of the pavement under study are affected by its initial condition and subsequent wear.

#### **3.2 Background**

During the past thirty years, much work has been directed toward developing rational planning for pavement maintenance and rehabilitation. Planning at the project level deals with specific deficiencies and the impacts of traffic and environment on pavement systems. It concerns itself with the best choice of a specific process to use in repairing damaged pavement. Network level planning, the backbone of a pavement management system (PMS), deals with the tradeoffs in project selection, which include the benefits and costs of each project in relation to all other potential competing projects (George et.al. 1989). A Pavement Management System (PMS) is a system that involves the identification of optimal strategies at various management levels and maintains pavements at an adequate level of serviceability. These include, but are not limited to, systematic procedures for scheduling maintenance and rehabilitation activities based on

the optimization of benefits and the organization of costs.

Among the methods used, to measure pavement performance is the Pavement Condition Index or Pavement Serviceability Index. (PSI). Initial values of the Pavement Conditions Index (PCI) are assumed to be at 100% while those of the PSI are scaled between a 1 and 5. The value of the PCI is fixed for any given section of pavement; with the final point of use determined by the user during data input. The location of this final point has significant impact on the maintenance needs and costs of rehabilitation. Allowing sections of pavement to reach a lower PCI for a fixed year of programmed reconstruction lowers their yearly maintenance costs but increases the user's vehicle operating costs (VOC) and the reconstruction costs of the roadway. Delaying the reconstruction year, for a fixed final PCI increases the yearly maintenance needs. If the predicted PCI at the end of the year is equal to or greater than the target PCI, no maintenance is needed for the next year. If the actual PCI is lower than the targeted PCI, rehabilitation is needed.

Pavements are complex physical structures, responding in complex ways to the influence of numerous environmental and load related variables and their interactions (George et. al. 1989: 1). The pavement condition prediction model therefore, needs to consider the evolution of various distresses and how they may be effected by maintenance. Since such an approach is highly complex, a compromise procedure combining several methods may be used (George, et. al. 1989). It is because of this complexity that pavement management systems usually use a family of similar roads (i.e. same age, use, repair history, etc.) for evaluation. Several modeling approaches are used to determine the future states of pavement conditions. A complete review of these methods is provided in Chapter 4 of this dissertation.

On June 10, 1999 GASB 34 was issued by the Government Accounting Standards Board. The statement was based on the concept that, "deferred maintenance of infrastructure assets, such as highways and bridges, is much more expensive over the long run than investing in an ongoing program of preventive maintenance and renewal".

Managers interviewed for this dissertation agreed, noting that if you choose as preventive maintenance only, short-term repairs, without major rehabilitation (full paving), the costs of maintenance actually went up. In some cases, preventive maintenance was being used too often thus increasing short-term expense. In addition, without the proper budget short-term preventive maintenance could not be done as well and in the long-run expenses were again increased. In some cases managers expressed an assumption that a postponed repair project just goes up in price and in-fact the type of repair does not change. However, little consideration appears to be given to a change in the classification of the road, to become a larger project, even when delayed for a period of up to three years.

Managers do not consider this a backlog, as it is “scheduled work”. However, the road condition is changing during the delay time and indeed the costs are usually based on the year of application, with a slight adjustment for inflation. Managers also indicated that the choice of roads to be repaired was not dictated by condition but by the volume of traffic on a given road. That most times it is the most used roads, which are repaired first. This means that lesser used roads in worse condition are often left until such a time as they may require work that is more extensive.

GASB 34 allows state and local governments to report on the condition of their infrastructure assets and the effectiveness of ongoing efforts to preserve these assets as an alternative to traditional depreciation. (In other words, managers can expense the asset rather than depreciate it). The purpose is to discourage deferred maintenance of critical assets. Managers indicate that it is the deferring of repairs that causes long-term cost to increase. Managers were also clear that cheaper short-term repairs were not the correct solution.

Section 4e of the Modified Approach allows, in lieu of depreciation, that a process has the following components.

- Maintains an up-to-date inventory of eligible infrastructure
- Performs condition assessment of eligible infrastructure assets at least every three years
- Summarize the results, noting any factors that may influence trends in the information reported



- Estimate each year the annual amount to maintain and preserve the eligible infrastructure at or above a prescribed level. (McNamee, P., Dorman, D., Bajadeck, D. and Chait, E 1999).

- 

### **3.3 Pavement Conditions**

The basic measurements of the condition of pavement sections are its existing distress. These are two classes, structural and functional, and several types of distress that are associated with each type of pavement. Furthermore, each type of distress can be caused by several variables, either environmental or load related. The two major classifications of damage are non-load induced and load induced. Non-load induced damages includes both weather and its effects on the rheological characteristics of pavement. Load induced damages are caused by use of hot mix asphalt (HMA) pavement (roadway).

#### Rheological Impacts

The study of rheological impacts as effected by the environment and how they effect pavement use can give us a better understanding of what these effects have on pavement longevity. Rheological impacts are those related to the deformation and flow of the asphalt.

#### ESAL Development

The second type of distress is load associated and is due to usage of a road itself. This is the main cause of load related deterioration that the road is subject to. This is usually measured in terms of ESALs (Equivalent Single Axle Load). The ESAL may be considered a measure of the relative load on pavement caused by different traffic loading under a reference set of conditions. This test load measure is used because it is practically impossible to measure physically load-induced damages with the influence of environmental factors (Note 1).

The PSI or PCI (Pavement Service Index or Pavement Condition Index) is traditionally represented by the graph shown in Figure 3.1. Pavement Serviceability is expressed as an index number. The significance of the number is that it establishes a relationship

between objective pavement conditions measurements and subjective ratings of road users. It is based upon the correlation of road user opinions with physical measurements of road roughness, cracking, patching, and rutting. (Fwa and Sinha, 1985 :25).

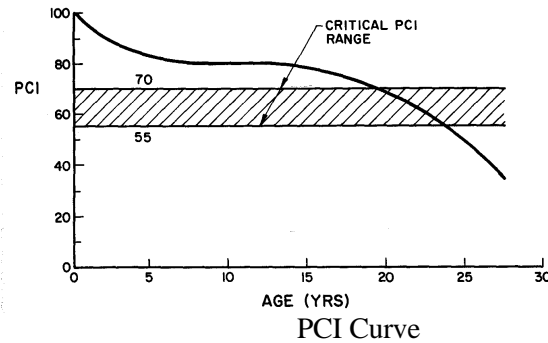


Fig. 3. 1  
From Shahin 1994: 163.)

In Figure 3.1, the critical value is shown as a range. The range depicted on the graph is due to the use of regression modeling and the confidence intervals of the predicted values created by the regression process. (See Regression methods- Section 4.1-4.3). It is based on this curve and a history of the road system under study that a critical value is determined. The critical value is important, as it is this point which determines the allocation of resources. The allocation of resources is dependent on both the critical PCI value and the amount of funding (budget) available. Managers have pointed out that:

“You need to be careful about the critical value selected. If you pick too high a number you can wind up doing a lot of preventive work that is not necessary. Too low and you are over spending”. (I7) “We use a critical value of 2.5 out of 5.” (I6)

Further, when repairs are accomplished for a section of roadway, “the section PCI is increased per the specified value in the input. A preferred method of accounting for the effect of global preventive maintenance on pavement performance is to let the user both specify the ultimate increase in pavement life and calculate the effective increase in PCI”

(Shahin 1994: 168). The effect on the PCI (PSI) is shown in Figure 3.2.

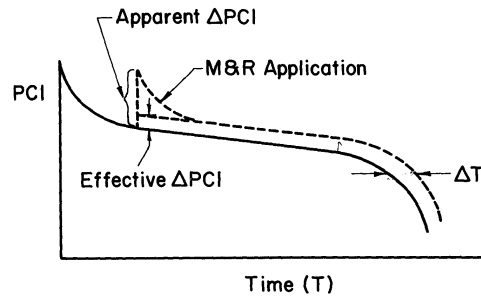


Figure 9-16. Determination of increase PCI ( $\Delta$ PCI) due to increase in life ( $\Delta$ T).

Fig. 3.2

### Quality Credit for Repairs

From (Shahin 1994 :169)

Whichever allocation is chosen the available budget will decline over time. The problem is created by a budget constraint. This constraint drives the decision making process into short-term thinking. In terms of system dynamics, the process fits into three archetypes. These are:

1. Fixes that fail – This situation is created when the symptoms of the problem are corrected and some temporary relief is created. Since the core cause is still present the problem returns, but more severe in nature. The use of short-term repairs, which seems to save money, keeps the road usable, but in the long run creates more cost.
2. Growth and under-investment - in this scenario the growth of an organization or community is not accompanied by the investment in structures that continue to support the growth. The supporting systems deteriorate followed by a decline in growth. In the road situation, constraints by budgets and an under investment in road infrastructure can lead to deterioration of the infrastructure and possible slowdown in regional development.
3. Tragedy of the commons- A common resource is used by multiple users. Each user tries to maximize their share of the resource. Because of these actions, the resource is depleted to a point where not enough is left to maintain any user. The commons is the federal and state budget availability. As these are used up, work is placed in backlog.

The backlog creates a need for greater repair expense and thus greater costs. This occurs at a time when there is more of a limitation on available resources.

In addition to budgetary constraints and the use of short-term repairs, increased development has led to an increase in the rate of damage to roadways, that were not built to manage either the type or amounts of traffic that is currently in use. The appearance of trucks and heavy equipment has a direct effect on PSI. Roads are designed with a specific set of Equivalent Single Axle Loads (ESALs) in mind. A given design may call for a road to have 1 million usable ESALs before it needs to be repaired. Trucks however, have a major impact on ESAL deterioration. As the ESAL effect accumulates, the greater is the deterioration of the roadway and loss to the PSI (Note2).

Some interviewees implied that roads that are in worse condition are sometimes put off until some future time, when they may deteriorate to the point at which a temporary repair is not an alternative, and major rehabilitation is needed. Therefore, a backlog or major rehab can build. While short-term maintenance projects are done, the amount of major rehabilitation is reduced due to a diminished budget. After some delay in time, major rehabilitation, eventually is undertaken on the backlog of needed work.

Environmental effects of weather, seasonal changes, and behavior under traffic, all cause distortions, which contribute to roughness. (Paterson 1987). Rutting and roughness develop as a result of the deformation of materials throughout the depth of the pavement. Traffic axle loading creates stresses and strains in the pavement, and under repeated loading cause cracking through fatigue of materials. Oxidation causes surface materials to become brittle and more susceptible to cracking. Cracks combined with poor drainage, permit excess water to enter, and increases deformation under the stress of traffic.

However, this is a weakness in the current process. There are two methods of measuring the PSI. The first is the methods of deduct described in Shahin (1994), which is based on empirical data and the use of algorithms, which measures the defect impact on the PSI. The second is the formulation of ESAL impact (Shahin 1994). Managers need to be

aware that the use of the former is appropriate for small discrete areas of repair, while the latter is better applied to large systems (Note 3).

It was determined that for the purpose of simulation in this model that the deterioration of road surfaces over time would be determined using a standard time of longevity associated with different types of repair. The longevity was based on a normal planned use rate. In other words, when an engineer plans the road life span he/she is taking into account a volume of use for the life of the road and consideration of environmental impacts. The life span is a reflection of the assumptions of normal use, made by the designer (Note 4).

### **3.4 Performance Evaluation**

Three generally accepted measures of pavement performance are safety, functional performance, and structural performance. Safety is generally measured by the change in frictional characteristics between the pavement and tires over time. Functional performance is a measure of how well the pavement serves the user over time and withstands an increasing number of axle load applications. Ride quality and roughness usually indicate the measure of a functional performance. The most widely known index that is used to measure these three attributes is the serviceability performance concept.

It is now common practice to apply engineering economics principles in the valuation of pavement life cycle costs for different strategies. It is also widely recognized that both highway agency costs and road user costs should be included in such economic analysis (Hass and Hudson, cited in Fwa and Sinha 1991). Agency costs include pavement construction, maintenance, and rehabilitation costs as well as engineering and administration costs. User costs typically include, vehicle operating cost and travel and delay time cost (Fwa and Sinha 1991). Fwa and Sinha (1991) also point out that in the life cycle costs evaluation one looks for the strategy with the least total costs computed over a selected period of analysis. They also point out that “it is relevant to study whether the least cost solution implicitly favors a higher pavement performance strategy”.

The PSI curve shown in Figure 3.1 is a representative curve. Other curves based on alternative methods have also been used in the evaluation of pavement conditions (Badner 1989). However, “the rate of pavement deterioration is not included in the calculation of the indices. In order to eliminate this common deficiencies, it was found that the pavement indices must be based on pavement performance which consists of two variables, surface conditions and the rate of deterioration” (Baladi Novack and Kuo 1992: 63).

It should be noted that the PSI curves, which are used as measures, are not totally accurate as given. The loss represented by traditional studies does not represent the true total pavement damage. This is because a certain level of routine maintenance is always present in practice. Some of the damages have already been recovered by maintenance work when a condition survey is made. This means that the total pavement damage is greater than that represented by the area between the maximum PSI value and the value of PSI at time  $t$  (Fwa and Sinah, 1985).

Essentially, pavement management systems deal with two key issues, these are:

- 1) The measurement of the condition of pavements; that is roads and highway systems, etc. and,
- 2) The determination of the allocation of resources for the purpose of maintaining the system in serviceable condition at the lowest possible costs for the longest possible time.-

Both the problems and methods related to these two essential tasks have been reviewed in Chapters 1 and 2 of this dissertation.

Today most agencies use any of several indices to evaluate road network conditions and status. Baldadi, Novak and Kuo (1992) have stated that, “highway administrators need to scrutinize the applicability of distress indices to real world problems and to the various decision making processes”( :71).

Fwa and Sinha (1985) have pointed out that there are two approaches to the evaluation of

highway pavement conditions. One method considers the gross performance by means of an aggregate measure such as pavement serviceability. The second type defines pavement conditions by specifying the amount of a given set of distresses, as described by Shahin (1994). It was determined that for a system dynamics model the use of an aggregate approach would be more suitable. One reason for not choosing to use a disaggregate distress function was due to the large amounts of data collection and handling that would be required. In contrast the data required for an aggregate performance approach is much less and more readily available (Fwa and Sinha 1985: 12). Fwa and Sinha (1985) point out

“that, although the disaggregate distress function approach is theoretically sound in concept, there can be considerable variation in the final results depending upon the type of distress considered, the form of the distress models adopted, as well as the weighting scheme used to assign weights to distress types”(23)

Stephens (et. al. 1983) adds that, “a degree of practicality must be included in a pavement management system. To be useful the required data must be obtainable”. Further, “it will be necessary to estimate the time shape for pavement state-time curves until some experience has been amassed. The values will never be absolute at the same site. Ratings can result from an infinite combination of soil, drainage, pavement structure, and loading. The values will be based on average conditions that result in a given modification of probability” (Stephens et. al. 1983: 17). Indeed, Forrester (1975a) has written that we should not include preciseness at the expense of relevance. It is better to err on the side of the causes rather than the accuracy of the parameter we believe is associated with the cause (:50 ).

There are several limitations to current methods in use in pavement management system. These include:

1. The value of the pavement distress index reflects the pavement condition observed during the survey. The value of the index alone does not reflect the rate of pavement

deterioration.

2. Any prioritized list generated on the basis of the values of distress indices without considering the rate of the change can be misleading. (Two sections may have the same indices, but be deteriorating at different speeds, which would effect when rehabilitation would be needed in the future).
3. For newly rehabilitated pavements that show no distress, the values of the various indices are the same. Yet, one section may be designed to last eight years while the other is designed to last fifteen years.
4. The distress indices alone cannot be used to assess the benefits of rehabilitation activities. For example, the improvement in the distress index (short-term benefit) for one or five inch overlay may be the same (no distress overlay). The long-term benefits, however, are likely to be different. Hence, the rehabilitation benefits cannot be related to the value of the distress index alone.
5. If rehabilitation benefits are measured only by the improvements in the value of the distress index, then rehabilitation decisions tend to favor a cheap repair. Because the expected service time of the cheaper repair is relatively shorter than a more expensive process the rest of the network is continually deteriorating, the backlog of pavement sections in need of repair will continuously grow if only short-term design life rehabilitation options are used.
6. The indices are not intended to be used to identify the percentage of damage contributed by each distress attribute. The values indicate the average amount of damage delivered to pavement sections by various distress attributes. (Baladi, Noval and Kuo 1992: 71).

### **3.41 Pavement Conditions and Measurement**

In the system dynamics model, two sets of graphic representations, can be developed. One of these represents a condition of no maintenance and a second, which represents maintenance on a routine basis. The difference between the two will allow the establishment of true total loss.



Based on the forgoing descriptions it is expected that the initial curve produced by the model should follow a decline in value, probably be a reverse S shaped curve and may show fluctuations in its value as repairs are made.

In order to create a more realistic dynamic than those procedures using regression methods, two impacts on the PSI were considered. These impacts were:

- 1) Initial condition of the pavement before use.
- 2) Factors that would effect deterioration in the pavement-traffic impacts.

The purpose of this process was to create a set of conditions that would account for the damage processes that pavement normally experiences as enumerated by Shahin (1994: 199).

Further, it was decided that the use of the concept of remaining service life would be beneficial to the model. The RSL (Remaining Service Life) is defined as: “the estimated number of years, from a given date (usually time of survey), for a pavement section to accumulate distress points equal to the threshold value” (Baladi et.al. 1992: 75).

For purposes of predictive modeling, the initiation of distress is defined by the time when a defect is first visible because this is the only feasible choice compatible with the data on road condition that is practicably measurable by network monitoring. (Paterson 1987 :11; Note 5)

In order to obtain a better understanding of these effects a review of pertinent material and traffic impacts was undertaken.

### **3.411 Rheological Impacts**

The study of rheological impacts as effected by the environment and how they effect pavement use can give us a better understanding of what these effects have on pavement

longevity.

Rheological impacts are those related to the deformation and flow of the asphalt. A complete review of these impacts would be beyond the scope of this chapter, but can be found in Roberts (1991), Shahin (1994) and Paterson (1987). These impacts range from issues of penetration, dependent upon the grade of asphalt used, viscosity, a measure of a material's flow, and the impact of age hardening, which continues during the life of HMA pavements and is subject to environmental and other factors

“I see a lot the work that's supposed to be 7-12 years being redone, two to three times. Now we are comparing apples and oranges. (three short-terms to one long term). Its due to many things; increase in traffic, undersurface is aging, lack of quality of the asphalt we get, work in winter, and a lack of skilled workers.” (Interview No.7, Note 6)

#### Air Voids

The physical property most often correlated to performance is air voids in the mixture. Research (Ford cited in Roberts 1991, Brown, Collins and Brownfield cited in Roberts 1991: 373). Santucci (cited in Roberts 1991: 373) has shown that the amount of air voids in the HMA mixture affects the stability and durability of pavement. (HMA pavement subjected to high cooling rates and low temperatures develop tensile stresses due to shrinkage. As the stress increases cracking develops. High asphalt cement stiffness at low temperatures is the predominant cause of this type of cracking).

#### **3.412 ESAL Impacts**

The second type of distress is load associated and is due to usage of a road itself. The main cause if the amount of load that road is subject to. This is usually measured in terms of ESAL (Equivalent Single Axle Load). The ESAL may be considered a measure of the relative pavement damage due to different traffic loading under a reference set of conditions

ESALs/yr.= ADT x DD x LD x ADTT x TF x 365

ADT=Average Daily Traffic

DD=Directional Distribution factor, assumed 50%

LD=Lane Directional Factor, 0.8 for outer lane, and 0.2 for inner lane

ADTT=Average Daily Truck Traffic in decimals (Note 6)

TF=truck factor

(Shahin has also suggested the use of a weighted TF(truck factor) calculated as :

$$\frac{[(\text{Percent Single Unit Trucks} \times \text{Single Unit Factor}) + (\text{Percent Multi Unit Trucks} \times \text{Multi-Unit Factor})]}{\text{Total Percent truck Traffic}}$$

Single Unit Factor=0.04-0.21

Multi Unit Factor=0.72-1.58

The formulation provided by Shahin allows for a range of testing in a simulation model. (Shahin, 1994: 206-208).. Although not used to effect deterioration, planned ESAL and generated ESAL are used in the model sector, which covers regional planning impacts and investment costs.

Fwa and Sinha have suggested a quantitative measure known as PSI-equivalent single-axle load (ESAL) loss (Eq. 3.1-3.3). This is formulated as:

$$\text{PSI-ESAL loss at stage } n = \int_0^{(ESAL)_n} [(PSI)_0 - (PSI)_t] d(ESAL) \dots \dots \dots \text{Eq. 3.1}$$

Where (PSI<sub>0</sub>) and (PSI<sub>t</sub>)=PSI<sub>i</sub> at time zero and time t, respectively, and (ESAL)<sub>n</sub>=the cumulative ESAL at stage n.

In cases where pavements do not have the same initial PSI, or where the beginning PSI levels of subsequent performance cycles of rehabilitation pavements are different, one may compute the complement of the PSI-ESAL loss known as the PSI-ESAL capacity.

$$\text{PSI-ESAL capacity up to stage } n = \int_0^{(ESAL)_n} (PSI)_t d(ESAL) \dots \dots \dots \text{Eq. 3.2}$$

According to the definition, higher PSI-ESAL capacity values mean better overall

performance. This relationship remains valid regardless of the initial PSI values of different pavements, the number of life cycles considered, and the types of pavement involved. The following representation is suggested for the purpose of benefit quantification.

$$(PPQI)_n = \frac{(PSI-ESAL \text{ capacity})_n}{(ESAL)_n} \dots\dots\dots \text{Eq. 3.3}$$

Where PPQI stands for pavement performance quality index, and n-the analysis period over which the subscripted parameters are computed. PPQI is in fact a weighted average PSI, computed with respect to ESAL for the analysis period considered. Its value will vary within the same range of 0-5 (0-100) as that used to define PSI. It therefore has a clear physical meaning and is more easily understood by highway engineers, planners and users alike. (Fwa and Sinha 1991: 38-39).

In representing the typical PSI time history, the dynamic model needs to capture the loss of serviceability. At any time, t, the condition of the pavement is given as (PSI)<sub>t</sub> and the corresponding deterioration by the concept of serviceability loss. The loss at any time is the difference between the initial PSI and the PSI at time t. A more useful plot would be between serviceability and cumulative traffic loading. “The use of a PSI-ESAL loss greatly facilitates the incorporation of traffic loading and environmental effects into performance analysis. The PSI-ESAL loss provides a means to measure pavement performance quantitatively on the same time frame basis as that used for evaluating loads and environmental effects” (Fwa and Sinah 1994: 31).

Fwa and Sinha (1985) suggest that if we plot PSI-ESAL loss against a quantitative indicator of level of routine maintenance, a relationship between pavement performance expressed, in terms of pavement damage and routine maintenance, can be evaluated. In addition, they have suggested a method of economic policy based on differentiating ESAL damage and rheological damage. Their suggestion, however, suffers from the fact that in practice the two cannot be separated out as distinct measures. The model,

however, that they suggest will be presented for completeness later in this chapter.

### **3.5 PSI Critical Value**

The critical value is a range. The shaded area depicted on the PSI curve (Figure 3.1) is due to the use of regression modeling and the confidence intervals of the predicted values created by the regression process. It is based on this curve and a history of the road system under study that a critical value is determined. The critical PCI is defined as: the PCI value as which the rate of change of PCI loss increases with time, or the cost of applying localized preventive maintenance increases significantly. (Shahin 1994: 163) The critical value is important, as it is this point which determines the allocation of resources. Allocation of resources is dependent on both the critical PCI value and the amount of funding (budget) available.

A pavement management system must have a threshold value at which the pavement condition is considered unacceptable. The threshold value could be any number between a predetermined upper or lower limit. Different threshold values can be assigned to different distress indices.

“You need to be careful about the critical value selected. If you pick too high a number you can wind up doing a lot of preventive work that is not necessary. Too low and you are over spending”. (I7) “We use a critical value of 2.5 out of 5” (I6).

Among all distress types, the one that reaches its threshold value first, threshold residual life should trigger the need for repair actions. It is that distress, which will bring the pavement to a level of unusable.

It was determined that the critical value would be used to control short-term repairs such as Patch and overlay treatments, and that residual life (RSL) would be used to determine when a major rehabilitation would be carried out.

In the simulation deterioration was determined using an average PSI per mile of road. Each class of road mile carried with it a specific PSI value. A full description of the formulation is found in Chapter 5 of the dissertation.

“The use of a PSI-ESAL loss greatly facilitates the incorporation of traffic loading and environmental effects into performance analysis because the PSI-ESAL loss provides a means to measure pavement performance quantitatively on the same time frame basis as that used for evaluating loads and environmental effects” (Fwa and Sinah, 1994: 31).

Field surveys supplemented by the judgment of engineers of the World Bank, suggest that it is possible to distribute a country's roads among three classes of conditions: Good, Fair and Poor (Abbas 1990a: 4). Each of the conditions has a dynamically different rate of deterioration, as pointed out by Harall (cited in Abbas 1990a.).

As pointed out by Stephens et. al (1983) and Al-Suleiman et. al. (TRR 1216), repairs raise the level of the PSI, but do not necessarily, increase the life span of the road. This problem has also been pointed out by Abbas (1990), and further Stephens has written, that, an overlay provided at one level may raise the PSI and add life to a road, but if the same overlay were placed at a more deteriorated level, the same conclusion could not be made. In fact, the rate of deterioration may be nearly the same as prior to the treatment (in this case, Stephens uses an Overlay as an example). He notes that, “any treatment delayed beyond the time at which it would have been adequate will deteriorate rapidly. It is then possible to assign to each level of pavement state a minimum treatment adequate to restore the pavement” (Stephens and Davis 1983: 15). Knowing when to apply a treatment leaves us with the problem of costs and of the lifetime added. Possible help in this area is provided by Al-Suleiman (TRR 1216: 11), who provides a chart of both cost for type of repair and the number of ESALs that each is supposed to supply back to the pavement at time of repair.

In essence, we are dealing with a continuous process of damage and repair, in terms of lane miles. This assumption can be supported by what Paterson (1987) has written:

“Maintenance work is defined as activities, which are carried out routinely to maintain the pavement at or above a planned level of performance. These activities are usually performed in discontinuous sections. They do not include rehabilitation work, which serves to restore the serviceability of the pavement concerned. Maintenance work refers to those activities that are carried out to recover the PSI-ESAL lose”.

Paterson then goes on to express the loss in terms of lane-miles, with different curves representing different strategies of expense (Paterson 1987: 159-161).

Fwa and Sinha (1990: 197) write that:

“traditionally highway maintenance and improvement programs have been developed as two distinct programs with separate sets of objectives. The day to day maintenance activities are typically handled by maintenance crews employed by the highway agency in charge. When a pavement section deteriorates beyond maintenance capacity of the agency crew, a rehabilitation project is developed and awarded to a contractor.”

In practice, due to differences in funding mechanisms and in scale and mode of operations, there is a tendency to run the two operations independently. Road pavement managers expressed the issue this way:

“For general maintenance- we do it,(state crews), but for resurfacing we hire a private vendor. We give contractors guidelines. Rehabilitation goes from overlays to major reconstruction. An overlay can last 10-12 years. We try to keep the road going with crack sealing, etc”.(I)

Again, according to Fwa and Sinah (1990):

“It is logical to consider that a highway agency would do certain adjustments to its routine maintenance program once a rehabilitation project on a given highway section is scheduled. For instance, it would not carry on elaborate maintenance operations on a section that has been scheduled to receive (major) work. Depending on the condition of the pavement and importance of the highway similar scheduling adjustments may also be required for other routine maintenance activities shortly before the rehabilitation project”. Fwa and Sinha, 1990: 198),

Again, managers expressed this logic, in their own words:

“Major problems with the roads are due to town development. If it’s a major problem but development is occurring, we do temporary repairs. We do it because the final repair is up to the developer. They are responsible for the roads around the development. This wait saves money. If an area requires new sewers, etc. we wait until its done. The problem is that sometimes an area needs minor rehab and the waiting turns it into a more major job”.  
(IAUB)

In the model formulation, road repairs were determined as affected when a road condition reached a specific PSI. This specific PSI was taken from Stephen’s chart combined with the classifications on the chart and the types of roadwork done at each level. (Appendix. A. The amount of allocation was determined using the critical value.

### **3.6 Residual Life**

Pavement service life under zero maintenance can be determined by the assumption that when pavement roughness reaches a terminal value ( $RN_T$ ) the pavement needs to be resurfaced or reconstructed.  $RN_T$  is equivalent to 2 or 2.5 PSI. (Alsuleiman, Sinha and Kuczek, TRR 1216: 10). According to Zaghoul (TRR 1539) “the expected reduction in pavement service life caused by a reduction of 0.3 in PSI (from PSI 4.2 to PSI 3.9) is 5.5 years”(105). Further, to prevent serious deterioration, it is recommended that a rehabilitation program be initiated “when the pavement service life reaches the 85<sup>th</sup> percentile value”, ...when 15 percent of the pavement reaches the terminal (failure condition)”(105).

### **3.7 Inspections**

The technique of window monitoring was developed in Kenya for the British Road Transportation Investment Model. It is this technique that was selected as the major five to ten year Long Term pavement and Performance Study of the American Strategic Highway Research Program.



The monitoring of deterioration of pavements in-service is a lengthy process, limited by the problems and errors of monitoring small changes of condition and by the range of pavement designs and standards available in the network. A spot observation of condition and back analysis of performance for a sample of pavements of different ages can be useful for a coarse validation or calibration of predictive models. For in-service deterioration, the greatest utility is realized by monitoring a sample of pavement during a medium period of five years, which provides a window or snapshot of part of the lifecycle of those pavements. It is possible to achieve reliable models of the whole life cycle from a manageable sample of pavements in a comparatively short period of time. (Paterson 1987: 126)

In addition to inspections, user satisfaction can impact management decisions to initiate repairs. The information on satisfaction usually comes in the form of complaints.

### **3.8 Complaints**

#### **3.81 Roughness**

Roughness is an important indicator of pavement riding comfort and safety and is the one pavement property that is most noticeable to the traveling public. From a driver's point of view, rough roads mean discomfort, decreased speed, potential vehicle damage, and increased operating costs. At the network level roughness is used for dividing the network into uniform sections, establishing value limits for acceptable pavement conditions, and setting maintenance and rehabilitation priorities (Shahin 1994: 65). Al-Omari and Darter (TRR1505: 58) have developed a relationship between rut depth and the IRI (International Roughness Index). Further the authors provide a graphic (1994 Figure 1: 58) of the relationship of the PSR curve (also measured on a scale of 1-5 with the IRI). This allows the model to convert PSI to roughness and use the measure in the formulation of complaints.

Three defects, roughness, rutting, and skid resistance can be used to determine road acceptability. "Together, they embrace the most important condition characteristics for

the road manager. Roughness gives an indication of the users' perception of the conditions of the road and serviceability" (Garcia,Snaith,and Tachtsi 1999: 96.). Rutting influences riding quality, safety, and indicates structural failure. Skid resistance may also be used as an indicator of safety (Garcia,Snaith,and Tachtsi 1999).

Discussions with managers indicate that:

"Its not only money and road conditions that drive our decisions. The politics get into too. We have complaints from citizens about the roads. If we don't respond, we get calls from the politicians or someone higher up. No one wants to be responsible for someone dying". Complaints are usually related to road roughness and are generally used as a surrogate measure of rideability or serviceability (I3).

Studies have shown that 95% of the information about the serviceability of a pavement is contributed by the roughness of the surface profiles. Generally a new pavement has a PSI (Pavement Serviceability Index) of 4 and 5, and is usually repaired when the PSI is between 1.5 and 2.5. When the road is repaired serviceability is restored to a higher level and the cycle begins again (Roberts et. al. 1991). Janoff (cited in Roberts,et. al. 1991) has shown that annual saving of \$600 per lane mile could result if the initial pavement smoothness was reduced from 35 to 5 inches per mile (555mm to 80mm/km). He concluded that from a cost-benefit standpoint, agencies could spend a considerable amount of additional funds to build smoother highways and still accrue savings due to reduced annual maintenance costs. Interviews seemed to support his contentions.

"A repair or minor work can get me 10 years of use. In the short-term contractors save us money. In the long-term it would be cheaper for me to buy the equipment and do it myself. We have a short-term focus because of the budget constraint"(I3).

"Roads normally need redoing every 15 years (pavement rehab). The question is, if you do a band-aid how much does the maintenance really cost you when you compare that to doing a rehab first. You do a major, it costs you \$5 per square yard. Maintenance runs you less than \$1 per square yard. If you redo the road (at 15 years) it costs about \$2.50 per square yard"(IM).

“If you don’t rehab then maintenance goes up to \$3-5 per square yard and you are doing it three times. But, we do a band-aid on it because we have constraints” (18).

Factors, which contribute to road roughness, are; traffic loading, environmental effects, and built in construction irregularities. “New pavement can have different initial roughness as constructed. Allowances for differences in ‘as built’ roughness can be provided by using the change in roughness as the input to pavement state” (Stephens et. al. 1983: 12), which, is then effected by exposure to traffic loading and the environment.

### **3.811 Roughness and Serviceability**

Serviceability has been defined as “the ability of a pavement to serve the highway user.” (Weaver NYSDOT). It has been noted that, “the serviceability and failure of an engineering design can only be defined relative to the purpose for which a design has been provided (Hutchinson, cited in Weaver ). As Carey has stated (cited in Weaver), “performance rests on serviceability and serviceability rests on surface profile. Thus, pavement evaluation begins with independent measurement of serviceability, and that is possible only by applying psychophysical principles to discover how pavement condition affects pavement users.” For example, when road users slow down, because of bad pavement conditions, they are unconsciously using the speed relations to raise serviceability to a more tolerable level. Anchoring the rating scale is an important part of the process. For every relation between human response and a physical stimulus, magnitudes of the stimulus exist beyond which a change in stimulus has no proportional change in response. These two points on the stimulus scale are the liminal points, and are the ends of the rating scale. Weaver had developed two end points 1) perfect-at a given speed the experience is so good that you doubt if you can detect any improvement, and 2) impassable-at a given speed the experience was so bad that you feared that you or the vehicle. Once the anchors have been established, a scale falling between the two can be developed. (See Appendix –A) Weaver (NYSDOT) has shown that the perceptions of the user are viable measures to be used in pavement management.

This concept is supported by observations in Paterson (1987) who reminds us that subjective assessment by panel rating was developed in the late 1950's. In the study quoted by Paterson (Carvey and Irick 1960, cited in Paterson), it was found that the 50<sup>th</sup> percentile of acceptability was 2.9 on a PSR (Pavement Serviceability Rating) and 2.5 for unacceptable.

### **3.812 Roughness and Costs**

#### 3.8121 Vehicle Operating Cost

Roughness also contributes to a change in vehicle operating costs. According to Karan and Haas, (University of Waterloo), "the operating speed of the highway is one of the major indicators of the level of service provided to the user and one of the major factors to be used in the analysis and justification of highway projects." Pavement conditions that effect speed and use can impact user time and costs. In Canada, the use of RCI (Rider Comfort Index), with a scale of 1-10 has been used in place of a PSI, with values of 0-5. In Canada, results of the study conducted by Karan and Haas (University of Waterloo) indicate that, as the pavement deteriorates, lower speed results in higher user costs. Therefore, a pavement strategy that provides a low level of serviceability over a longer period of time causes higher user costs than a strategy that serves the traffic on a smoother surface for the most time. In addition to the work of Karan and Haas (University of Waterloo), information supplied by the FHA (1998) shows the relationship between user costs and roughness on a per mile basis. Both sets of relationships can be found in the Appendix-A.

It is also known that for a given highway, vehicle travel time is inversely proportional to its speed. McFarland (cited in Fwa and Sinha 1991: 35) has shown that speed was insensitive to pavement serviceability on urban roads with present serviceability index (PSI) between 2.5 and 5, and on rural road with PSI between 3 and 5. The effects of serviceability level become significant only when PSI fell below 2.5 and 3 respectively, for urban and rural roads. Therefore, travel-time costs consideration will not favor a strategy that has PSI below 2.5 for a large portion of an analysis period. User costs are available for different PSI values form Berger (1991: 394, Appendix A). Research done

by Claffy (1971) provides direct information on speed and cost relationships for both cars and trucks.

It should be pointed out that if Maintenance and Rehabilitation is performed during the early stages of deterioration, before a sharp decline in pavement condition, over 50% of repair costs could be avoided. In addition to lowering costs, long periods of closure to traffic and detours can be avoided. The lost time adds to the life cycle and user costs of the system

### **3.8122 Delay Costs**

Zaghloul ((TRR 1539 :108) provides a list of estimated delay time costs. These are:

Average delay time due to rehabilitation activities = 5 minutes

Total rehabilitation time=60 days

Average Truck Costs =\$30 /hr.

Average Auto Costs=\$11/hour

Total Cost: = Vehicle type costs per hour\* 5/60\* Days\*(Percentage of average daily traffic (by vehicle type)) \* (Average Daily Traffics) \* {Direction (2- for two way traffic)}

Repair decisions are not made based on user costs or rehabilitation costs alone. From a pragmatic point of view, managers allocate based on a risk assessment. Their drive is to not only to keep roads in usable condition, but to also keep the rate of accidents, and their associated costs, to a minimum. Therefore, a discussion on the impacts of risk and resource allocation seems in order.

### **3.9 Accidents and Resource Allocations**

Forrester (1975a) has indicated that the original attractiveness of an area can create the problems that then lead to its becoming unattractive. For example, the case of small towns that have increasing development and more damage to the existing infrastructure

An unintended consequence of development (see development sector) may be increases in accident rates. This due to the fact that along with, “ the higher traffic volume, particularly large trucks, has come an increase in traffic accidents. Unfortunately, this is a

trend, which shows no sign of abating (Los Angeles Times 1996). In the New England Region, is the example of Route 128 also known as Interstate 95. In 1992, there were 421 crashes, while in 1997 the number reported was 491. In 1990 there were 120,426 cars a day at the I-93 interchange in Woburn, Massachusetts, but in 1997, this number had reached 144,992 cars a day. In Alabama, “take a two-lane road. Add some newly sprouted subdivision feeding motorists into congested traffic flow, mix an equal part impatience, speed and tailgating, and, police say that’s a thoroughfare that needs attention (Montgomery 1997).

However, the attention that is paid to accident prevention, may lead to more problems. In system dynamics, we often find counterintuitive behavior. In this case, Pavement Management System professional managers have expressed the following comments:

“We do the most used roads to keep user costs and complaints down. I’ll do I91 before I do a secondary road. We try to do these roads before they go bad. (CT).

The reasoning behind such decisions is easy. I have been told, that, “higher volume roads have more accidents. With higher volumes of use, you have a greater chance of a problem. Its risk that leads to repairs. “With high volumes you have a 70% chance of accidents, with low volumes you have a 30% chance, That’s my risk, that’s when I will do it” (INL).

Research has suggested, that during periods of what appears to be high, sustained volumes on a facility there will exist periods of turbulence or apparent instability in traffic performance. This may not be apparent from a system level view, but can give rise to local conditions that increases the probability of a crash. One can infer that, correlated with changes in volume, there will also be changes in vehicle speeds (Hughes 1999).

A review of traffic accidents, from one town, indicated that most accidents occur when the road conditions are better. (Traffic Reports- Massachusetts Highways, Grafton and Worcester, MA). Why? Higher speed. So in fact the better the roads the more the use,

the more accidents. An article in the Boston Globe entitled, implied that, highways (sic: are) stuck in loop of more cars, more crashes (Brown 1999;Note 7).

Reports from the San Francisco Chronicle (Paterson 1998) indicate that the average speed of drivers in the San Francisco area is about 67-68 mph. However, an increase from 55-65 mph was associated with an increase of 8.7% of fatal accidents over a two-year period, while an increase from 65-70 MPH was associated with a 9.7% increase in fatal accidents over another two-year period. In the same article the Insurance Institute for Highway Safety was cited a saying that in 12 states that raised there limits to 70 MPH, there were 500 more deaths in a nine-month period that would have been expected with lower limits. The State of Massachusetts reports a fatality rate of 7.72 per 1000 registered vehicles in 1996 (Mass Transportation Facts 1998)

David Begg (2001), Director of the Center for transport Policy at Robert Gordon University, Aberdeen England reports that in England 100,000 serious injuries occur each year, one third of all road casualties, related to speed. According to the research, for each one- percent reduction in mean traffic speed, deaths fall by about 7 percent. A 4 percent cut in mean traffic speed, less than 2 MPH in a 40-MPH limit, could mean 1000 extra people walking around next year.

Stephens (1983) warns us-

“If only the physical factors of the pavement are included, many highest priority pavements would be little used remotely located sections. A single form of rating applied to all pavements with priorities then based on the poorest condition could results in rebuilding projects only. This would be the poorest form of pavement management as salvageable pavements would be permitted to deteriorate and the average condition of the pavements in future years would be sharply lower than if some resources were constantly used for preventive maintenance of presentable pavements.” :12)

Finally, the work of Tanner (cited in Jorgensen 1966: 184), in Great Britain has shown, that in 122 studies of road sections resurfaced for purposes of routine maintenance:

1. Taken as a whole the differences in accident frequency could be attributed to chance.
2. Sites showing the greatest improvement in riding quality tended to experience considerable increases in accidents.
3. Improvements costing more than \$20,000 per mile, showed significantly (as much as 50% percent) increases in accidents. This was attributed to the fact that greater costs per mile yielded the best improvements, in the surface, with regard to those elements that facilitate higher speeds.

### **3.91 Skid Resistance**

What could cause the problem that appears to be occurring? An understanding of skid resistance may help!

Skid resistance is defined as the force that resists the sliding of tires on a pavement when the tires are prevented from rotating (Shahin 1994: 90). Hydroplaning occurs when water or contaminants separate tire and pavement surfaces. Under heavy traffic the pavement surface becomes polished. In general, skid resistance deteriorates in heavy traffic until it reaches equilibrium. There is no specific value at which skid resistance levels off and due to the seasonal variation of skid resistance there is only a mean equilibrium value. The research has shown that there is a higher correlation between the number of trucks, than with the total number of vehicles, and changes in skid resistance. The friction coefficient also decreases with increase in speed. It has been determined that on dry pavement, the friction factor changes very little with changes in speed, however, on wet pavement the decrease is significant.

Hass (1978) wrote that, considerations of time/traffic/climate based changes in skid resistance require periodic measurements, preferably on a mass inventory basis for investment program purposes. On a short- term basis, skid resistance changes can occur rapidly, usually because of rainfall. On a somewhat longer seasonal basis of, say, several years or several million vehicle passes, most pavement show a continual decrease in skid resistance (:12)



This problem is exacerbated by the fact that all Pavement System managers tend to respond to safety issues first. In addition, political pressure to satisfy constituencies increases the pressure on managers to respond.

“Safety takes precedence. If we get complaints from the fire or police department we do it right away (AU)”

Yet given all this some people still refuse to understand; as the State of New Jersey wants to raise its speed limits.(Smothers, 2001)

As the number of vehicles and speed effect the skid coefficient, a review of some of the issue effecting both is included.

### **3.10 Impacts of Traffic Volume on Use**

Psychology of waiting and change

People tend to change roads if the time of travel takes too long. Rock (1995) has used the term speed spillover (sometime referred to as speed adaptation or generalization) to describe a cause of highway traffic diversion. “An increase in highway speed could divert traffic from a rural 55 mph road to a 65 mph interstate”.

Berger (Berger, Greenstein and Hoffman 1991) reported on the time a user is willing to wait as part of a fifty minute trip, dependent on the condition of alternative routes available. McFarland (1972) reported that drivers have a discomfort level and that they will maneuver to decrease that level. However, many of the maneuvers that cause speed changes not only cause discomfort but also increase travel times. Motorists will adjust their speed to avoid events, which cause discomfort. On paved surfaces, motorists change their speed in relation to overall pavement smoothness and also make intermittent speed changes in relation to short stretches of road that are especially bad, or perhaps appear especially bad. McFarland (1972: 40).

When combined, these effects impact the volume of traffic on a given road, the speed of traffic and therefore the accident rate on a given road. The average daily volume is

generated by either traffic use of the road in general, or for a specific regions by the local development in the region.

### **3.11 Economic Development**

Economists, planners and others concerned with changes are well aware that a new highway may increase demand for goods and services in a region and that new firms will come into being as a consequence. (Gamberl, Raphael and Sauerlander 1966: 42) Furthermore, expenditures by highway users can have an indirect economic impact on local communities. In fact, regional differences in infrastructure have been shown to lead to regional differences in economic development (Kim, 1996). Abbas (1990), has written that,

“The significance of transport lies not only in the service it renders, but even more in the stimulating influence it exerts on economic activities. In newly developing regions, causal, dynamic, feedback relationships exist between elements of development, i.e. transportation, population, housing, the economy. For new cities significant influence on attracting industry, resettlement of people and the availability of labor”(Abbas 1990b: 18).

Or as put by Ogden (1991), “it is important to note that trucking and urban freight, impinges on a very wide range of economic and social activities, including such things as economic policy, industry development...road safety, transportation planning and policy etc” (:71).

Interviewees supported this concept as it applied to their situations in answers to a specific set of inquiries.

Question: Do road conditions effect development?

Answer: “Yes. Let me give you an example. A few years ago a trucking company wanted to put in a terminal in the state. The wanted better road grades to cut down on the costs of operating their trucks. We told them it would be too costly, so we decided not to do it. They didn’t come” (I7).

This sentiment is reinforced by the experience of others, as reported by Anderson (1998) and Burnette (1997).

Estimation of the changes taking place in a region because of a new highway requires two stages of analysis. There must be 1) some means of predicting the probable growth that will occur in terms of new firms and other institutions and 2) the increase in demands for goods and services created by the new highway

### **3.111 Relationship of Development to Costs and Feedback**

While regional development is important it often comes at a price that is not calculated as a cost of the development. Increases in traffic have dual effects on a region. The costs include increases in maintenance and repairs due to excessive road use and damage and an increase in traffic volume, often related to an increase in accidents. One interviewee put it this way.

“When a Mall goes up they own the roads from the main road to the stores. However, the town maintains the small roads. State roads don’t get hit too much because they are designed for heavy traffic. The small town roads probably get more use then they were made for”(I7).

The pavement manager’s view is that budgets are not a problem,

“We can always raise taxes to cover the cost increases”.

However, as taxes are raised to cover increases costs, how does the increase effect: 1) the desire to move to an area, 2) the future value of the homes in the area and finally, 3) the level of income per home owner who then might move into an area. In fact raising taxes could create a loss to the area of the revenues it requires to maintain the infrastructure, it developed when development in an area was occurring. While this is a proposed hypothesis there is some research to support this contention. Reese and Ohren (1999) have shown that, property tax rates are negatively correlated with growth management.

While it is difficult to measure economic growth resulting from transportation spending there are factors that can be cited to support funding for a robust transportation system. Dennis Donovan is a senior director of Wadley-Donovan, which advises corporations on site selections, has said; “companies will flock to less congested areas, because they offer a wider labor pool. If highways are congested, employees live near the workplace limiting the geographical area from which the company can recruit workers.”

Larry Donovan, a partner in TransNet Commercial, a Denver based research and acquisition firm, said. “infrastructure improvements rank high as companies looking to relocate expand” (Lee 2001). In Atlanta Sandra Johnson a veteran council member stated, “we’re beginning to have less land available. I don’t think we have much out there to continue at the level of growth we’ve had. Its got to slow sometime”(Stepp 2000)

It appears that there are complex cost decisions made when a company chooses a location. The cost of rentals, including tax does not seem to be a major deterrent. Although tax incentives have received much interest, the costs that are considered appear to be those associated with operations. Webber’s (1984) work on industrial location points out that companies look for the least cost of transportation when making a decision. In addition infrastructure variables, such as the cost of services (electric, oil, etc.), location to highways, airports and general modes of transportation may play a more important role in site location. Further, in regard to tax incentives “the evidence is uniformly negative. “Firms make their plans, find out about incentives available at the planned location, and then apply for the incentives.” (Harrison and Kanter, cited in Webber 1984: 71).

### **3.112 Costs of Development and Maintenance**

On the other hand development does effect the system. Managers of towns had this to say about the impacts of development on a system.

“We had a lot of development without inspection for proper drainage. Some of the system was also old, about 50 years old. With development the

old system could not manage the drainage”.(I3)

“Development has to meet certain guidelines. We are limited by law. We must leave the property in the same condition we found it. Therefore, we develop catch basins. But the basins require tremendous maintenance. It’s a maintenance nightmare. It comes out of our road budget. Development is not good for us. We get \$4000 in taxes from a house and it costs use \$5300 a year to maintain” (I4).

Before the Mall I used 2 trucks at \$30 per hour each, now I need 6 trucks at \$65 per truck per hour, not including materials it cost me \$4,000 last year. Remember there are two development issues; residential, where we get more cars and industrial were we get more trucks. With the Mall we got more trucks and they do more damage (I8).

### **3.12 Budgets, Repairs and Costs**

Managers have also indicated the following:

“We would many times prefer to do major rehab, but do stop-gaps instead because of the budget. The roads have been very neglected in this area. We are playing catch up. Money was not allocated in order to stay within the budget, now full repairs are need for what might have been a less expensive way “ (I3).

“Budgets are allocated based on predictions of road conditions. But how much is really allocated is based on political negotiations. Once we have a budget, we put all the current data into the software. It creates a list of projects, which are prioritized in terms of Life Cycle Costs and Benefits. Then it goes to a committee who decides” (I2).

“The information we have is part of a recommendation process. Its our info, the assessment committee recommendation and the politicians, that finally decide” (I2).

The issue then gets to the basis of the fair allocation of costs for repairs and to road users.

#### **3.121 Allocations**

“The state gives you so much, then you can’t have more. So we try to do the major jobs using state money. Anything left over we can use elsewhere “(I3.)

“The towns try to get the state to pay as much of the costs as possible. So they overbuild and look to get more money than the original project should be. I reject those applications that are inappropriate and this creates a backlog of

projects. The less costly projects are backlogged and they then become more costly and need major rehab instead of stop gap work” (I1).

### **3.13 Long Term Cost Impacts**

On June 10, 1999, 34 was issued by the (Government Accounting Standards Board). The statement was based on the concept that, ”deferred maintenance of infrastructure assets, such as highways and bridges, is much more expensive over the long run than investing in an ongoing program of preventive maintenance and renewal”. The managers interviewed disagreed, noting that without major rehabilitation, the costs of maintenance actually went up, and in some cases, preventive maintenance was being done, too many times, further, increasing short-term expense. In addition, without the proper budget short-term preventive could not be done as well and in the long run, expenses were going up. Also, there is the assumptions, that a project put off, just goes up in price and in-fact, does not shift to be a larger project, even when delayed for a period of up to three years.

The typical performance curve shows that pavements remain in good to excellent condition for several years following construction or rehabilitation. However, after about 7-10 years, the rate of deterioration rapidly increases until the entire pavement system must be replaced at a high cost. Because studies show that preventive maintenance is usually 20% of the costs of rehabilitation costs, more emphasis is being placed on maintenance and the application of life cycle management.

GASB 34 allows states and local governments to report on the condition of their infrastructure assets and the effectiveness of ongoing efforts to preserve them as an alternative to traditional depreciation. (In other words, we can expense the asset rather than depreciate it). The purpose is to discourage deferred maintenance of critical assets. In fact, the deferral is what managers told me during interviews, was what was causing long term costs to go up.

Section 4e of the Modified Approach allows, in lieu of depreciation that a process has the following components.

- Maintains an up-to-date inventory of eligible infrastructure

- Performs condition assessment of eligible infrastructure assets at least every three years
- Summarize the results, noting any factors that may influence trends in the information reported
- Estimate each year the annual amount to maintain and preserve the eligible infrastructure at or above a prescribed level

A graphic of the life-cycle approach demonstrates the impacts of periodic preventive maintenance treatment. In fact, the saw tooth-shaped curve (Figure 3.3) indicates that interim treatments can extend the service life of a pavement up to 60 years, and forestall the costs of replacement. However, a full analysis, using net present value and cost to benefits must be undertaken before any final decision can be made (McNamee et. al. 1999)

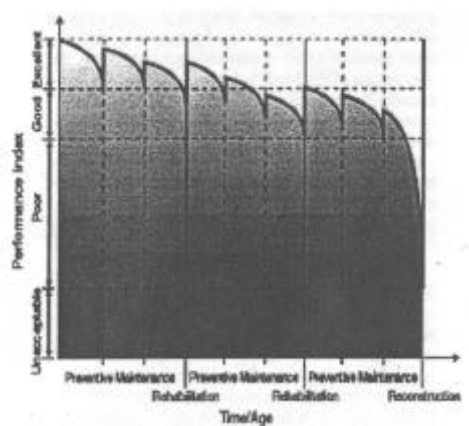


Fig. 3.3 Life Cycle Asset Management Approach  
From P rice Waterhouse Coopers p.3, 1999

### 3.14 Life Cycle Costs

#### 3.141 Maintenance:

Maintenance activities for paved roads are classified according to their frequency and their impact on the standards of the road. These are:

1. Routine Maintenance-pothole, patching, erosion control, painting, etc..
2. Resurfacing-full width resurfacing or treatment of existing pavement or roadway. The term preventive maintenance is synonymous with this level of work.
3. Rehabilitation-full width, full length resurfacing with selective strengthening.

4. Betterment (Improvement)-related to width curve and shoulder alignments.
5. Reconstruction-full width, full-length reconstruction of roadway pavement and rehabilitation of drainage.
6. New construction-full width, full-length construction of a road with new alignments and upgrading.

Maintenance has two effects, an immediate impact on the condition of the pavement, and an impact on the future rate of deterioration of the pavement. Usually maintenance is intended to improve conditions and performance, but certain forms, such as patching, may initially, increase roughness (Paterson 1987: 119). Patching maintenance reduces the roughness and costs slightly, but not back to the level that would have been applied in the absence of surfacing distress because patching itself is a defect, deviating in profile from the perfect planer surface (:122).

### **3.142 Pavement Management Costs**

Construction costs: Construction expenditures include quality control and field supervision costs, material costs, overhead, etc. (Usually estimated at a cost per square yard or mile for a specific type of rehabilitation). A project budget that can barely meet the needed construction costs could undermine the quality of construction. This means that by considering construction costs alone, the least cost evaluation technique generally does not lead to the choice of higher highway performance.

Rehabilitation costs: A lower rehabilitation option will, also, generally not favor a higher highway pavement performance strategy.

Maintenance costs: Past studies have shown that for a given higher maintenance policy, higher maintenance expenditures per unit length of a pavement would lead to better service life performance. However, a problem still exists. Two pavement rehabilitation strategies can provide serviceability above the minimum. Typically, the one with the lower costs, but lower pavement performance curve would be chosen. The costs are lower, serviceability is higher than minimum, but long term serviceability is lower.



Engineering and Administration Costs: More detailed and in-depth consideration in engineering design and planning, as well as more thorough inspection and supervision, will generally improve the quality of pavement construction, maintenance and rehabilitation work and hence the performance level of pavements. This usually means the commitment of more manpower and resources and higher costs. The least cost consideration is not likely to favor a better pavement performance.

### **3.143 User Costs**

Travel time costs: (See Vehicle Operating Costs Section 2.34)

Vehicle operating costs: While average vehicle speed generally decreases with decreasing serviceability, its relationship with various vehicle operating cost items are usually quite complicated. Claffey (cited in Fwa and Sinha, 1991) has shown that fuel consumption is related to vehicle speed in a nonlinear fashion. Berger (1991) has estimated the costs for operating several types of vehicles versus the value of the PCI. He points out that higher serviceability allows increased speeds, which also increases costs. It is only at a vehicle's optimal speed that serviceability is neutral. In addition, costs due to damages caused by Poor roadways need to be considered.

Accident Costs: These are available from the FWA study on road management and are used in the model to estimate additional Life Cycle Costs to the system.

Complaint Costs: These costs were estimated from discussions with managers of systems. As complaints come in, especially those from politicians, costs are associated with each repair. As the repairs are usually minor, the costs per complaint are small. However, the total costs and the allocation of manpower impact the availability to do more needed repairs. They effect the budget and the time allocated to other work.

### **3.15 Causes of Backlogs and Rise in Net Present Value (NPV)**

Interview information related to this issue revealed the following causes for some of the increase in long-term costs.

“We usually do repairs bases on usage, not condition”(I1).

“Roads have to be put into a program. The roads that are prioritized get done first. However, if we run out of money they are out on a waiting list for next year. However, if another project gets pushed in the first can be made to wait an additional year”. (I6)

“If a road is delayed,1,2,3 years, road work doesn’t change. The costs go up, but that’s with inflation”(I6).

As budgets tighten, government organizations and the public are demanding more accountability for the money that is being spent on public project. There has been a move to require data by policy makers to aid in the evaluation of performance and resource allocation (Stiefel 1989). Sharaf’s (TRR 1205) studied the effects of moving from one condition state to another and such an impact on life cycle costs. He wrote:

Under budget constraints highway agencies tend to delay pavement maintenance and rehabilitation (M&R) without analyzing, or sometimes realizing the effects of such decisions (Sharaf TRR 1205: 29).

His findings were that delaying pavement repair to a lower pavement condition results in higher costs in the long run. He found that if a pavement were left to deteriorate without repair to a PCI level of 0-20 (approximate PSI 0-1), then major repair costs would be about four times that of a 61-80 PCI (approximate PSI 3-4) level. In fact the delay is not only driven by value but by further deterioration, which manager’s in some cases seem to ignore in decision making. It has been suggested that for multiple year resource analysis decisions that use of high level planning estimates rather than detail budget data for the revenue expense for programs would be an appropriate planning method (Horsch, 1995). System dynamics make use of more aggregate then detail levels of data in its modeling process, although information, below the level of aggregation is used to support parameter development.

The primary objective of pavement management systems is to provide adequate service to users. Carey and Irick (cited in Paterson 1987) defined the concept of serviceability in 1960. A five-point scale defined the perfect level of services by a score of 5, and an

impassable condition by the origin, zero. The performance was seen as the trend of serviceability over time, depicted as a concave curve with an accelerating negative slope. Minimum acceptable levels of the PSI are usually taken to be 2 to 2.5 for primary roads and 3 for major routes, with 1.8 to 2 for secondary roads.

### 3.16 Damage Assessments and Policy Development

(The following process describes one approach to policy development as it effects the pavement system. It is placed for completeness but suffers from a weakness in its core assumption; that environmental impacts and ESAL impacts, which feedback to one another can be determined. As stated earlier, the process for doing so is not available at this time.)

One of the main problems that we are faced with is the evaluation of damage and its appropriate assessment to cause.

“The form of the mathematical model (Eq. 3.4-3.5) used to relate damage, axle load and configuration, and number of transits, has an important bearing on the results. For the relative damage effect, the damage (g) was expressed as a dimensionless or normalized fraction of the change in serviceability index, as follows:

$$G=(P_i-P)/(P_i-P_r)$$

Where g= the fraction of total damage, at the current present service ability p

P=present serviceability index of pavement condition

P<sub>i</sub>=initial serviceability index at time of construction(5)

P<sub>r</sub>=notional terminal serviceability index at which condition the pavement is

deemed to require rehabilitation, and at which g=1. (Fwa and Shina 1985) Eq. 3.4

Further -

ESAL loss capacity/Total Planned ESAL =percentage ESAL loss.

For each repair then:

Percent Damage Due to Trucks- {Percentage loss\* Initial Planned ESAL= replacement of lost ESAL}  
Dollars Spent \*ESAL/Dollar =ESAL Replacement Eq. 3.5

For purposes of model formulation, the value of P will be selected as the value of P when the RSL=15%. (Paterson 1987 :336)

Mostly, the effects result from the interaction between traffic and environmental factors, and the strict attribution of damage to one or the other becomes a complex if not impossible task” (Paterson 1987: 359-360)

### **3.161 Taxation Model**

G damage value x Percent of Damage Due to Trucks x Percent of Truck that a company provides.

The balance of g can be considered social and may be spread among homes, car ownership, etc..

The determination of car ownership can be made by evaluating home development in an area of interest and estimating the cars per home by using data from public sources, such as the almanac. For a dynamics model of car ownership one can refer to Bradley (1985).

## **Appendix 3A To Literature Review Impacts of the Research on Model Formulation**

This appendix describes the impacts of the literature review and interviews on some of the concepts and formulations used in the model.

### **3A.1 PSI Sector**

#### Deterioration Rates

The problem of determining road classification was dealt with based on information provided in Shahin (1994), Stephens et. al., (1983), Roberts and Kendal (1991) and Shahin (1994) provides a graphic representation of the road conditions as measured against time. The scaling seems to fit the measure of a typical PSI curve. Therefore, it was decided that the PSI values associated with his classification, which matched those of the World Bank, would be used as triggers to initiate any change in rates of deterioration.

Shahin (1994: 528) has pointed out the cost savings by doing early maintenance and rehabilitation. He estimates that during the first 75% of the life of the road quality drops by 40, it then drops another 40% over the next 17% of the life span. If repairs are executed during the second drop, or the next 17% of the life span, cost here are 4-5 times greater than if initiated in the first 75% of the life span, or during the first drop.

Therefore, the cost ratio of repairs done above the PCI critical is 20% of those done below or at a fair level. Work done below the fair level is 4 to 5 times greater.

Allocations were based on the critical value, which is calculated by the model as deterioration occurs or by a manager's choice. For repairs done above the critical value a repair rate and cost of repair associated with patching was used. For repairs below the critical value and above the RSL point of 15%, a rate of repair and cost associated with overlays was used. At the RSL point it was assumed that pavement work is done and the appropriate rates and cost was used. Based on these levels and the value of the PSI for

each type of road, a cutoff was determined for control of the transition from one type of road class to another.

After consultation and with the advice of faculty, it was decided that the following information could be used to develop the model sector dealing with road classification.

1. The most pragmatic approach to measure the PCI would be on a scale of 0-5.
2. Deterioration would be based on a normalized (expected use of road) for the life of a road. That is newly paved roads are expected to last 20 years for planned use, Overlay 7 years, etc. The years of deterioration would be adjusted for growth, in vehicle usage. Usage greater than the initial planned amount of cars would shorten the life span of the road.
3. Road would be classified based on Federal Highway classifications.
4. The concept of residual life (RSL), PSI and the critical value of the PSI would be used in determining the following:
  - a. RSL (Residual Life) would determine when a full pavement repair process was to start. The initial value used would be 50% as suggested in the literature. (Note that most managers wait until 2.5 percent is reached, even though it is indicated that 50% is the longest wait).
  - b. PSI critical value would be used to determine the level of repair and resources allocated to short-term repairs.
  - c. The PSI would determine classification of the roads.
5. Cost and time parameters for road repair would be obtained from interview data and literature as needed.

In order to build this section of the sector some assumptions were made. These were that:

- a. The initial value for each classification, by definition would be different. Thereafter deterioration would be based on the type of repair done to bring a road to a specified level. The starting point PSI would be based on the road classification.
- b. Issues such as road subsurface, initial asphalt classification, drainage impacts would be too detailed and variable in nature to include.
- c. A life span of 20 years would represent the typical road life span used in design.
- d. We are dealing with a continuous process of damage and repair, in terms of lane miles. This assumption can be supported by what Paterson(1987) has written.

### **3A.2 Flows and Levels**

The type of work accomplished determined the rates of flow. Deteriorated road would be repaired by patching or overlay. This brought the road to a lower level than its original classification. Deterioration of the new class of road was dependent on the type of work

accomplished. Therefore, road that was patched deteriorates at a faster rate than road that had overlay. However, the lowest level of poor and unusable road was only scheduled for full re-pavement at a contract costs. (Thus, work done by contract was separated from the work done as routine maintenance and cost out at contract costs, not internal maintenance costs. Further, the project work done for contracts and maintenance had separate formulations due to the differences in obtaining a contract and hiring full time employees).

Inspections were not incorporated to determine the classification and road conditions of highway for initialization levels. Instead, a sampling was used at the beginning of each year for the selection of PSI and road miles. This inventory was then used in developing the expected budget for the year. It was decided that by using the TIMECYCLE function of Powersim it was possible to represent the inspection process. A relationship between roads that might be incorrectly classified and inspections was formulated. The reasoning was as follows: roads that were incorrectly classified would be discovered at the time of repairs. The percentage of each type of road and its re-classification was unknown. Further, even if road rates were known, the impacts would have to be on better education of inspectors and not the number of inspections. Increasing the number would only cause more repairs and not, a better classification. The education process was outside the boundary of this model.)

### **3A.3 Residual Life**

Pavement service life under zero maintenance can be determined by the assumption that when pavement roughness reaches a terminal value ( $RN_T$ ) the pavement needs to be resurfaced or reconstructed.  $RN_T$  is equivalent to 2 or 2.5 PSI (Alsuleiman, Sinha and Kuczek, TRR 1216: 10) According toZaghloul (TRR 1539) “the expected reduction in pavement service life caused by a reduction of 0.3 in PSI (from PSI 4.2 to PSI 3.9) is 5.5 years”(105). (This would be approximately 15 years from PSI 5 to 0. The deterioration rate for the model was chosen at 20 years for full pavement work). Further, to prevent

serious deterioration, it is recommended that a rehabilitation program be initiated when 15 percent of the pavement reaches the terminal (failure condition). As the range in practical use has been shown to be lower, an RSL of 50% was chosen as the initial point of repairs for full paving.. However, as a policy space this was changeable by management decision.

Discussions with Dr. R. Mallick were combined with knowledge obtained from the review of the literature and interviews of pavement managers in order to develop road repairs formulations. Roads were classified as to status by using PSI values. Repairs were initiated if a road's PSI value hit critical points.

A choice of road repair strategies was developed, such that by entering the following control of the type of repair process was obtained:

- a) Zero would create a dynamic with no maintenance
- b) A value of 1 would allow maintenance, which combined with changes in input parameters, allowed policy testing.

Each repair replaced lost PSI. Each mile in the system carried a value of PSI quality per mile. As miles deteriorate or are replaced PSI changes. Delays due to management judgement were also included in the flows from excellent to Good road levels. When roads accumulated in the level of Poor roads either the value of the RSL or condition of the Poor road initiated repairs.

Types of repair are determined by comparing the PSI at time of repair with the critical value (average value critical of the system). The type of repair will determine expense for the highway miles being repaired. Expenses for all repairs will use actual costs.

A threshold for management decisions was established for repairs and accidents. This was based on how PSI (using a utility function) and accident rates (using a table function) effect a manager's decision. The effects of this threshold on budget allocation are developed in Section 5.1515 on accidents.



Effect of budget on repair rates and budget allocations:

If no funds are available, repairs cannot take place. The budget adequacy (Budget Available/Initial Budget at Beginning of the Year) effects both team allocations and paving contracts. As the master budget is drained for any reason, the capacity to repair roads is decreased. With a backlog build up future costs are accumulating, which drive up Life Cycle Costs.

### **3.A5 Accident Sector**

A section for accidents was developed to include accident occurrence and road conditions as these both effect the allocation of the budget to either high or low volume roads. One problem that was dealt with was the probability of a user changing their pattern of use and thus effecting the volume accident relationship. To accommodate for this a formulation for user satisfaction and road use choice was developed this was based on the work of Berger(1991) and McFarland (1974).

### **3A.6 Cost Benefit Related to FWA and Sinha Model**

By using system dynamics, the PSI curve generated by damage is the curve with no maintenance. When any repairs are done the costs can be divided into PSI to give a PSI/\$, or accidents/\$ ratios. Therefore, the value of each level of PSI can be established for each type of maintenance expenditure without major statistical methodology. In addition, by plotting comparative curves the marginal differences can be evaluated.

### **3A.7 Economic Development**

While the impact of damage due to cars is slight some consideration had to be given to new home development as new streets and roads are associated with this process. However, as the method for determining the construction of new roads is complicated; dealing with age cohorts, incomes and size, it was felt that it exceeded the boundaries of

the model. There is no reason to consider that new roads would not have a PSI of 5 and therefore fall into the category of Excellent roads.

However, given the information from the interviews and literature, there is no reason to believe that new development does not effect highway use and costs to the towns, etc, or that highways do not impact on development. As this model is not a development model and such a process would extend the boundaries too far, it was felt that a surrogate measure might be needed. In this model, home development and regional business development was formulated. The homes are included as car volume effects the skid resistance number. Business development, including the impacts of malls was formulated, as truck generate the creation of PSI damage.

Current repair processes can lead to increases or decreases in future costs. The amount of predicted future costs can effects future budgets. A manager responded to the possible impact of greater costs on the management of a system in this way,

- "We can always raise taxes to cover the cost increases".

The issue of taxation effects was not fully considered, as this pushed the model far outside the boundaries of its original inquiry. The reasoning for not including this area of formulation was as follows:

To date there is no datum or study currently available that indicate the exact amount of taxation that would cause homeowners to leave. Discussion with regional planners and commercial real estate agent indicated that industry decisions to locate are more centered on infrastructure and location than costs (Companies are concerned with their ability to ship goods to customers).

If taxes were to rise to a given level that would cause homeowners to leave, the next level of impact would be on small businesses. Again, no real data was available on when a business would leave. Contacts were made to state Small Business Associations and the

National Association of Small Businesses. No information concerning tax impacts have been collected by these groups (This is of interest, as if I were doing planning or developing a small business such data would be of extreme importance). However, from a system standpoint one might consider that as home occupation decreases and families move, small business might be forced to follow. The increase in families leaving might be due to increased costs, due to spreading of the tax needs across a lower level of home ownership. As small businesses leave, the area might become less desirable to live in. Large, industrial companies might then find that costs to recruit and maintain employees increased to a point where the advantages of location diminish. (Such a real life process occurred in Far Rockaway, New York. Here the city destroyed local residencies to make way for a highway system. The town lost its tax base, small business closed, the attractiveness of the area fell. Where once existed a thriving community, there now exist a depressed town with no movies (once had three), no restaurants, (once had four), low cost housing and higher crime rates. In addition, this is taking place in close proximity to beachfront property, which has never been redeveloped over a period of 30 years. The assumed causal relationship plus the process described in the next section would move the model outside its boundary and is probably enough for another dissertation, which might be attached to the current model.)

### **3A.7.1 Taxation Model and Funding**

The reader should be reminded of what one manager felt about covering cost increases. The pavement manager's view is that budgets are not a problem-“We can always raise taxes to cover the cost increases”.

In Missouri, there are two views of taxation to fund roads. Businesses are wary to pass along tax increases during economic slowdowns, but long-term transportation plans can go a long way in both attracting and retaining companies to St. Louis. If impact fees are down due to cutbacks in construction then demand for infrastructure improvements is also lessened (Stepp 2000). One of the main problems that we are faced with is the evaluation of damage and its appropriate assessment to cause.

“The form of the mathematical model used to relate damage, axle load and configuration, and number of transits, has an important bearing on the results. For the relative damage effect, the damage (g) has been expressed as a dimensionless or normalized fraction of the change in serviceability index, as follows:

$$G=(P_i-P)/(P_i-P_r)$$

Where g= the fraction of total damage, at the current present service ability p

P=present serviceability index of pavement condition

P<sub>i</sub>=initial serviceability index at time of construction (PSI=5)

P<sub>r</sub>=notional terminal serviceability index at which condition the pavement is deemed to require rehabilitation, and at which g=1. Eq. 3.6

For purposes of model formulation, the value of P will be selected as the value of P when the RSL=15%. (Paterson 1987: 336)

Paterson goes on to state’ “aside from the relative damaging effects of different axle loads and configurations, the amount of damage attributable to environmental effects is a major issue in pricing and taxation studies because the costs of such damage may be accounted as a social rather than user cost. Mostly, the effects result from the interaction between traffic and environmental factors, and the strict attribution of damage to one or the other becomes a complex if not impossible task “(Paterson 1987: 359-360)

Bhandari (cited in Paterson 1987: 361) has shown that high design standards are optimal under unconstrained budgets, this further implies that about one half of the maintenance and rehabilitation costs for a high standard network should be considered as non-traffic costs to be allocated whether as purely social cost or as a general highway network costs, By the same reasoning, much larger shares of the damage are attributable to traffic networks of low design and maintenance standards.

Fwa and Sinha(1985) present us with a reasonable approximation of attribution of causation for this situation. And, as Bhandari seems to suggest a rate, but does not indicate the rate for either situation, the model that Fwa and Sinha provides, coupled with the system dynamics approach offers us some great advantage.

A complete review of the concept and methods of attribution of cause by Fwa and Sinha (1985, 1991, 1990) is too large to repeat here. The complete process develops the concept of cost comparison on a normalized basis of expenditures. Different routine maintenance policies create different performance curves. Each of the curves has a routine expenditure,  $S$  associated with a given level of expense  $L$ . If it is assumed that maintenance is performed with the same technology, it is reasonable to assume that maintenance expenditures would be positively related to the level of maintenance performed. Routine maintenance expenditures can therefore be used as a meaningful indicator of the level of routine maintenance performed on a given pavement. By plotting PSI-ESAL loss against a quantitative indicator of level of pavement routine maintenance, a relationship between pavement performance, expressed in terms of pavement damage and routine maintenance may be derived by a suitable procedure. The relationship can be used to obtain the pavement damage at zero routine maintenance expenditure. This gives an estimate of the total pavement damage that would have occurred if no maintenance were to be performed on the pavement under consideration.

In fact, in a simulation model a table function could be used to accomplish this. However, there does not seem to be a reliable study that relates the feedback process that occurs between rheological damage and damage caused by ESALs. The ESAL, it should be remembered, is measured under conditions that eliminate the environment. The use of a deduct method, which measures cracks and calculates PSI based on cracks versus a PSI generated by ESAL loss has two distinct purposes (To be discussed in detail in this dissertation in the Chapter covering Additions to the Knowledge Base). Even Fwa and Sinha state that there is little work done on the relationship between ESAL and environmental damage and there is the assumption in their model of a given load and non-load related deduct development.

The simulation in this dissertation may be used to assign a measure of cost benefit-

PSI/Available/Dollars

The following formulation based on the work of Fwa and Sinha may be used to mark the costs of damage caused by trucks to an area and for the development of an 'ear-marked' costs to companies for use of the highway system.

Tax to trucks = (G damage value) x (Percent of Damage Due to Trucks) x Percent of Truck that a company provides

The balance of G can be considered social and may be spread among homes, car ownership, etc. The determination of car ownership can be made by evaluating home development in an area of interest and estimating the cars per home by using data from public sources, such as the almanac. For the dynamics of car ownership one can refer to Bradley(1985).

In the case of road damage, the prevalent cause of non-environmental damage is trucks. The problem that prevents such a formulation, as recommended by Fwa and Shina is that the relationship between cracking, and time and ESAL rate changes with time is not clear. A detailed study of such a process would greatly enhance policy development for road pavement management.

### **Resource and Funding**

Given the large sums spent on construction and maintenance an appropriate basis for recovering costs needs to be available. The allocation of costs among various classes of users involves two issues. First, what are the effects of vehicles on road damage and repair costs? Second, on what basis should repairs be allocated?

Note

1. Total ESALs planned for is calculated from the formulation taken from the Strategic Highway Research Program. (Cited in Bednar, available Appendix A, Shahin 1994, Fwa and Sinha 1991). The growth in demand for ESAL formulation is available from FHWA-COST LCC,

page 43.

2. The methodology using the accumulation of EASLs is suggested by Fwa and Shina (1991).
3. The need for two measures is created as there is no testing method that can duplicate the impact on the environment and ESAL damage at the same time.
4. Discussions with Dr. R. Mallick led to a decision not to incorporate this type of formulation into the model. The basis was the fact that each mile of pavement needs to carry an appropriate PSI value. From a system dynamics view, a designer considers traffic impacts and seasonal conditions, as best as possible into the design. A normal life of 240 months is based on some preconceived normal level of traffic utilization. Therefore, traffic volume would effect the normal life span in this model.
5. The model uses a perceived PSI and perceived roughness formulation to account for this effect.
6. When repairs are attempted under low temperature conditions a correct pavement compaction can not take place, which affects air voids, which affects pavement conditions (Roberts, Kendall, Brown and Kennedy 1991: 366). This is apparently a recognized problem as indicated by manager's views. Work is often conducted in the winter when temperatures are below those that would allow correct compression of the asphalt.
7. Some texts refer to the AADT as the Annual Average Daily Traffic. Shahin uses the ADTT in his formulation (Shahin 1994: 208)

#### Other considerations

- a) Interview s were assigned a number to protect those who gave them
- b The use of qualitative inputs in customer satisfaction

Psychophysics is the science of uncovering fundamental quantitative relations between human responses and applied physical stimuli. To give a rating we must construct it in our conscious minds. While we are doing so, our concentration varies, we have trouble remembering what we sensed, distractions intervene, and random thoughts intrude.

(Weaver NYDOT)

The parameter values for truck usage were taken from the records of the Massachusetts Highway Department.

Avg Daily % cars range

Auburn 80%

Worcester 86%

Sturb 90%

Grafton 78.5%

The details of specific parameter use and development is covered in the chapter on Model Formulation.



## Chapter 4

### Methods

“Any comparison or evaluation of models must begin with an understanding of the underlying paradigms within which models are made”.

*Meadows (1994)*

This chapter will review current methods used for predicting pavement conditions and recommend what is believed to be a better alternative method for predicting such conditions. The review is not meant to be highly mathematical, but is done as an illustration in order to point out arguments as to why a more effective method of modeling should be considered. It will do so by:

1. Describing current mathematical processes used.
2. Critiquing current methods.
3. Describing how specific methods are applied.
4. Recommending an alternative method and defending its choice.

#### 4.1 Current Pavement Conditions Prediction Methodologies

Pavement condition prediction models are imperative for complete pavement management systems. Information on pavement condition characteristics is critical to performing management functions. These characteristics include roughness, skid resistance and structure capacity in distress. Several condition indices have been developed to quantify these characteristics. For example, the international roughness index (IRI) for measuring roughness, and the skid number (SN) for measuring skid resistance (100 times the friction factor). Composite distress indices such as the pavement condition index (PCI) have been successfully used in pavement management systems. When correctly developed, a composite distress index will indirectly provide measures of roughness, skid, and structural integrity due to the relationship between the various distress types and each of the condition characteristics of each distress type.

Condition prediction models are used at both the network and project levels to analyze the condition and determine maintenance and rehabilitation requirements of pavement. Network level management concerns deal with issues such as: the current condition of the pavement, pavement inventory, and the cost to maintain the pavement at a specified minimum operational level. Project level management deals with decisions concerning the best methods and alternatives for pavement maintenance and rehabilitation. At the network level, prediction model uses include condition forecasting, budget planning, inspection scheduling, and work planning. One of the most important network uses of a prediction model is to conduct “what if” analyses, to study the effects of various budget levels on future pavement conditions. (Shahin 1994: 113)

Prediction models are used to project PCI levels in order to select specific rehabilitation alternatives to meet expected traffic and climate conditions. The models provide the major input to performing life-cycle cost (LCC) analysis to compare the economics of various maintenance and rehabilitation alternatives.

Many techniques are available for the development of pavement deterioration models. Performance prediction models may be categorized into two kinds: 1) Regression models, which include, straight-line extrapolation, regression-empirical, and polynomial-constrained least squares, 2) Survival Curves and 3) Probabilistic or Markovian models and 4) Dynamic Programming A critique of these methods follows.

#### **4.2 Criticism of Current Methods**

1. Similar to the regression model is a method called polynomial constrained least squares. This method has a constraint, which provides that the polynomial slope is not positive for any age of pavement (Shahin 1994: 8). If a constraint must force the slope negative then we are no longer sure if the independent inputs are really causing the deterioration that we are predicting mathematically.
- 2 The use of qualitative variables is not considered. In the case of a non-quantitative variable, such as the seasons of the year, a variable is created and assigned some

quantitative values. In addition, predictions have a range of statistically accepted variation. The process assumes that the relationship between variables is linear in nature. In some cases, a real value is not available. For example, in the case of seasons of the year, one cannot use summer as a variable. In such cases, a variable is created to represent the non-quantitative inputs. In this situation, summer may be represented by the value 1, winter by the value 3, etc. However, in the case of road pavement condition predictions, such a process creates a problem. Even within a season, temperature changes have an effect on expansion and contraction and the development of damage to the pavement system. The use of such a variable would not take into account variations of real inputs that occur during a given time of year.

3. A regression model may contain more than one independent variable, believed to be associated with a change in the value of Y. A central problem in the development of a regression model is the selection of variables that are good for the purpose of the analysis. Often the choice of variable is determined by costs, ease of obtainment and the importance of the variable as a causal agent (Anderson 1985: 29). In order to do this a correlation analysis is performed. If there is a high degree of correlation between the variables then they are likely to be used. Herein lies another problem, How do you determine if the variable is a causal agent? The problem is, of course, that correlation does not automatically mean causation. For example, statistically, having sexual contact has little correlation with getting pregnant. Just ask people who are trying to have a baby! However, having sexual contact is a direct cause of getting pregnant!

4. One of the key assumptions about a regression model is that any two observations of the values of Y are not autocorrelated (Netter 1990: 32). In addition, it has been observed in practice that information used in at least one set of inputs was by its design multicollinear. Using data, which was designed in such a manner creates difficulty in predicting the effects of each of the independent (related) variables on the dependent variable of interest. It creates a false correlation, a major error in the model in which the data was used.

5. Data used in regression analysis may be observational or experimental in origin. Observational data is collected with no control over its collection. For example, I can select variables of interest, such as age of employees and days of absenteeism. I can then

study the correlation of the two with regression analysis. Unfortunately, this does not tell me the causes of absenteeism. For example, young people may be out due to children at home and older people out due to real illness. The information does not help me in the solution of the absenteeism problem my firm is experiencing. Experimental data is collected when the dependent and independent variables are controlled. For example, I can collect data on productivity and training. I can randomly assign individuals who have been trained or not trained and then determine the correlation between the two variables. However, the information does not tell me anything about the work attitude of each of the groups and assumes that only training is the primary cause of productivity.

6. Indeed, in order to provide enough variation in the data, to allow for a better randomness of the data, a large enough sample size needs to be taken. This, however, is related to the period of time over which such samples are taken. The time span of the collected materials needs to be long enough to allow for natural variation, but not too long. How long is never given as a guide. In fact, in some cases cross sectional data may be used, resulting in a loss of important data during a period that has not considered.

Finally, a warning is given by the authors whose text was used as the basis for the general description of regression analysis.

“A statistical test that leads to the conclusion that  $B_1$  does not equal 0 does not establish a cause and effect relation between the independent and dependent variable. Other variables not included in the equation could be having (co-lateral) effects” (Netter, Wasserman and Kutner 1990: 86).

Indeed a review by Sterman (1985), paraphrased here, relative to econometric models points out many of the characteristics that create problems with the use of regression type models.

Such models consist of three stages, which are specification, estimation, and forecasting. In the first step, the structure of the model is specified. That is, the relationship between variables and the described behavior is established. The second stage is statistical estimation of the parameters of the model. These parameters determine the precious strengths of the relationships specified in the model's structure. However, statistical data do not reveal the nature and quality of the information used in making a decision and therefore cannot be used to indicate how changes in that information would alter future decisions.

In addition, statistical techniques only reveal the past degree of correlation between the variables. Historical data are assumed to remain valid in the future. A statistically significant relationship indicates that the variables in the equation are highly correlated and that the apparent correlation is not due to mere chance (Sterman 1985: 867-869).

### **4.3 Specific Applications of Regression Methods**

Bednar (1998) reviewed pavement performance curves, as used in several states. The Iowa Department of Transportation uses a linear regression technique to develop equations; these included independent variables for thickness, aggregate durability, base and sub-grade characteristics (Note 1). Other models, such as the one developed in Pennsylvania include such factors as soil/joint interaction factor, total joint thickness, and soil factor (Note 2). The Washington State Department of Transportation uses a PCR (Pavement Condition Rating) as does Maine (Note 3).

Regression models have been used to determine impacts such as age and roughness. These models have been applied to both flexible and rigid pavements, as well as overlaid pavements. Similarly, prediction models for the effect of routine maintenance have also been developed. These models were developed to determine whether pavement age or total accumulated ESALs at resurfacing is a better representation of pavement service life (Al-Suleiman, T. I., Sinha, K. C. and Kuczek, T. TR 1216).

### **4.4 Survival Curves**

The survival curve is used to determine the amount of time that a pavement may last before major maintenance or rehabilitation must be performed. Historical records are used to develop survivor curves, which are empirical probability functions that are used to predict the percentage of pavement length of a specific age that will need rehabilitation in the future. The basic tenet is that the decision to overlay at failure is subjective. However, in the past engineers have placed rehabilitative overlays and consistently estimated the end of life of pavement sections (Vepa, George, Shekharan TRR: 1524).

The formulation of a survival curve and its graphic are represented in Figure 4.1.

$$V = 1 - \exp(-q/W^r)$$

V= percentage of surviving pavement length (mileage).

q= location parameter (values in chart in Appendix -)

r= shape parameter (values in chart in Appendix -)

W= cumulative ESALs from the date of construction. (Eq. 4.1)

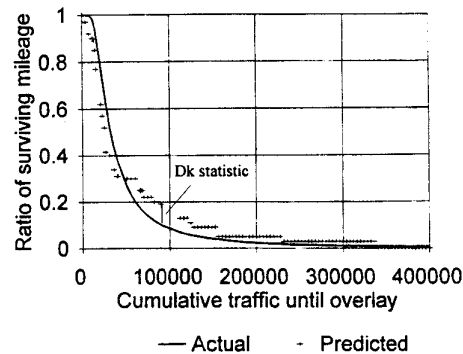


Fig. 4.1 Mileage Survival Curve

(From Vepa et.al. TRR 1524, p.1524)

[The recommended rehabilitation point is when 15% of the pavement's useful life has been reached].

#### 4.5 Markovian Chain Method

If the state of a given system can change in some probabilistic fashion at fixed or random intervals of time, we have what is called a stochastic process. A Markov process is a stochastic process, which has the property that the probability of a transition from a given state to any future state is dependent only on the present state and not on the manner in which it was reached. This is called the Markovian property.

In the analysis of problems, which can be viewed as Markovian processes, it is necessary to be able to define each possible state and to develop or obtain a set of transition probabilities between states. Further, a Markovian process, which meets the following conditions, is termed a finite-state first order Markov chain.

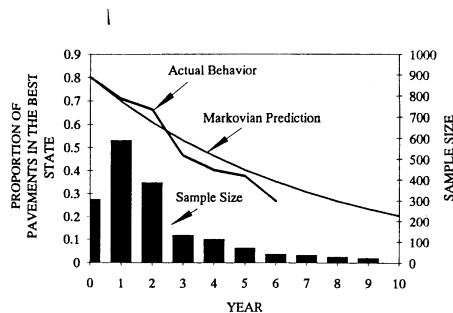
1. There is a finite set of states numbered 1, 2, etc. The process can be in one, and only one, state at a time.

2. The probability of a transition from one state to another is given for every possible combination of states, including when one state might equal another state. The transition probabilities are assumed to be stationary over the time period of interest and independent of how a state was reached.
3. Either the initial state on which the process begins is known, or a probability distribution of the initial state is specified (Trueman 1974).

The Markovian process can give an estimation of the probability of one state moving to another. This is based on repeated trials over successive periods of time where the state or outcomes of the system for a particular time cannot be determined with certainty (Anderson, Sweeny and Williams 1985). It uses historical probability data to measure change of state from, for example, good pavement to deteriorating pavement, and from deteriorating pavement to unserviceable pavement.

#### 4.51 Markovian Application

Arizona's Department of Transportation uses a Markovian model for its estimations of pavement conditions. A plot of the actual behavior of the road condition versus that of the Markovian prediction is shown in Figure 4.2.



Markovian Result  
(From Wang, Zaniewski and Way 1994: 373)

(Note 4)

In addition, in pavement management, different types of deterioration are occurring at the same time in any given section of pavement. The probability of a specific damage type, and therefore its measurement are constantly changing. In fact, Shahin (1994) states, “the technique requires developing a probability transition matrix to predict the way the pavement deteriorates with time. This holds true, continues Shahin, (1994: 123-124), “if

the assumption is made that the pavement condition will not drop more than one state in a single duty cycle". The cycle that is typically used is one year. In the real world, without the intervention of repairs, the state of any section of roadway can deteriorate to any of several conditions during a cycle. Further, interviews with pavement managers have indicated that many roads, due to budget constraints, actually deteriorate over a several year cycle. Thus, there is doubt as to whether the Markovian process can capture the real change in conditions occurring in this system.

#### **4.6 Dynamic Programming**

Dynamic programming is an approach to problem solving that permits decomposing one large mathematical problem which may be difficult to solve into a number of smaller problems, which are usually much easier to solve. Moreover, the dynamic programming approach allows us to break up a large problem in such a fashion that once the smaller problems have been solved, we are left with an optimal solution to the larger problem. The technique has been applied to many problems, which are multistage in nature. Often the stages are created by the fact that the sequences of decisions must be made over time. In most cases, each of these smaller problems cannot be considered independent of each other (The problem is stage dependent (Anderson, Sweeny and Williams 1985).

The foundation for dynamic programming is built on Bellman's principle of optimality, which states: An optimal policy has the property that, whatever the initial state and initial decisions are, the remaining decisions must constitute an optimal policy with regard to the state resulting from the first decision.

In general, information describing the problem at each stage is generally in the form of a specific value. There is only one state for each stage. The policy must optimize the objective function (Trueman, R.E. 1981).

##### **4.6.1 Problems with Dynamic Programming**

The dynamic programming method is an application of linear modeling. While it can be



turned into a non-linear model, this is often accomplished through transformation, which is a complex process that can cause errors in the parameters that are input to the formulation. In addition, the process, while making the graphic output curve look non-linear, is still linear in nature.

As a rule, Dynamic Programming considers a fixed or finite period of time. Unlike models that provide data on an on-going change basis (through real time feed back or loops), Dynamic Programming does not consider the real time related changes imposed by changes in the modeled environment. In addition, the real world has feedback effects. The pavement sector part of the system is effected by feedback from another part of the system (development). This sector (development) is effected by feedback from the pavement sector. Neither feedback may be linear in nature. Even if we tie together Dynamic Programming and Goal Programming, we are creating a linear solution to a non-linear problem.

As stated by Radzicki (<http://www.albany.edu/cpr/sds/DI-IntroSysDyn.energy.htm>), “only linear systems have exact analytical solutions. This is because, (1) they can be broken down into parts, (2) the behaviors of the parts can be determined, and (3) the behavior of the entire system can be found by adding together the behavior of the parts. In other words, the behavior of a linear dynamical system is merely the sum of the behavior of the parts. Since nonlinear dynamical systems do not have exact analytical solutions, their behavior can only be determined through simulation. In sum, the real world is nonlinear (i.e, has limits).” (:8-9)

While the model has been applied to pavement management, its application does not fit the needs of this dissertation. It is not recommended therefore that this linear approach be used to solve a non-linear problem (Note 5).

#### **4.7 Applications in Practice**

In one state, (Note 6) an expensive computerized model (i.e. a packaged software used

for road pavement management) is used to help determine resource allocation. However:

- The method used to assign a degree of deterioration and then used to forecast future pavement conditions is multicollinear in nature. The determination of the values used as input is mathematically calculated using a direct proportional base. The input of such data creates error in the regression analysis.
- The triggering of allocations is done by scoring, created with subjective inputs and is based on a low score of 65. The low score being chosen as it was used in college to represent failing. This information is then used to negotiate what should be spent.
- Information regarding road use, (cumulative ESALs), is collected and passed on to designers.

However, the designers and maintenance people never discuss the impact of design on actual deterioration and repair.(I2)

In another state, after the analysis is accomplished, the information is sent to a finance committee, which determines if other projects should get funded for the state before road repairs. This then allows less extensive projects to become major work the following year (I3).

What is revealed by the previous review is:

1. No standard model has yet been developed, as can be seen by a review of Table 4.1.
2. The complexity of the physical issues forces developers to select between a simple set of variables and possible relationships that might exist.
3. There is an assumption that independent variables have a linear effect on the dependent variable of interest, namely, the road pavement condition.

#### **4.8 System Dynamics Methodology**

“Management science models are largely linear formulations. The focus has been primarily on decision making and forecasting rather than on policy design”  
(Sushi 1993: 5).

STATE	DISTRESS INDEX
ARKANSAS	COMBINED INDEX (RIGID) = 0.6(DISTRESS) + 0.4(RIDE)
DELAWARE	COMBINED INDEX (FLEX.) = 0.5(DISTRESS) + 0.5(RIDE)
FLORIDA	PSI = 0.25(RIDE) + 0.75(SURFACE DISTRESS)
IDAHO	COMBINED INDEX = THE SQUARE ROOT OF RIDE AND DISTRESS.
KANSAS	COMBINED INDEX = 0.5(P.S.I. + CRACKING INDEX). RIDE, PRIMARY AND SECONDARY DISTRESSES, AND INFLUENCE VARIABLES ARE COMBINED TO GIVE 1 OF 216 POSSIBLE CONDITION STATES WHICH ARE GROUPED INTO THREE PERFORMANCE LEVELS: NO ACTION, MAINTENANCE ACTION AND REHABILITATION ACTION.
MARYLAND	ITEMIZED INDICES DETERMINED BY EACH CONDITION INDEX COMPONENT SUCH AS RIDE, DISTRESS AND TRAFFIC.
MASSACHUSETTS	PSI = 2(P.S.R.) + (D1 + D2 + D3 + ...DN)/(N + 2) P.S.R. = PAVEMENT SERVICEABILITY RATING (0 - 5).
MICHIGAN	DISTRESS POINT ACCUMULATION (0 = EXCELLENT, 50 = THRESHOLD VALUE OR REMAINING SERVICE LIFE OF ZERO).
MINNESOTA	POI = FUNCTION OF SURFACE RATING, RIDE RATING AND STRUCTURAL ADEQUACY RATING.
MISSISSIPPI	COMBINED INDEX = RIDE + DISTRESS
MISSOURI	COMBINED INDEX = 2(RIDE) + 5 POINTS FOR EACH OF THE FOLLOWING DISTRESSES: CRACKING, PATCHING, JOINTS, RAVELING AND RUTTING ON AC).
NEW HAMPSHIRE	COMBINED INDEX = 0.5(ROUGHNESS) + 0.5(DISTRESS)
NEW MEXICO	COMBINED RATING = 100 - [0.6(ROUGHNESS - 25) + 0.4 (DISTRESS DEDUCT)]/1.6
PENNSYLVANIA	OVERALL PAVEMENT INDEX = COMBINATION OF 13 INDICES.
TEXAS	FIVE COMPOSITE INDICES BASED ON UTILITY THEORY ARE USED WITH MULTIPLICATION FACTORS BETWEEN 0 AND 1.
VERMONT	COMBINED INDEX = 0.6(ROUGHNESS) + 0.25(CRACKING) + 0.15(RUTTING).
MONTANA	COMBINED INDEX BASED ON ROUGHNESS AND RUTTING.
NORTH DAKOTA	COMBINED INDEX BASED ON RIDE, DISTRESS AND AGE.
NEVADA	PROJECT LEVEL: DEDUCT SYSTEM, CONSIDER ALL POINTS. NETWORK LEVEL: DISTRESS POINT ACCUMULATION (0 - 49 = PREVENTIVE MAINTENANCE, 50 - 399 = CORRECTIVE MAINTENANCE, 400 - 699 = OVERLAY, AND OVER 700 = RECONSTRUCT).

Table 4.1 Index of Distress By State  
(From Baladi et. al.: 68.)

#### 4.81 Justification

Quantitative paradigms differ from qualitative paradigms in that the former represent social realities as a mathematical expression instead of a less rigorous verbal expression. (Anderson 1980). The question of whether or not verbal expression and modeling is less rigorous is the subject of this section of the chapter.

“The method of estimating coefficients from time series data almost always is a least squares method, particularly regression analysis. The assumptions underlying the

mathematical and statistical procedures may make for precise results but may cause the model to depart from reality” (DeGreene 1982: 139).

If these models do not capture the reality of the world then why are they used? As one interviewee expressed it: “as engineers we like the pure data, it’s a clean starting place”. Such methods have their place for solving problems that deal with specific variable(s). However, in their use little consideration is taken into account of the human decision making process. Again, we can look to Sterman (1985), who reminds us that “statistical data do not reveal the nature and quality of the information people used to make decisions, and therefore models based on such data cannot be used to indicate how changes in that information would alter future decisions.” However, where decisions are effected by decision making, an alternative model that can depict such situations is needed.

Another concern of using regression type models is linearity versus non-linearity. The real world is non-linear in nature and has constraints. Linear models work well within an acceptable range. It is at the point where constraints effect the system that system dynamics provides a better tool for analyses. One could argue that both linear and non-linear simulations are just that, a simulation of the real world and only a model. However, in some cases incorrect assumptions in the model and about the system leads to incorrect decision making. For example, the case of breakeven models typically taught in introductory accounting classes. The model is linear in nature and implies that after the breakeven point everything sold produces profit, therefore the correct decision is to keep making more of a product. A closer analysis, which takes into account the impact of the marketplace on price and revenues (an economics view) indicates that revenues drop and costs increase as more is produced. In fact, there is a region of maximum profit, and less or more production creates losses on both sides of this region. The constraints of the real world come into play. It is at the point where a constraint occurs that non-linear models are more effective in dealing with the impact of such constraints on the system. The constraint is the point at which the system can take on a new phase or behaviors.

According to Sterman (1985: 858),

“a model that ignores feedback effects is said to have a narrow boundary. Such models tend to rely on exogenous variables. There are two kinds of variables, endogenous and exogenous variables. They are the variables for which the modeler has an explicit theory. The values of exogenous variables may come from other models but are most likely the product of an unexaminable mental model.

An example is the case of Medicare HMOs. The government created Medicare HMOs to expand private coverage and access to care to older adults. However, at the same time they reduced the reimbursement to these private plans. The result of this decision was that the cost of care was not covered, premiums increased, and elderly patients dropped out of the plans. In many states, plans have stopped functioning. Today there are more uncovered Medicare patients than before the plan went into effect. The constraint created by costs and the feedback effect were not considered when creating the new system.

At least one author has realized that his work with regression analysis could not explain his results. He wrote: “the results indicate that much progress could be made in understanding the performance of organizations if more studies were conducted that looked at the system level characteristics of organizations and their relation to performance over time” (Denison 1990: 69). Further, “most often the goal of comparative research is the reduction of the incredible complexities of human behavior to a set of linear relationships”. As Mohrs (cited in Denison 1990) has shown, “this orientation tends to focus attention on explaining the variance in behavior rather than understanding the process by which it occurs”(Denison 1990: 89).

The regression and Markovian methods discussed have varying degrees of weakness. These weaknesses center on their inability to capture real world process that cause the problems that these techniques are meant to help solve. While even a computer simulation cannot and does not actually replicate the real world, it does provide a means of developing a better understanding of the relationships of processes that do effect real outcomes. For example, while regression analysis seems to include those variables

deemed important to road condition, the models that were reviewed leave out one of the most critical variables of all, the resources needed to repair roads and how they are deployed.

Traditional methods, which have been outlined in the preceding paragraphs, are usually “meant to deal with decision making not policy development. They deal with open loop systems, rather than closed loop systems, which provide for feedback relationships within a system” (Sushil 1993: 5). Traditional methods for predicting pavement conditions do not take into account the human impacts of decision making on the system or the processes in use in management of the system.

#### **4.9 Human Decision Making**

Research in cognitive psychology has shown that decision processes suffer from multiple weaknesses. These have been reviewed by Sterman (1994; 1998; 2000), who has listed among the problems we face such issues as our inability to deal with dynamic complexity, limited information, deficient mental models, erroneous inferences about dynamics and defensive routines. Decision makers suffer from what Simon has labeled, “bounded rationality”:-

The capacity of the human mind for formulating and solving complex problems is very small compared with the size of the problem whose solution is required for objectively rational behavior in the real world....(Sterman 2000: 26)

A full review of the problems that effect human decision processes can be found in Plous (1993). In addition to poor decision making heuristics the mental models that we harbor also hamper human decision making.

#### **4.91 Mental Models**

Mental models have been defined in many ways. They are internal representations of the external world (Cannon-Bowers, Salas and Converse 1993: 225). Forrester (1975b: 213)

wrote: “the mental model is fuzzy. It is incomplete. It is imprecisely stated. Further, within one individual a mental model changes with time and even during the flow of a single conversation . Their dynamic consequences cannot be simulated mentally”. While Senge (1990: 8) notes that they are “deeply ingrained assumptions and generalizations, or even pictures or images that influence how we understand the world and how we take action”. Of importance to system dynamists should be the idea that the “social meaning of a concept is not defined in a universal sense but rather through the intersection of individual’s mental models” (Carley 1992: 602). Therefore, in order to construct system dynamics models, having a shared mental model takes on important significance

Our mental models become a means of interpreting cause and effect relationships that are shaped by our values, beliefs and culture. They are an internal view of how the world works and which behaviors are appropriate for dealing with events in the world.

Doyle and Ford (1998: 19) have defined a mental model of a dynamic system (MMODS) as “a relatively enduring and accessible, but limited conceptual representation of an external system whose structure maintains the perceived structure of the system.”

According to Rouse (1986), mental models are the basis for estimating the state of a system. Such estimation includes the “estimation of state variables, developing and adapting control strategies, selecting appropriate control actions, determining whether or not actions led to desired results (goals) and understanding unexpected phenomena that occurs as the task progresses.”

In the field of system dynamics, it is argued that policy makers should not worry about whether or not to use a model, but rather, which model to use. In other words, “system dynamicists believe that policy makers should decide whether they wish to make decisions based on results obtained from their unaided mental models or from results obtained from some combination of formal and mental models” (Radzicki 1998: 8).

However, avoidance of the use of formal models can lead to what Edwards and VanWinterfeldt (1986) call “cognitive illusions”. The elements of every cognitive illusion are a:

1. Formal rule that specifies how to determine a correct (usually the correct) answer to an intellectual question. The question normally includes all information required as input to the formal rule.
2. Judgment made without the aid of physical tools, that answers the question.
3. Systematic discrepancy between the correct answer and the judged answer.

A formal model has advantages over the informal or mental model. These advantages are: 1) the formal model is explicit and communicable. A system dynamics model exposes its assumptions about a problem to criticism, experimentation, and reformulation, 2) a formal model handles complexity fairly easily. The computer can reliably trace through time the implications of any messy maze of assumptions and interactions of feedback (Pugh and Richardson 1981).

The decisions made by managers affect action, action effects the system, which then requires further decision-making. Most of these decision being made to maintain or improve the state of the current system (Figure 4.4). As the problem described in this dissertation deals with more than a single variable and with the impact of multiple decision makers it is felt that a better alternative than traditional management methods be chosen to aid in the decision processes of pavement management.

The loop in Figure 4.4 is a balancing loop. The desired system state increase the gap. As the gap increase, actions are taken to close the gap.



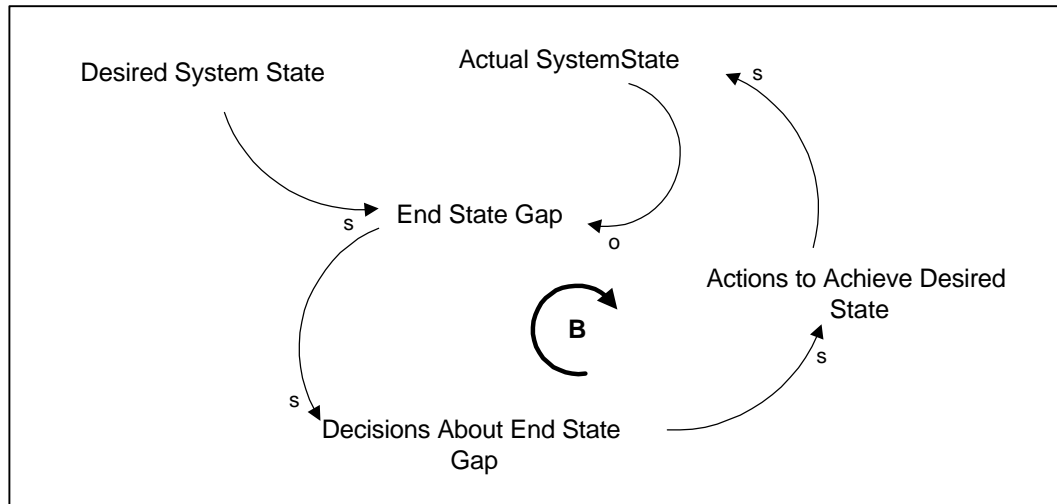


Fig. 4.4 Decision Making Loop

#### 4.10 System Dynamics

A system dynamics model is a representation of a real life system. It uses verbal, written and visual information and communication processes in its construction. A system dynamics model organizes the information, information flows and policy decision points of a system, into a computer simulation model so that that we may study the system to create policies for its improvement.

“In system dynamics a problem is defined as an internal behavioral tendency found in the system (Saeed 1998: 3). All the interviewees contacted for this dissertation agreed that although regression models are helpful, they are only one part of the process. The biggest problem was how resource availability, (i.e finances which constrain the pavement process, politics and other factors) effected road conditions.

Interviews highlighted what Saeed (1992: 257-258) wrote,

As a first requirement for delineating ... a reference mode, the search for data must expand beyond a single historical pattern concerning a specific organization and attempt to find a class of patterns observed in history at

various times and locations. Some of these patterns may even conflict with one another”.

In the interviews conducted, professionals at state and town levels disagreed as to the exact impacts of economic development on road conditions. The state felt that economic development did not adversely effect state roads but that it (development) might be effected by road conditions. The town professionals all felt that economic development effected road conditions but that conditions did not effect development. (The reasoning behind this becomes clearer when one realizes that most of the town roads were developed without consideration for heavy trucks as they were designed when cars and trucks were smaller and lighter as compared to state roads which, in many cases are newer and designed for heavier use).

In this dissertation, system dynamics will be used in order to develop a richer model of a pavement management system for policy analysis and improvement of management decision making versus the prediction methods currently in use.

#### **4.10.1 System Dynamics Methodology**

According to Randers (1980) the system dynamics method has several steps. These are:

1. Conceptualization
2. Formulation
3. Testing
4. Implementation

Each phase is designed to increase the validity and accuracy of the model as it tries to capture enough elements of the real system to make the abstract system usable for study and evaluation of the problem that exists. The result should be a model that allows for the development of policies to improve the state of the real system.

Conceptualization

Reference mode

During conceptualization the reference mode or problem statement is developed. The reference mode, as described in Chapter 1, is a graphic representation, over time, of the problem that exists. Conceptualization deals with the development and identification of a problem. What causes a problem to develop? What are the likely effects of a given policy? It is during conceptualization that we:

- 1-Collect the story and background of the current problem.
- 2-Define a problem dynamically using graphical representation.
- 3 -Choose the reference mode, which will establish a correct time horizon.
- 4- Establish a system boundary and use it to determine which system components are necessary to generate the behavior of interest and which components are unnecessary.

The reference mode serves as a tangible manifestation of the entity that is being portrayed by the model output. The reference mode is intended to solve the problem of specifying the study focus. Once the mode is created it provides a foundation for creating the initial model that is capable of reproducing the major dynamics of the reference mode (Randers 1980). The process used to develop the reference mode is a story based on interviews collected from members who have both tacit (unshared) and explicit (shared) knowledge of the system. The stories are then supported by information obtained by a search of the literature. Selection of participants was based on several concepts provided in the literature.

Unlike a laboratory research process, where we may look for matched pairs or stratification in participants (the correct percentage makeup of a group based on population demographics), interviews conducted for building a system dynamics model are based on knowledge of the system in question. However, people in a position to have the knowledge may not always want to share the information openly (Rubin 1995: 67). Such was the case where two states, Maryland and Maine, refused to participate in the interview process for this dissertation.

To extend what we hear from qualitative interviewing to other areas it is recommended that we consider two issues; the first is completeness, that is, you keep adding interviews

until you are satisfied that you understand the multicultural or multistage process. (You interview until you reach a saturation point, where little is added by additional interviewing). The second is the ability to find similarity and dissimilarity. In the process used in this dissertation, I attempted to find dissimilarity by using participants from different levels of the system. In fact, in one case, a dissimilar view of the impacts on development was found. The use of dissimilarity coincides with Vennix's (1997) view of using heterogeneous group members where possible. In addition, we look for consistency. Consistency is improved when it can be shown that core concepts and themes consistently occur in a variety of cases and in different settings. One way to evaluate for inconsistency is to search for cause. In the case of the disagreement about development, a logical cause was found due to the time of construction of the infrastructure involved. In addition, the conversational partner should see themselves in your descriptions. Rubin (1997) has labeled this communicability (: 91). This was achieved when the first version of the model was fed back to participants.

Interviews were conducted based on the works of Cunningham (1993), Erlandosn, Harris,E.L., Skipper, and Allen,S.D. (1993), Nadler (1977) and Rubin (1995). The process applied in this dissertation was the use of open-ended interviews. A full description of these methods and the actual interviews are found in Appendix B of the dissertation.

### 1. Dynamic Hypothesis

After the reference mode is developed, a second part of the conceptualization process is necessary. The modeler needs to establish a dynamic hypothesis. This hypothesis is built around a sector diagram, which details the feedback relationships within and between the major operating variables identified in the reference mode diagram. The variables are selected from the qualitative stories that are conducted during the development of the reference mode, from written data collected from reports, and quantitative data collected from records.

Forrester (1971) noted that, ‘the causal loop diagram (CLD) represents a distillation of feedback structures that was derived by conceptualizing the parts of the system and simulating their interaction (i.e. it comes after the model has been built). Saeed (Note 7) feels that the causal loops help to identify the variables in terms of defining sector relationships and are helpful to the modeler. Goodman (1988) has written, “causal loop diagrams are most useful during the early stages of model conceptualization as they help identify and organize principle components of the feedback loops of the system under study”. Kim (1994) feels that the causal loop diagram can help make our mental models explicit. Finally, Richardson (1986) has pointed out critical faults in the use of CLDs.

I believe that the CLD is a helpful tool in development. It helps to clarify the relationships that at times are messy in nature due to the multiple sources of different types of data that are being used to develop a working base for model development. While they do not represent the actual structure of the system that the modeler will develop, they tend to act as a guide in the development of the system by clarifying variables of interest. I also believe they help the modeler in clarifying the boundary of the system. The CLD allows the modeler to clarify whether a variable might be endogenous or exogenous to the system problem. It allows the modeler to use a visual representation of the variables when discussing the story that has been told to them by participants of the group involved in helping build the model.

Steps 2 and 3, Formulation and Confidence building in a system dynamics model occur at the same time. Interviews were used as the basis for establishing the problem statement. Using quantitative expressions obtained through a search of the literature reinforced interview assumptions. A full background of the problem and literature search and its implications on formulation are found in Chapter 3 of this dissertation.

## 2. Formulation

Formulation is the process of translating a model’s structure into equations. We are

moving from an informal concept into a quantitative representation. It is the process whereby the informal causal loop is put into a formulated equation “The necessary precision (unambiguity) of the formulation stage forces clarity of thinking that improves the modeler’s understanding of a system structure” (Pugh & Richardson 1981: 133).

### 3. Testing and Confidence Building

System dynamics modeling has been criticized for not employing a formal, quantitative method of model analysis. Although many methods for testing a model are available (see below), building confidence in a model is more appropriate than its statistical significance. In system dynamics, the building of confidence in a model is a gradual process. (Homer 1996).

The establishment of such confidence may be undertaken in several ways. System dynamics models are built for a purpose, to solve a problem. The confidence in a model lies not in its statistical proof but whether it helps to solve the problem for which it was built.

Since individual equations are claimed to be the cause (or capture rational processes) about system relations, each individual equation must be justified. If a model equation does not make sense then the model can be refuted (Barlas 1990). (Justification in this model is based on formulas and functions based on the search of the literature on road pavement management).

Confidence building is a process based on the use of good procedures in the development of a model. According to Churchman, validation is a social process, inspiring confidence in a better descriptor (Sterman 1984). During the development of the model for this dissertation, verification of the reference mode and structures by those whose stories were used, was accomplished before, during, and after the model building took place.

The system dynamics model is refuted if a critic can show that the relationship within a model conflicts with an established "real relationship", even if the output behavior of the model matches real behavior. Morecroft (1985) notes that an equation must be descriptive of the real expected world. Recommendations for the development of models have been made by Morecroft (1985) suggesting the use of partial model testing to expose the intended rationality of the decision making process. In addition, Homer (Note 8) has written that, "ideally all elements of structure should be based on information at a level more detailed than that of the model itself". Findings from a search of the literature or data from records pertinent to the system aid in the development of such lower level details (Note 9).

Further series of tests including: direct structure testing, structural confirmation, parameter confirmation, extreme condition test (direct and indirect), behavior sensitivity, phase relationship testing, system improvement testing, change behavior prediction tests and behavior anomaly tests have been recommended by Baralas (1996), and Forrester and Senge (1980). Sterman (1986) has applied statistical methods for analysis of models, using the Theil inequality statistics for the decomposition of the mean square error. Clemson, Tang Pyne and Unal (1993) have recommended a methodology for sensitivity analysis of parameters.

In the end it is the usefulness of the model and its ability to capture, for purposes of analysis, enough of the real system's characteristics that will allow those who build it to say they have confidence in its use.

#### 4. Implementation

Once the model is formulated it needs to be used for analysis and policy development. According to Saeed (Note 7) implementation, has a range of difficulty. Where an individual can change decision rules we have a space to create policy changes. Where a society needs to change it becomes more difficult as it is harder to change social roles than individual action. Indeed Robinson (1980, cited in Randers) warns:

Preconceptions are the set of generally unspoken beliefs, assumptions and expectations that surround the initiation of a modeling effort. In other words, preconceptions are the often implicit and unrecognized forces that shape the model before it becomes explicit, and continue to operate behind the model throughout its development (Randers 1980 :250).

According to Weil (1980) for a model to be successful “the results of the project must be implementable”. The results of the modeling process and recommendations need to be acceptable to those who must live with the resulting recommended policy changes. This is especially true in the case where a public policy needs to be developed. Those who have participated in identifying the problem, in many cases, are not those who can make a direct change in a system. For example, town pavement managers can recognize and accept the results of the model to be created by this dissertation. However, moving from a town level to a federal level may be quite a different situation.

One may ask the following question with regard to implementation: Why would a pavement manager worry about the long term, when their longevity in the job may not be long term? The question actually has two questions in it. What is the longevity of pavement managers? Do they care regardless of length of service?

A search of the literature did not reveal any direct answers. However, interviews revealed part of the answer, while reference to knowledge on motivation supplies the rest. Pavement managers at the town level, on average spend about 10-12 years in a position. At the state level this can be a career or up to 20 years. As far as motivation, the immediate answer was professionalism. From our knowledge of industrial psychology, it appears that money is not necessarily the main motivator. Issues such as self-esteem and competency (Argyris 1993 cited in Robbins 2001), self-actualization (Maslow 1954) and work well done (Hertzberg cited in Robbins 2001) appear to be stronger motivators than money. However, even when we consider this, managers have indicated that doing good work does have a financial reward side. Managers who keep spending under control but maintain their systems are often sought after. In some cases, towns will actually compete for a good manager. Therefore, salary also gets affected in a positive manner. From a psychological perspective, we have reinforcement of behavior.



Methods to improve consensus on action have been developed around the use of group model building. Anderson and Richardson (1997), Anderson, Richardson and Vennix (1997), Hodgson (1992), Richardson and Andersen (1995), Richardson, Anderson and Rohrbough (1992), Romme (1995), Vennix, Gubbels, Post and Poppen (1990) and Vennix, Akkerman and Rouwette (1996) have described such processes.

Finally, in some cases, models may need to be compared with time series data analysis to satisfy the end user of their validity. Using and understanding a new paradigm does not automatically imply trust in it, until it proves itself in the real world.

#### **4.11 Strengths of System Dynamics**

1. By using multiple sources of data system dynamics models are more contextual in nature due to the inclusion of typically more usable variables that are associated with a problem.
2. By making use of contextual information, system dynamics is able to extend the impacts of individual decisions across boundaries. It therefore, integrates real world decisions that are typically rationally bounded. By doing so it allows the user to see the full impact of what might be individual decisions.
3. It makes the thinking behind our decision making explicit and by doing so, it allows for the challenge of strategic decisions.
4. Policy makers can see results of their decisions before implementation and can learn, before doing, from mistakes in their thinking.

#### **4.12 Applicable Models**

System Dynamics modelers often use a library of structures that have been proven useful in other models to aid in the model building process. These structures are sometimes called generic structures. “They are dynamic feedback systems that support particular, but widely applicable behavioral insights. If meaningful generic structures could be

isolated and understood, they would form a body of system theory that could be transferred from situation to situation” (Paich 1985).

A search was undertaken to find work in system dynamics that would be useful in the construction of a pavement management system model. The work by Paich and Ladet in clarifying the effects of DuPont’s maintenance policies is an example of such an application. While the model appears to deal with the chemical industry, at its core are issues of timing and use of resources to prevent a situation from becoming worse and keeping total costs down. There is no difference in whether we inspect for equipment failure or road failure, no difference if we allocate resources on repair work or preventive maintenance in the chemical industry or pavement systems (Sterman 2000: 66). A model developed by Gailbraith (1989), that considers the allocation of resources in a constrained environment, although in the context of higher education, is another example of the possible use of existing stock and flow structures as an aid the development of policy for pavement management. Saeed’s work (1998) on the evaluation of financing road construction in China contains recommendations that may be used for development of policy relevant to balancing the current dynamics represented by the reference mode. Further, there is the work of Abbas (1990) on road development, which may help in establishing a guide to the resource allocation process for road rehabilitation.

#### **4.13 Recommendation**

In 1985 the following was stated:“ while many damage function models are available in the literature, there are hardly any theoretical models which could be used directly to compute the relative effects of load and environmental factors on pavement deterioration. Most models, being either regression based or empirical” (Fwa and Sinah 1985: 17). System dynamics allows us to overcome this shortcoming of the traditional approach.

Road management systems can be described as computerized, analytical tools that consider the whole life costing of alternative strategies for the road network. These tools

enable the testing of alternative management and planning programs for the highway sector (Abbas 1990: 1).

Based on the preceding analysis it is recommended that a system dynamics model be developed as an aid in the creation of policy that can aid managers in the improvement of current pavement management systems.

#### Notes to Chapter 4

1. In one of the cases presented rehabilitation and maintenance effects on the pavement performance were not considered; “these are a source of variation in the results”(Bednar, 1998 :94). This lack of including rehabilitation is of extreme relevance as when rehabilitation is performed it is assumed that the road condition returns to 100% of its original value. To exclude rehabilitation excludes a major part of the system. Further, the impacts of weather have not been included. The model suffers from leaving out highly relevant variables.
2. The Pennsylvania model used a composite score impact. However, although the graphic that accompanies the model is negative in nature, the formulation shows a positive impact in accumulations
3. A PCR (0-100 scale) has been developed by George (Rajagopal and Lim, (TPR 1215)).
4. The Markovian process is assumed to reach a steady state process where probabilities are no longer changing. Yet, in the real world pavement can be deteriorating at a much greater or slower rate than predicted by probability.
5. A search of the E.I. Compendix, covering a 30-year period, was initiated to locate articles related to DP and Pavement Management. One article, DeNuefville, R de. and Mori, Y. (1970). Optimal Highway Staging By Dynamic Programming, Transp. EngJ. Vol. 96 February, was found. Within the article can be found the reasons that DP should not be applied to a complex policy analysis. “The ability to reduce the total number of comparisons is accomplished by taking advantage of the assumed independence of the values of the investment”(13). Further, the basis of this article rests upon the work of other authors (Funk and Tillman cited in de Nuefville 1970), who assumed that the value of any investment is independent of the previous subsequent construction. This condition, which is essential for the applicability of dynamic programming, does not always hold in practice and must be considered carefully” (14). The process as described also evaluates optimal benefits based on the net-present value of the costs of compared projects and does not take into consideration the end quality of the repair process. In road pavement management, the same end quality can be achieved using several alternatives. In addition, no consideration is given to other intervening variables such as accident rates, development, life cycle costs, etc. The process as described has limited application to discrete projects and should not be used for policy development.

6. Identities of states contacted for this study are not revealed due to proprietary concerns. However, verbal confirmation is available. I5 represents interviewee 5(MRP).
7. Saeed-class notes Advanced Studies in System Dynamics Feb, 30, 1999
8. I5 represents interviewee 5(MRP)
9. Homer-(dates unavailable). Handout articles from class in System Dynamics, Worcester Polytechnic Institute.

## **Chapter 5**

### **Model Formulation**

#### Introduction to Formulations

Model formulation is the process of expressing the dynamic hypothesis in a mathematical format. It is at this step in the process of model creation that the hypothesis and system, as described by members of the system, is generated into a set of meaningful quantitative relationships to allow simulation. This chapter will deal with the details of the formulation of each sector of the model, as identified in the sector map of Chapter 1.

The formulations for each portion of the model are based on information obtained from interviews with pavement managers and a review of the literature. Where appropriate the information that was obtained will be used to justify why a particular formulation was used. In addition, as described in Chapter 2, in order to make the formulation as explicit as possible, personal thoughts explaining the reasoning behind the formulation will be included.

The sector map represents the framework of relationships that support the dynamic hypothesis (Chapter 1). In this map, the pavement serviceability sector subsumes the condition of the road, the PSI and the rehabilitation processes that maintain the road. Road conditions in the model consists of those factors which cause damage to the pavement system, methods of rehabilitation of the pavement system, the measure of the quality of the system (PSI), and the amount of miles within the pavement system under question.

A summary of the sector map, and sector relations are shown in Figure 5.1 for ease of reference.

The sectors represent the following relationships in the system:

I. Pavement Serviceability includes variables pertaining to:

- Road mileage and road quality
- Deterioration and repair rates
- Repaired and non-repaired road mileage

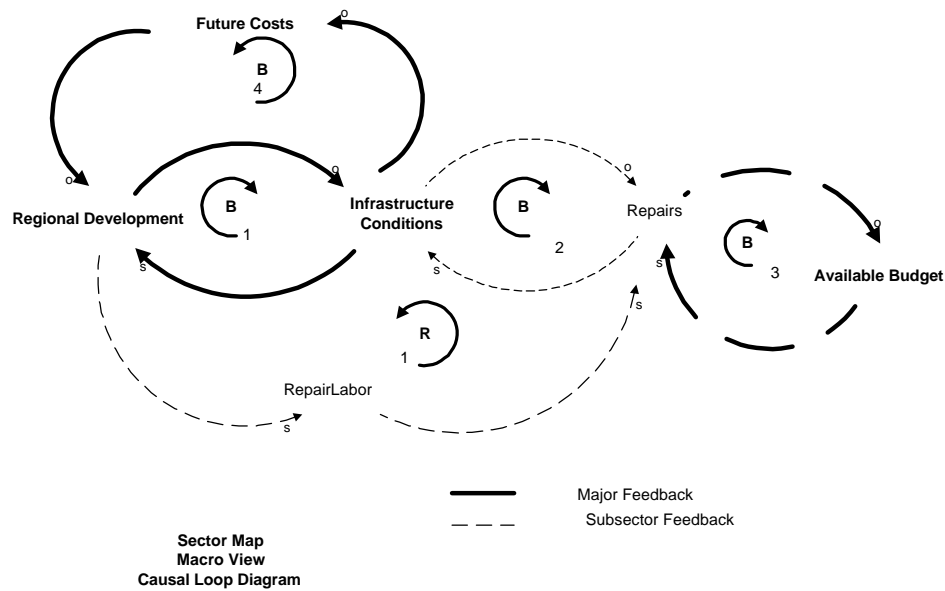


Fig. 5.1 Sector Map Causal Loop Relations

II. Financial & Budgets includes variables pertaining to:

- Budget Development
- Cost of repairs
- Control of repair types and mileage repaired
- Impacts of budgets on repairs

III. Development includes variables pertaining to:

- Housing, industry and retail development
- Generation of user volume of vehicles
- Land use
- Population change and human resources

IV. Future costs of road repairs

### Sector Loop Description

A (B) represents a Balancing Loop, while an (R) represents a reinforcing loop.

o-a change in the opposite direction

s-change in the same direction

B1-As Regional Development increases vehicle volume increases, creating more damage to the road system. The rate of development decreases in response to a decline in road conditions and in addition, some businesses may leave.

B2-A decline in road conditions requires repairs. Repairs tend to improve the condition of the road.

B3-As repairs are performed the available budget decreases, which causes the rate of repairs to decrease.

B4-As the infrastructure declines, due to increases in development and repairs are slowed, due to less budget availability, future costs of repairs increase. An increase in future costs has implications for tax policy and development. (A formulation representing this relationship was not developed in the model. A full explanation of the reason is given in Section 3A.7 as it relates to the issue of boundary).

R1-As Regional Development increases, more labor can be hired, which increases the amount of repairs and improves road conditions, which improves the rate of regional development.

Feedback relationships within and between each sector will be discussed at the end of this chapter.

## **5.2 PSI Sector and Road Conditions**

The basic measurements of the condition of pavement sections are its existing distress. There are two classes of distress, structural and functional, and several types of distress associated with each type of pavement. Furthermore, each type of distress can be caused by several variables, either environmental or load related. At the core of the Pavement Management System (PMS) is the condition of the system. The condition is dependent upon two processes, road quality, measured by the PSI index (as described in Chapter 1)

and road quantity or usable miles of road. Figure 5.2 represents the skeleton of the road system and depicts the relationships of usable miles within a system, and the general process that effects mileage type and quality.

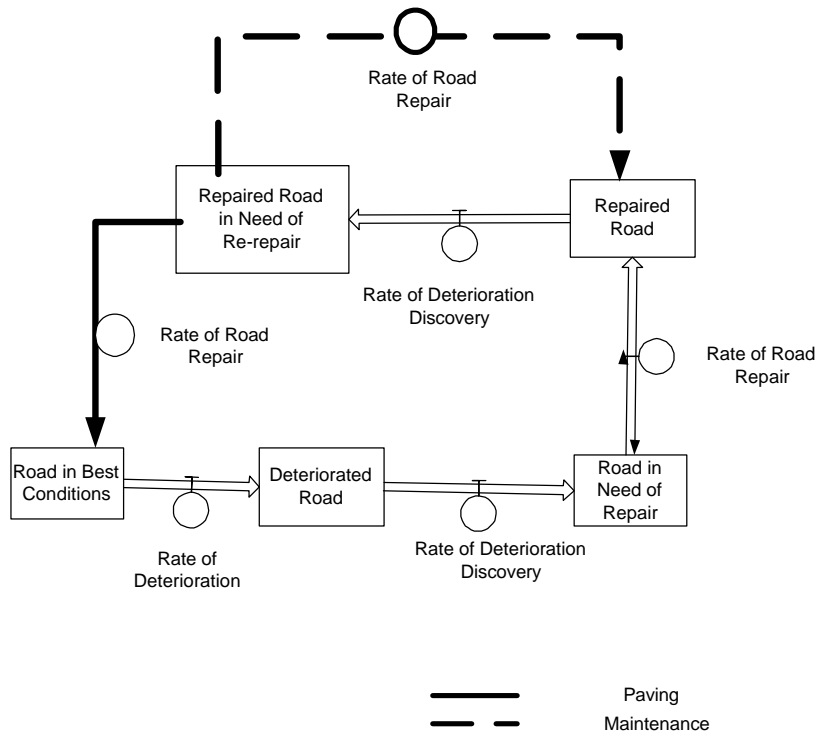


Fig. 5.2 Simplified road deterioration and repair process.

The diagram depicts the relationships between mileage states, represented by stocks and changes to the stocks represented by rates of flow. The diagram is a simplified version of the system dynamics model and shows an initial stock of road in best condition, which deteriorates at some rate. A second stock of deteriorated road accumulates the outflow of the deterioration. The deterioration of the road needs to be discovered in order that roads can be scheduled for repairs. The rate of discovery determines how much discovered road becomes available for repair. The stock, road need repair, represents road, which can now be scheduled for repairs. Several types of repair are available for damaged road. Roads can either be fully paved, (shown as a solid line) or can have maintenance



performed (shown as dashed line), to keep the road in use. Roads that have had a single preventive repair are shown in the stock Repaired Road. The stock of Repaired Road deteriorates, is discovered, and become road in need of Re-repair. Re-repair can be accomplished by either additional maintenance or by full paving. The stock of best road (BR) is defined in Eq. 7.1 as,

$$BR(t) = \int_{t_0}^t [(Rr4 - Dr1) * dt] + ER(t_0) \quad \text{Eq. 7.1}$$

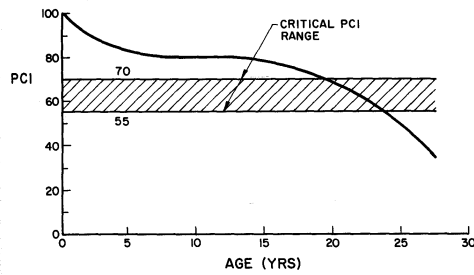
The representation in Figure 5.2 is a simplification of the actual system dynamics model, which contains several stocks not shown in the Figure.

### 5.3 Quality of the Road

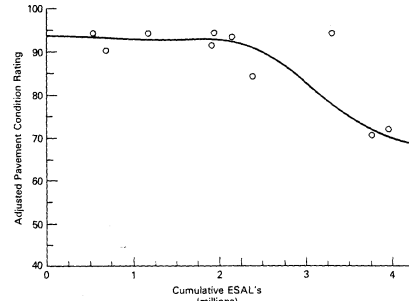
Several researchers (Peterson 1987; Robertts, Kendall and Brown 1991) have reviewed the rheological effects on asphalt. The damage caused by traffic has been well-documented (Shahin 1994; Fwa and Sinha 1985) and several methods of measurement are available (Bednar 1989). It was determined that the PSI Index was best suited for use in a system dynamics simulation.

The PSI/PCI (Pavement Service/Pavement Condition Index) is traditionally represented by the graph shown in Figure 5.3a. Pavement Serviceability is expressed as an index number. The significance of the number is that it establishes a relationship between objective pavement condition measurements and subjective ratings of road users. It is based upon the correlation of road user opinions with physical measurements of road roughness, cracking, patching, and rutting.

(Fwa and Sinha 1985: 25)



a (From Shahin, page 163)..



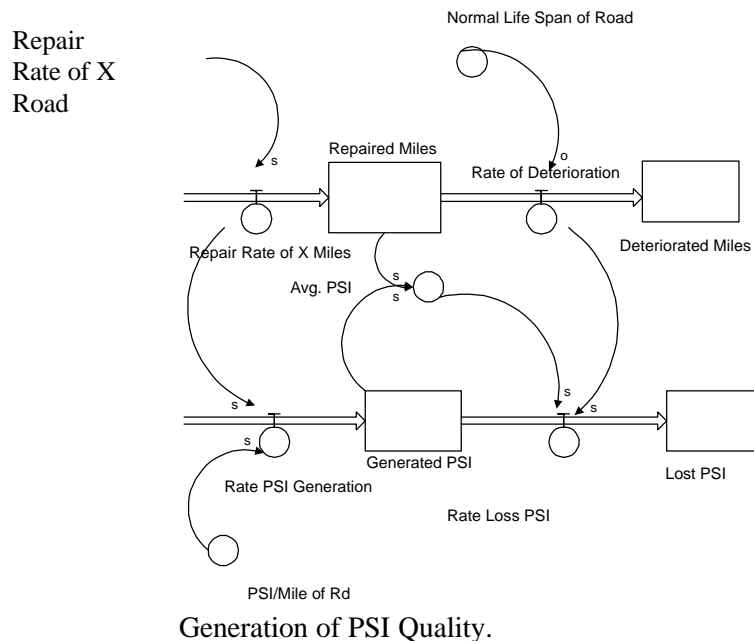
3b (From Bednar, 1994)

Fig. 5.3 Representative PSI Curves

A representative curve of a PSI is shown in Figure 5.3a. While this curve is a textbook representation, a curve developed from empirical research is shown in Figure 5.3b. Other curves may be seen in Appendix A of this dissertation.

The levels in the skeleton of the system were duplicated in formulation. For example, the rate of inflow in the skeleton of the system is labeled Repair Rate of X Road, the name for the equivalent rate in the supporting co-flow was Repair Rate of X Miles. This was done to allow the development of rates in subsections of the model. These rates were then carried into the skeleton of the system. It is the rate of inflow into the level of Repaired X road that is the rate of inflow into Repaired X miles of the generic structure shown in Figure 5.4.

Although, not a causal loop diagram the structure captures the dynamics of the generation and deterioration of miles in general. As more miles are repaired, each mile repaired adds to the level of the PSI. Taking a grand average and its mean value develops the average PSI per mile. As the life span of a repair made to a road becomes smaller, the amount of deterioration per period of time decreases.



Where

$$\text{GeneratedPSI}(t) = f^t t_o [(\text{RateGeneratedPSI} - \text{Rate Loss PSI}) * dt + \text{GeneratedPSI}(t_o)] (\text{PSI-Units}^*)$$

$$\text{RatePSIGenerated} (\text{PSI Units}/\text{Month}) = \text{ChgRateRepairs} (\text{Miles}/\text{Month}) \times \text{PSI} (\text{PSI-Unit}/\text{Mile})$$

$$\text{Avg.PSI} (\text{PSI Units}/\text{Mile}) = \frac{\text{GeneratedPSI} (\text{PSI Units})}{(\text{Good Miles} + .000001^{**}) (\text{Miles})}$$

$$\text{RateLoss PSI} (\text{PSI Units}/\text{Month}) = \text{RateofDeterioration} (\text{Miles}/\text{Month}) \times \text{Avg.PSI} (\text{PSI Units}/\text{Mile})$$

\*[Note: Italics are dimensions of measurement]

\*\*[In this model the prevention of division by zero is accomplished by adding .000001 to the denominator (miles).

The process of road management also depends on the ability to measure the PSI (Pavement Serviceability Index) which, along with other inputs, determines the extent of road repair and costs, the variable PSI was chosen as the starting point of the formulation of the road sector. The formulation used in this simulation was based on a generic averaging process. Each mile of road carries a normal level of PSI quality. For each mile

added or lost the value of the PSI changes accordingly. A separate PSI value level was formulated for each category of road specified by the FHA. The generic structure and formulation can be seen in Figure 5.4.

The pavement rehabilitation process is goal seeking in nature. There exists a desire on the part of pavement managers to maintain the system at its best performance, Figure 5.5.

As the PSI gap increases, corrective action to close the gap is deemed necessary. However, over time, due to deterioration, the gap reappears. It is the type of action taken that effects how soon the gap reappears and when action must be taken again. In the case under study, repeated action tends to be the rule rather than the exception. The process is due to the choice of repair types that tend to be short-term in nature, which is associated with a more rapid deterioration rate. Maintenance of the system at the level desired is not always achievable due to the fact that financial support for the rehabilitation processes is not always

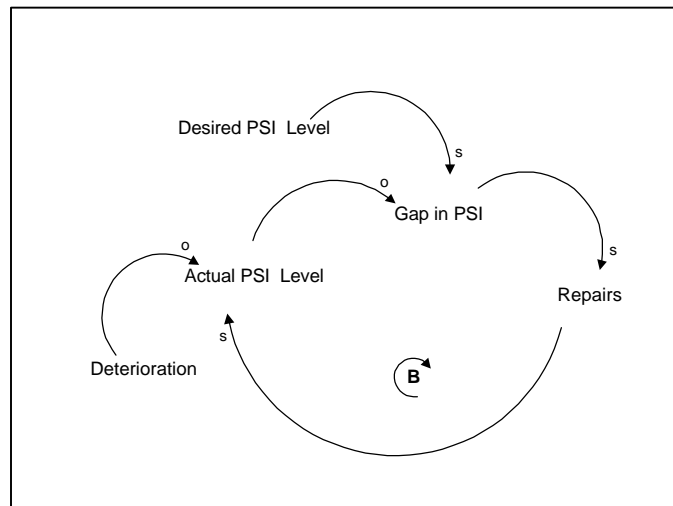


Fig. 5.5

Causal Loop Diagram of PSI Maintenance

available at a desired level. Morecroft (1983a, 1983b) has discussed in detail the rational process that we think we use in policy development and its testing. In this case, there appears to be a built in policy of increased repairs and spending with limited resources.

### 5.5 Feedback within the Sector

While the PSI is a measure of the quality of the road condition, the miles of road damaged also needed to be considered.. The work of Fwa and Sinha (1994) provided guidance for the development of the formulation that was used in the generic structure shown in Figure 5.4. The formulation allowed for loss of road to create a loss of quality.

“The use of a PSI-ESAL loss greatly facilitates the incorporation of traffic loading and environmental effects into performance analysis because the PSI-ESAL loss provides a means to measure pavement performance quantitatively on the same time frame basis as that used for evaluating loads and environmental effects” (Fwa and Sinha, 1994: 31).

The basis of deterioration, in this simulation, is the life expectancy of a road when maintained in excellent conditions under normal planned loads or truck use per day. Therefore, it is assumed that both the normal life span of Excellent road and paved road is 20 years or 240 months. Management and engineers with both academic and field application backgrounds have provided other deterioration rates, for non-Excellent roads, seen in Table 5.1.

Excellent road or Pave repair = 240 months Overlay Repair=84 months Patch repair=24 months
--

Table 5.1 Default Life Spans

## 5.51 PCI Value

“The critical PCI is defined as: the PCI value at which the rate of change of PCI loss increases with time, or the cost of applying localized preventive maintenance increases significantly” (Shahin 1994: 163).

The concept of the critical value (defined in Chapter 2, Fig 2.2) was formulated by capturing the change in the rate of the PSI curve. The maximum value of the change of the PSI curve was formulated based on the second derivative of the PSI curve,

$$d^2(\text{PSI})/dT^2 < 0 \text{ (T=time)}$$

To accomplish this a set of relations was developed as shown in Figure 5.6.

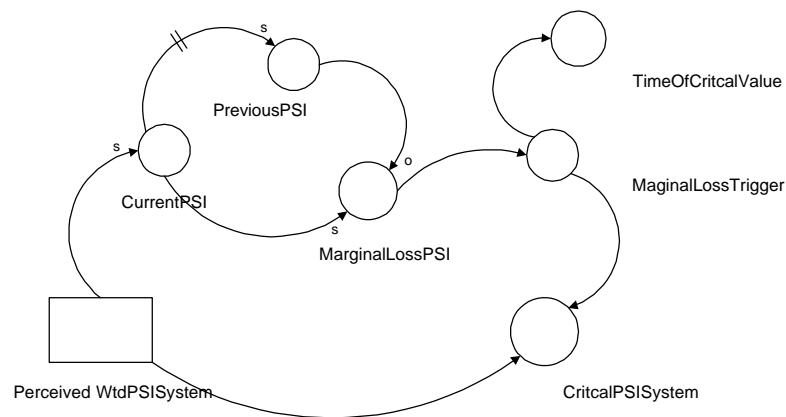


Fig. 5.6 Simplified Critical Value Structure

Formulation of Critical Value:

$$\text{MarginalLossPSI} = (\text{PreviousPSI} - \text{CurrentPSI}) * -1$$

MarginalLossTrigger = 1 when the Marginal Loss is negative

$$\text{CriticalPSISystem} = \text{SAMPLEIF}(\text{MaginalLossTrigger} = 0, \text{PerceivedWtdPSISystem})$$

(Note 1)

While not strictly a causal loop diagram the process that is formulated for Figure 5.6 is based on the marginal rate of change of the PSI. AS the deterioration rate of PSI increases, the previous value is less, and the rate of decrease is positive. When the rate reaches a maximum and starts to decline, the previous value is higher than the current value and the marginal change is negative. A negative value initiates a sampling of the PSI and time of occurrence.

Although slightly more complicated in the model, the core of what occurs is stated by the above formulations. The full structure can be found in the PSI System Critical Value Section of the Model.

In textbooks, the critical value relates to a single family of road and therefore there is one value for the family. As the model's PerceivedWtdPSI incorporates several families, several Critical Value points were found. This is explained by the dynamics of the rates of change of each family. As each family's rate of change affects the system, the rates of deterioration of the system changes. In order to capture a stable PSI a range of acceptance was created. A value above 4.99 was not considered as most Critical Values fall below this range. Therefore, a ceiling of 4.99 and a floor of 2.5 (used by managers) were chosen as an acceptable range.

When the marginal change reached a negative value, the previous value of PSI is sampled in the model, as well as its time of occurrence. This maximum value was the critical value point of the curve. (In this case as the shift was from a Weighted Value and not a single road's PSI a set value of 2.5 was used as the Critical Value. The final value of the CVP could be effected when testing operating assumptions.)

The critical value controls what type of rehabilitation will be provided. It determines what financial resources are allocated and aids in the determination of the type of rehabilitation applied. The control of this process is based on the recommendations found in Shahin (1994). Based on these recommendations for a PSI above the critical value, the method of repair is patch, while for a PSI below the critical value the method

of repair choice is overlay. The exact choice determined by the availability of funds.

To achieve the recommendation of Shahin (1994), the Effect of Managers Satisfaction on the budget adjusts the CV. As the budget declines the value of the critical value is lowered by the effect impact. This allows more Patch repair at a lower cost, to be carried out, then Overlay repairs. As the satisfaction increases, the value is brought back to its original level. Thus, the budget effects the spending and repairs accomplished as recommended by Shahin (1994: 166-167). The critical value is important, as it is this point which determines the allocation of resources.

“You need to be careful about the critical value selected. If you pick too high a number you can wind up doing a lot of preventive work that is not necessary. Too low and you are over spending”. (I7) “We use a critical value of 2.5 out of 5” (I6).

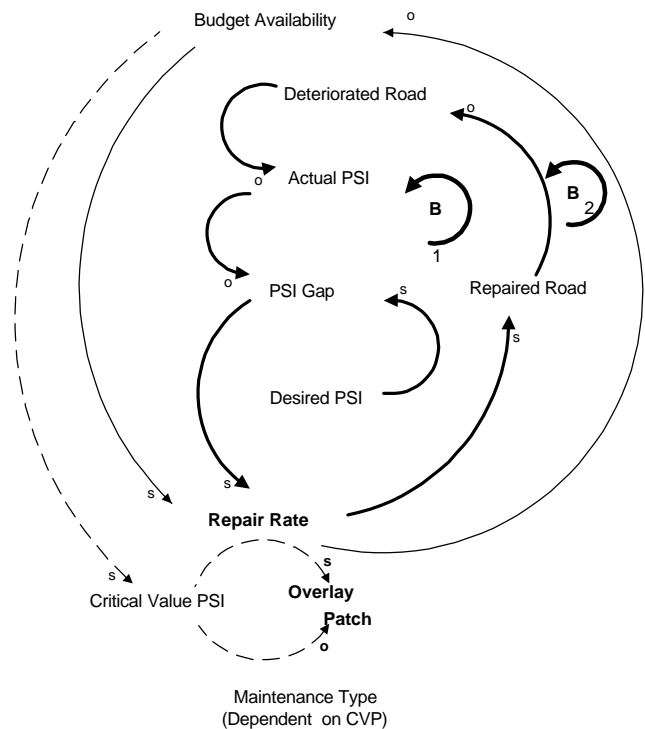
The formulation used in this simulation uses the critical value (CV) to determine at what time and which type of maintenance will be used to repair a road. The CLD for the CVP is shown in Figure 5.7. The CV determines the timing, rate of and type of repairs that will be made to a given road category.

### Critical Value (CV) Causal Loop

The balancing loop B1 is similar to the loop in Figure 5.5. The deterioration rate of repaired road is dependent on the type of repairs completed (e.g. Patch life span is 24 months while the life span of Overlay is 84 months). The repair and deterioration rates effect the PSI, whose deterioration determines the Critical Value. As in Figure 5.5, loop B1 is balancing as the gap created by deterioration of the road creates an action to repair road and restore the PSI. (In the model, the level of budget availability effects the Critical Value. Loop B2 represents the impact of budget availability (adequacy) on the CV. As the budget (adequacy) becomes lower, the critical value is lowered by a table function (effect), on the critical value. The effect of lowering the Critical Value is to cause the simulation to do more Patch repair at lower costs. Similarly, if the budget



available is adequate the CV is raised allowing more Overlay repair. In either case repair tends to increase the value of the PSI of the system and therefore close the probable gap.)



Maintenance Type  
(Dependent on CVP)  
Feedback Effect of Critical Value

Fig. 5.7

[Dotted lines indicate that the effect is not part of the CLD but that an impact on the CVP is due to budget availability, which itself is effected by repairs]

### 5.6 Road Classification and PSI

Field surveys supplemented by the judgment of engineers of the World Bank, suggest that it is possible to distribute a country's roads among three classes of conditions: Good, Fair and Poor (Abbas 1990a: 4). Each of these conditions has a dynamically different rate, pointed out by Harall (cited in Abbas 1990a). In this model the classification of roads was determined by information provided by graphic representations and data found in the research literature (Roberts and Kendall, 1991:

791, Shahin 1994: 2; Stephensen 1983: 16) and the Massachusetts Highway Department Report.

Based on these inputs five categories of road were used in the model, Figure 5.8. Each stock of road is classified according to the FHW system, as Excellent, Fair, Good, Poor and Unusable. Each of these classifications is based on the PSI value of a given set of roads. Roads that undergo deterioration and repair move into the next lowest category.

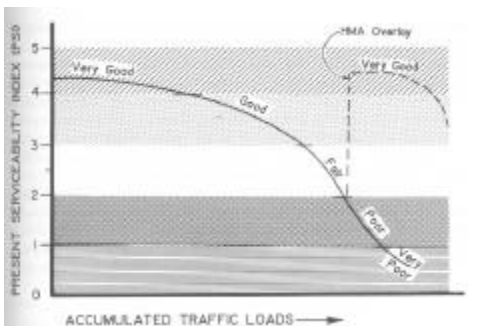


Fig. 5.8 Road classifications  
From Roberts and Kendall 1991: 479)

Management judgment about repairs was controlled by the development of a perceived value of road conditions. A perceived value is used as, “for purposes of predictive modeling, the initiation of distress is defined by the time when a defect is first visible because this is the only feasible choice compatible with the data on road condition that is practicably measurable by network monitoring (Paterson 1987: 117). The simulated curve of the PSI is shown in Figure 5.9.

The simulation assumes a starting point of all Excellent road and PSI of 5. Under most conditions, this is not realistic, but was chosen as a comparison to curves used in engineering texts. The shape and time duration of the curve was considered acceptable as the typical textbook curve deteriorates to zero over a 30-year period.

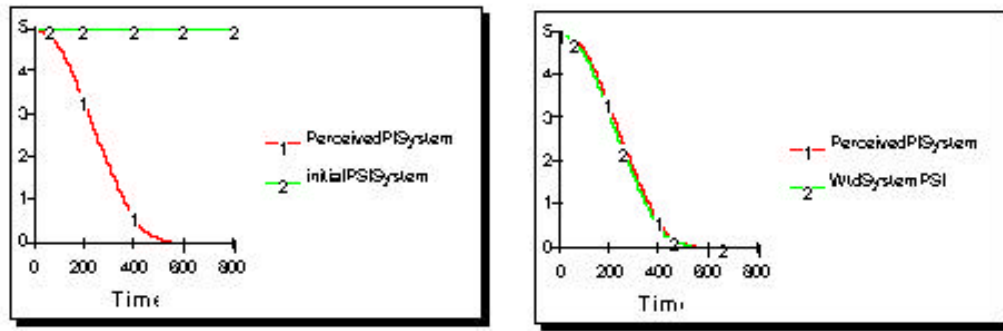


Fig. 5.9 a Perceived PSI Values                      b. Perceived and Weighted Values  
 PSI Curves

9  
**5.7 Development Sector**

The first cut of this section was based on the model found in Richardson and Pugh (1981: 165), Figure 5.9.

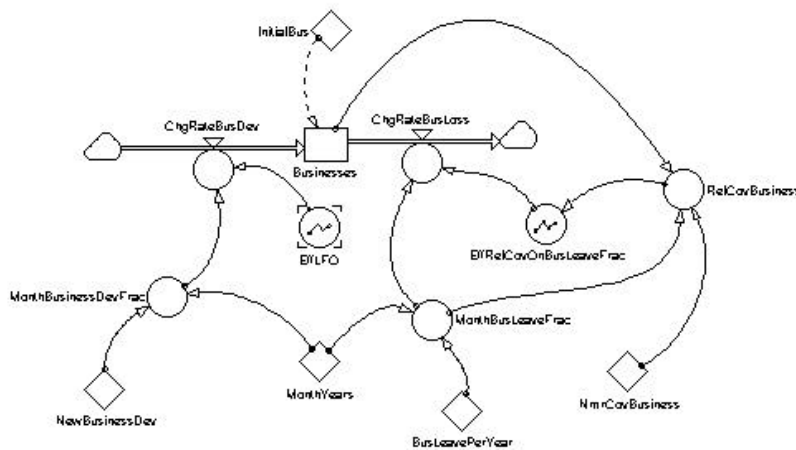


Fig. 5.10                      Generic Development Formulation  
 (Based on Pugh and Richardson )

However, information from interviews with planning agencies, commercial development real estate agents, civil engineers and road managers allowed a more detailed formulation based on the generic structure as outlined.

Town planning commissions supplied the amount of acreage in use for home, retail and light industry. The data also included current housing and businesses units, and acreage available for expansion and estimated growth of both business and housing. With this datum, a formulation for the number of trucks due to business development, cars due to home development, and the impact of land constraints on business and home development was developed. (Note 2)

The general formulation of the acreage in use and future constraints followed the same process:

The amount of square footage for business and industry was estimated from data supplied by commercial real-estate developers and agents.

The planning board of the town of Grafton, Massachusetts supplied the acreage per home. Home development and replacement rates were taken from planning data from the town of Manchester, Connecticut. (Both Grafton and Manchester are similar in their demographic composition).

The estimate of acreage in use for business and retail was determined based on the following relationships:

Each business requires x percent of the total acreage it is constructed on-  
therefore:  
$$\text{(Average Sq. Ft./Business/Percentage Required*)}/(\text{Sq. Ft./Acre}) = \text{Acreage use}$$
  
\*parameter data is listed in Table 5.1

The constraint on growth was developed as a ratio (Acreage adequacy = Total acres available for expansion/Acreage in use). As the ratio approaches the value of 1, the rate of business development slows to a zero value. In addition, the minimum acreage size per business was also used to slow development. If the acreage available became lower than the minimum lot allowable, no further development occurs.

Home development was formulated in the same manner using data on homes per acre. The development of a mall, which seems to have the greatest impact, was formulated by

using information supplied by several Malls as to average mall size (Note 3).

As industry, homes or retail business leave an area the appropriate acreage per unit is added back to the land inventory available for each variable. This allowed for the entry of new business, etc. to come into the area, Figure 5.11.

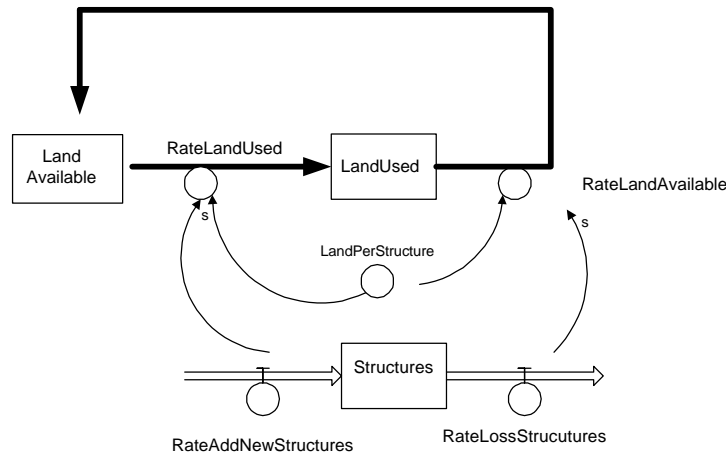


Fig. 5.11 Representative Formulation of Land Exchange Process

(An increase in the rate of structures added decreases the land available and increases the land in use, while an increase in loss of structures decreases the land in use and increases the land available.)

Development Variables and Values

Variable	Home	Industry	Retail	Non-Retail
Acres In Place	8134.29	796	127	*
Acres Available	3100	990	65	*
Initial Values	5694	102.51	352.04	400
Population Ratio	2.6/Home	NA	NA	*
Sq. Footage	NA	60000	15000	10000
Use Parameters	1.7/Acre	.2**	.2**	*

Table 5.1 Development Parameter Values

\*An assumption was made that small non-retail business would not impact the dynamics to any extent and that in most cases these are stable to the change in homes, and more or less constant.

\*\* Percent Capacity of Acre Used

NA-not applicable

The average number of trucks and cars for retail and light industry, as well as malls, was based on the data supplied in Table 5.2. The number is calculated based on a coefficient, by vehicle type, per 100 meters square of business space.

Development type (1)	Inbound Vehicles per 100 m <sup>2</sup> (Floor Area) per Day				
	Cars (2)	Courier vans (3)	Light rigid trucks (4)	Heavy rigid trucks (5)	Articulated trucks (6)
Offices	5	1.00	0.20	0.00	0.10
Retailing					
Regional Centre	20	0.20	0.50	0.30	0.05
Major Supermarket	50	0.10	0.20	0.20	0.10
Local Supermarket	40	0.05	0.50	0.25	0.10
Department Store	25	0.10	0.25	0.50	0.05
Other	20	0.40	0.50	0.20	0.00
Manufacturing	5	0.05	0.05	0.05	0.10
Warehouse	2	0.05	0.01	0.10	0.10
Light Industry and High Technology	5	1.00	0.30	0.25	0.05
Truck Depots	2	0.50	0.50	0.75	2.00

Table 5.2 Car and Truck Use Coefficients

From Ogden (1991)

The standard for Malls was taken from Aschman Associates and differs slightly from the above Table. Table 5.2 uses 100m<sup>2</sup>, while Mall impact uses 1000 Sq. ft. The coefficient that Aschman provides is 1.16 /1000sq.ft/day. (Barton-Aschman Associates 1995)

## 5.8 Human Resources

Roadwork cannot be accomplished without labor. Smaller towns have ratios of labor to population used to address hiring needs. The ratio is based on an assumption of the amount of roadwork needed generated by increasing population, a simple rule of thumb or linear relationship.

A formulation was developed using a simple set of assumptions based on the information provided by managers and corrected using an ordering function formulation adjusted for growth expectations, as suggested by Sterman (1987).

Two levels of labor are created by the formulation, the first based on the simple rules used by managers; the second based on the corrections made due to expectations. The allocation of labor resources is determined by utility functions driven by complaints and road conditions.

A comparison between, the amount of productivity, the PSI value and cost under three states of available labor can be performed. It may be that the amount of labor required to produce a needed level of repairs is not available simply because of hiring practices and allocation decisions. In addition, as hired workers also must manage complaints, the number of teams available for repair work is reduced. Therefore, a formulation that permitted hiring of subcontractors to manage complaints was added to the model.

## **5.9 Complaints**

Complaints about road use are usually based on roughness. End users do not know about PSI and its measurement. Roughness is an important indicator of pavement riding comfort and safety and is the one pavement property that is most noticeable to the traveling public. From a driver's point of view, rough roads mean discomfort, decreased speed, potential vehicle damage, and increased operating costs. Roughness gives an indication of the users' perception of the conditions of the road and serviceability" (Garcia, Snaith, and Tachtsi 1999: 96). Skid resistance may also be used as an indicator of safety (Garcia, Snaith and Tachtsi 1999). Roughness is measured by the IRI (International Roughness Rating). This rating is associated with the complaints of users. Garcia (1999) found that, "as a pavement ages with distress, the IRI increases and the PSR decreases. It has been suggested that rehabilitation is needed when 50% of highway users decide that a pavement ride is unacceptable for a given functional class of road highway and pavement type.

A road systems manager put it this way

“It’s not only money and road conditions that drive our decisions. The politics get into too. We have complaints from citizens about the roads. If we don’t respond, we get calls from the politicians or someone higher up. No one wants to be responsible for someone dying”.

Complaints are usually related to road roughness and are generally used as a surrogate measure of rideability or serviceability (I3).

The development of roughness was formulated using a transformation from PSI to IRI (International Roughness Index). This was based on the work of Al-Omari and Darter (TRR1505) who developed a relationship between the IRI (International Roughness Index) and the PSR curve (also measured on a scale of 1-5 with the IRI).

Studies have shown that 95% of the information about the serviceability of a pavement is contributed by the roughness of the surface profiles. Generally a new pavement has a PSI (Pavement Serviceability Index) of 4 and 5, and is usually repaired when the PSI is between 1.5 and 2.5. When the road is repaired serviceability is restored to a higher level and the cycle begins again (Roberts et. al. 1991) (Note 4).

A simplified complaint generation process is depicted in Figure 5.12.

Roughness was used as the means by which end users judge a road. The end user usually has no knowledge of PSI and therefore uses rider comfort as the basis for complaint. Once the change in roughness was developed a table function based on the work of Paterson (1987), which measured the percent of dissatisfaction based on PSI, was introduced into the formulation. Vehicle use per month was multiplied by the table function to give the number of dissatisfied users



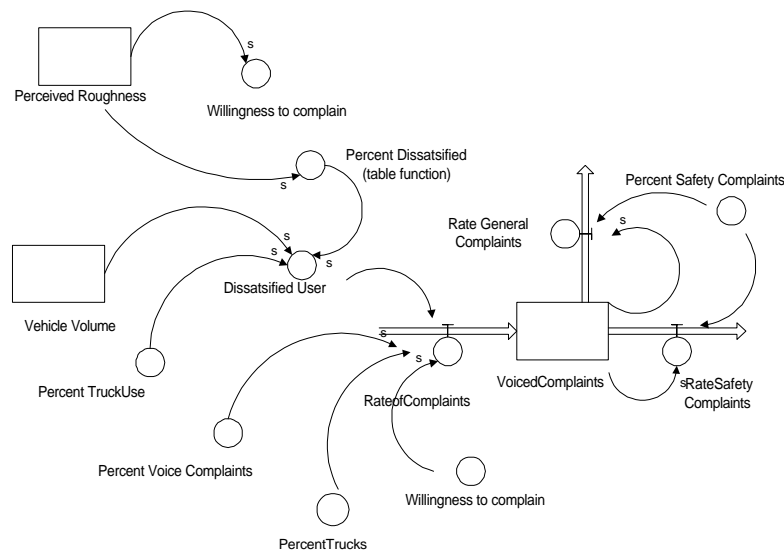


Fig. 5.12 Generation of Complaints –Model Structure

(While not a causal loop diagram, Figure 5.2 represents the relationships of variables effecting complaints. As the roughness increases, so does the willingness to complain. With an increase in use (especially trucks, whose drivers tend to complain due to economic impacts of Poor road, more complaints are registered).

Formulation for Figure 5.12

Percent Dissatisfied Users =table function capturing the relationship between PSI and complaints.(cited in Paterson 1987).

Dissatisfied Users(*Vehicles/Month*) =ChgRateUsers(*Vehicles/Month*) x Percent of Dissatisfied(*Dimensionless*) x PercentTruckUse (*Dimensionless*)

RateofComplaints(*Vehciles/Month*)= Dissatisfied Users(*Vehicles/Month*) x Percent Voice Complaints (*Dimensionless*)

RateOfSafetyComplaints(*Complaints/Month*)=VoicedComplaints(*Complaints/Month*) x PercentSafetyComplaints(*Dimensionless*)

RateofGeneralComplaints(*Complaints/Month*)=VoicedComplaints(*Complaints/Month*) x (1- PercentSafetyComplaints)

Based on service systems data (Zeithaml, Parasuraman and Berry 1990), this was multiplied by the rate of complaints levied by dissatisfied end users. It is estimated that only 4% of unhappy customers actually file complaints. In addition, managers have indicated that it is the complaints by truckers that guide repairs. This is due to the impacts the road conditions have on the economics of trucking. This population accounts

for approximately 11% of road use. Road managers have indicated that they usually respond when ten general complaints about an issue come in and four political complaints about an issue come in. Therefore, a value of 10 was used as a normal for an index of response for general complaints, while a value of 4 was used as a normal for an index of political complaints.

Total complaints were adjusted by a norm. The original complaint ratios were based on a low volume of traffic. The volume of traffic in the simulation was approximately 3 times that of the base volume used. Therefore, the base volume was divided into the simulated volume in order to create a multiplier to indicate the expected rates for the larger volume. The results can be seen in the section on the dynamics of the model.

Complaints were then classified as either related to safety, general, or political in nature. Rejected general complaints were used to determine the amount of calls a politician might receive. The rate of calls was again based on service systems literature ( Zeithaml et. al. 1990). The complaints from politicians and complaints from the general public were used along with an estimate of the average cost of each complaint to determine that portion of expenses that reduced the budget for necessary work. As the number of secondary responses increased, it was assumed that the call rate to politicians would decline.

## **5.10 Accidents**

During interviews with pavement managers working at both state and town levels, in the state of Connecticut, it was determined that managers see the pavement system as two subsystems; high and low volumes of use, creating two distinct categories of rehabilitation being required. During two interviews, the following were revealed:

“We do the most used roads to keep user costs and complaints down. I’ll do I91 before I do a secondary road. We try to do these roads before they go bad.”(I3).

High volume roads are kept up because of the risk of accidents. With a high volume, you have a greater chance of a problem. Its risk that leads to repairs”.

“We usually do repairs bases on usage, not condition”(I1).

Stephens (1983) warns -

“If only the physical factors of the pavement are included, many highest priority pavements would be little used remotely located sections. A single form of rating applied to all pavements with priorities then based on the poorest condition could results in rebuilding projects only. This would be the poorest form of pavement management as salvageable pavements would be permitted to deteriorate and the average condition of the pavements in future years would be sharply lower than if some resources were constantly used for preventive maintenance of presentable pavements.” (1983: 12)

Forrester (1975c) has discussed the concept of counterintuitive behavior in his writings. In this case, there appears to be such behavior occurring. A review of accident data from one area indicated that the majority of accidents occur under good conditions (Note 5). The information that was reviewed was supported by Tanner (cited in Jorgensen 1966). Tanner’s studies showed that in 122 road sections in Great Britain, resurfaced for purposes of routine maintenance:

- 1) Sites showing the greatest improvement in riding quality tended to experience considerable increases in accidents and
- 2) Improvements costing more than \$20,000 per mile showed significant (as much as 50%) increases in accidents.

This was attributed to the fact that a greater cost per mile yielded the best improvements in the surface with regard to those elements that facilitate higher speeds. The issue of increased accident rates was raised with the Connecticut State Police, Bureau of Public Safety. Immediately the response was, “of course we know that.” This was the same response from the state DOT managers. Apparently, pavement managers of smaller towns have a different mental model. In order to verify this, a request for data, from roadways before and after repairs was made.

This information was verified in an interview with the Connecticut State Police, in the Department of Public Safety.

“Drivers see a Good road and speed up, more speed, more accidents. We see it all the time. When there are potholes, people slow down, no one wants to damage their car.”(CTSP)

Contradictions to this come from the work of McFarland (1972) who reported an increase in accidents with lower condition levels. However, McFarland also reported on research that supported the findings from Grafton, Massachusetts. Jorgenson (1966) studied the states of Connecticut, Idaho and Oklahoma. In those studies, there was “considerable variability in the data studied, with many of the studies showing increases in accidents as a result of resurfacing operations. It is emphasized that reductions seen were on roads having a high proportion of accidents involving skidding, and that resurfacing projects on geometrically low standard roads which were not experiencing a skidding type accident problem tend to show an increase in accidents. The resurfacing probably creates a deceptive appearance causing some drivers to overdrive the highway” (McFarland 1972: 33). However, McFarland rejected these findings in favor of his own.

The formulation of the accident section captures the relationships in CLD of Figure 5.13. Accidents are related to the skid number (SN). The skid number is affected by the: 1) time of year (Shahin (1994: 91), 2) polished surface effect of the road created by the amount of vehicle traffics (Shahin 1994: 93), and 3) speed which is related to the PSI (McFarland 1972). Table functions were used to capture the relevant effects on the normal rate of accidents. Normalized accident rates were obtained from McFarland (1972).

### Causal Loop Diagram

Speed increases as the PSI increases. An increase in speed causes a decrease the Skid Number (SN), and therefore increases the accident rate. This tends to increase the managers spending on repairs, which improves the PSI, thus creating the reinforcing loop. The effect of an increasing volume is to decrease the SN due to a polishing of the road surface. However, with an increase in volume speed tend to be reduced, which

increases travel time. This increases travel time and a desire to switch to another road (with some delay). This decreases the volume of traffic, which increases speed. Balancing loops B1 and B2 are similar, but represent Primary (B1) and Secondary (B2) roads. (The impact of increased travel time is discussed below, but the tendency is to reduce road volume, thereby increasing speed and polishing).

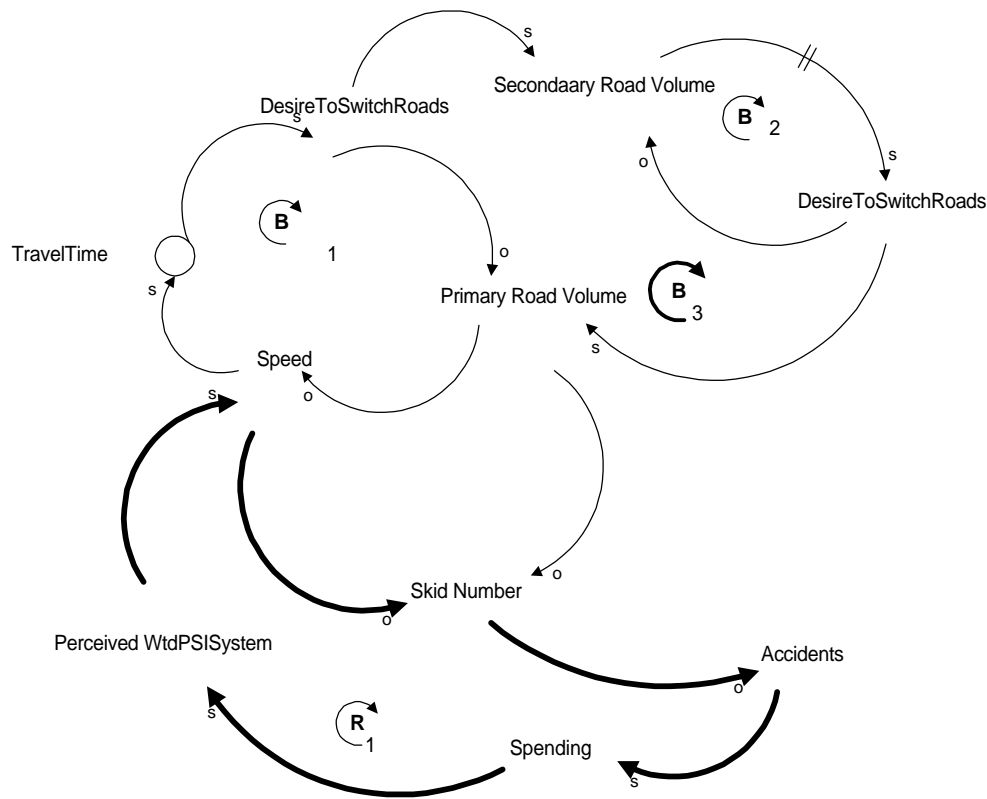


Fig. 5.13 Causal Loop Diagram Effects of Variables on Accident Rates

To make the impact of speed clear, the rate of accidents was formulated to include and exclude the effect of speed. A ratio between the two outputs was developed to show the effect that speed had on accidents as a multiplier of non-speed related accidents. Current policy creates a reinforcing loop (R1). The result-speed increases and more accidents are generated.

## 5.11 Shift of Road Use

In addition to the rate of accidents, a method for the shifting of road usage dependent on traffic volume and waiting time due to construction delays was also formulated. People tend to change roads if the time of travel takes too long. Rock (1995) has used the term speed spillover (sometime referred to as speed adaptation or generalization) to describe a cause of highway traffic diversion. “An increase in highway speed could divert traffic from a rural 55 mph road to a 65 mph interstate”. The formulation took into account an expected shift that would occur from high volume roads to lower volume roads due to dissatisfaction by the end user. The formulation therefore allowed a shift from high volume road to an alternative road and back again, based on increased times of travel due to repairs or traffic (Figure 5.13 Balancing Loops B1 and B2).

The formulation for the impact of time was based on the work of Berger, Greenstein and Hoffman (1991) who reported on the time a user is willing to wait as part of a fifty minute trip, dependent on the perceived condition of alternative routes available. McFarland (1972) reported that drivers have a discomfort level and that they will maneuver to decrease that level. However, many of the maneuvers that cause speed changes not only cause discomfort but also increase travel times. Motorists will adjust their speed to avoid events that cause discomfort. On paved surfaces, motorists change their speed in relation to overall pavement smoothness and also make intermittent speed changes in relation to short stretches of road that are especially bad, or perhaps appear especially bad. McFarland (1972: 40).

In order to capture the renege off the road of the road user, the increase in travel time, using the formula provided by de la Garza (1998), Table 5.3, was compared to the time that triggered a shift of road use as described by Berger, Greenstein and Hoffman (1991). When the increase in travel time exceeds the threshold of waiting, when compared to the perceived travel time of an alternative road, vehicles shifted from one type of road (high or alternative road) to another type of road. The process, Figure 5.14a and 5.14b,

captures the renege rate of the queue, where the rate of service exceeds the waiting-time on line (travel on the lane)].

**Method of de la Garza**

<p>(Avg 24 hr. Traffic/Mile/24)=Avg. Hourly Traffic/Mile  <math>T_o\{1+0.15(V/C^4)\}=T_n</math>                  Where  <math>T_o</math>=Initial Time (min)={60/MPH}  <math>V/C</math>=Volume/Capacity=(Avg.Hourly Traffic/Mile)/(No. of Lanes x 2200)                  Calculated New Time=<math>T_n</math> x Miles</p>
--

Table 5.3

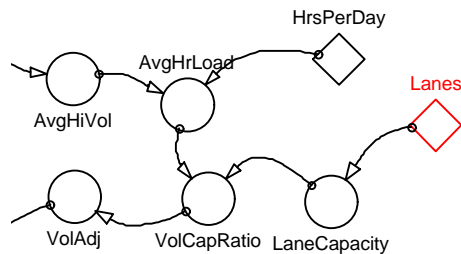


Figure 5.14a Method of deLaGarz-structure in model

$AvgHrLoad (Vehicles/Hr) = AvgHiVol (Vehicles) / HrsPerDay (24)$   
 $LaneCapacity (Vehicles) = Lanes (Dimensionless) * 2200 (Vehicles)$   
 $VolCapRatio (Dimensionless) = AvgHrLoad (Vehicles) / LaneCapacity (Vehicles)$   
 $VolAdj = VolCapRatio^4$  (raised to the 4<sup>th</sup> power)

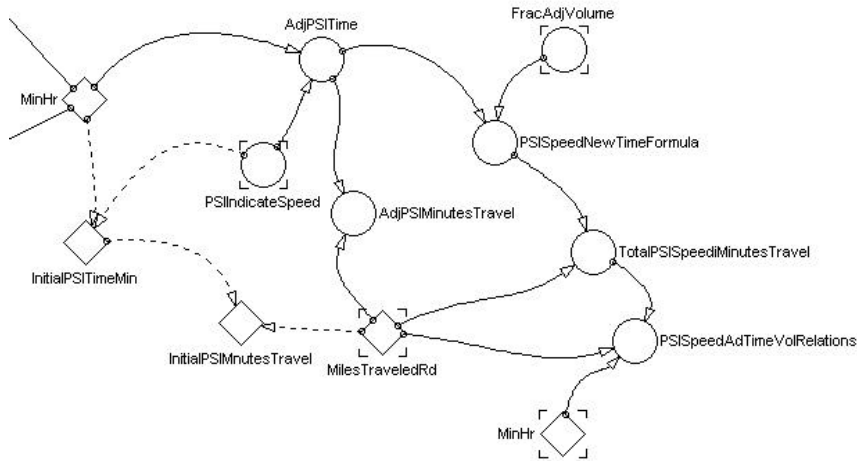


Figure 5.14b Adjustment of Time of Travel-(based on de la Garza)- structure in Model

## Formulation of Speed and Travel Time Adjustments

$\text{FreqAdjVolume}(\text{Dimensionless}) = 1 + \text{VolAdj}$

$\text{MinPerHr}(\text{Minutes/Hr}) = (60)$

$\text{AdjTime}(\text{Minutes/Miles}) = 1 / (\text{PSIIndicateSpeed} / \text{MinHr})$

$\text{PSIIndicatedSpeed} = (\text{Miles/Hr})$

$\text{AdjPSiMinutesTravel}(\text{Minutes}) = \text{MilesTravel}(\text{Miles}) * \text{AdjTime}(\text{Minutes/Mile})$

$\text{PSISpeedNewTimeFormula}(\text{Minutes/Mile}) = \text{AdjPSITime}(\text{Minutes}) * \text{FracAdjVolume}(\text{Dimensionless}) / \text{MilesTravelRd}(\text{Miles})$

$\text{TotalPSISpeedMinutesVolRel}(\text{Miles/Hr}) = \text{MilesTraveledRd} /$

$\text{TotalPSISpeediMinutesTravel} / \text{MinHr}$

In addition, the cost of vehicle operations (Claffy 1971, Karen and Hass University of Waterloo) due to pavement condition, the cost of waiting (Zaghoul TRR 1539) and cost of accidents were also generated by the model and included in the life cycle cost of the system.

(Note 7).

### 5.12 Budget Development

The budget sector was formulated to accommodate information revealed during interviews into the model. These information included:

1. The budget received is often only 20% of that requested.
2. Because of the short-fall managers need to select how much work they can accomplish during one year.
3. At the end of the year, managers spend down all they have left, as anything left is taken back by their governing agencies.
4. Managers tend to allocate based on mental calculations. These calculations are based on available funds and costs per mile of repair, by type of repair.
5. Managers may weigh inputs for selection of a critical value start point. For example, managers tend to put most of the weight on road conditions rather than complaints. As there is no connection between the PSI and actual usability, they may be over-repairing.

#### 5.121 Budget Formulation



This section was formulated to capture the level of a road, by category, requiring repairs at the end of a year. Two budget processes allowing four modes of budget allocation were created

### 5.1211 Fixed Budget

An estimated budget was developed based on the cost of each class of road and using the concept of expected probabilities. After the total estimated dollar amount for all roads was generated, this amount was multiplied by an assumed probability set. (As the model could start in several road configurations and therefore conditions, several runs were made to determine an average set of values used in the calculations).

First, total system miles were evaluated for the probability of a repair. Secondly, the miles that were chosen were adjusted by the probability associated with the repairs. Each year's budget was based on the percentage of miles that might be repaired by paving, overlay or patch work, Figure 5.15

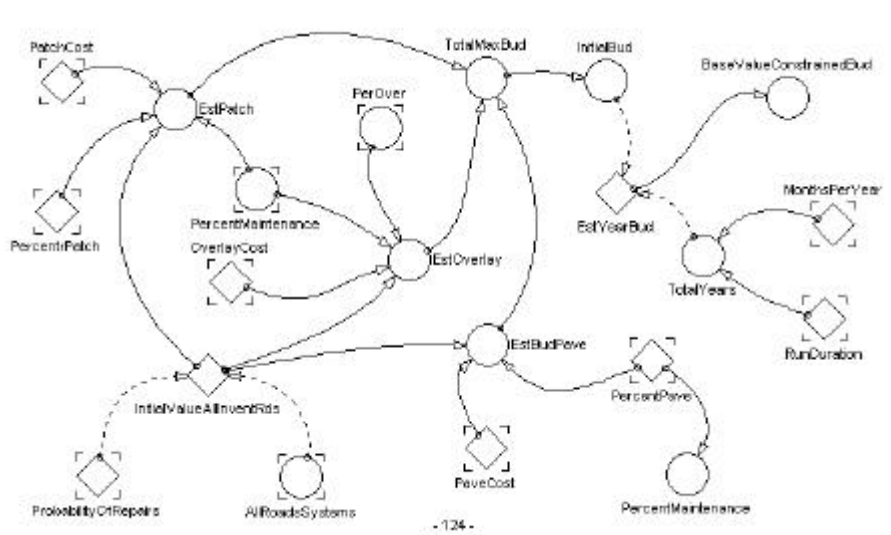


Fig. 5.15 Estimated Initial Budget –structure in model

It was determined that an initial estimation of 25% (ProbabilityOfRepairs), of all miles being repaired was an appropriate starting point. Further, in one state paving of roads is determined by the legislative body, which requires 10% of roads in need of repair to be paved. As such, with a 50% chance of need of repair, a 5% initial pave (PercentPave) rate was chosen.

Initially there is a 50% probability of a road being maintained. Therefore, the remaining percentage, 95%, was adjusted by a 50% probability of occurrence by category (e.g. patch or overlay).

The amount of road requested for repair was multiplied by cost:-

Miles x .05 x Cost of Paving

Miles x .5 x .95 x Cost of Patch

Miles x .5x .95 x Cost of Overlay

The total expenditures were then divided by the total periods of the run, to give a fixed budget. This fixed budget could then be allocated with or without a reduction each year. This budget was then reduced for successive years to mimic the constraints that managers indicated they operated under. Each year the fixed initial budget was reduced by an increasing rate of loss to a maximum percent of budget of 47%, which eventually became the budget allocation..

#### 5.1212 Variable Budget

A second method allowed for a sampling of road in need of repair. This was then used to generate a budget for the year as needed rather than a fixed allocation as in the method described above. This budget could then be reduced each successive year or allowed to stand as requested.

In addition, the budget in use could be adjusted via a multiplier that allows the awarding of a range of estimates, up or down from the original value. This was developed to allow a “full rich” budget for the year. This process was formulated in this manner because

managers indicated that after applying for a budget they never really knew what they would receive back from the state.

“Budgets are allocated based on predictions of road conditions. But, how much is really allocated is based on political negotiations. Once we have a budget, we put all the current data into the software. It creates a list of projects, which are prioritized in terms of Life Cycle Costs and Benefits. Then it goes to a committee who decides” (I2).

A single budget level became the source for all expenditures, including costs of complaints. In addition, the outflow was formulated to clear the level at the end of the year. This motivates managers to spend the total budget available by the end of a fiscal year. The process reduced the allocated budget by any dollars remaining in the level.

#### 5.1213 Allocation via Utility Functions

The use of a utility function to capture the decision-making processes of a manager is incorporated in the formulation to account for the allocation of resources, the rates and types of road repairs, based on weighting of importance

#### 5.12131 Budget Allocations

The problem of resource allocation has been discussed by system dynamists and written about by those in public administration and is the fundamental problem in economics. While system modelers define the problem as trying to develop a best method of allocation, those in public administration define it as a one best method. Indeed the object of finding a best method has been brought into question by Lynch (1989), who states, “ that the theory of public budgeting should not focus entirely on the narrow question of best allocating resources. Using such a question tends to encourage us to assume there is a one best way for a decision on resource allocation” (Lynch: 322). By the right decision, “we mean choosing the truly preferred alternative, or obtaining the true rank order of alternatives, true defined relative to the decision maker’s preference function. The preferability of the selected alternative is dependent on the individual

preference system of a decision-maker, and this system, as a rule, is implicit and has no exact description. If it is implicit and individual, with no exact description, it falls into the category of subjective” (Larichev et. al 1995: 9-10).

The behavioral psychologist Herrnstein (cited in Stodder 1997), suggest that economists even decide based on what values gives them the best subjective value. Hardly a scientific management approach. One might ask about the validity of using subjective measures. Nagel (1991) recommends the use of these subjective measures in decision models used in public administration.

Methods for evaluating such subjective values fall into two categories (Shrivastava, Connelly and Beach 1995). The first is policy capturing that assumes a subjects can provide overall evaluations based on attributes, but that they do not have reliable access to the process for linking their evaluations to their differential weightings of the attributes. The second value, elicitation, assumes that subjects know their weights and can state them, but may be unable to link these weights reliably to overall evaluations. In studies, subjective weights were compared with weights derived by structural modeling techniques, with the statistical weight assumed to be the correct one” (Harte and Koele 1995: 50). These studies concluded that in terms of how adequately different sets of weights can predict a subject’s judgment, all subjective and verbal weights appear to perform well (50).

Daniel Bernoulli reasoned that the value or utility of money declines with the amount of money won or on hand. (cited in Plous 1993). This was followed by the work of Von Neumann who developed the expected utility theory approach. He proposed this theory as a normative theory of behavior, describing how people actually behaved as compared to how people ought to behave. (cited in Plous 1993 : 80). Etzioni writes’ “the central thesis here is that the majority of choices people make, including economic ones, are completely or largely based on normative-effective considerations, not merely with regard to selection of goals, but also of means.” (Etzioni cited in Zey 1992: 90).

The problem we are faced with seems to stem from the concept of optimization. Methods available vary from simple proportion (simple percentages (based on the squeaky wheel concept), to more sophisticated algorithms, such as the ALLOCP found in Vensim, based on the works of Woods ([www.vensim.com/allocp.html](http://www.vensim.com/allocp.html))

In this model, the decision to allocate resources was based on the concept of multi-attribute utility theory. Managers indicated during all interviews that they used road conditions to allocate resources, at the same time safety was a key issue. Managers allocate more money to avoid the possibility of an accident. Further, they do respond to complaints of truck drivers and do pay attention to the amount of budget resources they have available.

The use of multi-attribute decision making is not new. It can be found in many forms. Linear or goal programming is one model used to satisfy reaching a goal associated with a constraint. The use of multi-attribute utility applies to situations where conflicting multiple objective exist. Each objective may be associated with an attribute (measure) that provides utility (satisfaction) to the decision-maker. Another issue is how do attributes compare in terms of importance (Clemens and Reilly 2001: :605), or the weight of the attribute in question relative to another attribute

Backus (1999) recommends the use of a form developed by McFadden (1974), the application of a Random Utility Maximization (RUM ) and Ford (1999) has developed a formulation for its execution. The form recommended by Backus and executed by Ford can be combined with one found in Clemens (2001) labeled an Additive Utility Function. The additive utility function is simply a weighted average of single utility functions.” (Clemens and Reilly 2001: 605)

Utility functions are typically associated with risk aversion and the utility of the value of money (Clemens and Reilly 2001: 530). The mathematics of a utility curve may take on several forms among which are:

$$U(x) = \log(x)$$

$$U = 1 - e^{-x/R}$$

Further allocation of resources can be considered in terms of performance. Resources going to functions that perform well. Measures of performance have been suggested by Banks (TRR 1634) and among these are, travel time, average speeds, accident rates, and customer satisfaction determined by opinion surveys. With this in mind a survey was developed and sent to pavement managers to determine the weights they apply to specific measures of performance and how these might effect the allocation of budgeted resources. The survey included such areas as complaints, accidents, road conditions and resource availability. Respondents were asked to indicate, by charting how the importance of each attribute variable effected the weight of the importance of each attribute as it changed value. By doing so, a more dynamic set of weights was created that could be applied to the development of a set of utility functions to be used in the formulation of the budget allocation process (Note 6).

#### 5.12132 The Additive Utility Function:

The question at hand is how do attributes compare in terms of importance? In the case of road management systems, is life span more or less important than cost of repairs?

The additive utility function assumes that a utility can be assigned a value of 0 for worst and 1 for best levels that can be assigned a specific objective. The additive function is simply a weighted-average of different utilities under study.

For an outcome that has levels  $x_1 \dots x_m$  on  $m$  objectives, the function is calculated as follows:

$$U(x_1 \dots x_m) = k_1 U_1(x_1) + \dots + k_m U_m(x_m) =$$

$$\sum_{i=1}^m k_i U_i(x_i)$$

The total of the weights  $\sum_{n=1}^m k_n$

As applied to the road repair process the formulations would appear as:

Utility or  $U_i(x) = (x - \text{worst value}) / (\text{best value} - \text{worst value})$

Where:

p =price and ls =life span.

Patch repair=P

Overlay repair=Ol and

Paving repair=Pa

Therefore the form of the formulation would be:

Patch =  $Pk(U_p) + Pk(U_{ls})$

Overlay =  $Olk(U_p) + Olk(U_{ls})$

Paving =  $Pak(U_p) + Pak(U_{ls})$

As an example-

Overlay Work

$U_p = (\text{cost of overlay} - \text{cost of paving}) / (\text{cost of patch} - \text{cost of paving})$

$U_{(ls)} = (\text{life span overlay} - \text{life span patch}) / (\text{life span paving} - \text{life span patch})$

In this case, the value of k (weights) based on costs were provided by managers and assumed to be usable [see Harte and Koele (1995: 50)].

In addition the utility function suggested by Backus (System Dynamics Web site), developed by McFadden (1974) and formulated and provided by Ford (1999), the multinomial equation, takes the form of:

$$\text{Allocation Share} = \frac{e^{U_p}}{\sum_{i=1}^n e^{U_p}}$$

The utility functions were combined to create a distribution based on the percentages of each utility. These percentages were used to determine the percentage of types of repairs made to miles selected for repairs.

### 5.13 Miles of Road Repaired

A utility function was formulated based on the damage to each category of road. This was chosen over a utility function based on the PSI, as the change in the system as a whole, was related to a weighted-average of the PSI for each category of road. The utility function based on each road category gave a more discrete level of control over the amount of miles chosen for repair of each category of road. For example, if the PSI was used the amount of Excellent road chosen for repair would be greater than the amount necessary, as Excellent road need not be repaired as fast as poor or Fair road.

The only exception to this was Poor road. Poor road is usually always under repair. Thus, in the model the user has the choice of setting the amount of Poor road chosen for repairs by using the PSI or the effect of the residual value (RSL) on the amount of poor selected for repair.

The rates were chosen based on the following logic. As a road losses 50% of its value there is a desire to improve the PSI value. The road category that has the lowest PSI and would change the value in an upward direction is Poor road, followed by Fair, then Good. The model simulates the delayed selection of each road with change in road condition. Road selection going from 0 to 100% repairs for each category.

The formulation for repairs and allocation consisted of

1. The selection of the amount of road to be repaired each year based on a sampling of road in need of repair. This was accomplished using a formulation that combined a SampleIf function with a Timecycle Function.

BudgetStartTrackTimer =SampleIf (TotalMilesAvailableRepair=0,Time)  
Rate=  
(Timecycle(BudgeStartTrackTimer,12,TimeStep),TotalMilesAvailableRepair\*(1/TimeStep),0)

2. The development of the budget dependent on the amount of mile selected for repairs.
3. The development of utility values based on the budget.



4. The allocation of total budget based on the additive utility functions.

(If the utility of patch was high during low budget availability, the percentage of allocation to patch was also high).

#### **5.14 Future Costs**

A determination of future costs was formulated by an estimation of repairs to be done. All road that was available for maintenance was compared to all road that was repaired. The balance of un-repaired road was allocated based on the percentages of road repaired in the system to date. Paved road was treated in the same manner, except the percentage left was 100% to be paved. The amount of each road was multiplied by its cost adjusted for the future cost effect of interest using a net present value approach.

#### **5.15 Policy Space**

The model was formulated to incorporate decision assumptions made by road pavement managers. These decisions became part of the operating characteristics of the system. Alternative assumptions were incorporated into the model to test their effects.

#### **5.151 Repair Process and Quality of Repairs**

##### **5.1511 Winter Repairs**

Managers have complained that the costs of repairs are due to excess rework.

“I see a lot the work that’s supposed to be 7-12 years being redone, two to three times. Now we are comparing apples (3 short-terms) to one long term. There are several reasons, which are: increased traffic, undersurface aging, a lack in the quality of the asphalt we get, a lack of skilled workers and work done in winter” (CTDOT).

The literature warns about the issues of winter repairs. Roberts (1991: 336) has documented the impact of temperature on the compaction of asphalt. At low temperature the time available for compaction is reduced. If compaction is not complete, more voids are created that allows for a weaker asphalt and more rapid deterioration of the roadway. While the productivity may be effected by the weather, the deterioration rate of such repairs also increases.

Statements such as the one above prompted the creation of policy space in the model for testing alternative work methods or decisions made by managers.

The formulation used to capture this process is shown in Figure 5.16. In this structure, a seasonal switch (WinterControlOn) turns on and off the repair rate for winter.

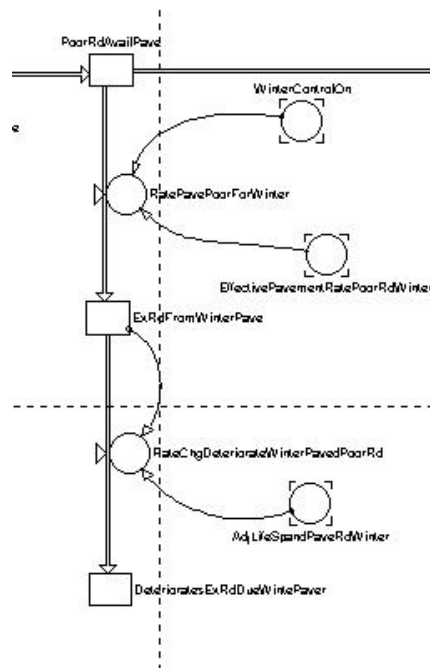


Fig. 5.16

Winter Repair Policy Space-model structure

In this structure, a seasonal switch turns on and off the repair rate for winter. The same switch turns on and off the normal repair process. This allows for the collection of road repairs made during the winter in a separate level than those made during other seasons of the year. The deterioration of road repaired in winter is at a rate three times that of normal deterioration. Both the normal rate and increased rates of deterioration are now accounted for in the deterioration of Excellent road, that is developed due to paving. The structure allows for testing of repair policy as effected by season.

### **5.1512 Quality of Repairs**

Managers tend to be liberal with the assignment of quality to repairs they accomplish. Usually assigning a higher value than is appropriate..

“Roads have to be put into a program. The roads that are prioritized get done first. However, if we run out of money they are out on a waiting list for next year. However, if another project gets pushed in the first can be made to wait an additional year. If a road is delayed, 1,2, 3 years, road repair doesn’t change. The costs go up, but that’s with inflation”(I6).

“Managers tend to assume that repairs are done to an excellent state, often we see they are not, but we can’t effect their decisions” (CTDOT).

The assumption that managers tend to use is based on recommendations found in the literature. It seems that managers are giving too liberal an interpretation to what is written. Further, in the real system, when repairs are accomplished for a section of roadway,

“the section PCI is increased per the specified value in the input. A preferred method for accounting for the effect of global preventive maintenance on pavement performance is to let the user specify the ultimate increase in pavement life and calculate the effective increase in PCI”, Figure (5.17), (Shahin 1994: 68).

In response to the statement regarding delays in work, a formulation, to delay the shift of a road from one class to another, by three years, was incorporated into the budget model. The miles selected for the shift was cost out at the next highest cost of rehabilitation.

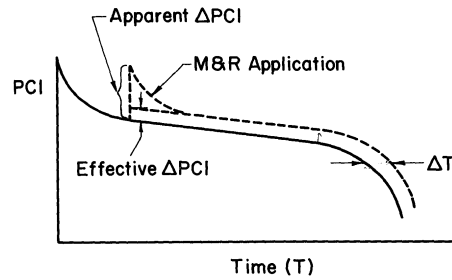


Figure 9-16. Determination of increase PCI ( $\Delta$ PCI) due to increase in life ( $\Delta$ T).

Fig. 5.17 Effect of Repairs on PSI Quality  
(From Shahin, 1994 :169)

This was done to express the possibility that roads, which were delayed in repair often shifted the level of repair needed and that the cost were greater than those expressed by managers. Roadwork was delayed on Excellent road that deteriorated to become Good road under two sets of conditions. One set allowed deterioration at the normal rate for Excellent road (240 months), but the shift to Good road is delayed 36 months. This road was then repaired in a similar manner as other roads (e.g. either patched or overlay). As an alternative the same road was allowed to deteriorate in the same manner, however, a percentage of the road was classified as either 1) Good road and overlaid with no Patch repair done or 2) Poor road that was overlaid or paved. The formulation allows testing of the managers biased assessment of repairs against a more rational assigned value. The difference in the dynamics of the system can then be evaluated

### 5.1513 No Maintenance

If a maintenance method of 0 is selected, no maintenance is performed on the system, Figure 5.18. This was created for two reasons. The first was for comparative purposes to a constrained budget reference mode. The second was to act as an on-off switch for selection of any policy where a manager decided to stop repairs, in the model as simulated or in a gaming mode. Managers may select a maximum maintenance level that when compared to the systems PSI will stop repairs. The simulation then responds to start and stop as the PSI goes above or below the selected level of repair.

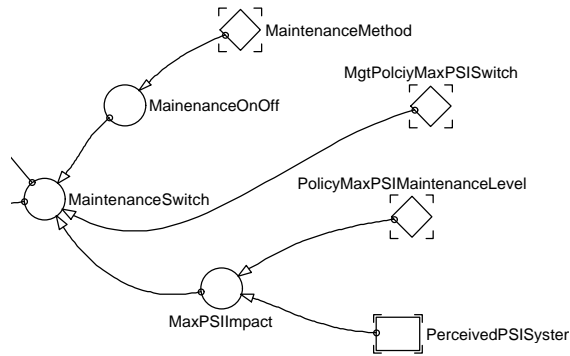


Fig. 5.18 No Maintenance Control-model structure

The MgtPolicyMaxPSISwitch allows a choice between MaintenanceMethod and choosing to apply the PolicyMaxPSIMaintenanceLevel. The control is a simple if then else statement, where

$$\text{Maintenance Switch} = \text{If}(\text{MgtPolicyMaxPSISwitch}=0, \text{MainenanceOnOff}, \text{MaxPSIImpact})$$

$$\text{MaxPSIImpact} = \text{If}(\text{PerceivedPSISystem} > \text{PolicyMaxPSIMaintenanceLevel}, 0, 1)$$

### 5.1514 Control of Poor road Pavement

The use of an on-off switch allowed for repairs of Poor road, controlled by Poor road conditions versus the pavement of Poor road, controlled by the residual life cycle value and PSI, Figure 5.19

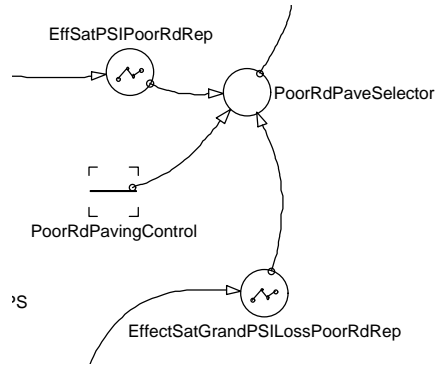


Fig. 5.19 Control of Poor road Paving-model structure

#### Repair RSL Trigger and RSL Effects

A percentage of degraded value was chosen to represent the RSL if the system.. The RSL normally recommended for a system varies between 85 % and 50% of the highest value of the system, PSI 5 (Zaghloul TRR1539). The formulation is;

Percent RSL \* Normal PSI (5).

If the PSI of the system drops below this value paving is initiated.

#### 5.1514 Regional Road Planning

Pavement managers are usually not included in the design process of roads and regional planning.

“The information we have is part of a recommendation process. It’s our info, the assessment committee’s recommendations, and the politician’s inputs.  
 “Sometimes we should do a road for maintenance and repair, but if we run short it could wind up that another year pushes it into full rehab, which costs more than the original repairs”.

“We don’t talk to the designers, we just pass off the information”.(RI)

Therefore, managers and regional planning appear not to have an effective method for determining the needs of an area as it develops. The use of traffic flow is the only method available.

A method for determining the impacts on design was formulated in an attempt to improve the process of decision-making (Note 8).

### **5.1515 Accidents**

The impact of accidents on the system proved to be the most serious defect found in the managerial process of the system. Managers tend to repair roads as accidents increase. This policy, however, tends to increase the chance for more accidents to occur. The dynamics of this process will be examined in detail in the chapter on policy analysis of this dissertation.

In order to capture the space for this policy evaluation a set of formulations capturing the accident rate was developed. The rate of increase in accidents above an accepted standard level was converted into policy that overrides the utility functions under normal conditions. The values from the utility functions are either raised or lowered in response to the accident rate. As accidents increase the amount allocated to maintenance decreases. This increases the desired level of paving. Paving the road is the fastest way to increase overall PSI of the system. As the rates fall, the values for choice of repair shifts back to those chosen by the utility functions.

The impacts of budgets also come into play.

“Generally we use one budget, when it gets to 30% we allocate differently”  
(Grafton, MA)

When budget adequacy falls below the 30% level, utility function levels are again chosen over those a manager might select for accident repairs. The formulation allows a

comparison of an unconstrained amount of spending versus a “rational” allocation of resources.

## 5.16 Feedback between and within Sectors

A diagram representing sectors and their relationships indicates the feedback within the sector and between sectors of this model.

### Sector Feedback (Figure 5. 20)

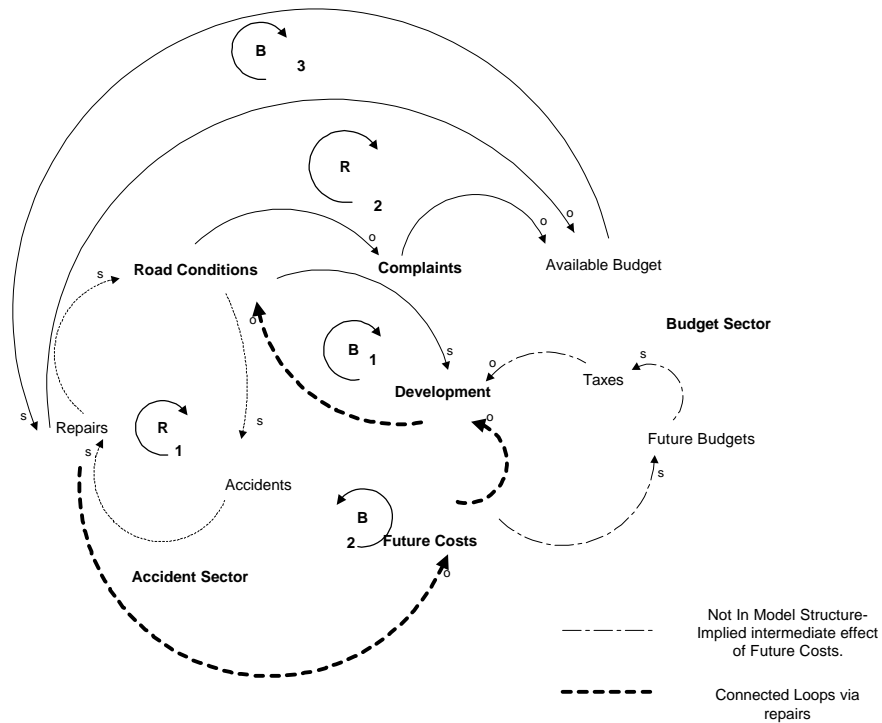


Fig. 5.20 Causal Loop Diagram -Major Subsections

### Sector Relations

B1-A decrease (increase) in road conditions causes a decrease (increase) in development, however, as development increases(decreases), road conditions decrease (increase).

B2-An decrease (increase) in current repairs reduces (increases) future costs. (If future costs increase, budget increases can cause increases in taxation, which can lead to loss of development)

B3-An increase in repairs causes a decrease in available budget, which causes a decrease in the rate of repairs.



R1-Improvement in the road condition increases accidents, which triggers repairs and an improvement in road conditions

R2-A decrease in road conditions causes and increase in complaints, which reduces budget availability and reduces repairs, which causes a decrease in road conditions and increases complaints.

[Note: It has been suggested that the term increase and decrease may not truly represent the exact effects expressed. The concept of an increase or decrease greater than would have occurred without the effect on the variable may be a better term to use. A decrease in repairs does not increase the budget, but slows the rate of decrease of availability and allows repairs to be carried out for a longer period of time then otherwise would occur with less budget available.]

### Sub-Sectors

### Complaints (Figure 5.21)

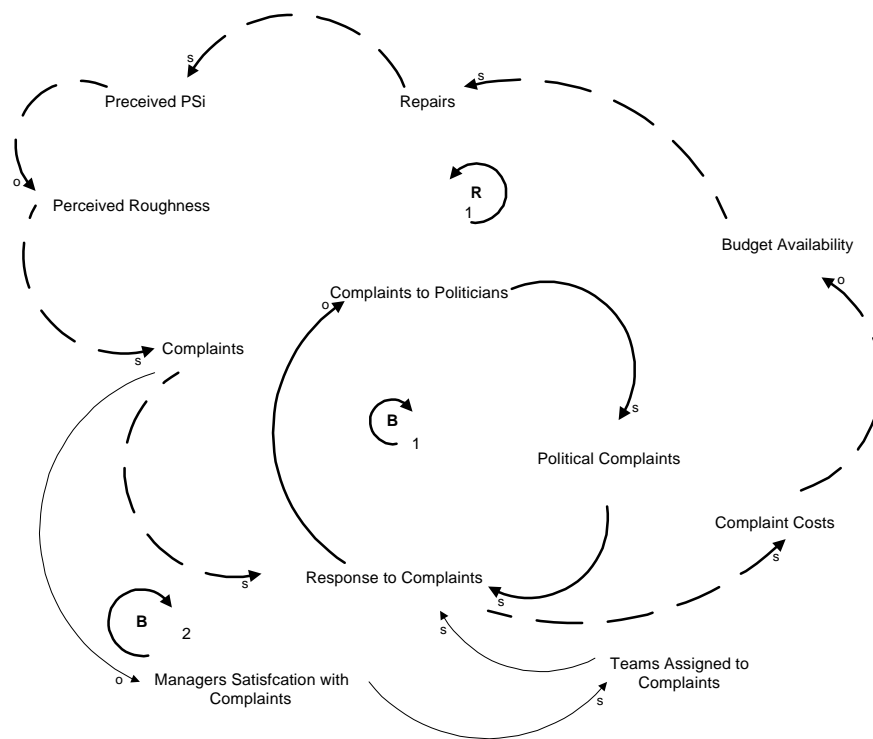


Fig. 5.21 Complaint Management Causal Loop Diagram

## Complaint Loop Description

B1-As the response to complaints increases (decreases), complaints to politicians decreases (increases), causing complaints by politicians to decrease (increase), thus decreasing (increasing) the pressure to respond to general complaints.

B2-As the managers satisfaction with complaints decrease (increases) more (less) teams are assigned to deal with complaints. This increases (decreases) the available budget as the cost of complaints increases (decreases). The effect is to reduce (increase) the amount of budget left for major repairs, thus lowering (raising) the PSI.

R1- As the PSI is lowered (raised) the perceived roughness is raised (lowered) thus increasing (decreasing) the number of complaints generated. (This loop connects back to B1 and B2)

## Accidents-Figure 5.22

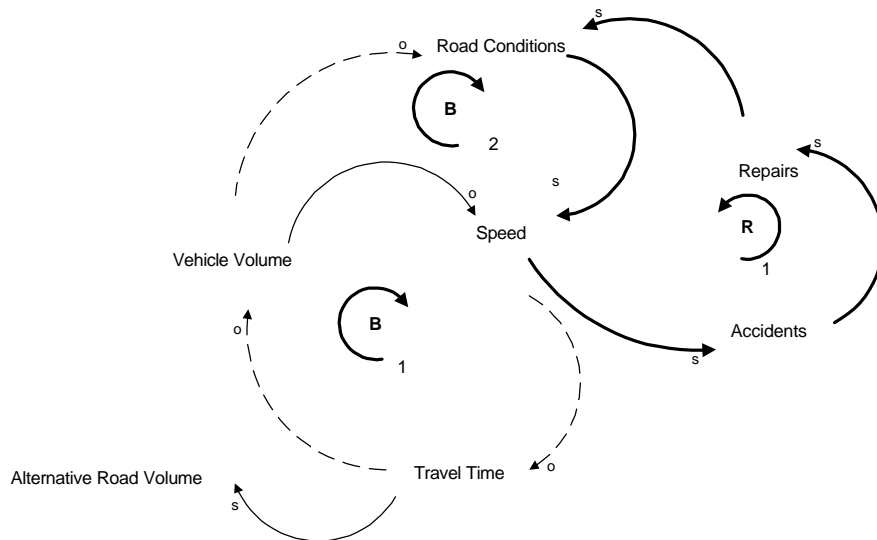


Fig. 5.22

Accident Creation Feedback Loop

## Accident Loop Description

R1- As the road condition improves speed increases (decreases) and the accident rate increases (decreases). This led to an increase (decreases) in repairs, with an increase (decreases) in road conditions.

B1-As speed decreases (increases) travel time increases (decreases) which caused vehicles to leave the road (and seek new routes of travel). As volume decreases (increases) speed increases (decreases).

B2-As vehicle volume decreases (increases) less (more) damage to the road surface takes place and the rate of accidents decrease (increases).

**Regional Development** Figure 5.23

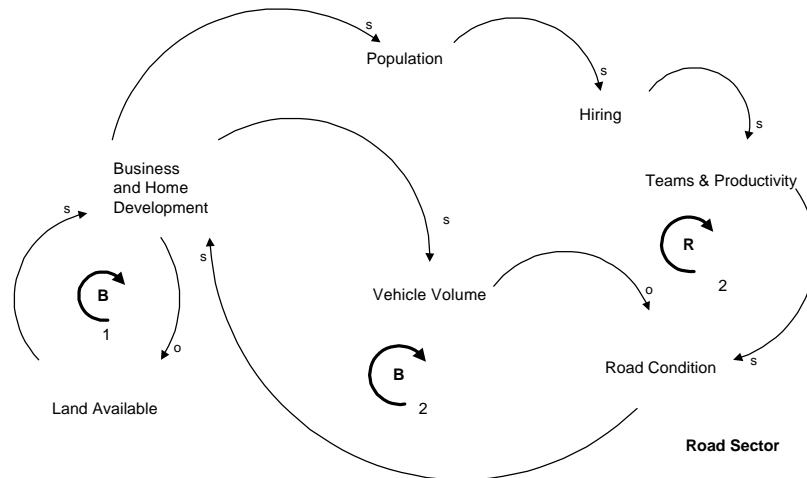


Fig. 5.23 Regional Development Effects Causal Loop Diagram

**Regional Development Loop Description**

R1-As a region attracts new businesses and homes, it brings population and more vehicles to an area. The increase (decrease) in population allows an increase (decrease) in labor and ability to repair roads. An increase (decrease) in road conditions causes and increase (decrease) in the amount of development. (If repairs do not keep up with deterioration, the development of an area can be negatively effected. This can lead to a decline in the population and local economy).

B1- an increase (decrease) in development causes a decrease (increase) in the land available for development. (The land available is a constraint on maximum development).

B2- An increase (decrease) in development leads to an increase (decrease) in vehicle volume, which causes a decrease (increase) in the condition of the road, leading to a decrease (increase) in development.

**Land** Figure 5.24

Land in most towns is zoned for specific use. The amount of land available for each use acts as a constraint on the “sprawl” that can take place. In the model if the amount of land required for each structure was greater than available, by zoning, then the structure

was not added to the level. As levels (industry or home ) decline land is again made available.

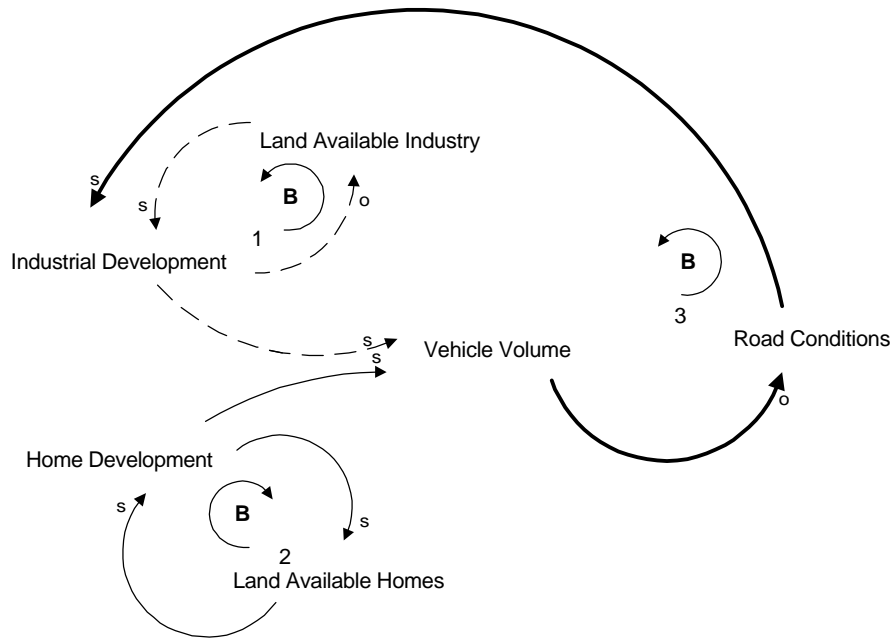


Fig. 5.24 Land Development Loop

### Land Loop Description

B1 and B2 (similar loops)-As development increases (decreases) the amount of land available decreases (increases).

B3-as development increase (decreases) the volume of vehicles increase (decreases) thereby causing road conditions (PSI) to decrease (increase). The decrease (increase) in road conditions causes a decrease (increase) in development.

Note Industry Development was not used to effect home development. Variables other than industry can effect home development. In this model, however, infrastructure has a direct impact on industrial development.

### Budget Impacts Figure 5.25

The allocation of resources controls the amount of repairs that can occur. Managers control the allocation via selecting the amount of and type of repairs will be carried out.

The amount of each type of repair is controlled by the budget, via impacts on the Critical

Value, which controls the amount of Patch and Overlay work accomplished, as well as the amount of paving. Paving is controlled by the length of each paving contract, which is effected by the adequacy of the budget. Team productivity is also controlled by the available budget.

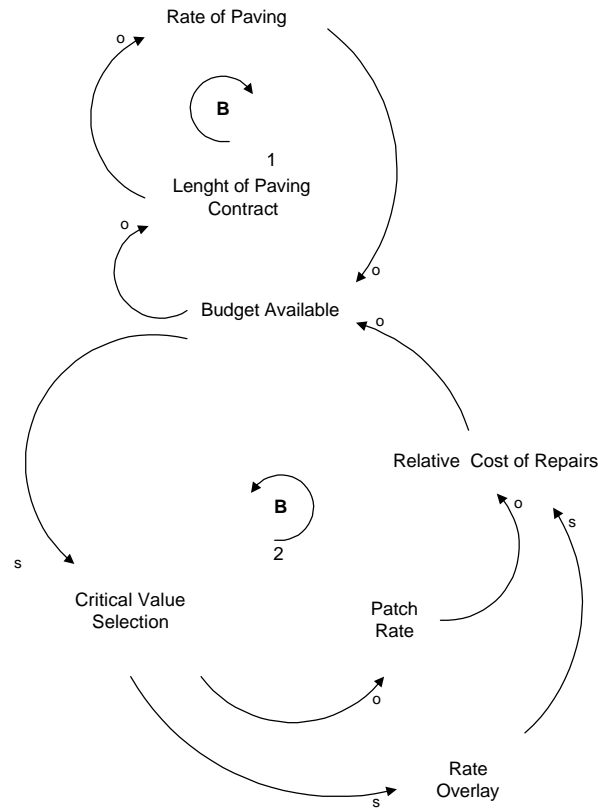


Fig. 5.25

Budget Causal Loop

### Budget Loop Description

B1-As the available budget decreases (increase) the length of paving contracts increase (decreases) thus decreasing (increasing) the amount of Pave repair accomplished each period.

B2- As the available budget decreases (increases) the Critical Value of the system is decreased (increased). This allows more Patch repairs at a lower cost, thus slowing the decline in budget adequacy. As the budget adequacy increases, the Critical Value is

raised and more Overlay work relative to patching is carried out, thus decreasing budget adequacy and permitting patching to replace overlay as the method of choice for repairs.

## Notes to Chapter 5

1. A multiplication of  $-1$  was used as normally the deterioration rate is increasing while the PSI decreases. In this case, as the PSI is a weighted value of all PSI no exact rate of deterioration is available. In the generic structure, Figure 5.4, each PSI level is an accumulated value of PSI units from which an average PSI is calculated. It was found by testing other versions of the process that the use of a  $-1$  achieved the same results as using a rate of change method.

2. Managers had suggested that increases in the cost of maintenance of the system could be passed along to homeowners. When this occurred, there was an initial desire to construct this into the model. This was done in the first cut of the model but removed in the final version. The removal was motivated by concerns for the issue of boundary and model purpose. A systems view of the managers' thoughts led to the development of a mental model that described the following set of relationships.

Home development could grow until land ran out. With a fixed number of homes, as taxes increased, the cost of staying might drive homeowner away. As homeowners left, retail business might also have to leave. With small business and population decline, larger industrial businesses might have difficulty recruiting. Tax increases and cost increases due to operation conditions might go up to the point where they might leave. As the boundary continued to expand, I became aware that I would be exceeding the limits for the purpose of this model. The tax policy issues was not an initial consideration of the model and was left for a future time.]

3. Total land available for each type of development noted was used to control the process by first order control. The generic structure in Figure (N1), was used as the basis for the formulation that was developed.

In Figure N1 the EffLFO is dependent on  $\text{FracLandOccupied} = \text{LandInUse} / \text{TotalLand}$

#### 4. Roughness and Serviceability

Serviceability has been defined as “the ability of a pavement to serve the highway user.” (Weaver NYSDOT). It has been noted that, “the serviceability and failure of an

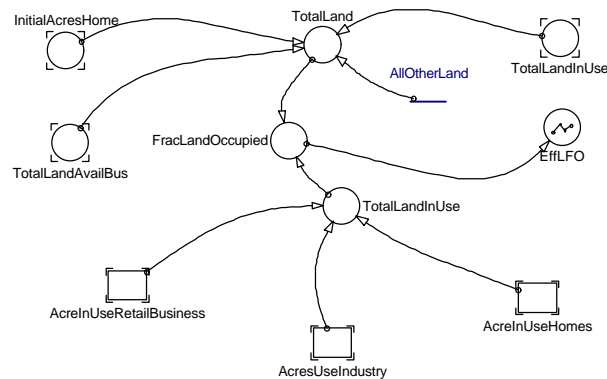


Fig. N1 Total Land Available

engineering design can only be defined relative to the purpose for which a design has been provided (Hutchinson, cited in Weaver). As Carey has stated (cited in Weaver), “performance rests on serviceability and serviceability rests on surface profile. Thus, pavement evaluation begins with independent measurement of serviceability, and that is possible only by applying psychophysical principles to discover how pavement condition affects pavement users”. For example, when road users slow down, because of bad pavement conditions, they are unconsciously using the speed relations to raise serviceability to a more tolerable level. Anchoring the rating scale is an important part of the process. For every relation between human response and a physical stimulus, magnitudes of the stimulus exist beyond which a change in stimulus has no proportional change in response. These two points on the stimulus scale are the liminal points, and are the ends of the rating scale. Weaver had developed two end points; 1) perfect-at a given speed, the experience is so good that you doubt if you can detect any improvement, and 2) impassable-at a given speed, the experience was so bad that you feared that you (or

the vehicle) would be damaged. Once the anchors have been established, a scale falling between the two can be developed. Weaver (NYSDOT) has shown that the perceptions of the user are viable measures to be used in pavement management.

This concept supported by observations in Paterson (1987) who reminds us that subjective assessment by panel rating was developed in the late 1950's. In the study quoted by Paterson (Carvey and Irick 1960, cited in Paterson), it was found that the 50<sup>th</sup> percentile of acceptability was 2.9 on a PSR ( Pavement Serviceability Rating ) and 2.5 for unacceptable.

5. During the period from 1992-2000 there were 1713 accidents reported:

1492 were on two lane highways

The average speed was 87.2 mile per hour

Surface conditions were dry in 61.3% of accidents

1395 accidents or 84.8% occurred when the road had no defects while 4.3% occurring with ruts, holes, bumps or other defects.

1,080 or 66.4% occurred in daylight.

1,039 or 57.2% occurred with clear weather.

504 or 22.4 % were associated with moving violations.

6. Discussions of this topic range from easy to use formulations using a weighted share methods, suggested by Richardson (1999-system-dynamics@world.std.com), to a sophisticated process found in Vensim, the ALLOCP, based on the work of Woods ([www.vensim.com/allocp.html](http://www.vensim.com/allocp.html)).

The basis of the algorithm appears to be a linear programming model or warehousing algorithm found in many standard Operations Research or Operations Management textbooks. While the method works, it makes an assumption, that attractiveness is not changing and resources will be allocated to the most attractive location until satisfied. The process does not appear to take into account that as ones desires are satisfied, the need to satisfy that desire decreases. The process does not satisfy the problems faced by



managers in a multivariable fuzzy situation and does not truly capture the psychology of the allocation process. These discussions can be found at: [System-dynamics@world.std.com](mailto:System-dynamics@world.std.com).

7.

From Zaghoul (TRR1539 :108)

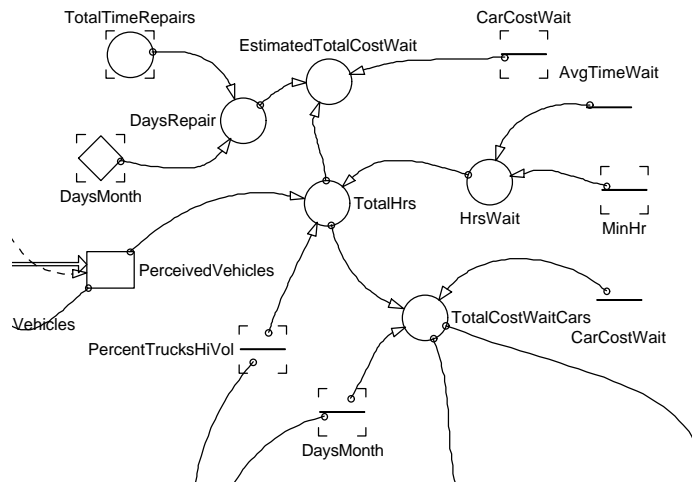


Fig. N2

Waiting Time –structure in model

Where:

$$\text{TotalCostsWaitCars (Dollars/Month)} = \text{CarCostWait (Dollars/Hr)} * \text{TotalHrs (Hours/Day)} * \text{DaysMonth}$$

Note that the total time in repairs is the sum of all time in the system during repairs. This was estimated by dividing the outflow rate into the level (Miles Available For Repair/RepairRate), which is closer to an estimate of coverage.

[A similar calculation is carried out for the costs of trucks in the system]

8. There are two methods suggested for the design of a road. One is the AASHO Interim Guide, which uses the development of a structural number to guide pavement thickness.

The structural number (SN) is determined as:

$$SN = a_1 D_1 + a_2 D_2 + a_3 D_3$$

and

D1= surface thickness in inches

D2= base thickness in inches

D3=subbase thickness in inches

Where the values of a1,a2,a3 are taken from the AASHO Interim Guide Coefficient Values (:547)

These values are then combined with a numogram and converted into asphalt thickness.

The second method is the Asphalt Institute Design Method. This method calculates the expected Design Traffic Number (DTN), then uses a numogram to determine pavement thickness.

The DTN calculation uses the:

Initial Daily Equivalent 18,000-lb.single Axle load (ESAL)

California Bearing Ratio (CBR) obtained from a numograph), Figure N2.)

Regional Factor (as a numograph)

Design Period

Annual Growth Calculation (based on the first year of growth:  $\text{Factor} = ((1+r)^n - 1) / 20r$ ).

The Asphalt Institute of Design Method was chosen based on the ability to create a table function that pivoted around a normalized ESAL value and a set CBR value. Figure N2 contains the inputs to the formulation. A constant CBR was chosen and using the ESAL inputs a determination of asphalt thickness was made, standardized and put into a table function.

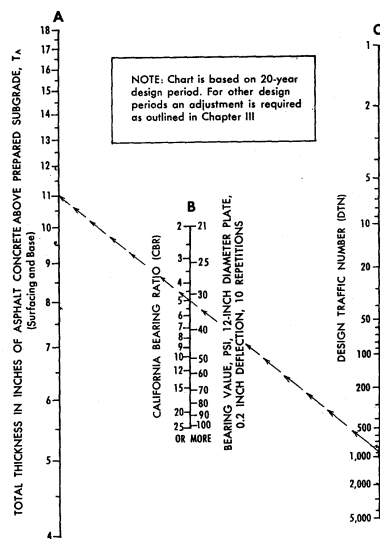


Fig. 16-24. Asphalt Institute design curves. (Courtesy of the Asphalt Institute, Ref. 10)

Fig. N3

Numograph Used for DTN Calculations

The process that was used was:

- The estimated DTN was calculated.
- The value of the DTN was used to determine an initial thickness of asphalt.
- The initial value of the DTN was divided into the chosen value of a DTN array.
- The normalized value was used in a table function as a multiplier of pavement thickness.
- The pavement thickness was adjusted by a factor determined from the deterioration effect on roads.

The Pavement Adjustment Factor was developed to help predict the future volume capacity required. This was done in order to determine what the volume of a new planned road would be, and how thick the road should be, to prevent lowering of the normal Pavement life span of 240 months.

NormalPavementLifeSpan\* Effect of Volume on Deterioration =  
AdjustedLifeSpanLongevity

AdjustedLifeSpanLongevity /Normal PavementLifeSpan = EstPlannedVolumeAdjustment (EST)

The EST is the value needed to plan the road for the increased volume effect.

If the volume is 20,000 ADT and the multiplier 1.5 then planned volume should have been 30,000 vehicles. An estimate of new thickness is made to accommodate a volume of 1.5 x planned vehicles in terms of asphalt thickness. The thickness of the road was converted into a total volume of cubic feet and then multiplied by the cost per cubic footage of asphalt.

The increased costs can be compared to the initial planned costs and total operating-costs, under each design. The resulting differences in operating costs can be compared to the initial investments. A Net Present Value analysis can determine if the increased initial investment will pay for itself over the design period. In the same manner, the impacts on life cycle costs can be analyzed.

Unfortunately, in the real system cost benefit analysis is made difficult as managers tend not to relate costs of repairs to categories and rates of specific types of repair to deterioration effects. In the simulation, there is no such limitation. While the relationships are dependent on some assumptions these are better than no evaluation. In the system the cost per PSI can be used as one benefit, other measures might be repair costs to accident rate, total costs of complaints, vehicle operating costs per PSI, etc. Economic evaluation methods are found in the Federal Highway Guide or alternatively in most standard texts on Highway Engineering

## Chapter 6

### System Dynamics and Policy Tests

This chapter will describe the analysis of the dynamics of the road pavement management system.

The reference mode (Figure 1.1) of Chapter One is reproduced for convenience. (The run is shortened to allow a clearer visual of the dynamic). In addition, although a Pavement's life span could be 20 years or 240 months a period of 800 months was chosen for the simulation. The selection of this time span is based on the work of McNamme (1999). McNamme estimated that roadway given intermittent service can extend its life-span up to 60 years or three times the expected life span, therefore the road system could show up to 720 months of deterioration time.

In developing a system dynamics model, the reference mode must be maintained during the development of the model regardless of the number of levels or operating characteristics of the system model under development.

#### 6.1 Reference Mode

The reference mode, presented in Figure 6.1 as a hand drawn behavior over time, can be compared to several runs of the model.

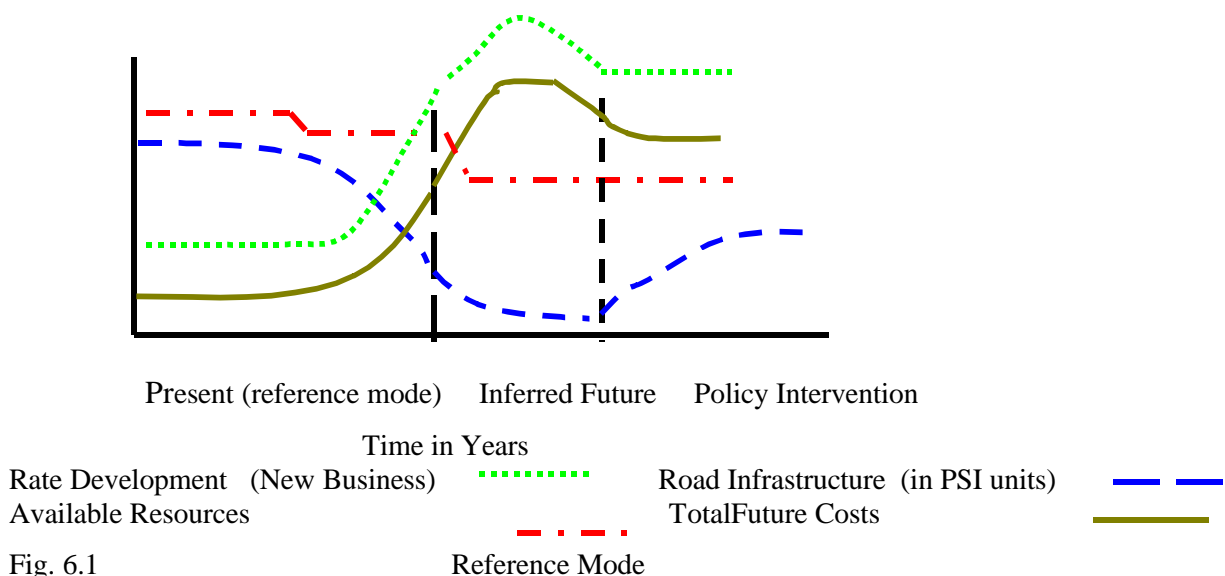


Fig. 6.1

Several mixes of road were evaluated in developing the reference mode (Note 1). This was necessitated due to the fact that small towns do not keep active inventories of roads (this even though FASB 34 requires it). The reference mode selected to represent the simulation is seen in Figure 6.2.

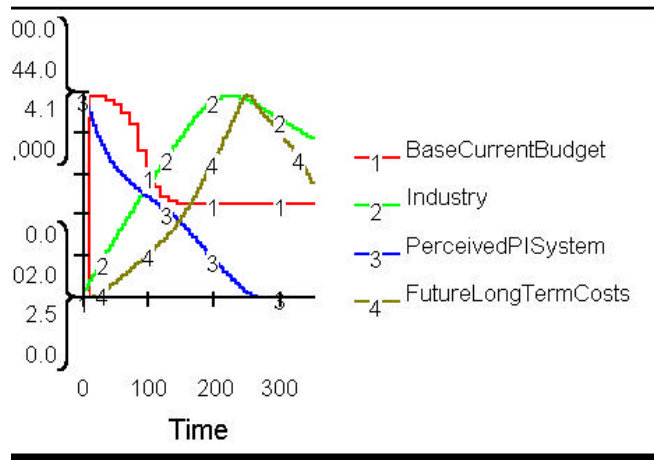


Fig. 6.2 Simulated Reference Mode

ExRd=1500 GoodRd=330 FairRd=600 PoorRd=500 (Values in miles)

The operating conditions that are in existence, for this run of the simulation, include managerial assumptions used in operation of the system. These are:

- Repairs are carried out in the winter.
- Roadway that becomes backlogged for repairs does not change category.
- More money is spent on repairs as accident rates increase
- The budget that is obtained for the first year is reduced for successive years until a floor of 47% of the original is received. (Managers indicated that they were receiving a budget in each successive year that was lower than the previous year. As there was no way of knowing how long this would continue it was decided that at some point the allocation had to level off. The model can be run in a mode that allows the amount of budget to shift to a higher value in the middle of a run).
- High level managers indicated that most supervisors of repairs tend to give completed road repairs a better score of quality than is appropriate.
- Long range planning that could include Pavement Manager's inputs is not in place.
- Hiring of labor is accomplished that uses a method that does not account for growth in utilization (Note 2).

- A Mall has been introduced into the area of development under consideration. The Mall's impact is part of the cause of the increase in deterioration in the real system and is included in the run (Note 2).

An evaluation of the dynamics of the problem will be presented by using the key variables: development, road conditions or PSI, the budget, and long -term costs.

The first behavior to be evaluated will be the relationship between development and the road conditions.

## 6.2 Road Conditions and Area Development

The initial presentation of the problem indicated that increased development was causing an increase in road deterioration. The base formulation of deterioration is given as:

$$\text{Deterioration Rate (Miles/Month*)} = \text{Miles of Road (Miles)} / [(\text{Normal Road Life Span (Months)* Effect of Volume on Deterioration}] (1).$$

\*Dimensions in Italics

As development is taking place we expect to see a decrease in the life span of a given road type. The decline is due to the effect that traffic has on the generation of damage to roadway surfaces. As the life span decreases the rate of deterioration increases, causing a decline in the PSI of the road. Further, as road conditions deteriorate the rate of development begins to slow. The decline acts as a balancing loop, as the decline is accompanied with a lowering of vehicles in a given area. The loss of vehicle volume effect allows the life span to return to its normal level. The dynamics can be seen in Figure 6.3, a-d.

Figure 6.3b (arrow) indicates a rise in vehicle use as development occurs. Vehicles leave the system for two reasons, 1) a decline in the use of vehicles (such as occurs with a decline in development) and, 2) slow travel time. Although, not covered here, as traffic increases or road conditions deteriorate, vehicle time of travel increases and users choose alternative highways [see vehicle volume change Sector 6.4 ]. A short-run, with no Mall development is compared to a run with development of the Mall.. As the volume of traffic increases (arrow A), Figure 6.3 b, life span decreases (arrow B), Figure 6.3c.).

The decline in vehicles is related to the decline in road conditions, Figure 6.3d.

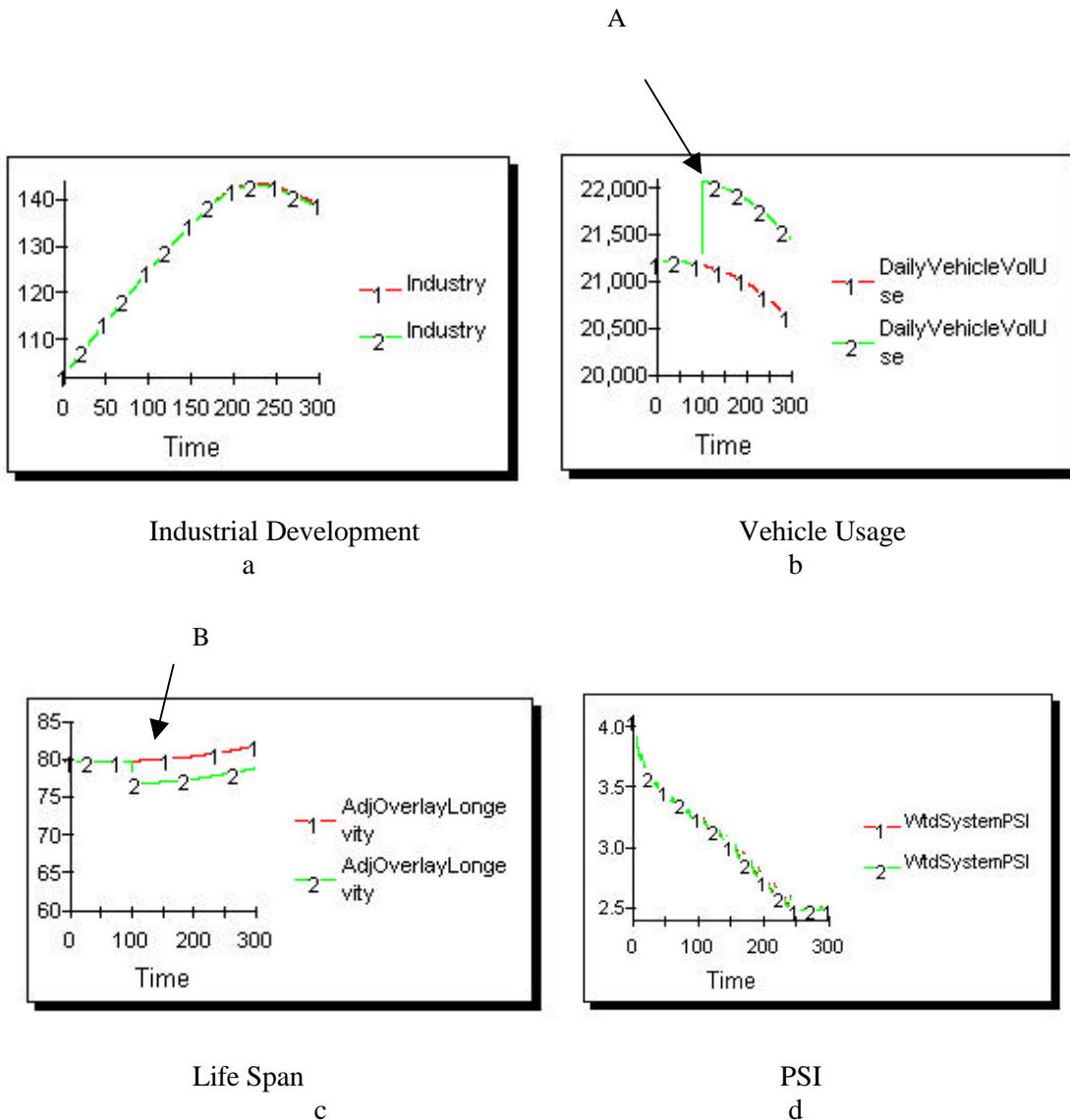


Fig 6.3 The dynamic relationship between development, vehicle usage and road conditions.

Curve 1: No Mall  
 Curve 2: Mall

[A short-run was used to allow for clarity of the impact. In Figure 6.3 c Overlay is used as an example, but the same dynamic holds true for patch and pavement repairs.]

The causal loop diagram representing this dynamic (balancing loop) is shown (Figure 6.4) as:

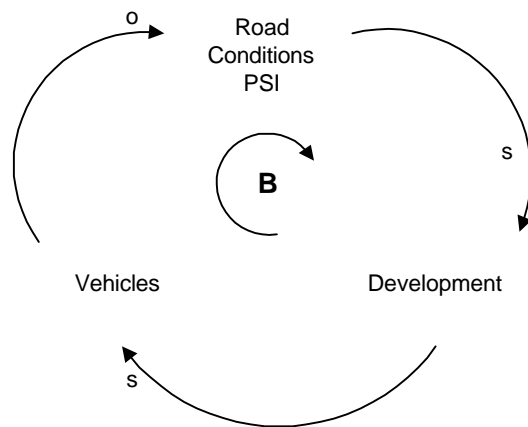


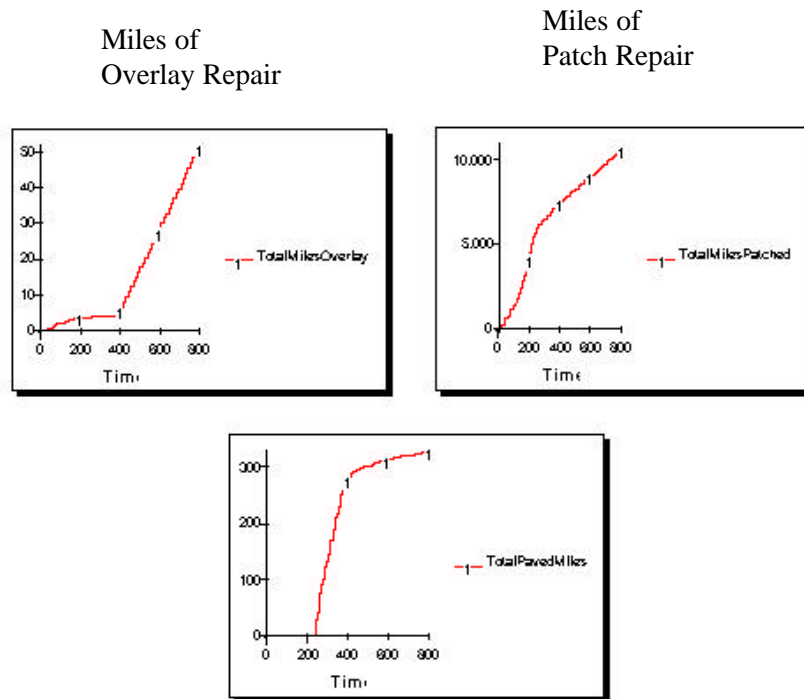
Fig. 6.4 Development Road Condition Balancing Loop

### 6.3 Repairs and Long Term Costs

Long term future costs are dependent on the maintenance policies implemented at the current time. In the reference mode, paving is carried out in response to either the perceived accident rate or road quality (PSI). The amount of repairs accomplished depend on 1) the amount of road chosen for repairs, the type of maintenance selected, and budget available to pay for the repairs selected. In this simulation the resource allocation is accomplished using a utility function [see Decision Making Dynamics Sector 6.5 ]. When the budget is adequate paving is the preferred repair process, when the budget adequacy is diminished Patch or Overlay repairs are chosen. The difference in the miles available for repair and repaired adjusted for future value determines the future costs to be incurred by the system.

In Figure 6.5, the impacts of current policy can be seen. While total Overlay and Pave repair of the system can be seen, the preference is for short-term Patch repairs. Overlay is not performed until the level of the system's PSI is below the system's PSI critical value. Note that initially Overlay is also preferred to Pave repair.. The PSI deterioration decreases in response to the increase in Patch and Overlay repairs.





Miles of Repair by Category

Fig. 6.5

The cost distribution of the repairs is shown in Figure 6.6. Although total Pave repair is least in amount of miles, the total costs of Pave repair exceed that of Overlay and Patch. (A reminder, that repair that is undertaken when a system is at its lowest point can be four times as expensive as when undertaken earlier in the decay process.)

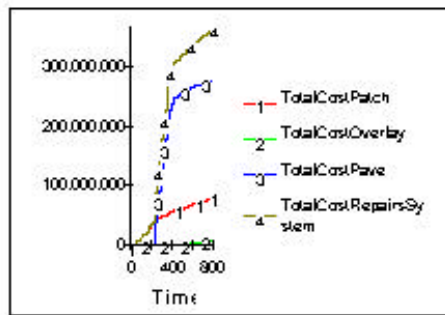


Fig. 6.6

Cost of Repairs at Current Costs

The impacts of the process are revealed in Figure 6.7. Paving has the most impact on the improvement of the system. Road that is paved is returned to excellent condition. In the reference mode, this can be seen where the PSI tends to stabilize during the paving process. As the amount of paving is reduced, the future costs of the system tend to increase and the system starts to deteriorate, see Figure 6.5. When paving is carried out a reduction in the future cost of paving is created (Figure 6.8). The reduction in the future costs of Pave repair exceeds the amount of future costs of Overlay and Patch repairs.

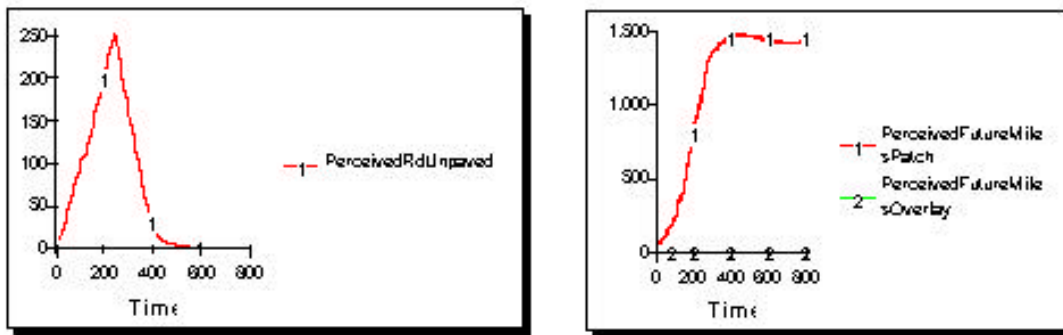


Fig. 6.7 Future Repair Needs

Figure 6.8 indicates the future costs of all repairs.



Future Cost of Maintenance

Future Cost of Paving

Fig. 6.8 All future costs

The reason future maintenance costs are higher is due to the road in need of future maintenance. The amount of non-repaired road that requires maintenance can be seen in Figure 6.9. Relative to Pave repair, the amount of other types of repair not done is large. However, the costs of these repairs relative to the cost of Pave repair are lower. Clearly, the total amount of road chosen for maintenance is larger than that for paving. The process captures what pavement managers have indicated about the preferential use of short-term repairs.

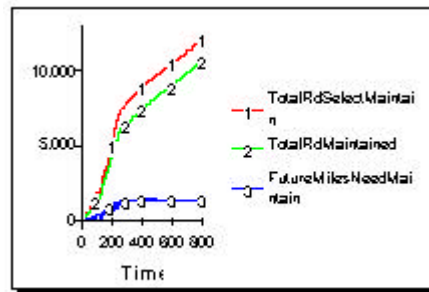


Fig. 6.9 Repaired Mileage, Non-Repaired Mileage, Future Repair Needs (All maintenance)

Managers indicate that,

“The state gives you so much they tell you can’t have more. So, we try to do the major jobs using state money. Anything left over we can use elsewhere. In the short-term its beneficial. Given equal conditions on a road you do the Overlay work and get away with it. You then use the money saved to do work elsewhere.”(AUB)

The causal loop diagram of this process is seen in Figure 6.10. The relationships of the loop are given under Repair Loop relationships

### Repair Loop Relationships

A budget is allocated once a year. As repairs occur the available budget is reduced, thus reducing the budget adequacy (the ratio between the original budget and budget available for spending). As the budget adequacy is reduced, the ability to carry out repairs is reduced. As the reduction in repair rates occurs there is a decrease in the rate of spending

and budget adequacy. Increases in repairs create increase in the quality of road conditions.

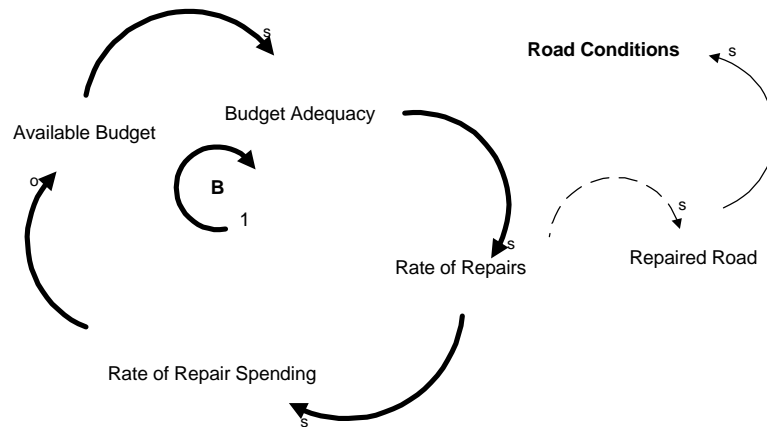


Fig. 6.10 Budget Repair Loop

#### 6.4 Road Volume, Accidents and Complaints

Roadway condition and traffic volume effect the utilization patterns of drivers. A Poor road will not normally be the road of choice (See comfort and road shifting in the literature review of this dissertation), while dense traffic patterns and longer trips time creates decisions about renegeing off the road in use. To accommodate this phenomena a secondary road system was added to allow for the normal exchange of traffic between road systems. The results of this exchange are seen in Figure 6.11.

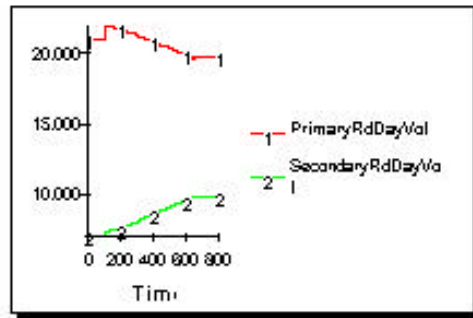


Fig. 6.11 Adjusted Traffic Volume for Two Road Systems

This pattern in Figure 6.11 is expected. As in many queuing situations users learn when to avoid waits and the pattern of use of a system finds its own level. As traffic builds on the primary road, speed decreases (Figure 6.12) and travel time increases (Figure 6.13). As travel time increases due to Poor roads and volume, more traffic will switch to an alternate road system. As the secondary system's volume increases travel time increases and drivers will renege from that system as well.

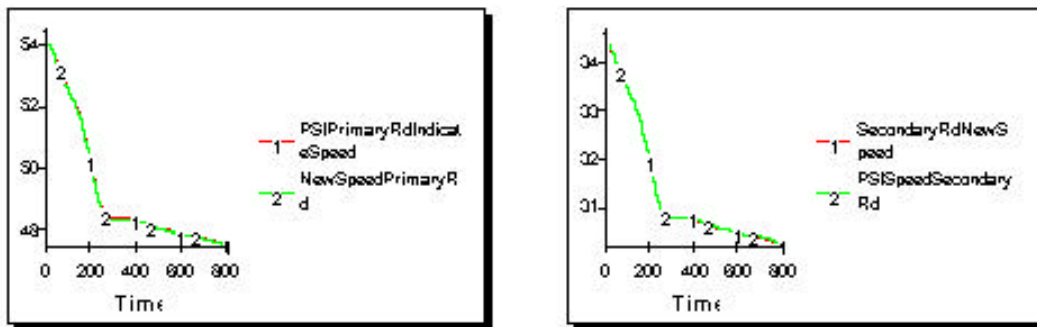


Fig. 6.12 Effect of volume on Speed (Method of de la Garza)

In this case, only two road systems are available. In addition, users of secondary road will not renege from that road system if they believe that the primary road condition (PSI) is so poor, that an increased time of travel is more valuable than damage to the automobile. The threshold of waiting is shown in Figure 6.14 (Note that the threshold is

surpassed as travel time makes a shift in rate)

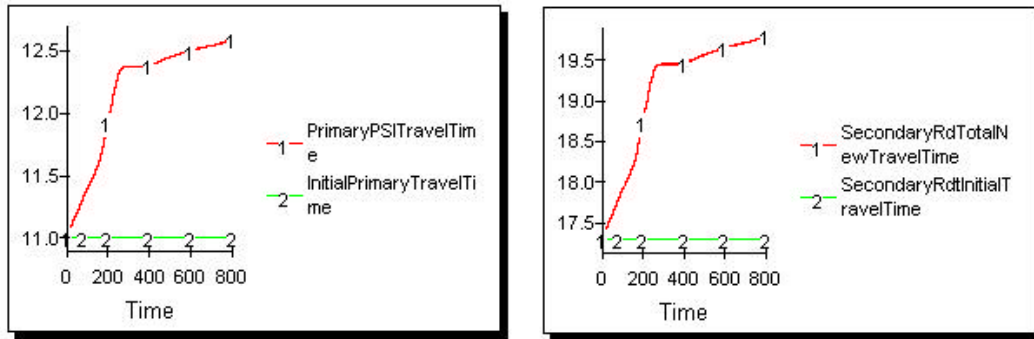


Fig 6.13 Increase in travel time versus original time of planned travel

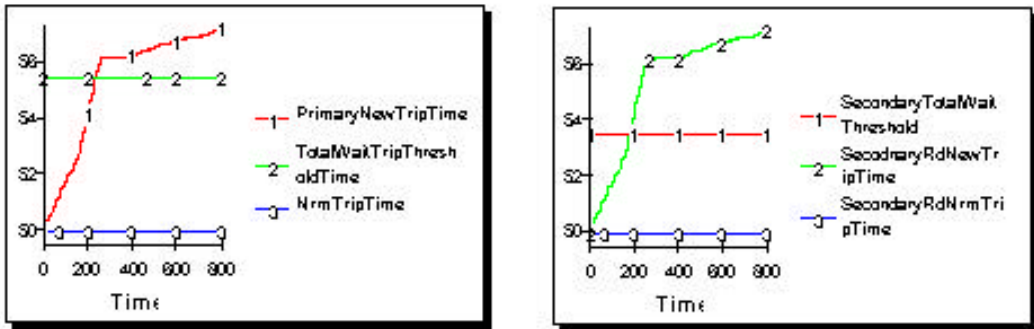
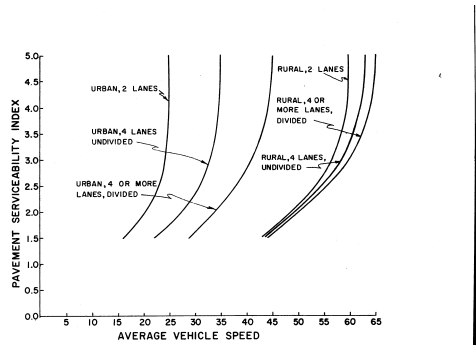


Fig. 6.14 Thresholds of Waiting

### 6.41 Accident Rates

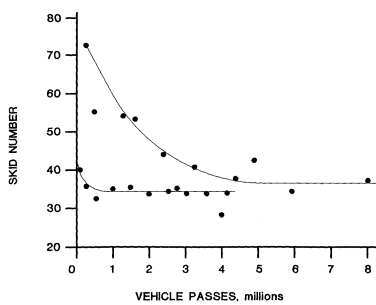
Accident rates are related to the skid number value. The skid number as defined in Chapter 4 is a measure of lateral resistance. The lower the skid number, the greater the probability of accident occurrence. The decline in the skid number value is related to 1) an increase in speed or 2) polishing of the road due to vehicle traffic. In addition, the value of the skid number varies with season. A set of graphic relationships from Shahin (1994) is shown in Figure 6.15 a-d.



Average Vehicle Speed Related To Pavement Serviceability Index by Type of Road

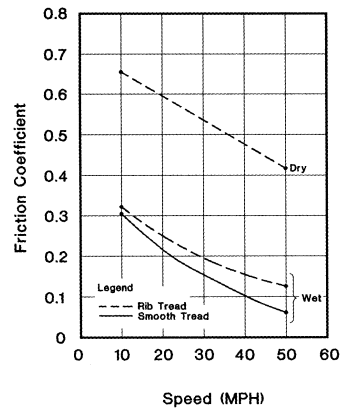
(From McFarland 1972)

a



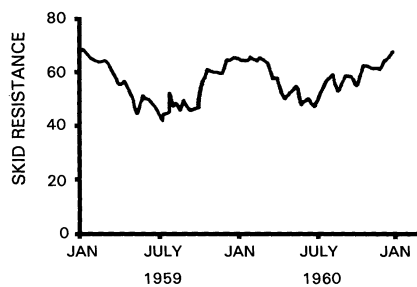
Loss of skid resistance as function of traffic exposure (Shain 1994: 93)

b



Speed related to Friction values on asphalt-seal surface (Shahin 1994: 96)

c



(Seasonal Change Skid Resistance)

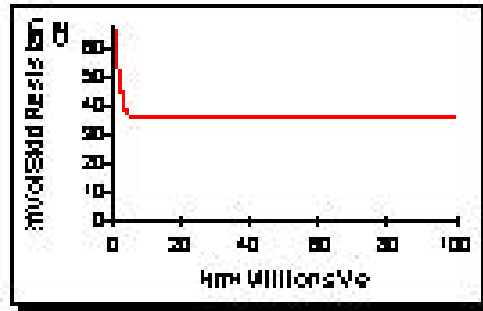
d

(Shahin 1994)

Fig. 6.15

Visuals Of Parameters Provided By The Literature

The simulated effects are seen in Figure 6.16 a-d.



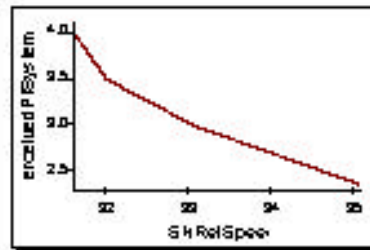
Simulated Volume Effect on SN

a



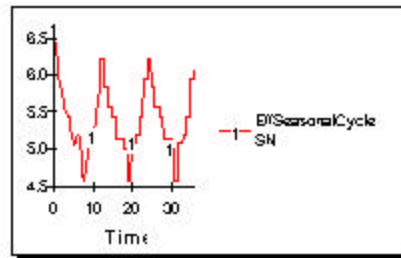
Relationship of Speed To SN

b



Relationship of PSI to SN

c



Relationship of PSI to SN Simulated Seasonal Effect on SN

D

Fig. 6.16 Simulated Graphics of the Literature

[The run time in Figure 6.16d is shortened to show repeated yearly impacts]

McFarland's (1972) accident rate was used as a standard. This rate was adjusted to the simulated vehicle miles (in 100 million-mile units) and was used to normalize the



simulated accident rate. The effects of speed and season were used in generating the simulated rate. [The curve labeled number 2, in Figure 6.17, is the same as the curve numbered one, but adjusted for the seasonal effect.]

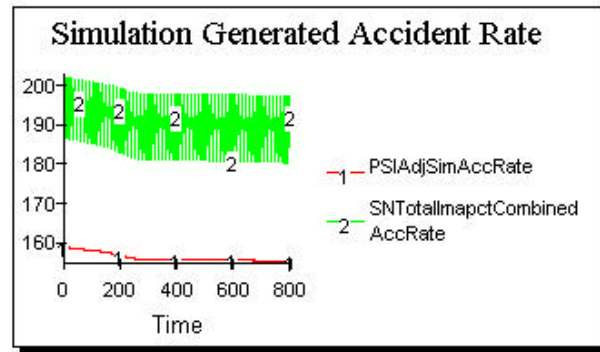


Fig. 6.17 Simulated Accident Rate

The current policy as applied to road repairs and its impact on accidents was discovered to be a major finding of this simulation study. As such a full discussion of the incorrect assumptions and dynamics will be found in the Chapter, 7 Recommendations and Additions to the Knowledge Base.

## 6.42 Complaints

Complaints arise due to user dissatisfaction. Complaint generation and formulation have been described in chapter 4 of this dissertation. The dynamics are shown in Figure 6.18 through Figure 6.20.

“Roughness is an important indicator of pavement riding comfort and safety and is the one pavement property that is most noticeable to the traveling public. From a driver’s point of view, rough roads mean discomfort, decreased speed, potential vehicle damage, and increased operating costs” (Shahin 1994: 65).

The relationship between the PSI and roughness are seen in Figure 6.18. As the road condition deteriorates, perceived roughness increases.

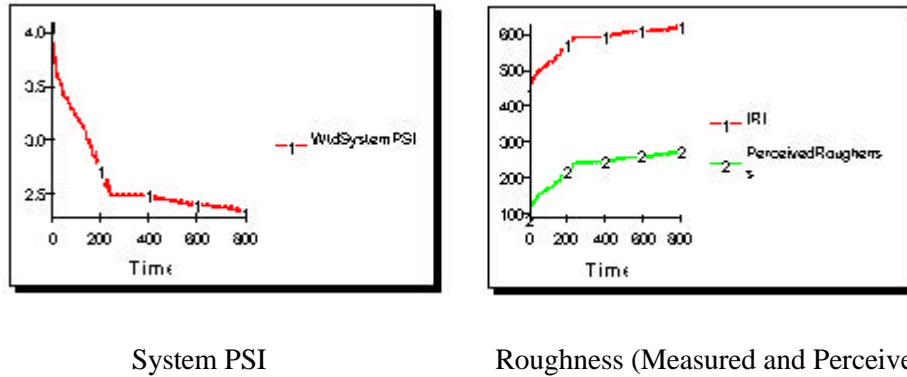


Fig. 6.18 PSI and Roughness Relationship

With an increase in roughness user satisfaction decreases (accompanied by increasing cost) to satisfy user demands and safety repairs, Figure 19.

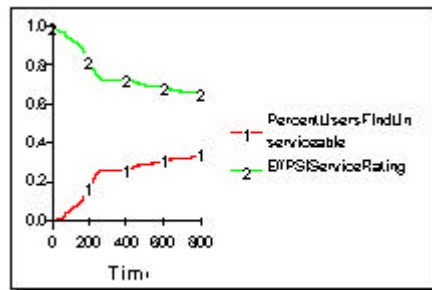
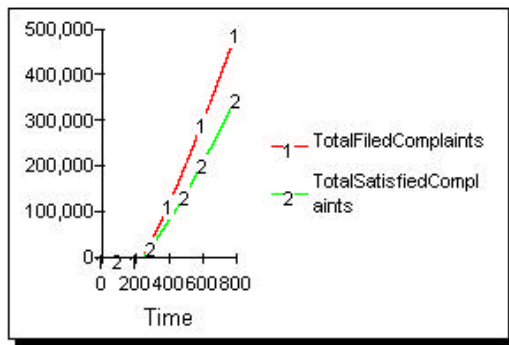
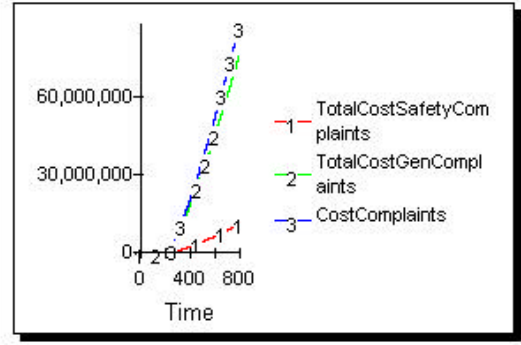


Fig. 6.19 User Dissatisfaction

The number of managed complaints and associated costs are seen in Figure 6.20.



Managed Complaints

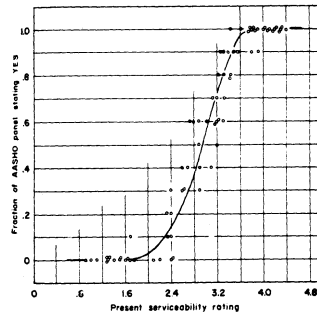


Cost of Complaint Management

Fig. 6.20 Complaint Management

The generation of complaints was accomplished using information provided by Paterson (1987). Figure 6.21a is Paterson's data point set while Figure 6.21b is the table function used to control the complaints generated in the simulation..

Acceptability of serviceability by subjective assessment



Highway Serviceability and PSI Paterson: (1987: 12)

a

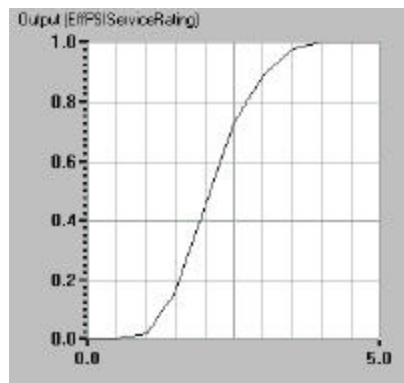


Table Function Used to Capture Function

b

Paterson's Serviceability Function

Fig. 6.21

## 6.5 Decision Making Dynamics

Control over the allocation of resources is deemed central to the process of maintaining roads in a safe and useful condition. The formulation of the allocation process has been described in detail in Chapter 4. The relationships and impacts of the allocation process are described in the following paragraphs.

### 6.51 Selection of Road Repair Rehabilitation

The additive utility function is controlled by the satisfaction with the budget available. The function as formulated allows for more paving with higher budget availability or adequacy. The selection of maintenance as a percent of work chosen, increases with a decline in available funds, Figure 6.22a and Figure 6.22b. While difficult to see Overlay, which is intermediate in cost and life span, shows up as a middle of the “road” selected repair process as budget adequacy declines. The typical choice process is, Patch in preference to Overlay and Overlay in preference to Pave repair.

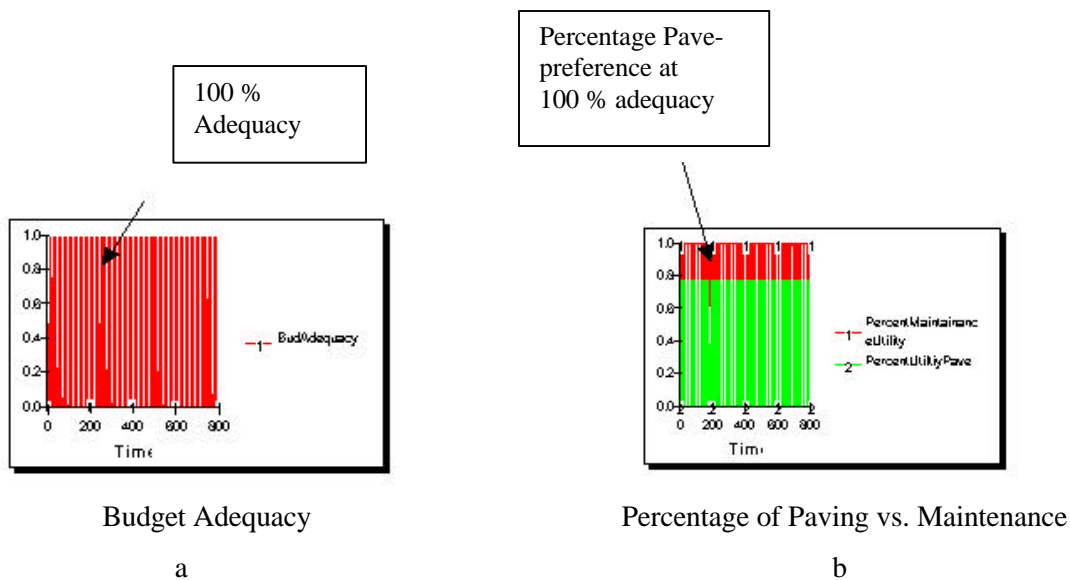
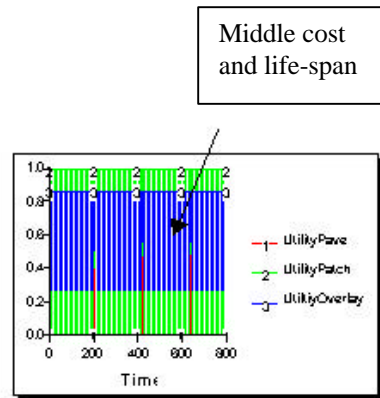


Fig. 6.22 Continue next Page



c Overlay—Curve #3

Fig. 6.22 Relationship between Budget Adequacy, Utility and Repair Choice

“We do roads that are supposed to last 20-30 years and they last 16. We can do repairs that last 7 to 10 years to keep the roads up to par.”(Interview-GM)

“ But funding won’t allow it. You do something to keep overall costs down, You want to reduce clams and complaints. So constraints make us more selective.” (MNCT)

## 6.6 Labor

The hiring of labor in the reference mode is based on a replacement as quit concept. (A second formulation, described in Chapter 4 was created so comparisons between both processes can be evaluated, Figure 6.23). It was felt with inadequate labor supply, a short-fall in productivity could lead to a decline in road condition for no other reason than poor planning at the local level.

Teams are employees of the local departments of transportation. These teams are responsible for Patch and Overlay repairs. Teams are allocated as a percentage of road in need of maintenance. The adequacy of the budget effects the allocation of teams and repair productivity.

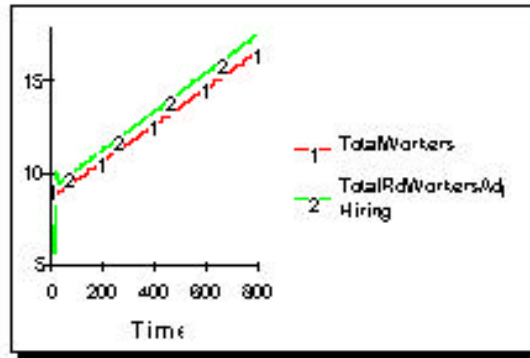


Fig. 6.23 Results of Adjusted and Unadjusted Hiring Practice

[Curve 2 is adjusted for growth and development, while Curve 1 is a simplified model for hiring to replace losses.]

## 6.7 Paving

Employees of the system do not perform Pave repairs. Such repairs are contracted to vendors in place. Therefore, a separate method for determining the amount of pavement work was necessary. To control the amount of paving, the effect of budget adequacy is used to change the length of paving contracts. As budget adequacy falls the time desired for completion of a contract increases. The effect is to decrease the amount of paving required per period, which reduces the number of contracts, and thus productivity in terms of Pave repair accomplished.

### 6.71 Critical PSI Value (CVP)

Budget adequacy also impacted the critical value of the system. As budget adequacy decreases the critical value is lowered. Lowering of the critical value allows more Patch repair to be carried out at lower costs. With a higher critical value less Patch and more Overlay repairs, at higher costs, are accomplished. This captures the constraint in the allocation of available funds as described by Shahin (1994) in previous sections of this dissertation.

The critical value chosen for this model was a PSI of 2.5. At 100% budget adequacy the CVP is equal to the chosen CVP. In the case of the reference mode this value is 2.5. As

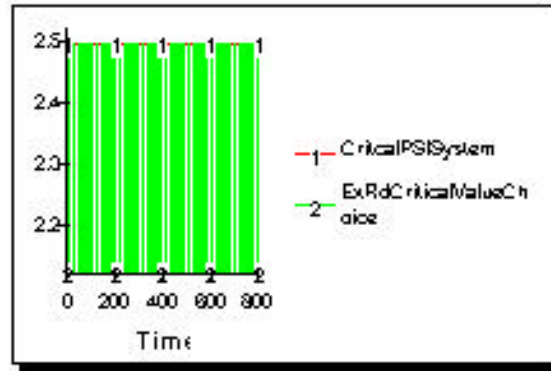


Fig. 6.24 Response of the Critical Value to Budget Adequacy .

the budget adequacy falls, the CVP is lowered. The lower the CVP the more Patch repair is undertaken. As Patch repairs are less costly than Overlay or Pave repairs the decrease in available funds is slowed down. Variation in the value of the CVP can be seen in Figure 6.24.

### 6.72 Repair Choice

The amount (percentage) of miles chosen is determined by using the systems PSI and the amount of miles of damage to a particular road category. The section of Poor roads is based on the PSI. Roads are paved when the value of the system is below a PSI of 2.5. In this model, as Poor roads are at a value of PSI 2, they are constantly being paved. The amount of Poor road selected is determined by, 1) the relative amount of road that has deteriorated and become unusable and 2) the amount of repairs accomplished. The repair of excellent, fair and Good road is based on the amount of deterioration of each of these categories respectfully.

As the accident rate increases in this simulation the utility choice of maintenance or paving is effected by the accident rate. The effect is to decrease the percentage of

maintenance, which has the effect of increasing the percent of Pave repair undertaken. As the budget adequacy falls below 30%, the utility function again becomes the method of choice for controlling the choice of repair type. The 30% threshold was chosen as managers indicated that when 30% of the budget remains they tend to slowdown and consider how much of each type of repairs should be undertaken. In this case, the 30% threshold acts to dampen the response to the accident rate, but is not overzealous. More details of this process will be discussed in the section on knowledge added in this dissertation.

## 6.8 Life Cycle Costs

In addition to actual costs incurred and projected future costs, the pavement management process also considers the effects on total system life cycle costs. Life cycle costs, Figure 6.25, include those related to accidents, vehicle operating cost, and the cost of waiting during repairs (formulation based on the work of Zaghoul (TRR 1539: 108).

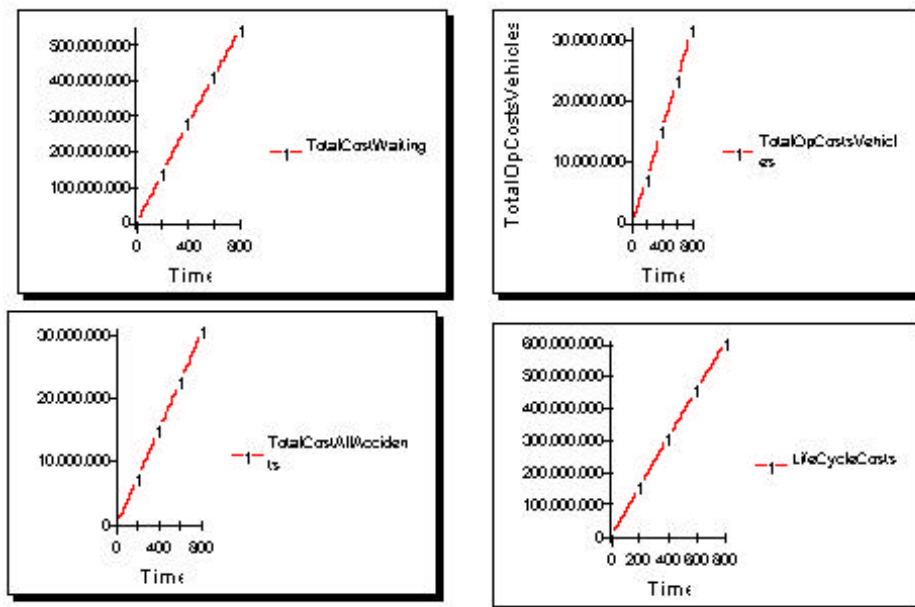


Fig. 6. 25

Life Cycle Costs as a result of Policy Choice



The next section will select key variables that will be compared to the base reference run. Changes in the assumptions made by management will be enacted as policy changes and the results on the selected key variables will be evaluated for their effects on the improvement of the operations of the system problem.

## **6.9 Policy Testing**

Saeed (Working Paper) has suggested the development of a policy space. In the simulation model, developed for this dissertation, several modes of operation have been considered. The model can be simulated starting with either a mix of road, with a PSI below 5, or with all Excellent road or PSI equal to 5. There are four budget modes available, these are:

- 1) A constrained budget (reference mode) that allocates a fixed amount at the start of the simulation and is reduced each year until a constant 47% of budget is allocated to the system.
- 2) A semi-constrained budget, where the amount requested is dependent on the mile needed to be repaired and is reduced as in the constrained mode.
- 3) A constant budget.
- 4) Constant (able to be multiplied)
- 5) A budget which can be increased, by the use of a multiplier parameter, of a requested budget.
- 6) Short-fall carry over-each year's short-fall is added to the next year's budget.

Current operating assumptions are listed in the introduction to this chapter. Each of these assumptions require evaluation. A matrix (Chart 6.1) indicated the possible mix of experiments available. For reasons of practicality, experiments will be carried out with mixes of road with a PSI below 5. This was chosen as most road, except new, is valued at this level.

	Mixed Road PSI less than 5				All Excellent road PSI equal 5			
Policy	CB	SCB	UCB	MB	CB	SB	UCB	MB
Winter Repairs								
Category								
RSL								
Quality Assigned								
Accident Repair								
HR Hiring								
Regional Planning								

CB:--Constrained Budget, SCB: Semi-Constrained Budget, UCB-Un-Constrained Budget, MB-Multiplied Budget

Table P 6.1 Policy Test Matrix

In addition, several assumptions, such as the preference of weights used in the utility mode or rules governing paving and the timing of budget availability, can be relaxed to explore their impacts.

### 6.91 Quality Assigned to Repairs

It was discovered during interviews that managers tend to record a better quality of repair than is required. If a repair should give back to a road a PSI of 4, managers tend to give back more. In this simulation, Good road is normally scored as 4 and Fair road as 3. The operating values in the reference mode are Good road as 4.3 and Fair road as 3.3.

Small towns are not alone when it comes to this problem.

“At this time the existing enhancement program is approximately \$10 million over-programmed primarily as a result of cost increases experienced by projects selected for funding in previous years. As such, there is the possibility that all of the first year funding made available under the new legislation and perhaps a portion of the second year will be used to complete these previously selected projects.” (Project Development Process Review January 2000. Appendices-Southwestern Regional Planning Council Appendix 16 :3)

In evaluating the impacts of current policy, the expectations were that the current policy would create a perception of a higher quality PSI. However, a higher quality road creates more spending. (See Note 3 for an explanation of this apparent counterintuitive behavior) More current spending drives down future costs. However, in reality real future costs would be higher. Therefore, managers are operating under a perception that does not prepare them for the real costs of the system in the future. The simulation and data collected verify this process.

Under the existing reference mode condition, a test, comparing the correct versus incorrect quality assessment was run. The results of this comparison are seen in Figure 6.26 a-e and Table 6.1a.

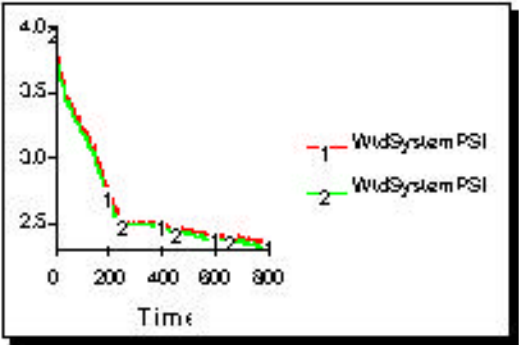
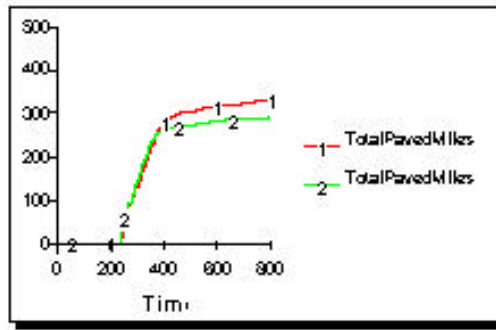
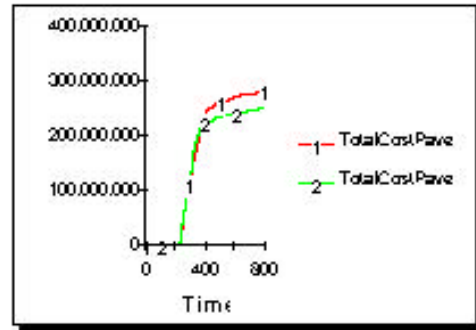


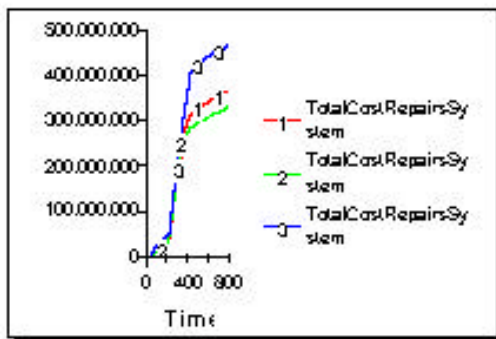
Fig. 6.26a  
 Curve 1 is the incorrect PSI (base run) with repairs given a higher than normal rating



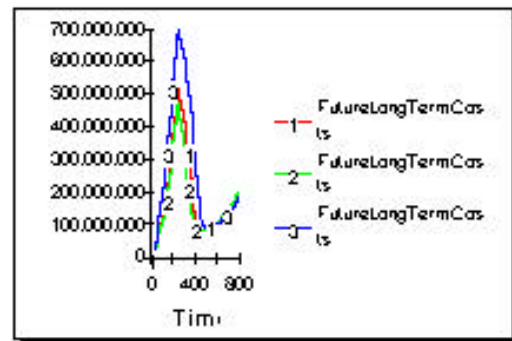
Paving Repairs  
b



Current Spending  
c



Current  
d



Future Costs  
e

Fig. 6.26 b-d Relationship Between Repairs and Cost

In addition, a simulation run using a non-constrained budget was executed, the values for all three runs are seen in Table 6.1 (Values for current spending and future costs were captured on an excel spreadsheet and are presented for clarity).

FutureCosts	CostRepairs
186,396,528.00	470,589,772.00
204,817,888.00	333,105,156.00
196,612,655.00	370,958,763.00

See Figure 25 d-e and note 3

\*Lower row is from the base run with incorrectly assigned higher PSI.

Middle row is correctly assigned PSI

Upper row is from a run with incorrectly assigned PSI and unconstrained budget ( Note greatest total paving and lowest implied future costs in row one).

Table 6.1

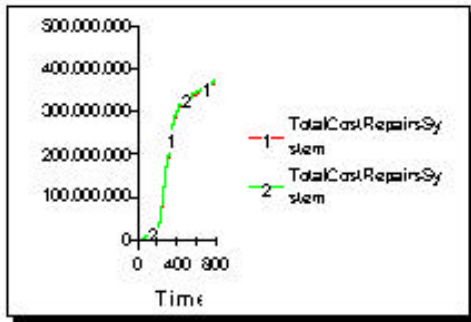
Data from the base run shows that:

Higher applied quality increases current planned expenditures and reduces apparent long-term costs. Lower expected future costs would lead to improper budget planning and an inability to carry out future projects correctly (The effects are revealed in the report sited from the state of Connecticut above).

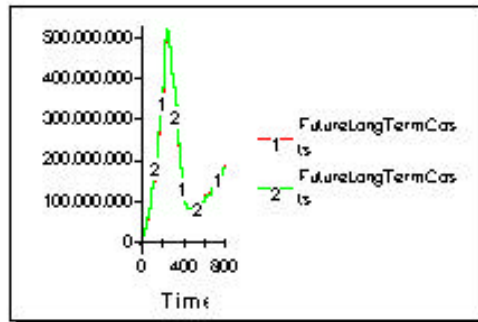
It appears that this practice needs to be changed. In addition, allocating more resources only exacerbates the problem as seen in (row one Table 6.1). Therefore, either change the practice or maintain a constrained budget.

### **6.10 Winter Repair Policy**

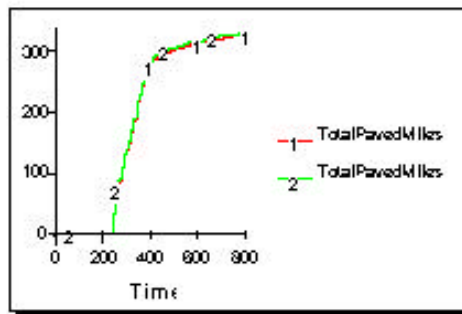
As detailed in Chapter 4 on formulation, managers do repairs in winter, causing a more rapid deterioration of roads and an increase in the number of times repairs need to be performed. The current formulation does not allow paving of Fair and Good road in winter. Further, paving in warmer seasons is prevented until the PSI of the system falls below the residual life value of the PSI, currently set at a value of 2. Paving of Poor road in winter is permitted based on 1) accident rates demanding better road conditions or 2) the PSI falling below the residual life value. In addition, Poor road is overlaid in winter months. A run comparing no winter repairs to the base-run policy (winter repairs allowed) was carried out. The results of this test prove interesting (Figure 6.27 a-c). If repairs are not permitted in winter, current repair costs are higher accompanied by slightly lower future costs. Total repairs for all categories are slightly higher (Paving repairs are shown as an example). The PSI of the system, however, is slightly better. (Table 6.2). During the winter, the repair productivity is 75% of normal non-winter productivity. This parameter was used to accommodate the difficulty of dealing with the effects of poor weather conditions on both repair capabilities of crews and lost days of work.



Total Cost Current Repairs  
a



Future Costs  
b



Miles of Paving  
c

Fig. 6.27 Comparison of Winter vs. Non-Winter Repairs  
(Curve 2= No winter repairs)

In addition, the deterioration rate of road paved in winter is three times the normal deterioration rate, accounting for multiple repair processes.

Per.PSI

2.362152

2.361989

FutureCosts	CostRepairs	TotalPave	TotalCostPave
191,787,044	375,014,088	338	287,467,279
196,612,655	370,958,763	334	283,965,133

\*Upper row of PSI and Costs: No paving in winter.

Table 6.2

The PSI improves as more Pave repair is achieved. The overall impacts do not seem to have a major impact on the system's current characteristics, except for reducing long-term costs and increasing current spending slightly.

As stopping repairs in winter improves the PSI, does not increase costs excessively, and lowers future costs, I would think preventing winter repairs would be a more appropriate policy. Note, however, this is a personal value judgement.

### **6.11 Correct Categorization of Roads**

The dynamics of this experiment require a detailed evaluation of current assumptions. The reference mode is formulated with an incorrect approach to classification. Managers apparently believe that road that is not repaired, but is aging, does not deteriorate to the extent that a more costly future repair is required. The formulation in the model is designed to distribute road repairs in two modes as follows:

Reference (base)

Incorrect classification

Patch not selected for repair flows into a 36-month delay process and is repaired either by Patch or Overlay repair.

### **6.12 Correct Classification of Roads**

Patch not selected for repair flows into the same delay but is repaired using Overlay only. A sensitivity analysis evaluating the impacts of assigning some portion of non-repaired excellent miles to Poor road was also performed. The results will be discussed after the preliminary discussion of classification output.

An analysis of the dynamics reveals that when incorrectly classified more road flows through both fair and Good road, Figure 6.28.

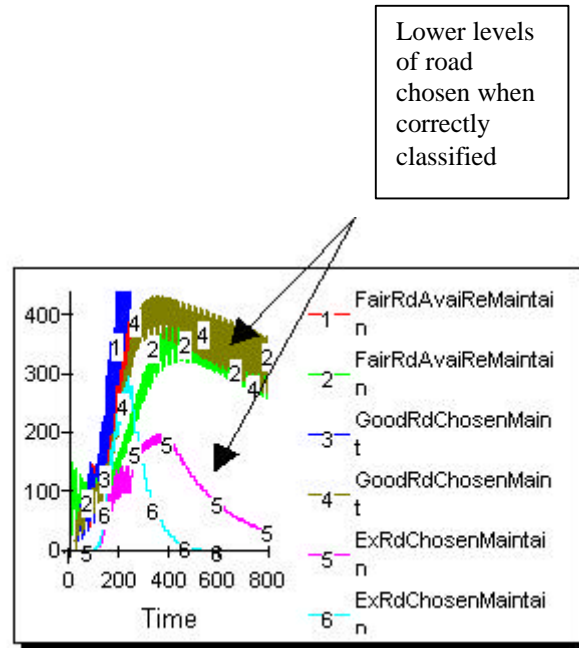
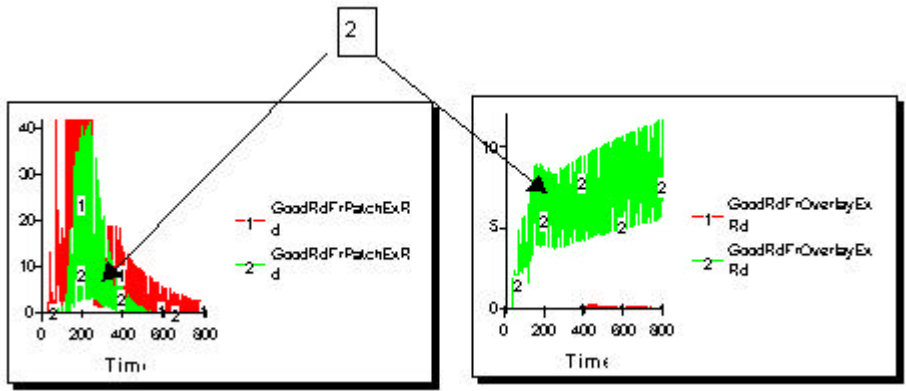


Fig. 6.28 Chosen for Maintenance  
 Curves 2,4,6 are correct classifications-note how each is less than its counterpart Curves 1,3,5.

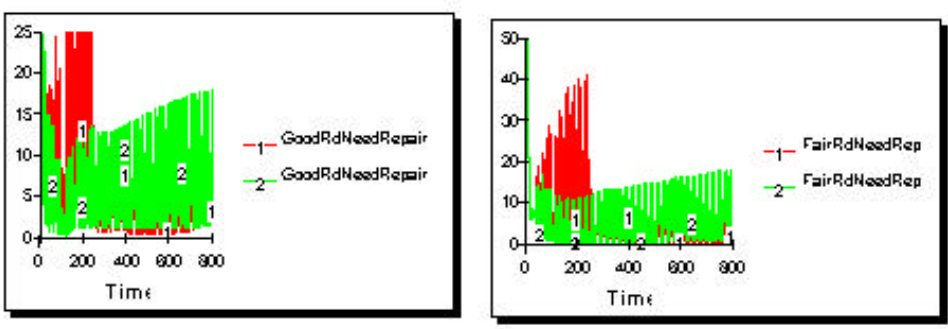
When correctly classified a trade-off is made, as road that would have been Patched is now overlaid, Figure 6.28a. In addition, the amount of Good and Fair road requiring repairs is reduced. Figure 6.29 (Figures 6.29a and Figure6.29 b show all road that has been maintained. The differences between the two levels of road are due to the amounts of delayed road only and the method of repairs, as all other rates were not changed).

The change in costs related to the change in classification of road is seen in Figures 6.30 through 6.32.





Amount of Good road created from maintenance of  
Patch chosen for repairs\*  
(Curve 2 is the result of correct classification)  
a



Amount of Repair Needed By Good and Fair roads\*  
b

Fig 6.29 Amount of Needed Repairs

The trade-off comes at a price. The life span of Overlay is greater than Patch, but costs more, Figure 6.30.

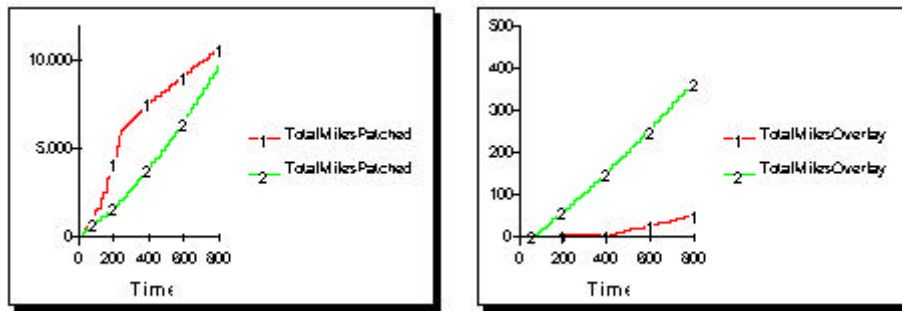


Fig. 6.30 Costs and Change in Maintenance Due to Classification of Roadway

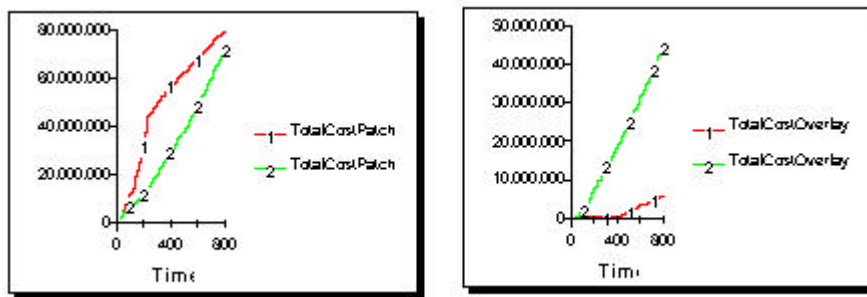


Fig. 6.31. Cost Shift Between Patch and Overlay

The relative cost of current maintenance are increased, Figure 6.30

However, overall current costs are reduced, Figure 6.32 and Table 6.3.

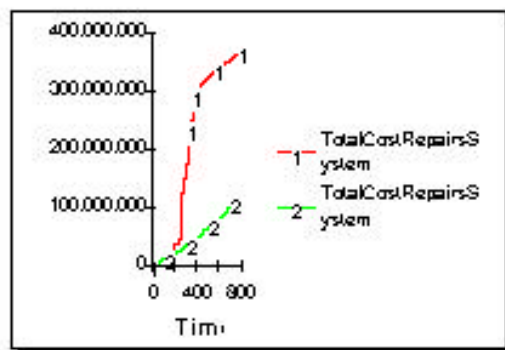


Fig. 6.32 Overall Current Costs

This is due to the large amount of paving not performed

TotalPave	TotalCostPave	TotalOverlay	TotalCostOverlay	TotalPatch	TotalCostPatch
0.8254234	701,609.90	367.0407	44,778,964.00	9,698.59	72,739,428.00
338	287,467,279	51.79879	6,319,453.00	10,830.31	81,227,356.00

Upper row is correct classification of miles

Table 6.3

The amount of Overlay performed with a longer life span than Patch reduces the near term amount of repairs needed. However, the simulation bases future costs on the amount and type of work predicted as needed. (The formulation described in chapter 4, predicts more Overlay in the future as a choice based on the amount of Overlay used during current repairs). Figure 6.33 indicates that the amount of future maintenance (a) will fall while estimated paving (b) required will rise. This is expected as the Overlay creates a longer life span, eliminating the need for near future Pave repairs, but leaves much road unpaved.

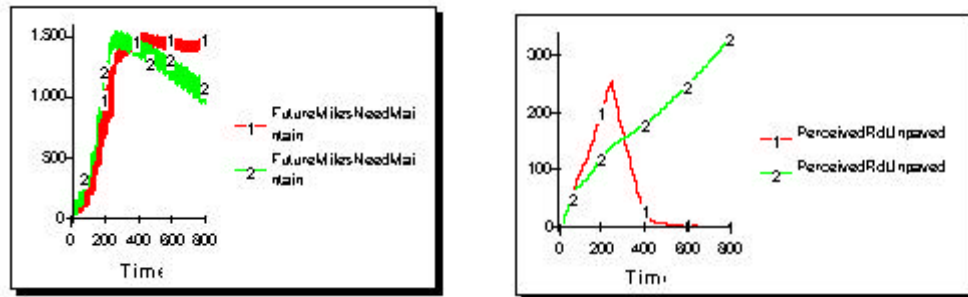


Fig. 6.33 Predicted Maintenance Needs

Estimated Paving Left

Therefore, predicted future Pave and Overlay costs are extremely high, Figure 6.34. The improvement in PSI value comes at lower costs, as Overlay is less expensive, but leaves the system with what is probably too great an increase in future costs.

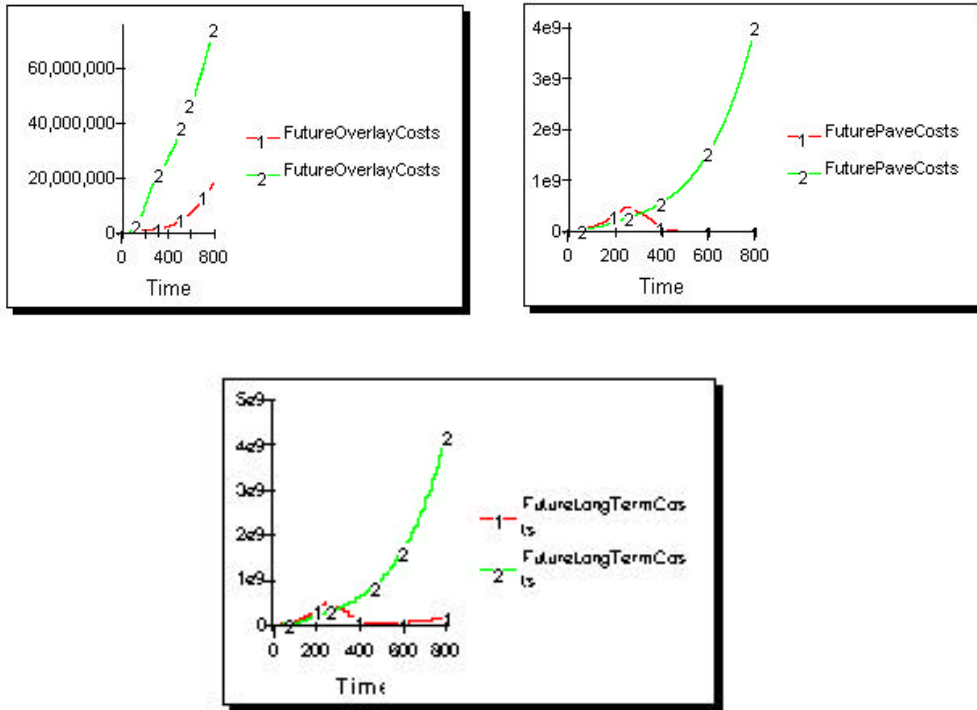


Fig. 6.34 Estimated Future Costs to the System

However, the impact on the current state, by correctly classifying the roadway and doing appropriate repair, is to improve road quality and therefore have a positive effect on a region's development, Figure 6.35.

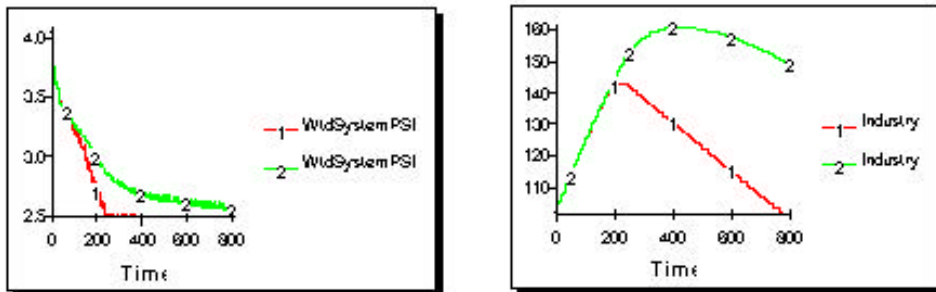


Fig. 6.35 Overall Effect on Quality of the System and Impact on Development

As the classification process effect short and long terms costs, and PSI, a sensitivity test was run on the effect of changing the percentage of miles chosen for the correct delay process to determine the effect on the system. (Previous runs were 0% and 100% correct). The percentages used in the sensitivity test were 50% and 25% allocation of Excellent road to Good road (with delay) and the balance of the non-repaired road deteriorating to Poor road. The results provided a better understanding of the dynamics of incorrect classifications and implications for a better understanding of policy change impacts.

As the percentage of road assigned to delayed repairs decreases (i.e. less road deteriorates to Good road and more road is deteriorating to a Poor road level) more Overlay repair is carried out. The result is a change throughout the system).

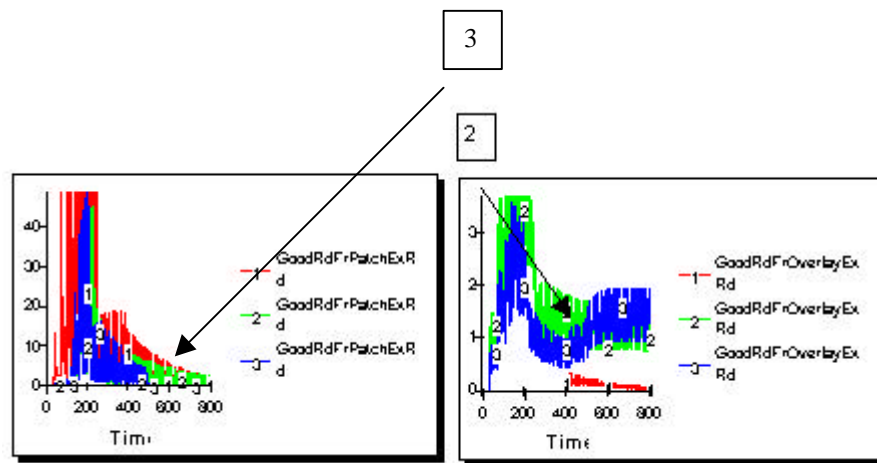
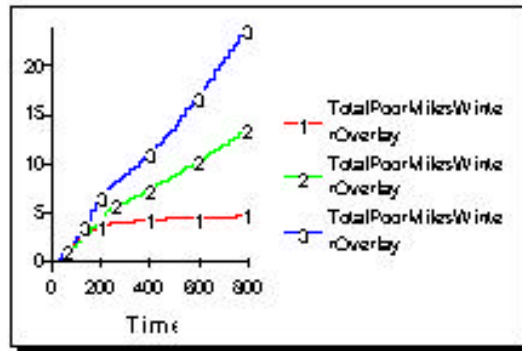


Fig. 6.36 Shift in Overlay and Patch Work Accomplished on Good road (Curve 1 = base run or 100% Incorrect)

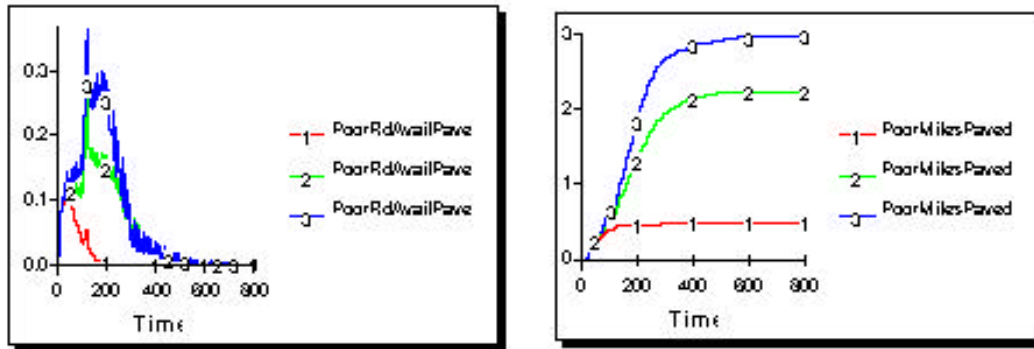
1. As expected, the amount of both Overlay and Patch work performed decline, as more miles are shifted to Poor road, 50% and 75% respectively (Figure 6. 36). Curve 2, show the effect of assigning 50% of non-repaired road to Poor roads, while curve 3, represents the effect of a 25% allocation. Before 200 months, the budget has not become constant and the Critical Value Point has not been reached. Patch repair will be the method of choice, but note that with 25% of road correctly classified the amount of road achieved from Patch declines.

The level of Patch continues to decline after the budget and CVP shift as now with a correct classification, no Patch repair of delayed Excellent road is taking place.

2. As more miles are shifted to Poor road, 50% and 75% respectively, the amount of Poor road overlaid, Figure 6.37a and paved, Figure 6.37b, increases.



Impact of Correct Classifications on Overlay of Poor Miles  
a



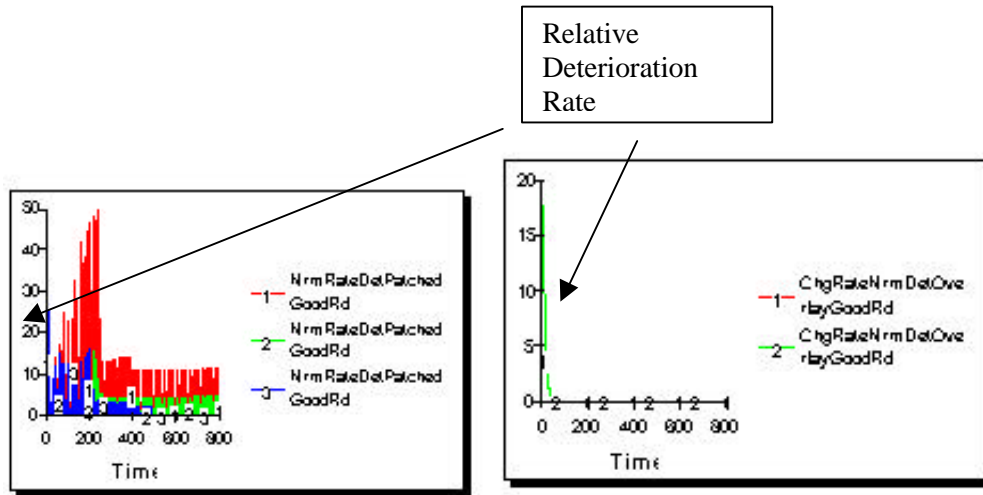
Impact of Correct Classification on Paved Poor Miles  
b

Fig. 6.37 Impacts of Road Classification

In addition, the rate of deterioration of Patched road is greater than the rate of deterioration than overlaid road, Figure 6.38. The total amount of deterioration declines as the percentage of road declines going into the delay process.

The amount of Good road created and the resulting Fair road are shown in Figure 6.39. Clearly, any increase in the amount of Good road is due to the increase in Overlay of

Excellent road as less Patch repairs are performed. This occurs even though overall Good road from Excellent road decreases, due to the drop in the percent allocated.



Relative Deterioration Rates of Good road by Category of Repairs Performed

Fig. 6.38

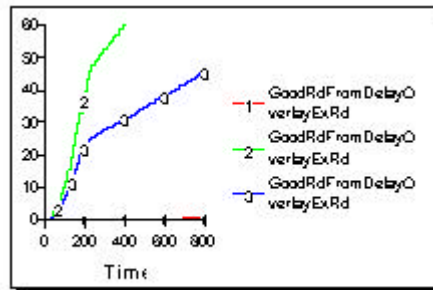


Fig 6.39

Amounts of Good road from Delayed Excellent road

The decrease in the amount of Good road is due to the percent selected for delayed Excellent road.

What is taking place? (It is important to note that Overlay and Patch repairs are also accomplished on non-delayed Patch. The graphics were used to show the effects of delayed processes, while spreadsheet outputs capture the total effects).

Apparently, a more correct classification trades Overlay for Patch repair and in the process shifts the amount of paving required. At 100%, or no road classified as poor, the system puts off Pave repair as Overlay improves road conditions. With a decrease in correct classification the PSI tends to improve to a point, Table 6 4.

Per.PSI

2.089243  
 2.222623  
 2.577968  
 2.361989

Upper row = 25% to Good, Second row =50% to Good, Third Row=100% to Good,  
 Lower row = base run

Table 6 4

At 100% assignment of delayed Patch being overlaid, rather than patched, the current cost of Pave repair is reduced. No road flows directly to Poor road. At 50% and 25% of road assigned to the delayed process, 50% and 75% of road, respectively, flows directly to Poor road.

While more Poor road is available for paving, Figure 37, more Poor road can also be overlaid, Figure 40. The increase in Overlay occurs because Poor road, which is not repaired in winter, can be overlaid during this season. The total volume of Overlay decreases as less road passes through Good and Fair roads. The volume of Overlay from Poor road is greater than the loss from Fair and Good road and total Overlay is increased. As Overlay increases there is a tradeoff with Paving. With more road being classified as Poor and less paving the PSI tends to fall.

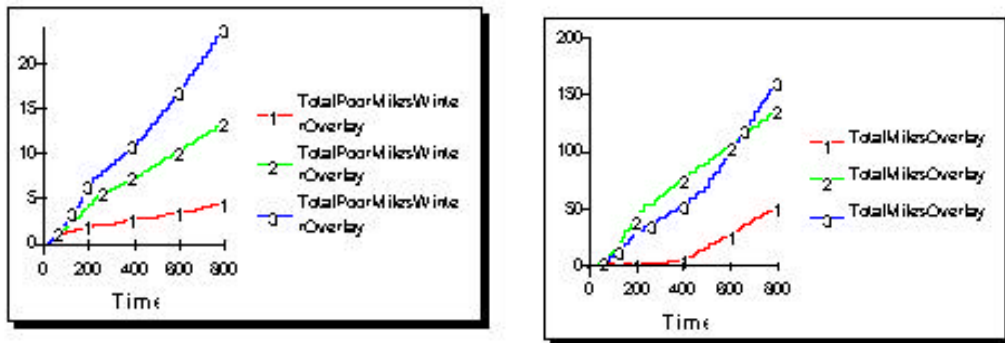


Fig. 6.40 Overlay of Poor road  
 Percent assigned to delayed road: Curve 1=100%, Curve2=50%, Curve 3=25%



The system is trading both Patch and Overlay for Pave repair. Note that as Overlay increases the cost of Pave repair and Patch go down and when Overlay decreases the cost of Pave and Patch go up. Table 5a shows Pave costs and 5b the costs of Patch and Overlay performed.

Cost of Paving

TotalPave	TotalCostPave
124.9222	106,183,846.00
135.6868	115,333,800.00
0.8254234	701,609.90

a

Bottom Row 100%, Middle Row=50%. Top Row=25%

TotalOverlay	TotalCostOverlay	TotalPatch	TotalCostPatch
163.2922	19,921,650.00	2,867.93	21,509,477.00
137.365	16,758,525.00	4,040.41	30,303,059

B

Bottom Row =50%, Top=25%

Table 6.5

As total current costs are reduced future costs increase, Table 6.6.

FutureCosts	CostRepairs
523,718,770.00	147,614,973
363,211,935.00	162,395,385.00
4,235,508,475.00	118,220,003.00

Table 6.6

The implications for the system are consistent with what managers have reported. It appears that any lower current costs, even those created with better choices of short-term maintenance, decreases current paving and increases the future expected costs of the system. If 100% of road is treated, with Overlay, long-term costs are too high to be acceptable. If 25% of road is treated with Overlay, the PSI of the system is too low. At roughly 50% of delayed road being overlaid, the PSI falls into a mid-range of PSI 2.22, the current costs of repair seem acceptable, and future costs are more acceptable than the alternative repair recommendations.

## 6.12 Residual Life Value

As the impacts of the last test dealt with the impacts of an operational policy on paving it was determined that it would be appropriate to evaluate the paving process. The evaluation was accomplished by changing the Residual Life Percentage. The base run uses a value of 50%. This RSL value was adjusted from 50% to 65%, and 85%. The values were not lowered, as recommendations from the literature review, indicate that these are the only acceptable values.

The results of the run are seen in Figure 6.41. As the residual percentage point is increased, the system initially does better. However, each time the system reaches the Critical Value point the system quality reversus and values of systems that were initially better become worse.

As the RSL increase, the total current costs become slightly higher, Figure 6.42a, while future costs become considerably lower, Figure 6.42b.

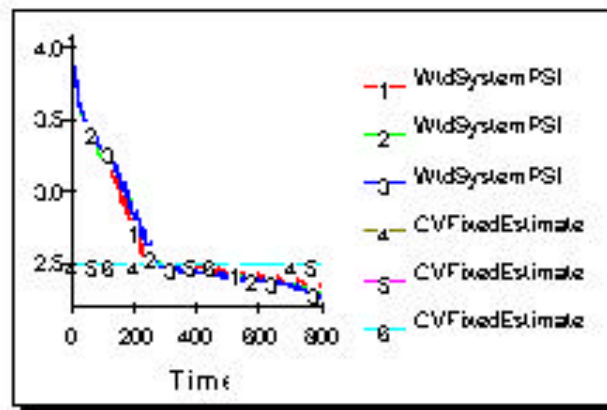
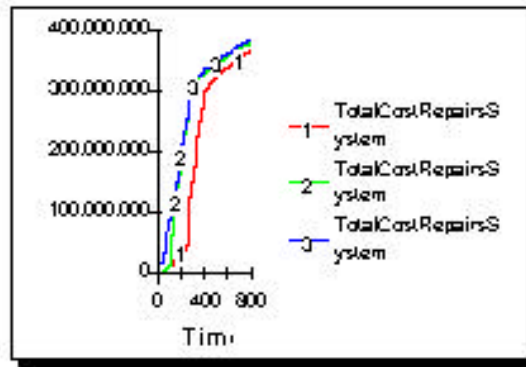


Fig. 6.41 Change in PSI with an increase in RSL Percentage Value  
Curve 1=Base Curve 2=.65 Curve 3=.85

Although, overall the system does better, Figure 6.43, for a relatively, overall, increase in current expenditures it still does not avoid collapse.

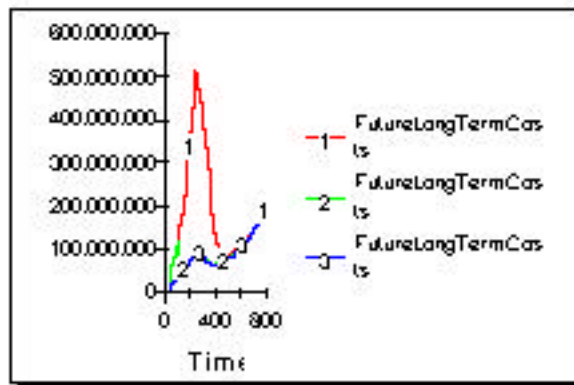


a

Fig. 6.42

Total Current Costs

The findings reinforce those of the previous section. As the system starts to use Overlay the relative gain in the PSI decreases. Improvements using Pave repair, have the best impacts on the system.



b

Fig. 6.42

Future Costs

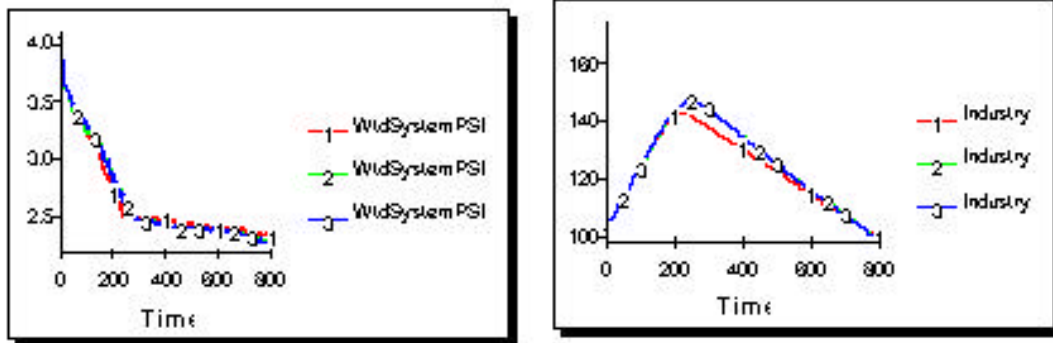


Fig. 6.43                      PSI                                      Industry Response

The preliminary results show a reversal of the PSI quality, just below the Critical Value Point of the system, Figure 6.44. What causes those dynamics?

As the RSL is increases, the time at which Pave repair is initiated from all sources is reduced. An overall increase in Pave repair occurs and Overlay is also initiated sooner, Figure 6.45.

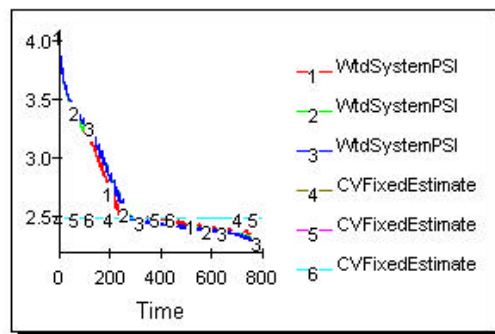


Fig. 6.44      PSI of System and Relationship to Critical Value Point

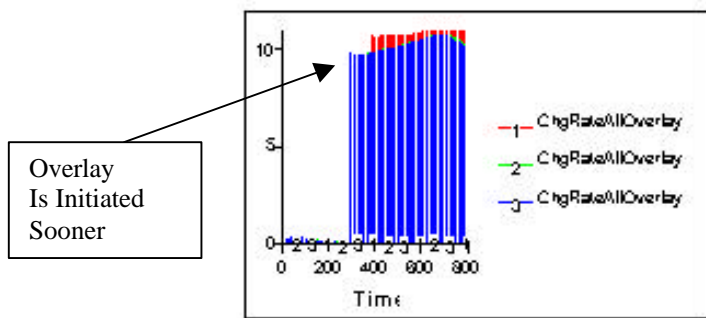


Fig. 6.45                                      Overlay Repairs

This is due to the following process. As Poor road is paved it becomes classified as excellent and the amount of road that deteriorates per unit if time actually increases, so that the time to reach the Critical Value Point (CVP) is shortened. (While Pave repairs are used as an example, this holds true for all forms of repair).

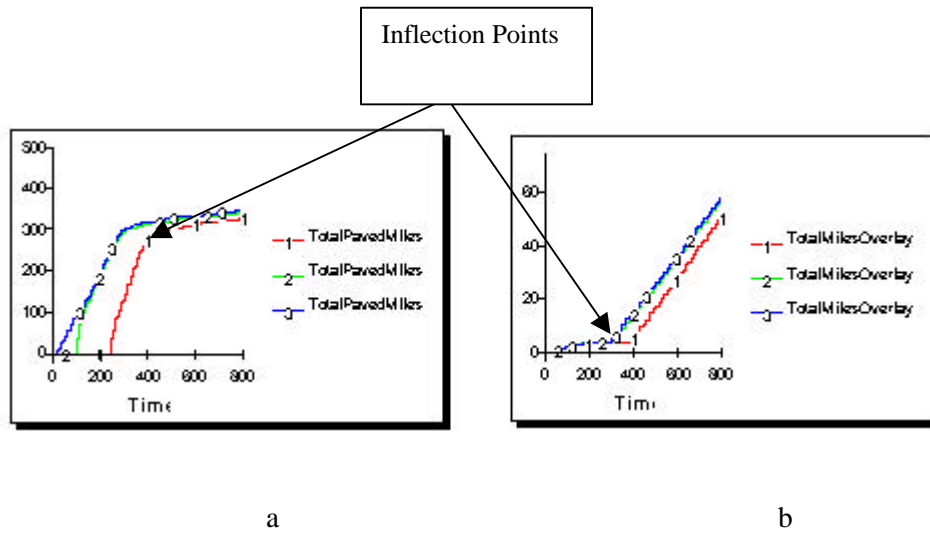


Fig. 6.46 Overlay versus Pave Repair of Roads

The data in support of this explanation is seen in Table 6.7.

TotalPave  
 352.9235  
 348.4988

DetRatePave  
 1.470514583  
 1.452078333

Top row RSL=.85

Lower RowRSL=.65

DetRatePave=(Expected total miles/Deterioration Rate of Paved repair)

Table 6.7

When the CVP set at 2.5 and the RSL is .5, both Pave and Overlay repair initiate at the same time. The point of inflection for Pave repair coincides with the inflection of Overlay. At this point, the budget favors Overlay repair as opposed to Pave and Patch repair.

Paving, which starts sooner and costs more, utilizes the initial phase of the budget (months 1-200), Figure 6.47. When the budget falls and becomes constant, and the CVP point is reached, Overlay becomes the preferential repair process. The findings also reinforce those of the previous sections. As the system starts to use Overlay, the relative gain in the PSI decreases. Improvements, using Pave repair, have the best impacts on the system.

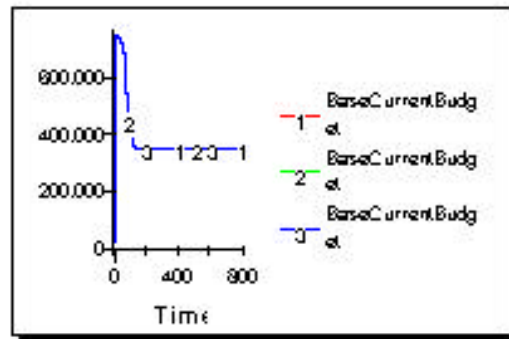


Fig. 6.47 Current Budget

While Overlay is increasing Patch repair is decreasing and the rate of all paving decreases (note inflection) as can be seen in Figure 6.46b. and the reduction in paving seen in Figure 6.48 With a higher RSL Pave repair starts sooner but is curtailed as Overlay is initiated.

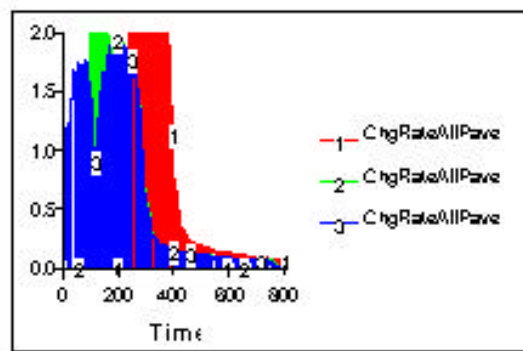


Fig. 6.48 Comparative Rates of Paving

Note the Pave repair drop off for both Curve 1 and 3 both start after 200 months. Curve 3 starts sooner with a higher RSL).

### 6.13 Critical Value Evaluations

In order to evaluate the effect of Overlay on the PSI and its impacts on Pave repair, a set of tests evaluating the Critical Value Point alone and in combination with the RSL were performed. The Critical Value Point of the base run is a PSI of 2.5. This was tested at a PSI value of 2, 2.5, and 3 to evaluate the effects of the change. The expectation was that a higher Critical Value Point should create a better PSI, with reduced Pave and less Patch repairs being preformed.

Figure 6.49 indicates that an increase in the CVP causes Overlay repairs to start at an earlier time. The graph vertical scale has been reduced to allow clarity in the visualization of the time of Overlay initiation.

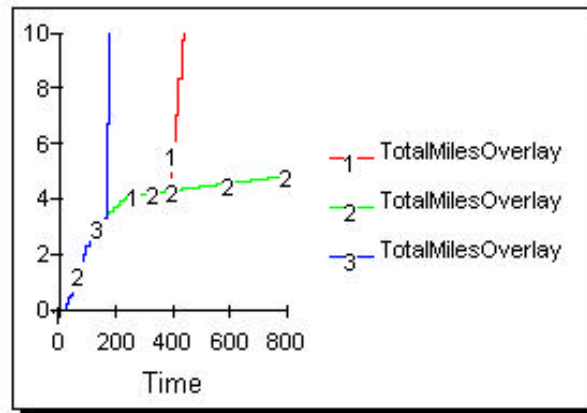


Fig. 6.49 Initiation of Overlay Repairs in response to change of the CVP

Both the time before the system falls below a PSI of 2.5 Figure 6.50a, and the time the system is either above or equal to PSI, Figure 6.50b are improved by increasing the amount of Overlay. At the same time, both the PSI, Figure 6.51a, and the state of development, Figure 6.51b, also shift in a positive direction.

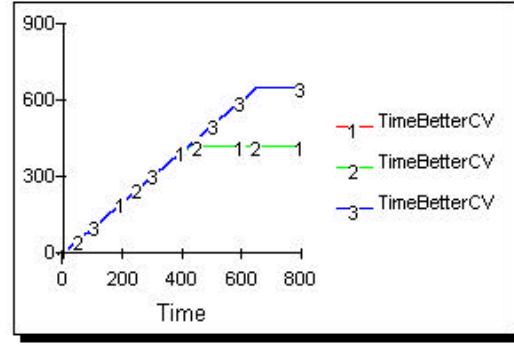
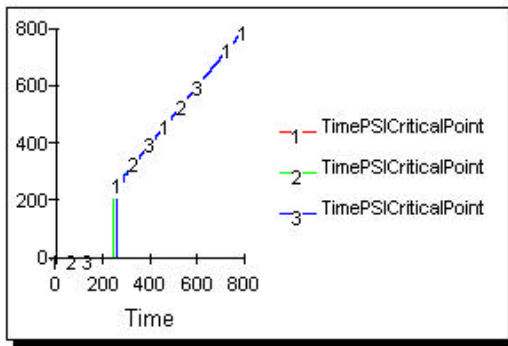


Fig. 6.50                      a                      Time Before System Lower than 2.5                      b                      Time system above or equals 2.5

(Curve 1=CVP 2.5, Curve 2=CVp 2, Curve 3=CVP=3)

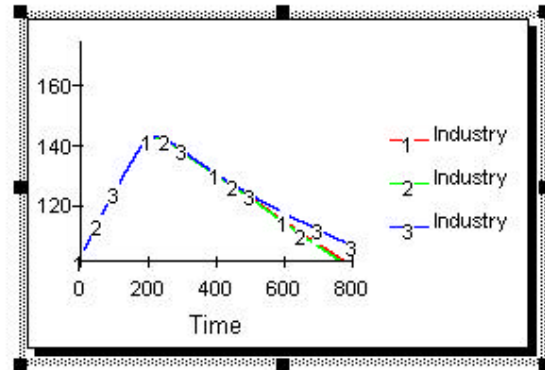
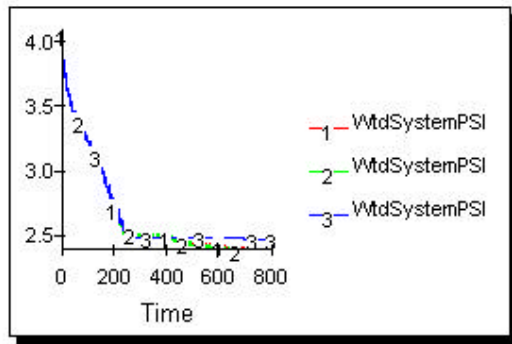
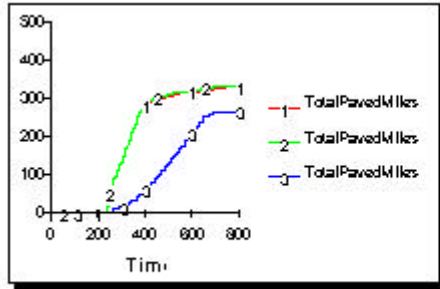


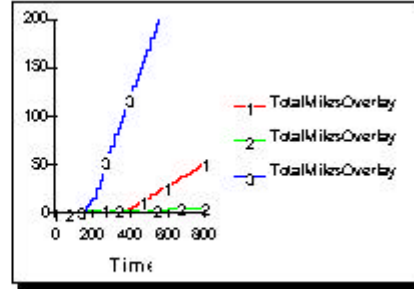
Fig. 6.51                      a                      PSI                      b                      Industry

Total miles overlaid increases, Figure 6.52a, thus reducing paving Figure, 6.52b, and overall costs of current spending, Figure 6.53a. However, the system is then faced with larger future costs, Figure 6.53b, and Table 6.8.





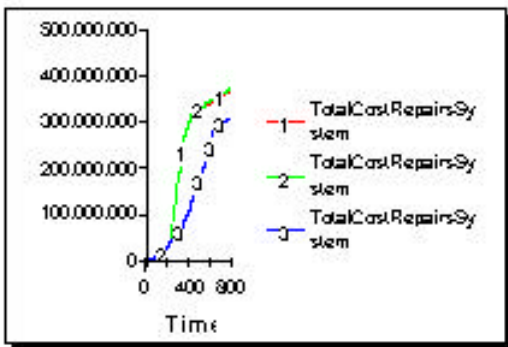
a



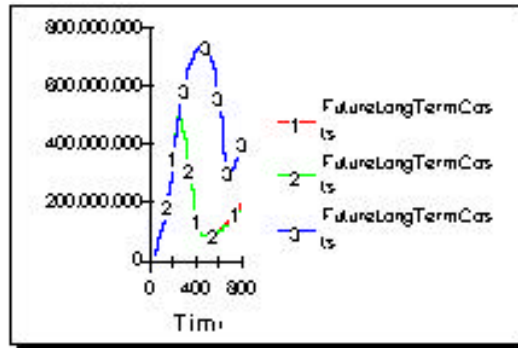
b

Fig. 6.52 Total Paving Response to CVP

Paving Overlay to CVP



a



b

Fig. 6.53 Current Spending

Future Costs

Values from the spreadsheet are shown to clarify the results

FutureCosts	CostRepairs
406,424,933.00	312,279,264.00
177,981,539.00	375,648,749.00
196,612,655.00	370,958,763.00

Top Row: CVP=3, First Row: CVP=2.5, Bottom Row: CVP=2

Table 6.8

(Note: As current costs decline, future cost increase)

### 6.131 Critical value and RSL Cross Impacts

To determine if there was an interaction between the CVP and RSL several tests were performed. The mix used in this test were CVP of 2 and 3 and RSL values of .75 and .85

CVP=2, and CVP=3 with an RSL=.65

CVP=2 and CVP=3 with an RSL=.85

The PSI shows very little change when the value of the RSL increases by 20%, Figure 6.54. However, when a CVP of 3 is used Overlay is initiated before Pave repair, combined with less Patch repair work. As Overlay increases relative to Pave repair the PSI decreases.

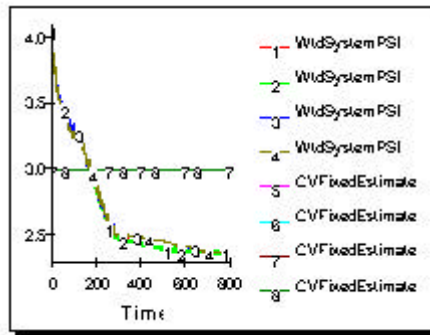


Fig. 6.54 Critical Value and RSL Combined Impacts on PSI

While difficult to visualize, in Figure 6.54, the values in Table 9 reveal an interesting relationship. As Overlay increase relative to Pave repair the value of the PSI decreases. The effect is due to a combination of the two processes. Paving occurs at the rate of 1 mile/month and Overlay at 5 miles/month. While a month of Overlay is worth five times the value of Pave repairs, paved road deteriorates over 240 months and overlaid road over 84 months. The Pave repair lasts almost three times as long. (Further, except for Overlay work done on Poor road, Pave repair is the only means to increase the road value to excellent or a PSI of 5. More Overlay means that roads are passing through Good or Fair roads, with a lower PSI value. The difference in the lower Overlay life span appears to account for an overall drop in the PSI.

TotalPave	TotalOverlay
308.1305	305.6819
312.4583	308.768
359.5466	4.671276
354.8686	4.894008

Upper Row CVP= 3 RSL .65  
 Second Row CVP=3 RSL .85  
 Third Row CVP 2 RSL .85  
 Lower Row CVP= 2 RSL .65  
 Table 6.9

Per.PSI  
2.371421  
2.371475  
2.373512  
2.373894

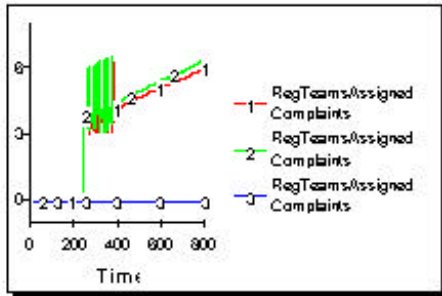
Note: When paving is high terminal PSI is higher than when Paving is low.  
Paving is high when Overlay is low and vice versa.  
Table 6.9 (Continued)

Substitution of Overlay for paving eventually lowers the PSI, as has been shown in other sections.

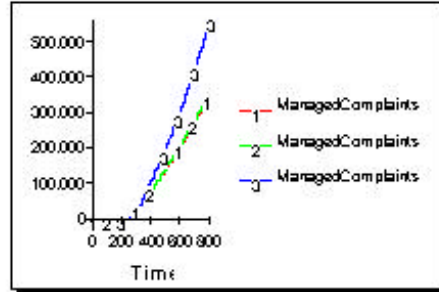
#### **6-14 Human Resource Hiring**

Current policy is population dependent. The ratio in use is one new-hire per 1600 population (Set by the town planning board from which information was obtained). No adjustment is normally made for quits or growth. To test the possibility that present policy may lead to lower than needed labor recruitment, and lower repair capability, simulation runs comparing the current policy against a policy designed to consider future needs were done. Additionally, teams are now assigned out of the number of employees the town now has which do repair work. Currently, the same crews that do repair work manage complaints. A policy allowing for hiring of crews as needed to manage complaints was also tested. This entails additional costs, which are not included in the normal budget process. (It was assumed that the reduction of the budget by the extra costs would effect the allocation of repair crews. The balance between freeing crews for repairs only, versus the slow down in repair productivity caused by a lower available budget is an unknown and needed to be evaluated).

The addition of a separate source of labor, Figure 6.55a, clearly helps in the management of complaints, Figure 6.55b. With the addition of extra teams, the number of complaints managed shows a marked increase, Table 6.10. The additional cost in salary is seen in Figure 6.56.



a



b

Fig. 6.55 Crews Assigned To Complaints Managed Complaints  
Curve 1=non-adjusted hiring Curve 2=Adj. Hiring Curve 3 Hiring Subcontractors

TotalComplaintActivity	TotalAcceptedComplaints	ManagedComplaints
582,196.80	25,287.74	556,909.00
496,833.60	139,191.90	357,641.70
493,462.50	142,333.60	351,128.90

Upper Row HrSector=0 Teams=0 (Hire extra help)  
Middle Row HR Sector=0 Teams=1  
Lower Row Base Run HR Sector=1 Teams=1

Table 6.10

However, notice that the number of complaints that need to be managed also increases.  
Why?

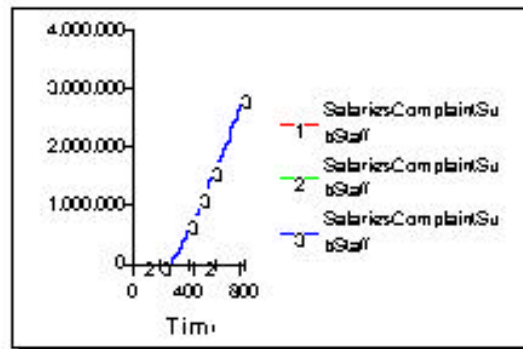


Fig. 6.56 Additional Costs to the System

The simulation of the PSI of the system shows that it does better before reaching the CVP, Figure 57. This dynamic had been discussed in previous sections. With an increase in decline of the PSI, once the CVP is reached more complaints are generated.

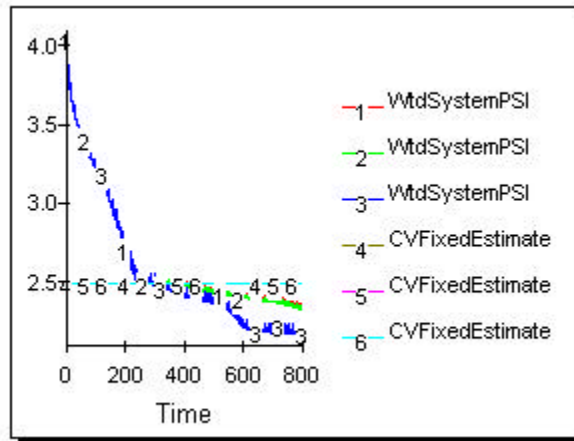


Fig. 6.57

### PSI

The original expectation was that with more crews available for repair, the PSI would be better. The PSI is better until the CVP is reached, as explained in previous sections. With an increase in labor and costs, a tradeoff between more expensive Pave repair, and less expensive Overlay and Patch repairs is made. The Overlay increase occurs at the CVP. The total exchange lowers the overall PSI after the CVP is reached. The process is shown in Figure 6.58.

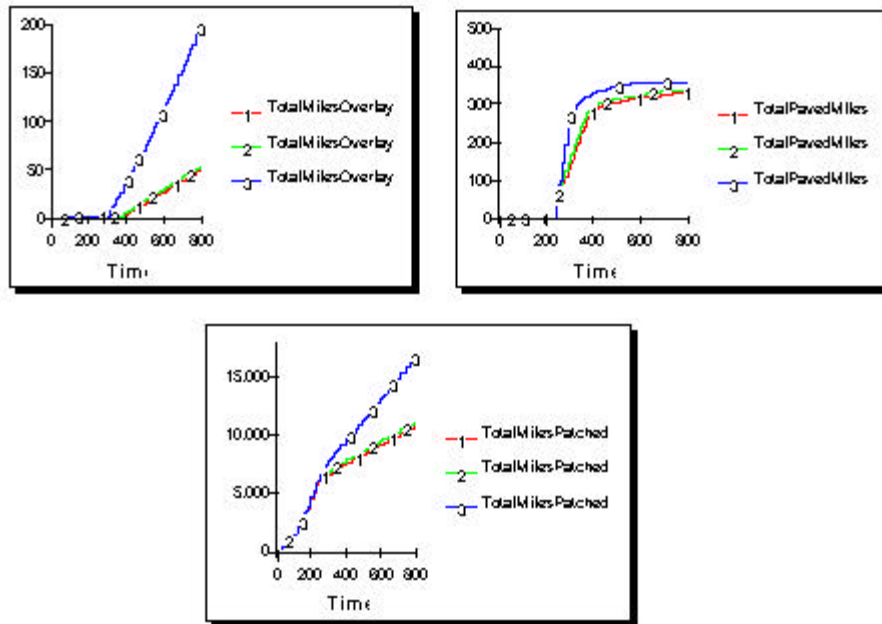


Fig. 6.58 Impact on Types of Road Repair with An Increase in Available Labor

Evaluation of the human resource effect suggests increasing the labor supply by hiring a separate crew is not a good idea. The idea of adjusting hiring practices is less costly, improves overall repairs, but the final PSI still declines when the budget constraint point is reached, Figure 6.57. The reason appears to be that by spending more of the budget on complaints, less is available for repairs when extra crews are hired. On the other hand when more regular employees are hired (costs included in repair process as given), then more or the selected work (by the utility function) is accomplished. Either policy decreases the road quality, increases complaints, but allows for more management of the complaints. The issue is what business are we in? Complaint management or road repairs?

### 6.14 Poor road Paving Control

Current policy recommends that no Paving occur until the RSL equals 50% ( when the PSI of the system is below 2.5). An alternative would be to allow Pave repair of Poor

road to be dependent on the state of the Poor road, independent of the PSI of the system. A test was performed keeping the same decision rule (table function), but changing the input into the rule. The inputs were 1) from the PSI of the system to choice of miles repaired and 2) from the Poor road damage effect to the effect choice of miles repaired. The comparison of the current base policy and the new policy is seen in Figure 6.59.

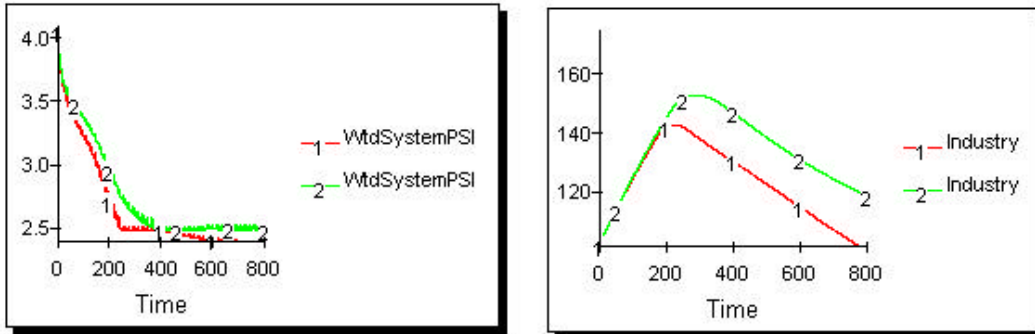


Fig. 6.59 Effect of Decision on PSI to Poor road Conditions (Utilizing the same decision rules)

What is causing the PSI shift?

In the first run (curve 1), the PSI controls the amount of Poor road selected for repair.

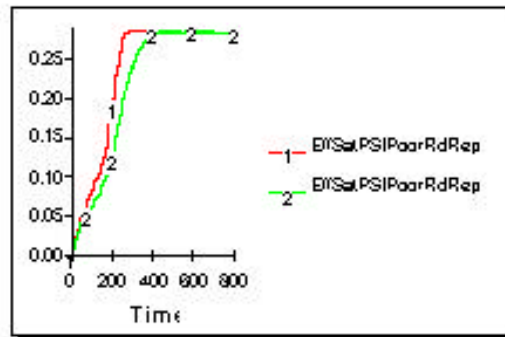


Fig. 6.60 Effect of Manager Satisfaction on Poor road Repair

When under the control of the PSI the effect of satisfaction with Poor road is a slow climb Figure 6.60. As management satisfaction decreases, under the PSI policy, the effect on the percentage of Poor repaired increases. However, the climb to .25 takes almost 200 months.

When the condition of Poor road is used, the percentage of repairs jumps to 100% at an earlier time and falls off over twelve months to zero Figure 6.61 (bar and arrow are used as the reading is difficult to see on the vertical axis of the graph). Road conditions are improved enough so that the overall PSI improves. The impact can be seen in Figure 6.60. It now takes longer for the PSI controlled policy effect to be implemented.

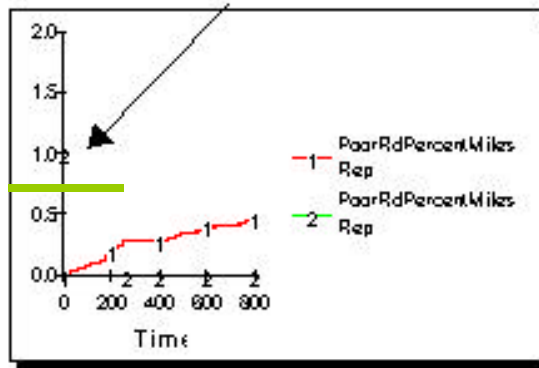


Fig. 6.61 Percentage of Poor road Chosen For Repair

The impact of the “quick” start is seen in Figure 6.62.

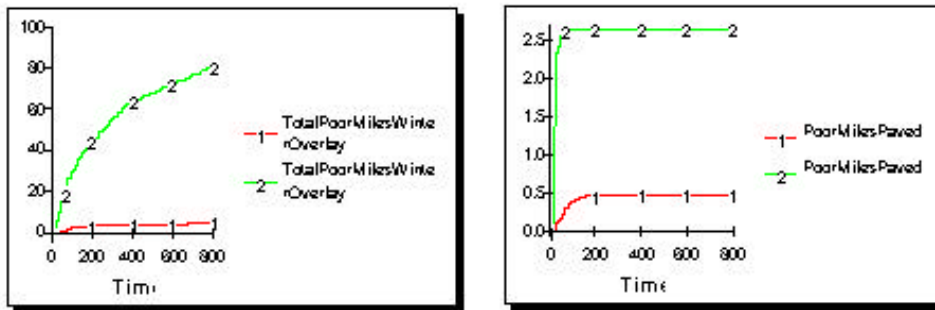


Fig. 6.62 Impact of Quick Start on Poor road Repair

While more Poor road is available for repair sooner, the method of choice is Overlay, (controlled by the utility function). The choice lowers current costs but increases future cost Table 6.11.

FutureCosts	CostRepairs
2,988,678,693.00	188,361,124.00
196,612,655.00	370,958,763.00

Table 6.11



Due to the substitution of Overlay for Pave repair on Poor road, current costs are reduced and future costs increase. This pattern appears to be recurrent under many of the test conditions. As long as managers are forced by current budget constraints to use lower cost, short-lived maintenance, the future costs of repairs will always climb.

### 6.15 Mixed CVP and Correct Categorization of Roads

As the CVP and the correct classification of roads effects the PSI, a set of runs were performed to assess the interaction of the two variables. The combination examined CVP equal 3, combined with Percentage of Correct classification of 50% and 25%.

As compared to the base run CVP of 2.5 and percentage allocation of correct roads of .5, the higher the CVP and the percentage categorization correct, the higher the PSI, Figure 6.63a. The increase is accomplished with Overlay, Figure 63b. As in previous runs, with less paving current costs are slightly lower and future costs are slightly higher.

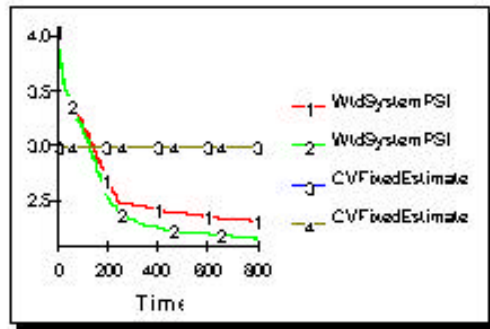


Fig. 6.63a PSI in Response to CVP& Categorization  
Percent Correct = 50% (curve 1), and 25% (curve 2)

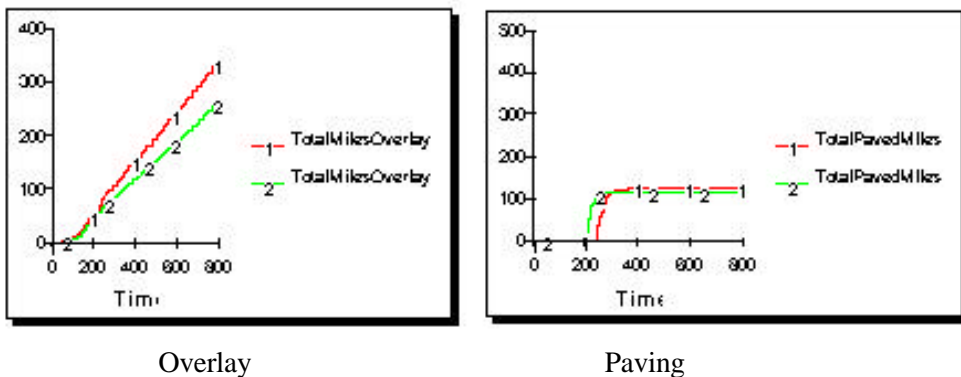


Fig. 6.63b

## 6.16 Summary of Findings

The following operational policies were examined and recommendations for change associated with each is as follows:

1. Incorrect assignment of quality for repairs: The practice creates problems for the planning of future expenditures and should be stopped.
2. Repairs in winter: This practice creates fewer repairs, and increases the rate of deterioration of roads that are repaired in winter. Although, not having a major impact on the system, as was expected, the practice should be stopped.
3. Incorrect classification of roads: Correct classification of roads improves current PSI values and regional development, at an increased cost. An appropriate balance of classification needs to be established so that the correct amount of Overlay and Patch are traded for Paving. The percentage used in the simulation can be varied to determine a suggested mix. Currently, the allocation of 50% seems to be acceptable.
4. RSL: Current recommendations in the literature are to use an RSL as high as 85% and low as 50%. It is not recommended to go below 50%. The simulation suggests that the higher the RSL the better the current PSI.
5. CVP: Currently, pavement managers use a CVP of 2.5. The higher the CVP value, the more Overlay repairs are performed with a higher end PSI.  
(An evaluation of policies 4 and 5, results in a suggestion that managers consider both values together, rather than as independent decisions. The mix of the two affects both current and future costs).
6. Hiring practices: Hiring more employees with current budget practices in effect tends to decrease overall road improvement. More hiring requires an increase in funding..
7. Budget Utility Function: The current utility function captures manager's preferences for using less costly current repair processes. Overlay becomes the repair of choice. This is the result of Overlay being in the middle ground of cost and life span [6.5 Decision-Making Section, Figure 6.22c]
8. Poor road Repairs: Current policy is to wait until the system reaches its RSL. The recommended change is to determine the start based on Poor road conditions.

A base run compared to a run with correction of the enumerated policies is seen in Figure 63.

9. As the CVP increase the percentage classified correct should be reduced. An increase in CVP allows for more Overlay, a decrease in the percentage to Good road increases the amount classified as Poor road and also increases Overlay. However, while current costs are reduced, future costs increase. In addition, this combination creates the lowest cost to benefit combination. (Best dollar value per PSI)

While the following is performed for total policy evaluation and completeness, a warning by Teece (1997) seems appropriate.

“Learning is often a process of trial, feedback, and evaluation. If too many parameters are changed simultaneously the ability of firms to conduct meaningful natural quasi experiments is attenuated.” ( :275 )

The same can be said for policy development. The final policy was developed after numerous experiments to determine individual impacts on the system. The results of these experiments lead to the following insights.

If increasing the trade off between Overlay and Paving causes a decrease in the system's PSI level, then a policy needs to be designed that balances both. Consideration needs to be given to:

1. A higher RSL value initiates Pave repair sooner.
2. Allowing Poor road to determine initiation of repairs increases the percentage of road repaired earlier, but also increases the amount of Overlay.
3. Lowering the CV allows less Overlay repair. This happens as Overlay repair does not start (for all roads, except Poor roads), until the CVP is reached.
4. Increasing the percent of correct categorization raises current costs slightly, increases Overlay for Poor road but decreases Overlay performed elsewhere. (A correct categorization of 100% creates future costs that are too high).

Several combinations of parameter values were evaluated. The final selections and the combinations of parameters are seen in Chart 6.2. (Parameter values may be found in the model section Parameter Set Control). The policy comparisons were performed on the

base-run, a policy correcting current operational assumptions and, the correction of current operating assumptions in the unconstrained budget mode.

### **6.161 Policy Choice**

The mix was designed to balance Pave and Overlay repairs. Cost was a not given consideration. However, as Paving repairs are reduced, current cost decrease while future costs increase. A policy choice must be made based on an entire set of impacts. In this case, what impact does policy have on the road system, and on development? If development can be increased or made stable, the cost of maintaining the system may be affordable.

### **Results**

Policy Combination 1 was an improvement over the base run and as expected Policy 2 showed even more improvement. (The effect of budget changes will be evaluated in more detail in this Chapter in the section on budget changes. Both combinations succeed in creating a set of final values that are an improvement over the current policy. These improvements are:

An increase in PSI quality

An increase in development

For a savings in costs of approximately \$80 million, in today's dollars, we can expect to incur an increase of future costs of approximately \$270-275 million. (Estimated lump present value is \$28 million after 60 years. This was not done as an annuity as the stream of costs was not equal each year).

Industry does not collapse but finished somewhere between both of the higher future cost alternatives. (These are final values and are dependent on changes during the simulation. The results in system improvement are seen in Figure 6.65.

Policy Test Settings

Parameter	Base Run	1	2
HRSelector	1	1	1
HRTeams	1	1	1
PoorRdPave Control	0	1	1
Budget Mode	0	0	2
CVP	2.5	2	2
RSL	.5	.85	.85
Delay Category	0	1	1
Percent Delay Correct	0	.75	.75
Winter Control	1	0	0
Correct Quality	1	0	0

Table P6.2 Policy Test Setting  
Note 6

Lower current costs and increased future costs (See Table 6.12)

PSI and Industry

.PSI	Industry
2.495411	125.1683
2.492721	124.7743
2.361989	100.6869

Associated Costs

FutureCosts	CostRepairs
464,894,505.00	297,078,452.00
472,096,157.00	290,415,687.00
196,612,655.00	370,958,763.00

Lower row –base run

Middle row-Policy 1

Lower row –Policy 2

Table 6.12

Policy 2 was tested with an unconstrained budget. If the budget is part of the problem it would be expected that at the CVP there would be an improvement with the extended budget. (It should be remembered that with this policy the base CVP of 2.5 and RSL of .5 are no longer aligned. With a CVP of 2 and an RSL of .85 paving has begun, and the point at which Overlay begins and Patch repairs stop is the Policy CVP or 2 in this case. As the improved system, does not reach the CVP, all work except for Poor road repairs, is Pave or Patch repair. The difference can be seen in the amount of Poor road that has been overlaid and the change in total Overlay performed, Figure 6.66. The trade off is Overlay for Pave and Patch repairs, coming from an increase in Overlay from Poor roads.

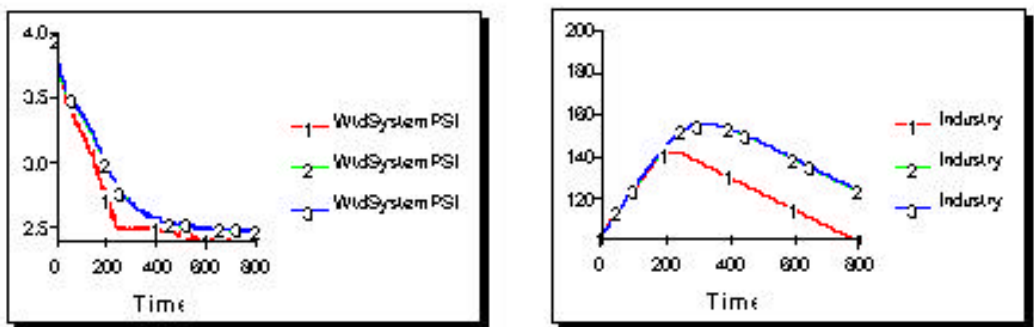


Fig. 6.65 PSI Industry  
(Curve 1 is the base run, Curve 2,3,4 are Policy change runs)

Cost structures are seen in Figure 6.66.

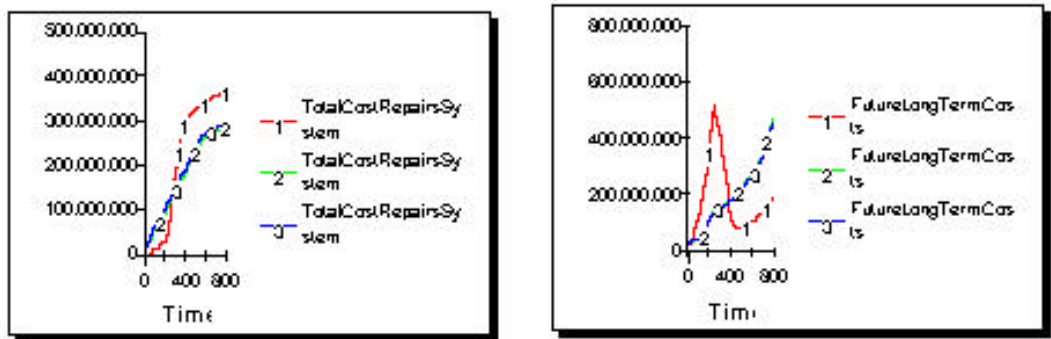


Fig. 6.66 Current Costs Future Costs

The total trade off, in costs, for the two policies that were selected can be seen in Figure 6.67.

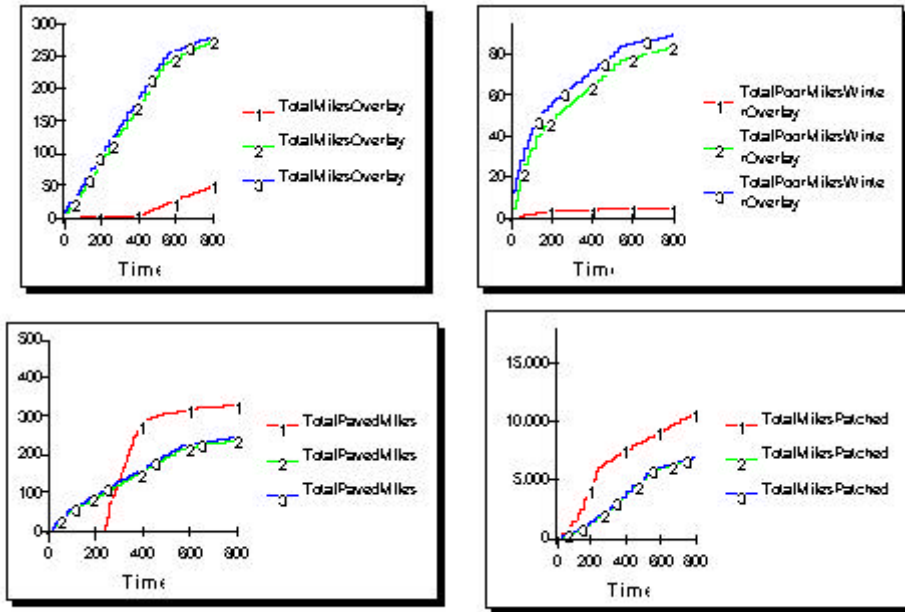


Fig. 6.67 Trade Off In Repairs Generated by Policy 1 and 2 As Compared to the Base Policy

A final run was conducted using an alternative budget mode, Full Rich. (Same as number 2, but multiplied by a factor value between 2-3). The result of this run is seen in Figure 6.68.

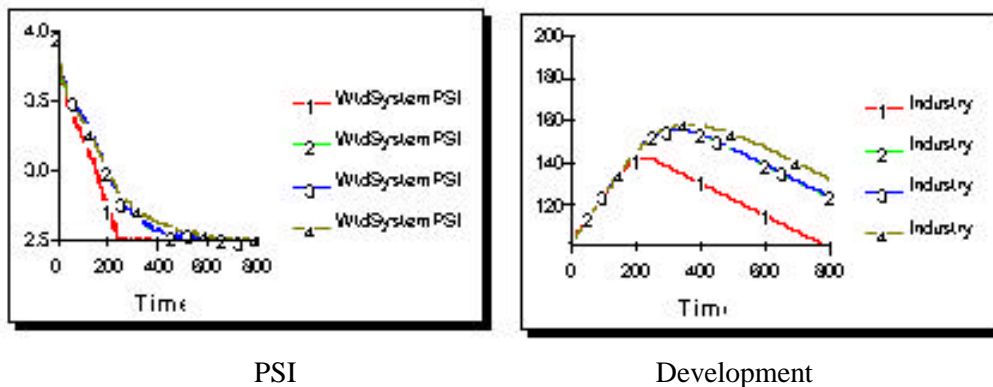


Fig. 6.68 Results of Rich Budget

While the PSI shows a small increase in quality, Industry appears to improve in greater proportion than the increase in the PSI. (An evaluation of a spreadsheet shows an increase of PSI by .01 units and an increase in Industry of 8 units)

However, budget policy releases an increased set of funds as required. A large increase in the funds, Figure 6.69, earlier in the process creates earlier Paving repairs, Figure 6.70.

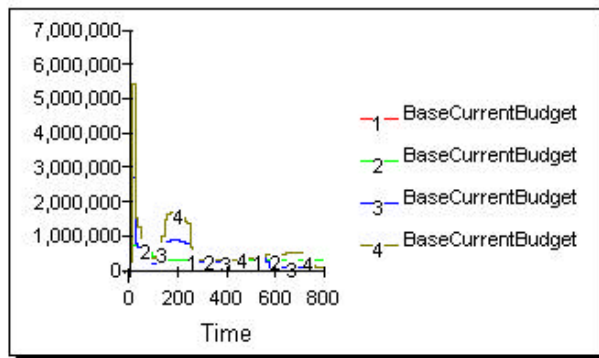


Fig. 6.69 Budget Values

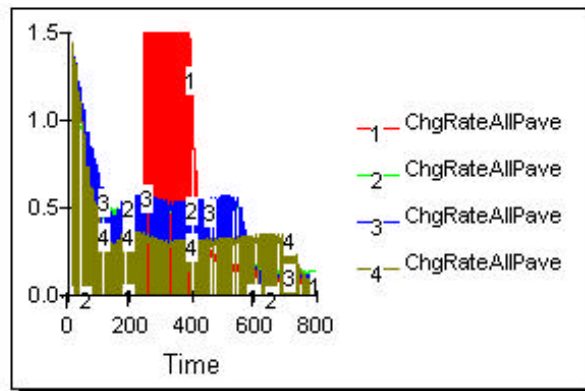


Fig.6.70 Paving Response to Budgets

The early improvement in the system has impacts that are seen later. In fact, total Pave. Overlay and Patch repairs are reduced, Figure 6.71.



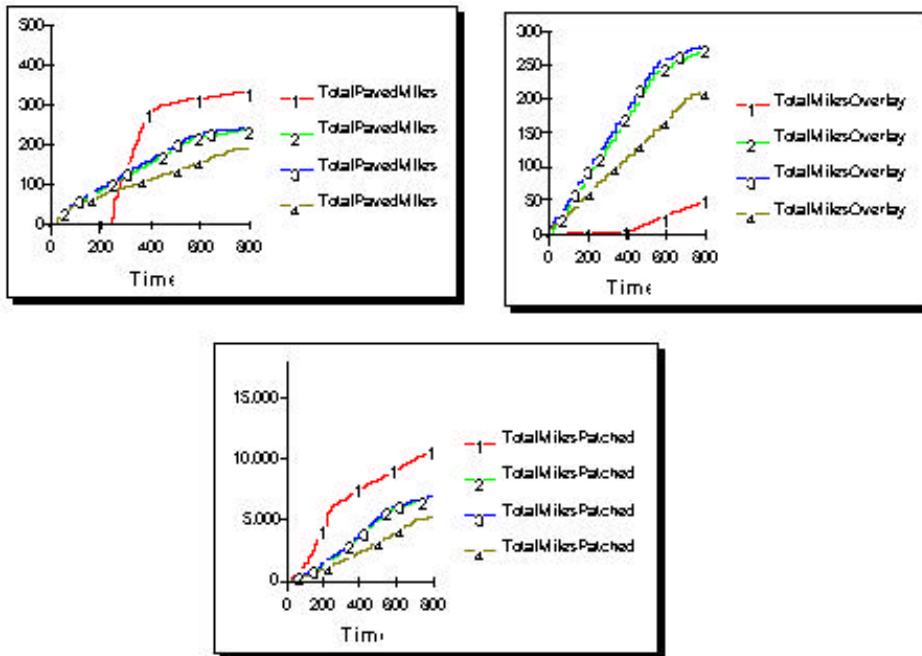


Fig. 6.71 Repaired Miles

Total current costs are reduced and future cost rises minimally, Figure 6.72, Table 6.13.



Fig. 6.72 Comparison of Current and Future Costs

The run supports what previous simulation runs have told us. Namely, that the sooner Pave repairs can occur the better the system quality and results.

Per.PSI

2.509115  
2.495411  
2.492721

FutureCosts	CostRepairs
580,861,562.00	230,609,158.00
464,894,505.00	297,078,452.00
472,096,157.00	290,415,687.00

Upper row- Multiplied Unconstrained Budget –factor of 3

Middle row-Policy 2 Unconstrained Budget

Lower row-Policy 1

Note: an increase in up front expenditures has tremendous effect later in the system. The time lag is probably greater than we might expect, and certainly not in the time frame of managers. In addition, the cost to benefit is among the lower ranges produced.

Table 6.13

### 6.17 All Excellent road Conditions

The preceding analysis resulted in an examination of the current preference for maintenance repairs. In order to evaluate this policy a change in the preference of weighting used in the utility function was introduced into the system. In this mode, the utility function allows more Paving. This was accomplished by creating a second table function and adjusting how it effected the control of the utility function. The adjustment allows the budget to decline to lower levels before paving is stopped.

Before the test using a changed utility was performed and evaluated, a set of tests on the system was preformed using all Excellent road. This was done for completeness. In the test using all Excellent road the policy assumptions are corrected and the budget modes, as described in the previous paragraphs are used. (Total road mileage is the same).

Excellent road:

Base Run

Operating Assumptions Corrected

Unconstrained Budget and Operating Assumption Corrected

The base run produces an end PSI of 2.9, Figure 6.73. . No paving has occurred and all repairs seem to come from Patch repair. This occurs because Excellent road deteriorates through all the road category stages. The process takes time as can be seen in Figure 6.74. In fact, the increase in other roads systems does not start until almost 200 months.

Due to this delay, it is only Excellent road that is being repaired. The repair type available is Patch, as Overlay is not initiated until the CVP point, which is not reached.

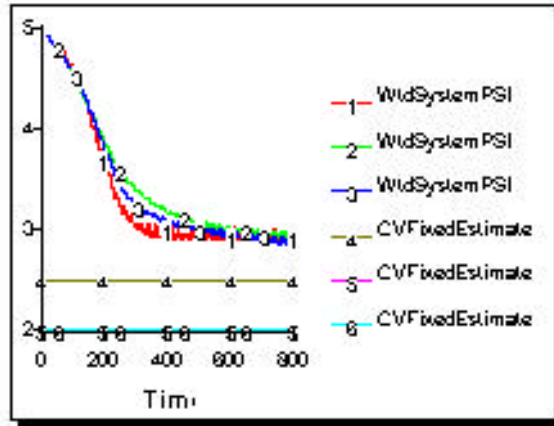


Fig. 6.73 Excellent road PSI

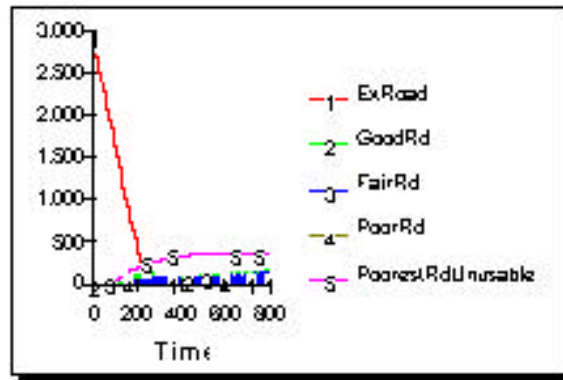


Fig. 6.74 Road Inventory

The second run corrects the operating assumptions. The condition allows Paving to start earlier. The result is a marked improvement in the system. By placing 75% of the delayed miles into Good road for Overlay repairs only the amount of Overlay increases. Pave and Overlay repair become the repair of choice and Patch repairs decrease. The combination raises the PSI but increases current costs.

A budget on demand has a different impact than with a mixed road. As the road is Excellent it takes time to deteriorate as seen in Figure 6.74. The need of repairs is delayed. When Pave repair is initiated, the timing and amounts of allocations of the budget, is delayed by the system, Figure 6.75

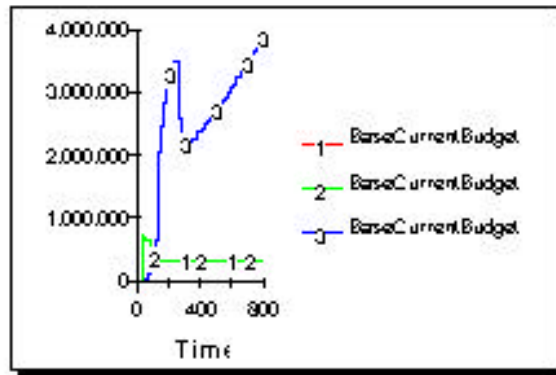


Fig. 6.75 Current Budget

With a low starting budget, due to the condition of the road, Overlay is carried out on Excellent road but paving is delayed until the road deteriorates to Good road, which is then available for Pave repair. No Overlay or Pave repair will occur from Poor road until its level becomes greater than zero, an even greater time delay, Figure 6.76

Table 6.13 compares the simulated runs of Excellent road repairs. Allowing funding based on demand increases costs and lowers ending PSI. This occurs as Patch repair work is the dominant method of repairs and Poor road is the only level that Overlay repair, creating Excellent road can come from. This is due to the fact that the CVP point is never reached. For Poor road to have Overlay work done there has to be Poor road available. As the road starts in excellent condition this process takes some time to occur.

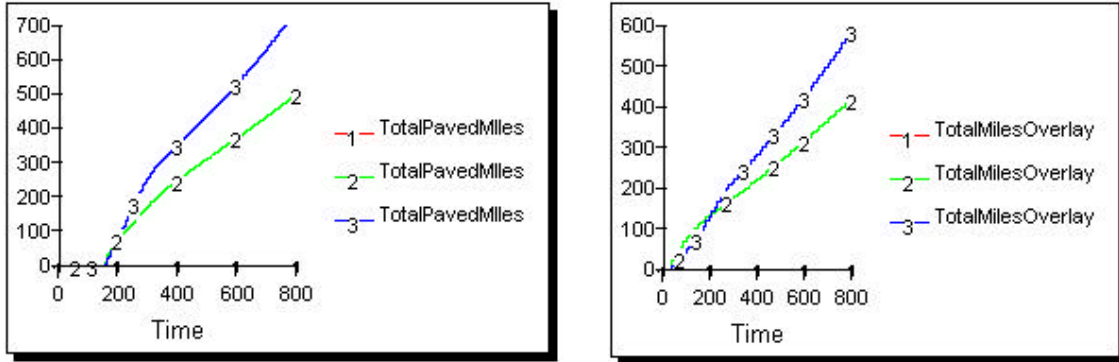


Fig. 6.76

Paved Miles

Overlaid Miles

Putting more funds in up front (top rows of Table 6.14) appears to have the same impact as the runs that did not start with all Excellent roads. Considering the effects, the policy for Excellent road appears to be to simply change incorrect base assumptions and accept a mid-range current cost, which at the same time brings down future cost.

**Per.PSI**

2.891628  
 2.956602  
 2.941618

**Cost Of Repairs**

823,612,777.00  
 550,090,793.00  
 218,668,581.00

Lower row is base run, Middle row: Assumptions Corrected Top row: Multiplied Budget on Demand

Table 6.14-Excellent road and Budget Shift

**6.17 Budget Relaxation**

In this mode, the utility function has been relaxed to allow more Pave repair. As the amount of available budget decreases, more Pave repair is allowed than with the original utility function. The formulation is the same, but the impact of the budget (table function) has been adjusted. (Simulation runs are based on a set of mixed road).

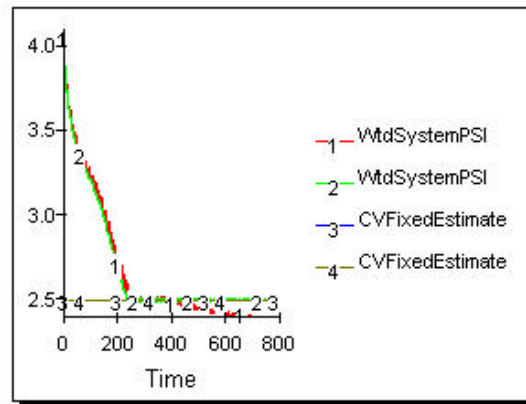
The following tests were accomplished.

Set 1

A base run- no correction of operating assumptions

Unconstrained run-no correction of operating assumptions

Relaxation of the utility does not provide any improvement while the PSI is above the CVP, Figure (6.77a and 6.77 b). This is because the system cannot take advantage of the relaxed mode. The relaxed utility allows more Paving and reduces both Patch and Overlay repairs. Serious paving cannot occur until the PSI hits 2.5, Figure 6.76b and 6.77c. At that point Pave repair increases at a rapid rate and the costs of the system may become too expensive to bear, Figure 6.78.



PSI

Fig 6.77a Changed Preference Utility Function but No Correction of Operating Assumptions

Curve 1=Base run

Curve2=Relaxed Budget

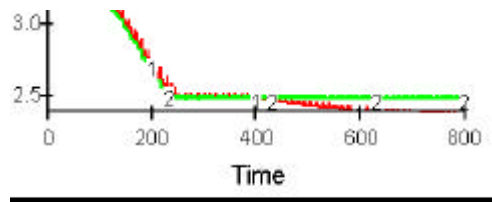


Fig 6.77b

Curve 1=Base run

PSI Curve enlarged for clarity

Curve2=Relaxed Budget

While the PSI seems to be slightly better with the unconstrained budget, the difference in costs, or cost increase to achieve this is extremely high, (Approximately \$1.5 billion, Figure 6.77d, in current dollars for operating costs and approximately \$24 billion, in future costs over the life of the system). Why? Because Pave repair does not start until the CVP level is reached, a large backlog of work is created.

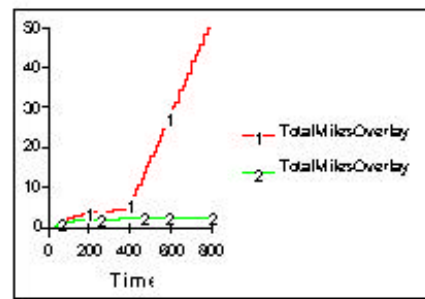
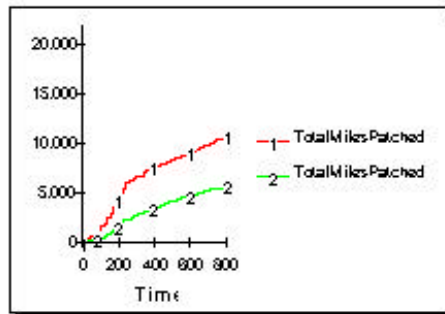
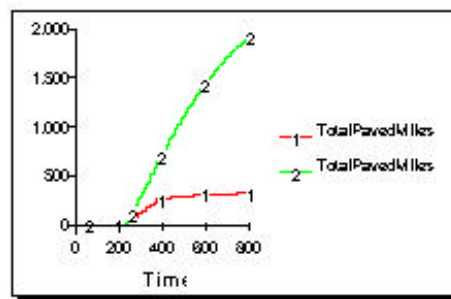


Fig 6.77c Shift in Repairs Due to Using a Changed Utility Preference Function

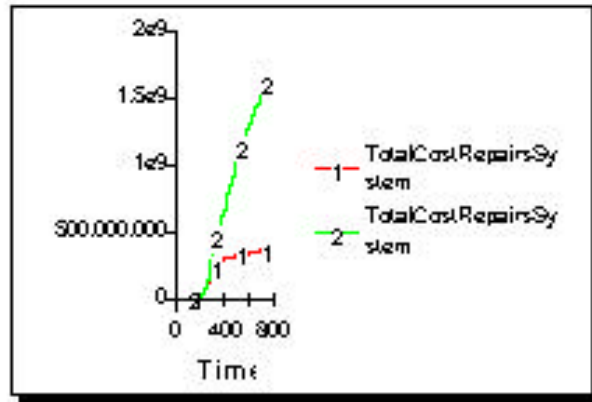


Fig. 6.77d Operating Costs

Figure 6.78 shows paved and Unpaved Road (The cost of un-repaired road is adjusted for future value and the costs are astronomical.) The dynamic indicates that unless the budget can keep up with the relaxed utility, no shift in policy is recommended.

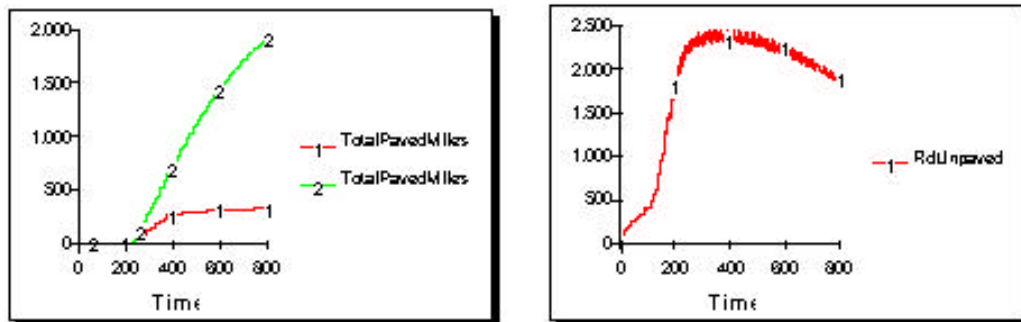


Fig 6.78 Effects on Paved Road

To test this recommendation an additional test was performed correcting operating assumptions and using a relaxed budget mode to accommodate the changed utility preferences function.

#### Set 2 Changed Budget Utility Preferences

A Base Run– correction of operating assumptions

Unconstrained run-correction of operating assumptions



Run 3 is the result of correcting the operating assumptions that managers are currently using. By implementing the new policy, the system can take advantage of the relaxation of the utility function. Paving can not only start earlier but is also the repair of choice.

The PSI improves from the base by approximately .42 PSI Units/Mile. However, the operating cost increase is almost \$4 billion dollars over the life of the system. Figure 6.79 shows the change in PSI and response by Industry.

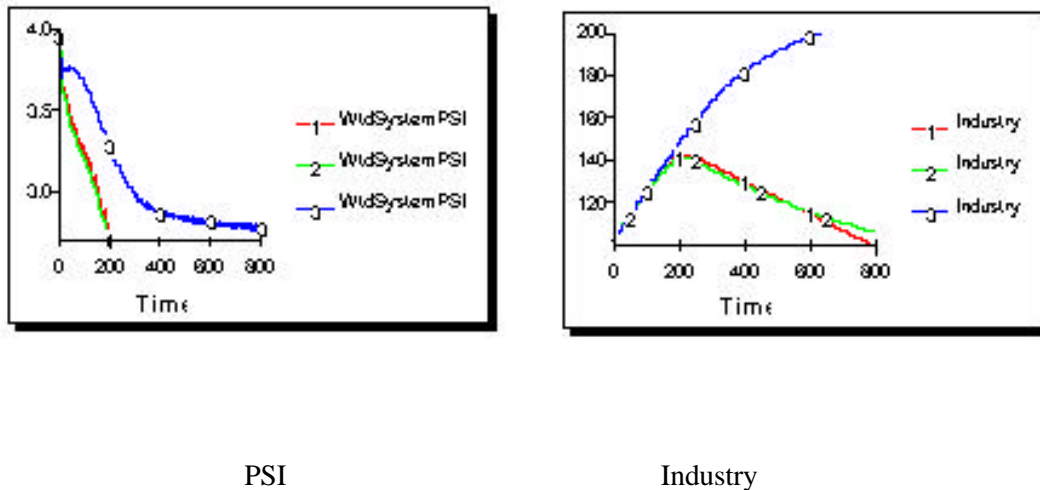


Fig. 6.79 Response to Policy Test

However, Overlay repair of Poor road is also achieved as the system chooses an earlier start for Poor road repairs. The increase in Overlay creates relatively less Pave repair than could have been done and now future Pave repair needs increase, driving future costs even higher, Figure 6.80.

(Spreadsheets indicate that there is an additional 3000 miles of Pave repair added and a combination of 3000 miles in Patch and Overlay. The increase in long and short-term repairs is proportional. The effect appears to be a reduction in how available funds are allocated)

With an on demand budget an interesting dynamic takes place, Figure 6.81, curve #4, shows an overall decline in the PSI rather than improvement.

With a relaxed system repairs in the first phase of budget availability (i.e. above the CVP) favors Pave repair. However, with assumptions corrected more Overlay work can occur. In addition, with an on demand budget, the amount of work depends on the road condition. In this case, the budget peaks at approximately 400 months. It is at this point that Overlay becomes constant and the PSI starts to drop below the curve generated in run number three, Figure 6.81.

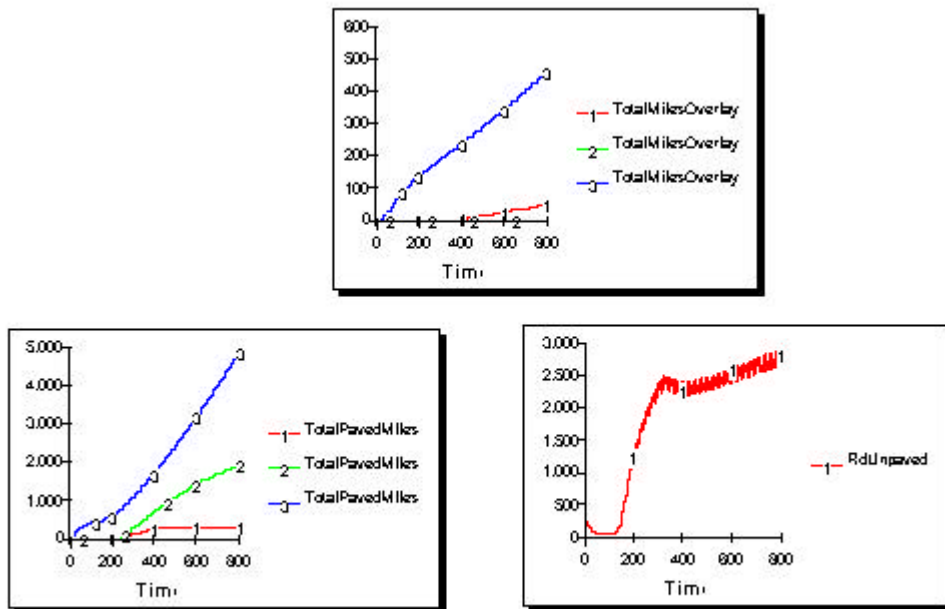


Fig 6.80 Comparative Miles of Repair

It is also at this point that the rate of Paving and Patch shows a slight increase. As Patch repair increases the PSI drops off. The response is in the preference of the utility function. The original function selected Overlay and Patch in preference to Paving. The changed function selects Pave and Patch repairs in preference to Overlay repair, Figure 6.81. With a greater amount of funds, Pave and Patch repairs increase. (The outputs on the spreadsheet show that as the budget is relaxed to meet the demands of the changed utility function Overlay doubles, but Paving and Patch are almost triple). Table 6.15.

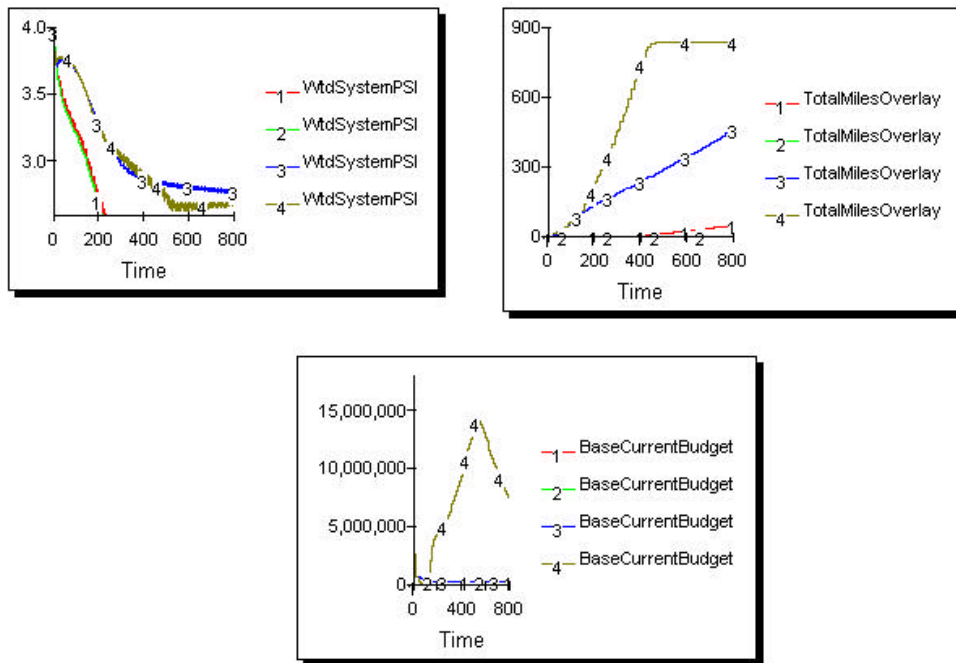


Fig 6.81 Shift in PSI Related to Budget Availability

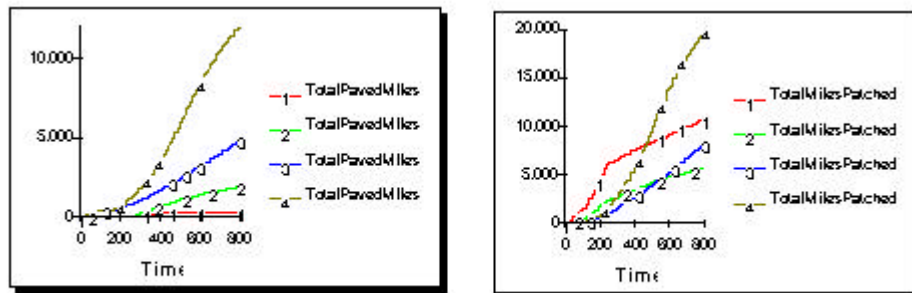


Fig 6.82 Pave and Patch Repairs

Until the PSI value is reached repairs are a mix of Patch from all roads and Overlay and Pave repair from Poor roads. Note that when the CVP is reached should be the point that Overlay increases, however, this does not happen. Instead there is an inflection and Overlay seems to become constant, Figure 6.81

TotalPave	
	12,040.33
	4,887.03
TotalPatch	
	19,728.95
	8,237.42
TotalOverlay	
	839.4838
	460.8496

Table 6.15-Comparison of Miles of Repair by Type

With an earlier start and early improvement of the system and a utility that gives preference to Paving and Patch repairs, less miles are in need of future maintenance, Figure 6.83. With less miles needing maintenance there is less budget required.

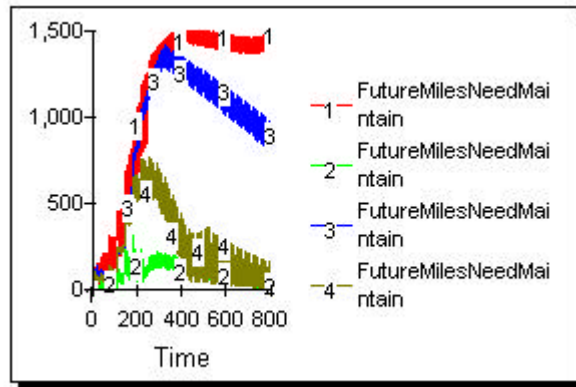


Fig. 6.83 Future Maintenance Needs

This is especially true of Pave repair, as is seen when a comparison of Figure 6.84 is made to Figure 6.78 and Figure 6.80.

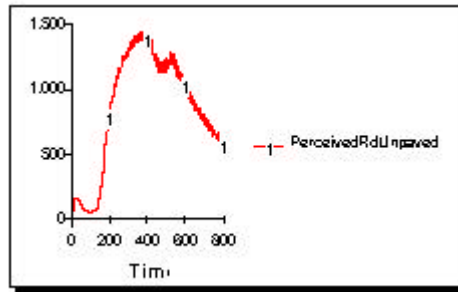


Fig. 6.84 Future Paving Need with Relaxed Budget and Utility Preference Changed

If the total amount of funding was acceptable, the recommendation is to allow more flexibility in the amount of Pave repairs while allowing a budget on demand. Of the options created by relaxing the utility function, which permits more Pave repair, this combination offers the least current and future costs. (Under normal conditions however, there appears to be a greater improvement to the system via correction of the weak assumptions versus too great a relaxation of the budget utility relative to the cost increases incurred.)

### 6.18 Budget Policy Correction

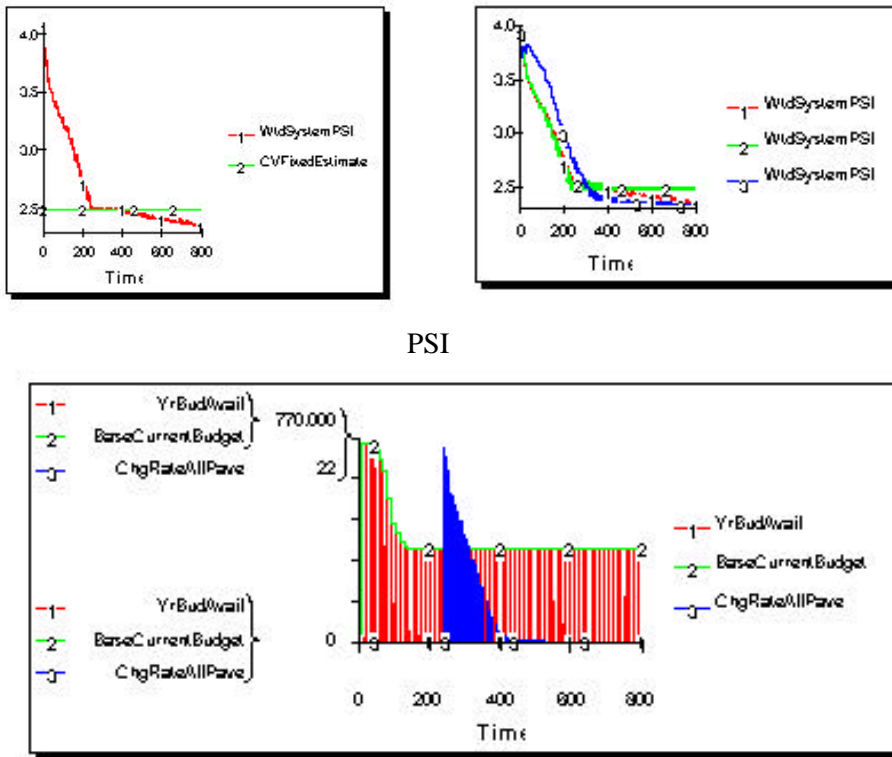
The current set of policies has been tested utilizing several forms of budget allocation. Either the budget that was available was constrained, or continued to diminish over time, the budget was allocated based on demand or allocated based on a multiple of that amount demanded.

The formulation of the current budget (of any type i.e. constrained, unconstrained, etc) bases the amount of funds available on an estimation of roads that will be repaired. The allocated budget controls the amount of team assignments and productivity or the number of months and contract of paving.

The current formulation generates a difference between the costs generated and spending, or between a desired level of needed operating costs and spending. The amount spent is based on the budget allocated, not on the budget needed. Costs are therefore indications of the amounts of work needed. A formulation was created to correct the old policy and

generate a new policy. The formulation tracks the net short-fall between spending and required funds, and adds back to the current years budget, the short-fall from the previous year.

A new base run was performed, that was followed by implementing the policy on the base run. (No correction of any operating assumptions was made). A third run was performed with corrections of the operating assumptions. Each run is shown separately as some of the output graphics tend to overwrite the output already in place, making comparison difficult. (Comparisons of the PSI, the amount of budget available, spending, costs, and paving accomplished. are presented in Figures 6.85, for the base run).



PSI

Yearly Budget and Paving  
Base Run

Fig. 6.85 Base Run Effects on Paving and PSI

The second run implements the new budget policy of correcting the shortfall. However, even with the new budget the constraint of current operating assumptions prevents the system from taking advantage of the extra funds. Paving of the majority of road does not start until the RSL hits 50% of PSI 2.5, PSI Figure 6.86a –Figure 6.86 (Note: Remember small amounts of Pave repair are coming from Poor road).

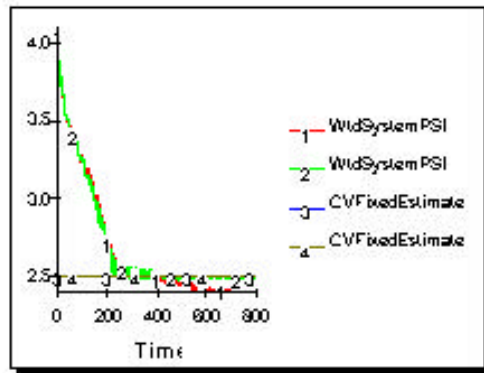


Fig. 6.86a PSI New Budget Implemented

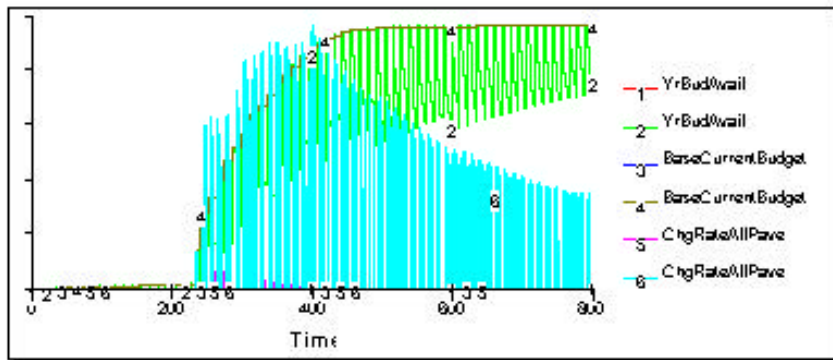


Fig. 6.86b Yearly Budget and Paving

Note that in Figure 6.86b

1. The first run's Pave repair and yearly budget are not visible as they are so small compared to the corrected values really demanded or desired.
2. The budget continues to grow and reaches a steady state. As the system catches up with needed repairs, the shortfall is decreasing.

- The rates of Pave repair fall off with a constant budget, similar to base run behavior. (See Validity).

A final run was performed with operating assumptions corrected, Figure 6.85c.

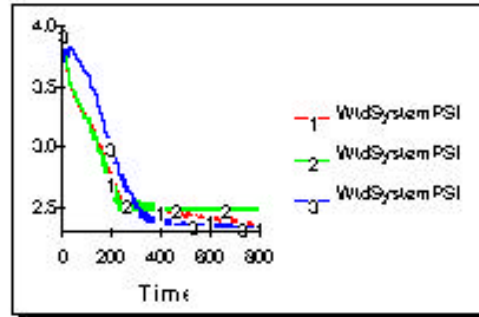


Fig. 6.86c

PSI

Run 3 shows similar behavior to previous runs with assumptions corrected. The system does better above the CVP point than below. The cause is similar to what has been discussed in previous sections. Figure 6.87 shows the relationships of road repairs by type.

Implementing the recommended corrections allows more Overlay and Patch to replace Pave repair at the new CVP point. As before, the substitution of Overlay and Patch reduces costs and PSI too. But, as before the overall characteristics of the system are improved.

For this scenario, the results of the last run are the best. As a comparison to other runs, it is not. However, the run shows that throwing money at the system is not the answer. The operating policies must change.



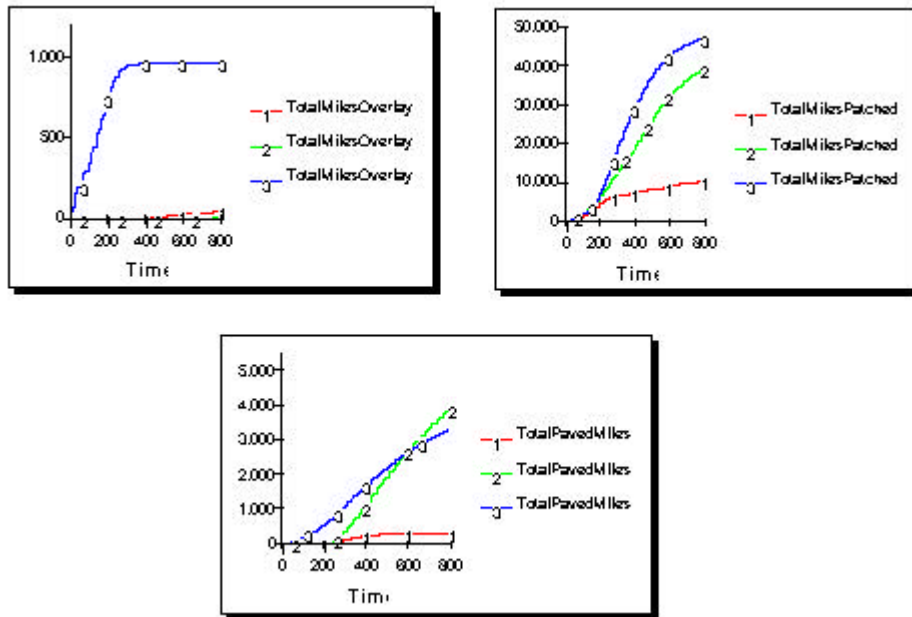


Fig. 6.87 All Road Repairs by Type

Note that in all previous sections although there were increases in fixed budgets the amounts received were not able to keep up with the amount or repairs really needed. This reflects what managers have said about the real process.

“Generally, we get about 30% of what we ask for in budgeting. We have a single budget for all allocations”.

Even if we desired to budget for the increased costs and system improvements there are some unintended consequences of too good a road. This issue, as related to the budget, was left for last, as it is the major weakness uncovered in the management decision making process. A detailed analysis will be found therefore in Chapter 7, Additions to the Knowledge Base.

The results of all the runs point to the following patterns that continue to show up.

1. Any attempt to substitute short -term maintenance for long term repairs leads to lower costs and higher future costs.

2. The quality of the road under such conditions appears to start out better, but with time declines to a worse condition, then if long -term repairs had been made earlier.
3. While managers have indicated that it is funding that is creating a problem, the simulation shows that the availability of more funds does not solve the problem.
4. A combination of small amounts of improved funding with major changes in operating policy has the greatest impact.

### **6.19 Regional Planning**

Finally, the current practice is not to include pavement managers in the regional planning process. To correct this, a section of the model that determines the design of the roadway formulations were developed for

1. Planned for current operations
2. Needed for current operations
3. Should be developed for future operations

The section calculates the cost of roadway and attempts to compare current roadway investment with the cost (spending) of operations. If the spending on operations, discounted to current value can pay for the investment than an improved road should be recommended. (In these runs the operating assumptions are corrected.) The first run is a base run, the second is with the traffic volume adjusted as recommended by the planning output.

Figure 6.88 shows the differential cost that needs to be accomplished.

In this run, the impacts of the system feedback can be seen. The first run is a base run, which utilizes a planned vehicle volume of 20,000 cars per day. As the actual volume rises above planned volume, deterioration rates increase. The run generates a correction factor for future expected road design, Figure 6.89. (The formulation for this correction is covered in Chapter 4).

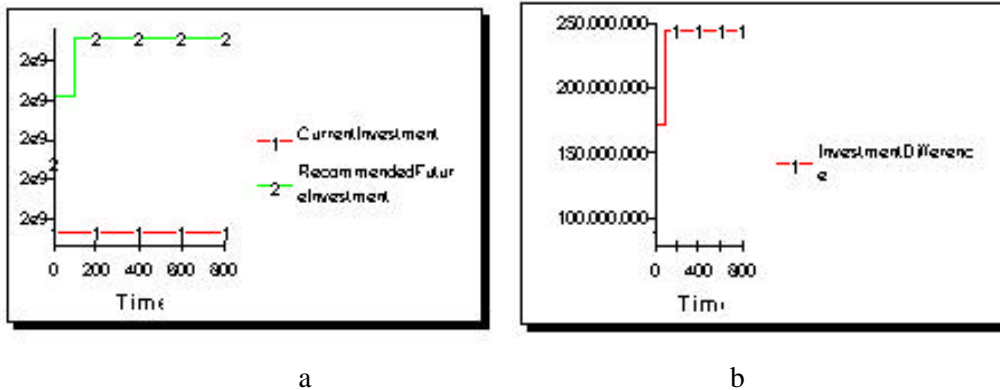


Fig. 6.88st of Current Investment Differential to Be Accomplished  
 Note-Figure b contains the difference between the two investments seen in a.

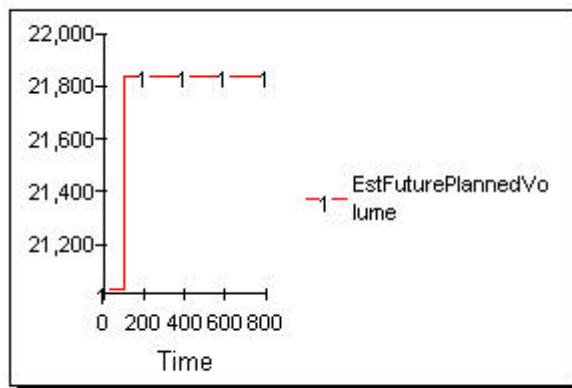
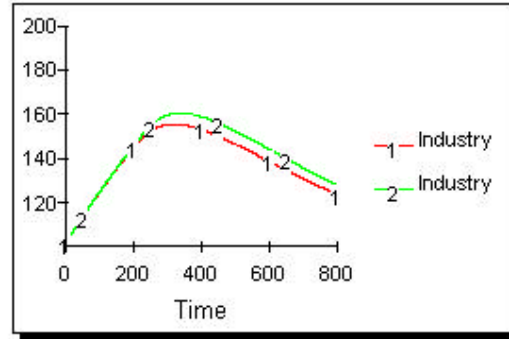
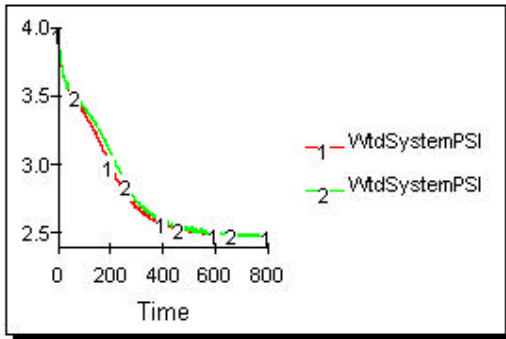


Fig. 6.89 Recommended Planning Volume for The System  
 Original Planned Volume=20,000  
 Estimated New Volume=21, 847

A second run utilizing the suggested new volume was performed. In this run, the suggested volume was used to estimate the costs of a new road system capable of managing the new higher volume.

The quality of the system is better than the road built with an incorrect volume specification. With a better road, Figure 6.90a industrial development also improve, Figure 6.90b, and there are less complaints. (As the costs of complaints are reduced and more funds are available for repairs).



PSI

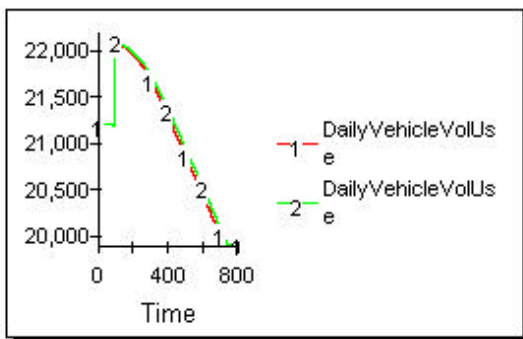
a

Industry

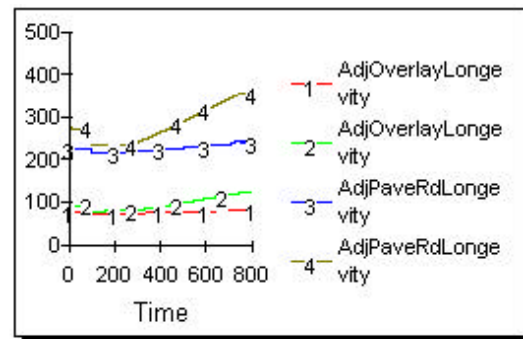
b

Fig. 6.90 Response to Planning

This is expected as the volume of cars has been planned for and the effect of the increase, Figure 6.91a, in planned volume is to reduce the deterioration of roadway by increasing longevity of the road repairs, Figure 6.91b.



a



b

Fig 6.91 Daily Traffic Volume

Life Span

[I expected that cost of repairs would decrease. To my surprise this did not occur.

What appears to be happening is the result of feedback, combined with the current budget policy. This policy requires that managers spend down a year's available budget.]

There is a decrease in complaint activity, and associated complaint costs, Figure 6.92 associated with improvement of the road quality.

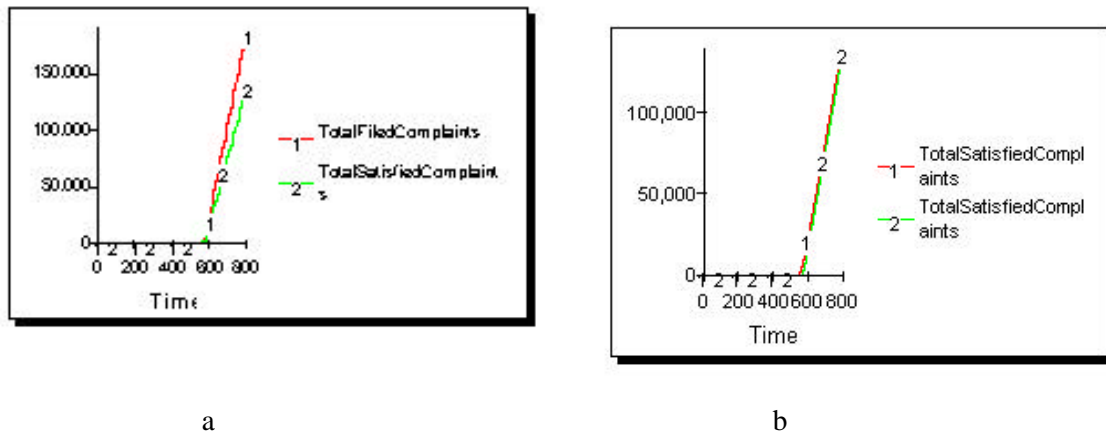


Fig 6.92 Total Filed Complaints

Total Satisfied Complaints

With complaint cost reduced, more is available for repairs. There are small increases in Pave, Overlay, and Patch repairs accomplished, Figure 6.93

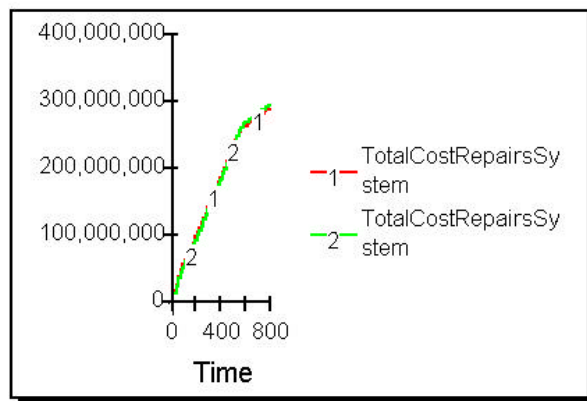


Fig. 6.93

Total Cost Road Repairs

The increase in costs was a surprise! Money saved from complaints is spent on road repairs that might not be necessary. However, in this case the ability to construct a new road and the cost savings even when discounted, do not create any advantage.

The overall investment difference needed to build a new road is \$ 245,831,514. The overall savings of the discounted road costs and adding back the extra cost of unnecessary complaint management is \$1,942,685, hardly enough to make up the investment difference.

In addition, although the PSI improves overall the cost of repairs before and after the building of a new road is so close that the construction does not pay. (It should be remembered that the simulation is taking the view that all miles in the system will be replaced as all repairs of the simulation are allocated to the entire system. Repairs of distinct areas of a system may generate different findings). Further, if a road is needed then proper estimation of the volume will still save costs in the long term when compared to under estimation.

**Final Comparisons of the Reference Mode (Base Run Compared to Alternative Policies)**

**Base Run**

The base reference mode along with traffic volume and adjusted road longevity is seen in

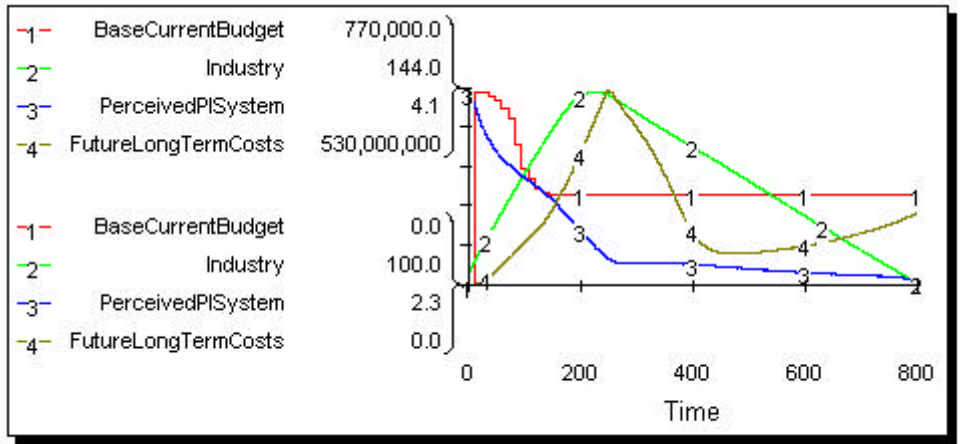
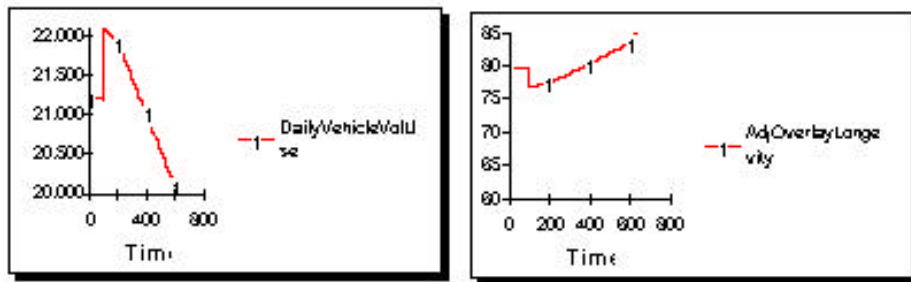


Figure 6.94. (These variables are also used in Figures 6.95 through 6.100).

Reference Mode-Base Run



Traffic Volume

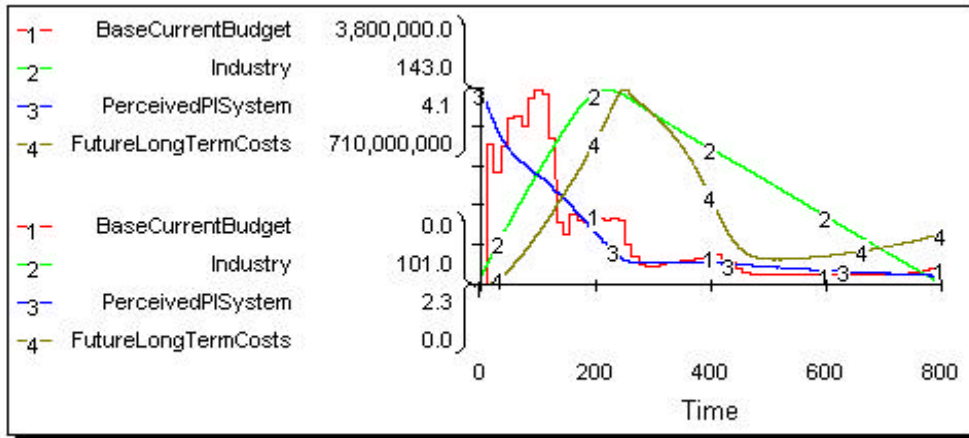
Adjusted Life Span

Fig. 6.94 Base Run Final Comparison

Note how with a falling PSI the traffic decreases followed by an increase in life span.

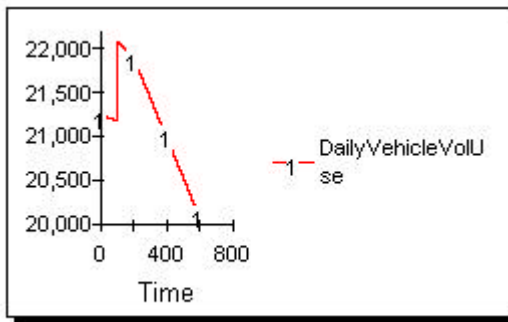
The next run uses an as demanded budge with no correction of the base operating assumptions.

**On Demand Budget –No Correction of Operating Assumptions (Figure 6.95)**

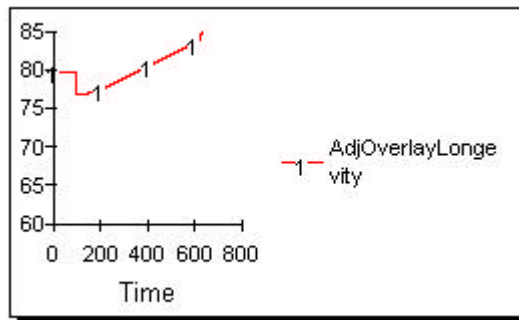


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Reference Variables-On Demand Budget



Traffic Volume



Adjusted Life Span

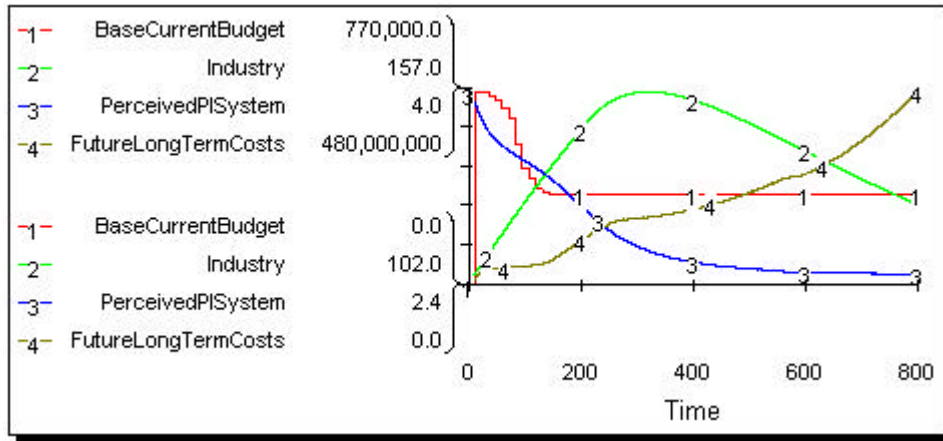
Fig. 6.95 On Demand Budget-No Correction of Operating Assumptions

Note that with a larger budget the conditions have not varied much. The system is still collapsing. Additional resources do not help to improve the system.

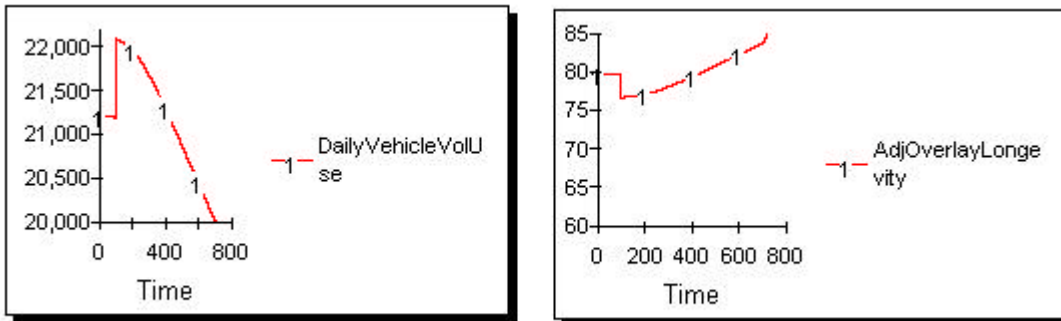
A test with corrections of operating assumptions with a constrained budget was preformed.



**Constrained Budget and Operating Assumptions Corrected (Figure 6.96)**



Reference Variables Constrained Budget



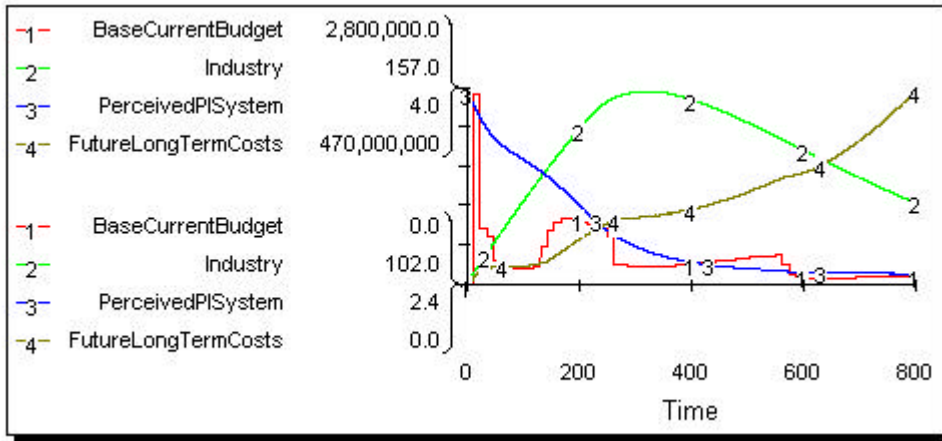
Traffic Volume

Adjusted Life Span

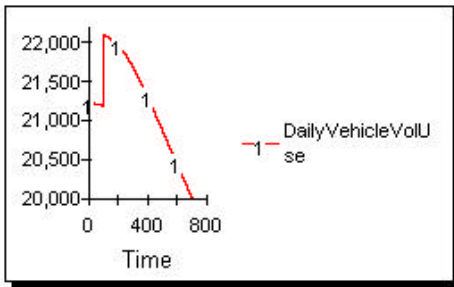
Fig. 6.96 Constrained Budget And Operating Assumption Corrected

Correcting the base assumptions tends to improve the system somewhat. However, the improvement is not enough to prevent a decline in industry. The PSI is slightly better than the base reference mode, a PSI of 2.38 and PSI 2.49 for the test.

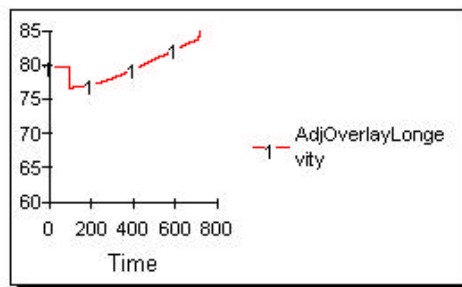
**On Demand Budget and Corrected Operating Assumptions (Figure 6.97)**



Reference Variables –On Demand Budget and Corrected Operating Assumptions



Traffic Volume



Adjusted Life Span

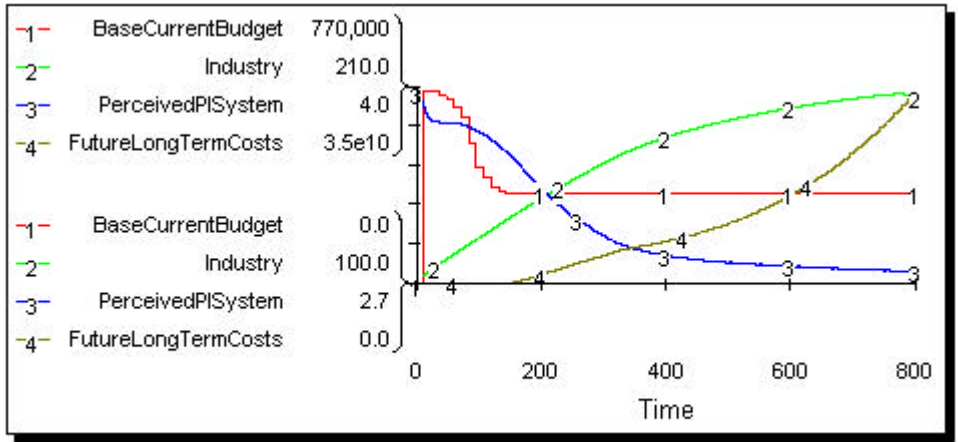
Fig. 6.97 On Demand Budget and Operating Assumptions Corrected

Additional resources do not create a great improvement of the system.(Note the constrained and on demand budgets produce similar results). The best improvement seems to come from changing operating assumptions.

Figure 6.96 shows a run with only the operating assumptions adjusted. Note the system does better than when additional resources and no adjustments are made. Yet, the budget is a constrained budget.

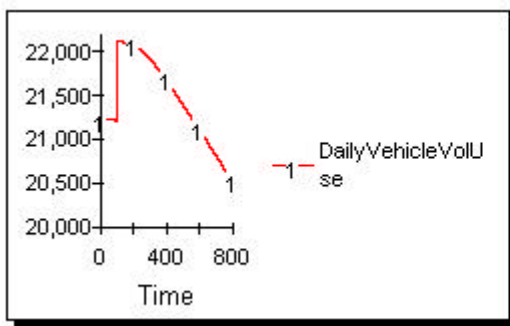
Changing operating assumptions, as shown, is not enough. Managers have a preference for the use of short-term repairs. What if the budget was constrained and this preference was changed?

**Constrained Budget and Operating Assumptions Corrected (Including Use of the Changed Repair Preference Utility) Figure 6.98**

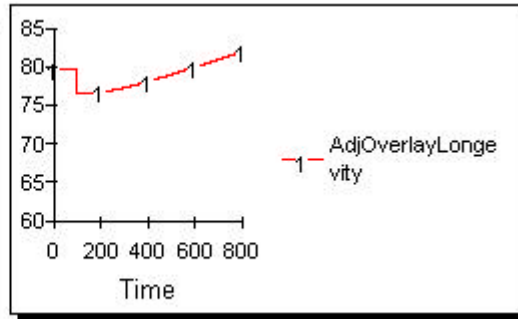


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Reference Variables -Constrained Budget, Operating Assumptions Corrected And Change in Utility Functions



Traffic Volume



Adjusted Life Span

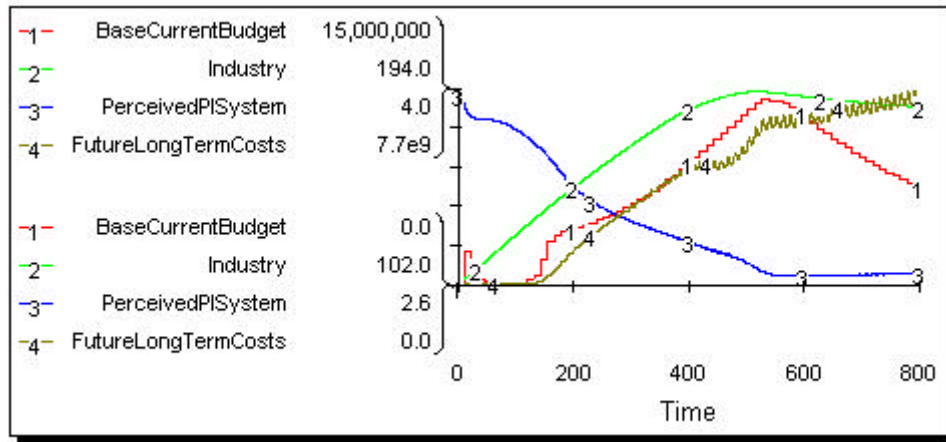
Fig. 6.98 On Demand Budget with Operating Assumptions Corrected and Change Utility

Note that although then PSI has fallen it levels out at about PSI 2.78 to the point where industry is not negatively effected. In addition, industry is growing. Vehicle traffic has

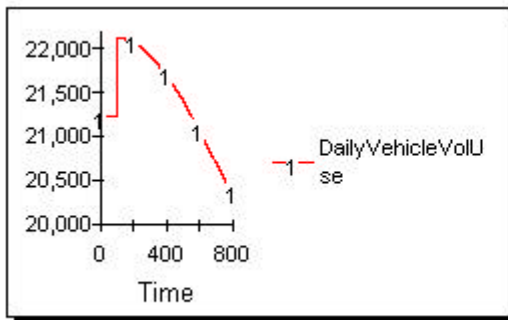
declined off the primary road but the decline is less. (This is likely due to a better PSI and more industry). The run is based on operating assumptions and a changed of the utility function).

A run with the budget and preferences relaxed and assumptions corrected is shown in Figure 6.99.

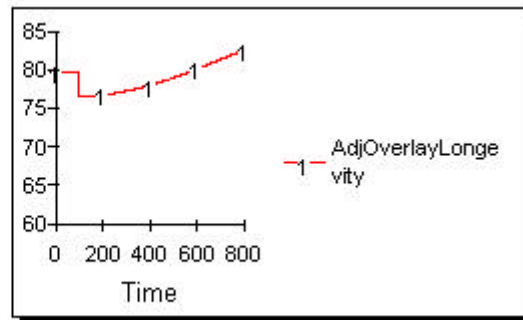
**On Demand Budget and Operating Assumptions Corrected and Repair Preference Changed.** Figure 6.99



Reference Variables and On Demand Budget



Traffic Volume



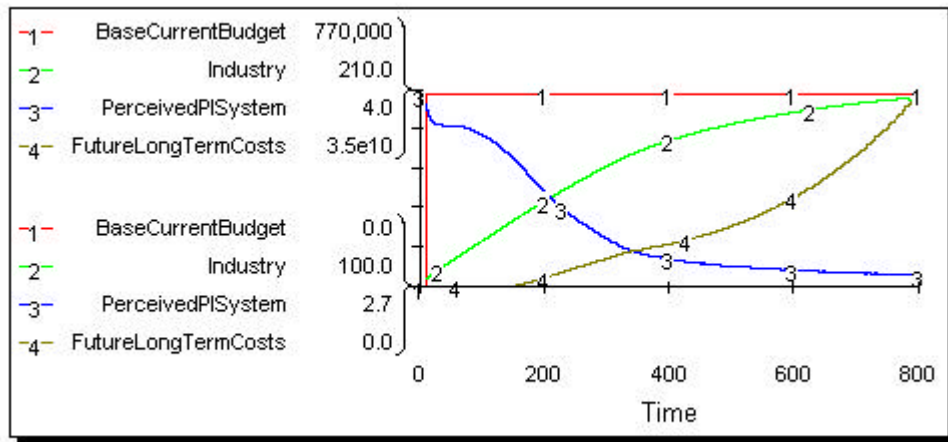
Adjusted Life Span

Fig. 6.99 Constrained Budget, Operating Assumptions Corrected and Changed Preference

The last test shows that the ending results are not as good as with the constrained budget. Why? As in previous runs in this dissertation, the budget is on demand. In the early phases, more road needs repair and budgets are larger. With less road being demanded there is less budget for repairs, which tends to have the effect of the constrained budget. Therefore, the relaxation of preferences cannot effect the outcomes.

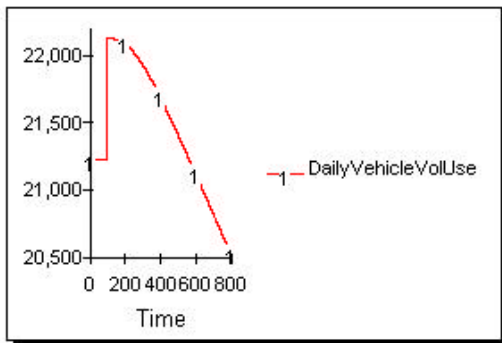
Finally, a test was run with a constant budget and all operating conditions relaxed.

**Constant Budget and All Operating Conditions Relaxed (Figure 6.100)**

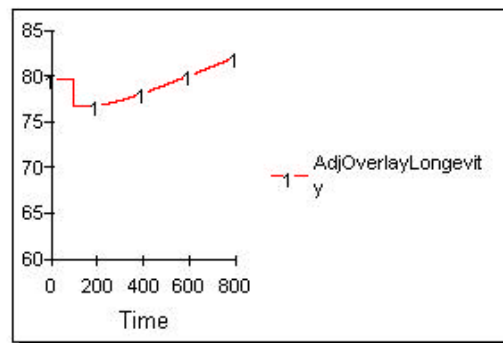


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Reference Variables and Constant Budget and Operating



Traffic Volume



Adjusted Life Span

Fig. 6.100

Assumptions Corrected and Repair Preferences Changed

This test verifies that the system can be sustained without an increase in funds. A constant budget with all operating assumptions corrected and a relaxation of decisions (change in preferences) does no better than with a constraint. The important thing to observe is that without correcting operating assumptions and changing the preference for the types of repairs currently used, additional resources do not help to improve the system characteristics. The claim that what is needed is more resources is not validated by the model. (Note-Although the constant budget mode and constrained mode look exactly alike on the graphic output, spreadsheet data indicates constant budget cost to be higher with higher Pave, Patch and Overlay repairs. The final mix of repairs with a constant budget creates a PSI .004 PSI units less than a constrained budget).

While relaxation of the constraints in the system improve the system, future costs tend to increase. However, one might assume that with an increase in industry and population base that generation of taxes would help defer costs. The recommendation is that in the future a research project based on regional development effects and taxation policy be developed to add to the current model.

The last policy concern deals with pavement manager's response to accident rates. This was found to be one of the most serious problems encountered. As the findings effect academic research and pavement management, full coverage of the issue will be developed in Chapter 7, Addition to the Knowledge Base.

## **6.16 Model Validation**

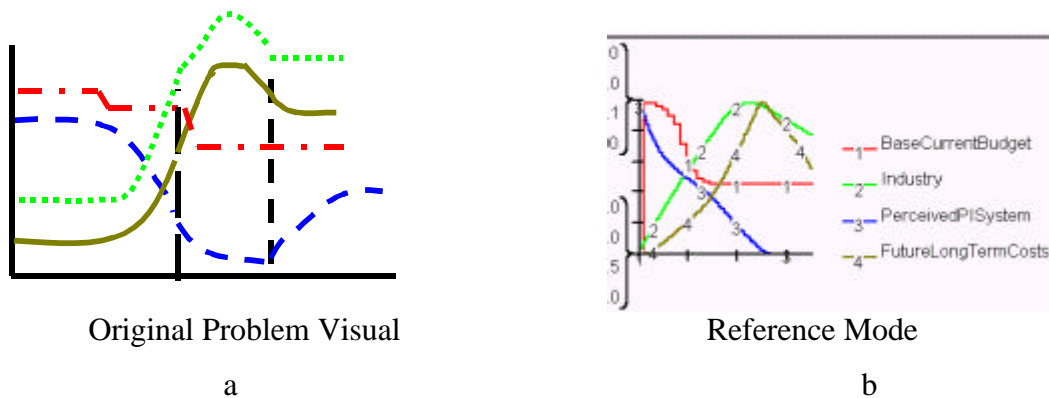
A major criticism of the system dynamics methodology is the absence of "formal objective, quantitative model validation procedures, which are supposed to be fundamental to scientific inquiry" (Barlas and Carpenter (1990 :148). Individual model equations claim to be causal statements about system relations.(Barlas 1990 :149) However, model are not true or false, but lie on a continuum of usefulness. Model validation is a gradual process of building confidence in the usefulness of the model.

Validity cannot reveal itself mechanically as a result of some formal algorithms (Barlas 1990 :157).

System dynamics models claim to capture cause and effect relationships. Such causal descriptive (white box) models are statements as to how real systems actually operate in some aspects. Generating an accurate output behavior is not sufficient for model validity (Barlas 1996). The model needs to explain how the behavior is generated. To aid in the defense of system dynamics models methods of validation have been suggested by Sterman (1984), Barlas (1996), Forrester and Senge (1980). Several of these recommended tests can be applied to the current model. An example, of the application of these methods, will be given from the model formulated in this dissertation.

**Symptom Generation Test:** Asks if the model recreates the symptoms of difficulty that motivated the construction of the model? In most cases one can say that model that does not, has not adhered to a basic concept. That concept is to maintain the reference mode described as the core problem for which the model was designed.

The initial behavior over time graphs is compared to an enlarged section of the output of the models reference mode for comparison, Figure 6.101. In the comparison of the two patterns, the pattern match is clear. The model appears to pass this test.



a) Rate Development      ..... Road Infrastructure (in PSI units)      .....  
 Available Resources      - - - - - Total Life Cycle Costs      \_\_\_\_\_  
 b) 1= Budget    2= Development    3=PSI      4 =Future Costs  
 Fig 6.101      Comparison of Reference Mode-Initial and Simulated

**Structure Verification Test-** This test compares the structure of a model with the structure in the real system. The structure must not contradict structure of the real system.

An example of such a structure would be the impact of vehicles on the deterioration of the paved asphalt road. In the real system trucks generate ESALs, whose cumulative effect is a deterioration of the PSI quality. In this model, a shift in vehicle volume effects the life span of roads, Figure 6.102 and Figures 6.94-6.100.

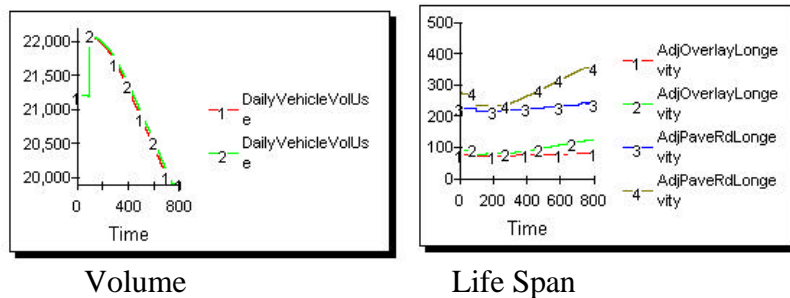


Fig. 6.102 Volume vs. Life Span

**Parameter Verification Test-** Does the structure of the hypothesized decision rule identify the relative pressures created by the information inputs.

In the current model, several functions (from the engineering literature) and how they effected the system were incorporated into the formulation process. Values such as the Critical Value of the PSI and Residual Life values were used as controls in the operation of the model. These values were related to the same controls as in the real system.

Examples of formulations in the model are:

- Budgetary effect on the CVP was built into the system as described in Chapter 4. The formulation captured the requirements recommended in Shain (1994 :166-167).
- Dissatisfied user generation using the functions provided in the literature on psychographic research.
- Waiting time Functions provide by Berger
- Increase in Travel Time-Methods of de la Garza



The formulations used capture the psychological decisions, which are related to the renege process of a queue. Drivers can relate the real system response to crowded highways or construction. Yet, the model uses accepted mathematical equations to capture the pressure to shift due to traffic pattern changes. Section

**Extreme Conditions Test**-the model must be able to operate correctly under extreme conditions. In this model, the value of zero miles in the system was tested. This test was done to assure that no function would operate with values that were not realistic.

**Extreme Policy Test**-the formulation, which added back the short-fall in the budget, produces a paving result with similar patterns. The reference mode budget becomes constant when the reduction in the percentage received becomes constant. The amount of Pave repair follows this budge trend. In the short-fall budget mode, (extreme funding), the budget reaches a higher, but never the less constant steady state. In this case, the amount of Pave repair also follows the budget pattern.

**Behavioral Sensitivity Tests**-tests the sensitivity to model behavior to changes in parameter values.

A 30% increase from an RSL of .65 to .85 causes a 1% change in Pave repair, a .02% change in Patch repairs and a 1% change in Overlay. Even a 50% shift in the Critical Value when combined with the shift in the RSL causes no major changes in the system,

Table 6.15.

PSI	Industry
2.371421	104.4994
2.371475	104.3135
2.373512	100.3374
2.373894	100.5308
Top Row CVP=3 RSL= .85	
Second Row CVP=3 RSL= .65	
Third Row CVP=2 RSL= .85	
Bottom Row CVP=2 RSL= .65	

Table 6.15

**Pattern Prediction Test-** tests whether or not the model generates qualitatively accurate patterns of future behavior. (The output of this test was indeed a strong indication that the system was capturing the dynamics of the system correctly).

The output of the reference mode was compared to the output of a base run of all Excellent road. The initial PSI value of the base run is 4.1, while the initial PSI value for Excellent road is 5. (Therefore, initial roughness is higher for the reference (mixed mile run) than for Excellent road.. According to Jannof (cited in Kendall et.al. 1991) the cost of maintenance of the better road should be less. (The final cost of repairs (taken from a spreadsheet, which recorded the runs, for the reference mode and all Excellent road are given in Table 6.16

CostRepairs

\$370,958,763.00

\$218,668,581.00

Upper row =Mixed Road

Table 6.16

When these final costs were observed, data, on costs, was extracted from spreadsheets, which recorded all costs for the total time of the run. This data was transferred to the software KaleidaGraph (Note 7), where it was plotted. The plots are seen in Figure 6.103.

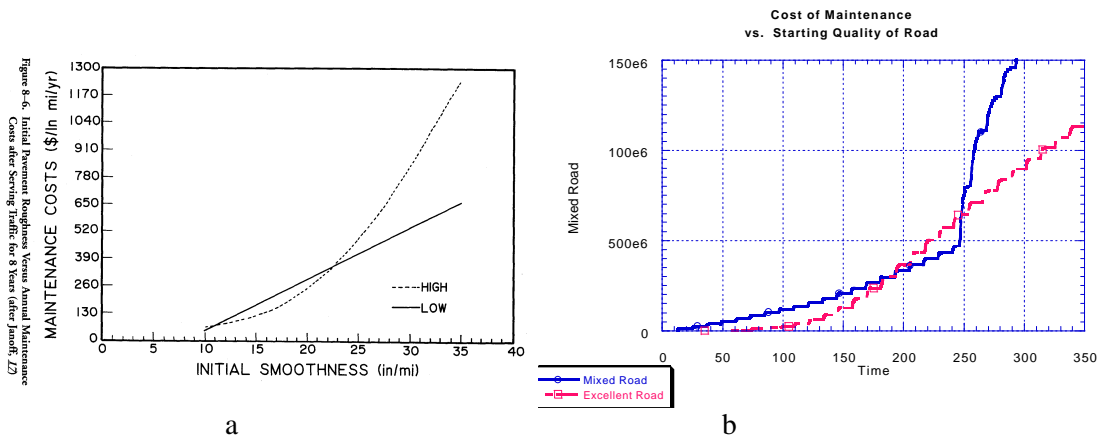
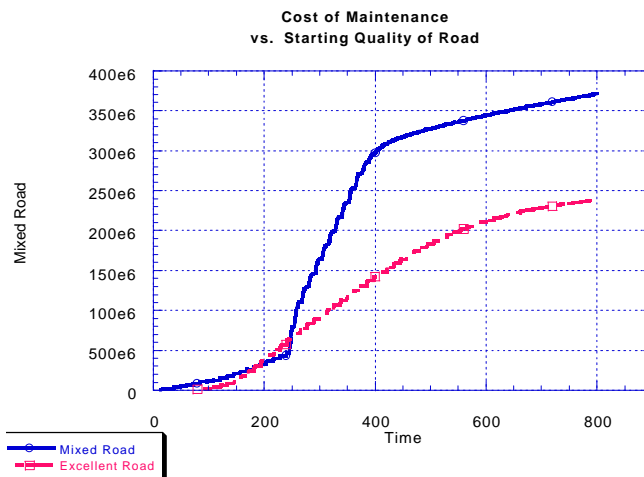


Fig. 6.103 Engineering Predicted Cost vs. Simulated Predicted Cost

The graphic from Kendall, (1991: 491), Figure 6.103a, is scaled in cost per inch. Figure 6.103b shows the start point of the graph produced from the data in the spreadsheet that recorded the entire run. Note the closeness of pattern in the two. The model appears to generate cost structures that match the findings in the literature. The model, however, is not formulated to do so. There is no structure, in the model that dictates that excellent starting conditions should result in lower costs than more rough starting conditions. The dynamic structure of the model generates the pattern of the graphic produced by KaleidaGraph. In addition, the entire run, Figure 6.104 shows that these conditions exist for the entire run of the simulation.

Janoff (cited in Roberts, et. al. 1991) has shown that annual saving of \$600 per lane mile could result if the initial pavement smoothness was reduced from 35 to 5 inches per mile (555mm to 80mm/km). He concluded that from a cost-benefit standpoint, agencies could spend a considerable amount of additional funds to build smoother highways and still accrue savings due to reduced annual maintenance costs.



Comparative Cost of Maintenance

Broken Line-Excellent Maintenance Costs

Solid-Mixed Road Maintenance Costs

Run of 800 months

Fig. 6.104

Simulated Predicted Cost Savings

Managers have reinforced these findings.

“Roads normally need redoing every 15 years (pavement rehab). The question is, if you do a band-aid how much does the maintenance really cost you when you compare that to doing a rehab first. You do a major, it costs you \$5 per square yard. Maintenance runs you less than \$1 per square yard. If you redo the road (at 15 years) it costs about \$2.50 per square yard”(IM).

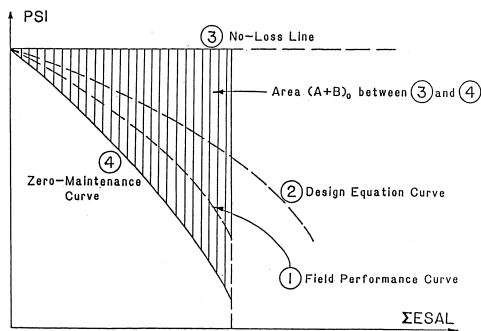
“If you don’t rehab then maintenance goes up to \$3-5 per square yard and you are doing it three times. But, we do a band-aid on it because we have constraints” (I8).

The model generates the behaviors predicted by the literature and what managers in the field have to experience. But, it does so as the dynamics are correct for the system.

### Usability of the Model

The final issue is use. Engineers who have seen the model find it captures the conditions under which they operate and in fact comment has been made that, ”they feel they are really managing their system””

Finally, Fwa and Shina (1985) have suggest the use of the PSI curve should be related to costs to allow the generation of benefit to cost data, Figure 6.105. Does the model generate similar behavior patterns for different maintenance costs that can be used for a benefit-cost analysis?



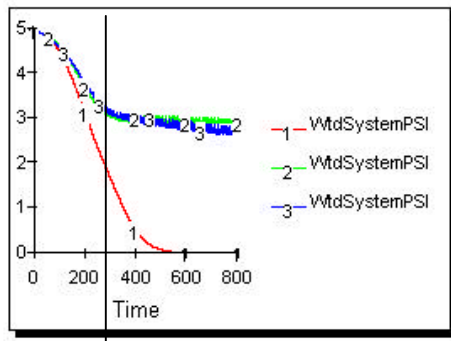
a

Total Pavement Damage Defined by Zero Maintenance  
Pavement Performance Curve  
From Fwa and Shinha (1985 :44)

Fig. 6.105

Cost Benefit

(continued next page)



Comparative MaintenanceCurves-PSI

b

Curve1= No Maintenance

Curve 2 =Base Run

Curve 3= Unconstrained Budget and Assumptions Corrected

Fig 6.105 Benefit Cost Curves

By comparing the cost of repairs against the condition of the system, at a given time, managers can improve their decisions on expenditures as suggested by Fwa and Shina (1985).

### Weakness of the model

A model is not the real world. The intent is to simulate processes in the real world and interpret the output of the simulation, with an understanding of the model's limitations.

As the quality (PSI) of the road improves, development increases. The design of the simulation includes a process for an increase in spending as accident rates increase. Therefore, as the PSI increases, accident rates and industry output appear to be higher. According to managers, this drives them to spend more on improvements in the hopes of reducing accidents

After repairs are performed in the simulation, it is unlikely that industry will move in because managers assume the road to be of higher quality. Drivers perceive the road as used, not as perceived by managers. Industry attraction and accidents would be based on the actual road conditions. However, to do so in the model would require a reproduction

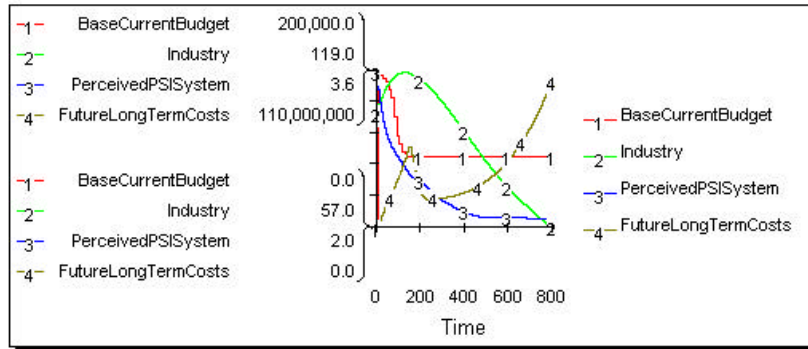
of the entire PSI process for drivers, separate from that used by management. This was not done because the process would not offer any more insight than those gained. Recognition of the weakness itself allows for understanding of a simulation's limitations.

Conclusions based on the simulated accident rate, while showing conclusions opposite to those recommended in the literature may be premature. There are multiple variables unaccounted for that can also increase the accident rate. Such variables include time of day, drug or alcohol use by drivers, direction of travel as related to solar glare, the geometric design of the road, wetness of pavement, etc.. Before attempting to implement the suggested policy, research is needed to evaluate highway accident rates by classification of cause and the sequence of such accidents (i.e. before or after type of pavement improvement).

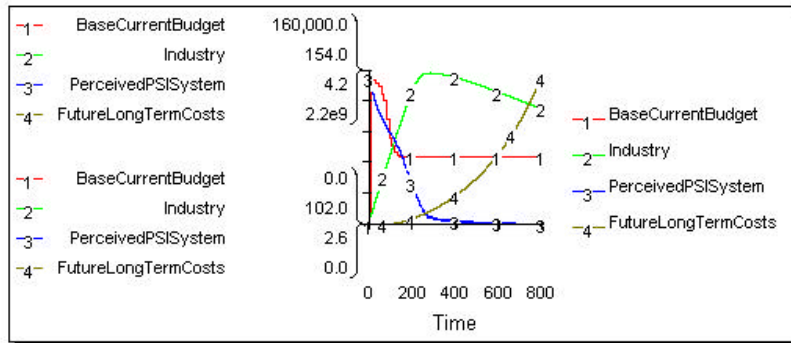
Data for development was taken from the towns of Grafton, Massachusetts and Manchester, Connecticut. The data showed expected growth for a period of ten years. This data was used to develop the trends in area development. The model generates rates for a period of 800 months. The range of reliability may be exceeded, but a short-run of 10 years would be less than the expected life span of roadway. In fact, however, finding any accurate predictions of growth for any area, for any period, would be highly questionable.

## Notes

1.



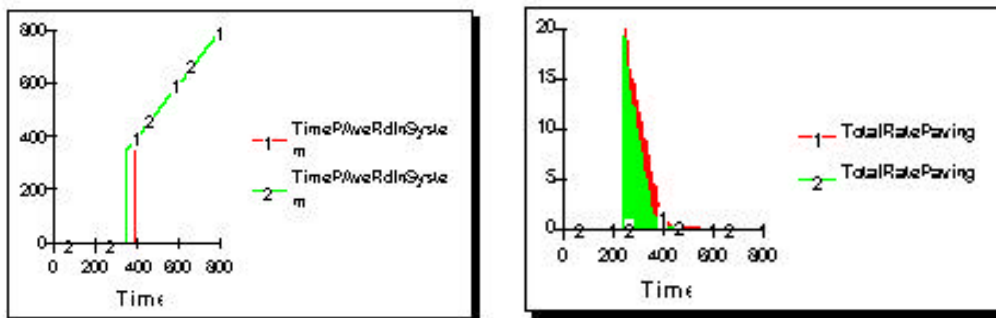
ExRd=300 GoodRd=0 FairRd=300 PoorRd=150



ExRd 300 GoodRd 125 FairRd=80 PoorRd=75

2. Each of these assumptions has been found to be in direct contrast to what can be considered a better management set of policies. This holds true except for the development of a Mall, which is not under the control of pavement managers. The introduction of the Mall occurs at 100 months in the model. The addition of the Mall is included in the reference mode. The extra traffic and trucks created are part of the problem that managers are dealing with.

3. Upon initial evaluation, the values did not make sense. A thought experiment was carried out to evaluate the possible causes. One possible explanation is that higher quality road increases the time that road appears to be available to the system for deterioration. With more time in system, a longer time to reach the point when Pave repair initiates and more road accumulates for Pave or other repairs. With more Pave repair comes an increase in current spending and lower future costs (To test this thought a duplicate model was used for testing, so as not to feed to a spreadsheet and corrupt what was already collected). The results of the test confirm the thought experiment.



Time in System

Total Paving

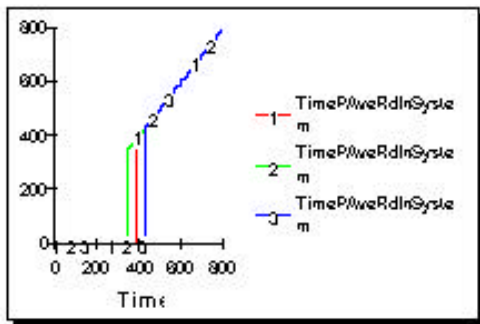
Curve 1-Higher quality PSI

Curve 2 Lower (actual) quality PSI

FigN3 Time In System Curves

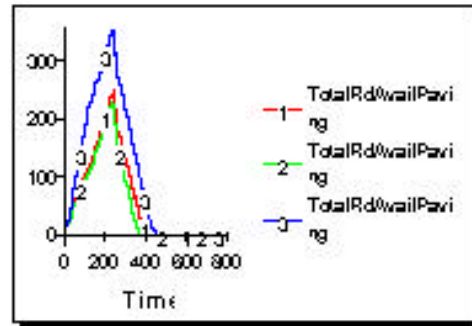
A run using an unrestricted budget mode shows even more time in system. A graph showing more total road paved is seen in the actual simulation but, the total Pave repair carried out is great enough to overwrite the graph seen in Figure N3, thus making interpretation of the data difficult. However, more Pave repair is accomplished. As seen in Figure N3.1.





Time in System –Unconstrained Budget

a



Road Available Paving

b

Fig N3.1 Time in System Unconstrained Budget

#### 4. Assumption of the model:

Accident rates and industry output appear to be higher. According to managers, this drives them to spend more on improvements in the hopes of reducing accidents. (The simulation was formulated to reproduce these processes). However, it is unlikely that more accidents would occur or more industry move in, in the real world system, because managers assume the road to be of higher quality. Drivers perceive the road as used, not as perceived by managers and their response. Drivers and industry attraction would be based on the actual road conditions. However, to do so in the model would require a reproduction of the entire PSI process for drivers, separate from that used by management. This was not done because the process would not offer any more insight than those gained. Recognition of the weakness itself allows for understanding of a simulation's limitations.

During all the runs of the simulation, the costs of repairs, rather than spending on repairs were used. This choice was made, as spending has a first order control to prevent negative values of the available budget. The budgetary adequacy controls the productivity of repairs via allocation of teams.

Spending was not chosen, however, because no separate budgets are used in the real system. [ In addition, future costs have no first order control system, but are based in work available but not accomplished. Comparing future costs with current spending would create a gap in the relative measures used].

Additionally, the real system does not use separate budgets for each repair process. Separate budgets would allow the development of individualized controls for each team assigned for each type of repair. As the real system does not do this, it was decided that the simulation should not either. The cost of repairs acts as a surrogate measure. The levels of actual allocations and spending are, however, available in the model.

The difference in the values between budget allocated and cost is a matter of bookkeeping. First-order control over the production process is maintained through the budget available.

The fact that separate budgets do not exist may be a real weakness of the system, Separate budgets might force better planning and spending as the “common” pot can no longer be raided as needed. A representation of the feedback control is seen in Figure 4N1.

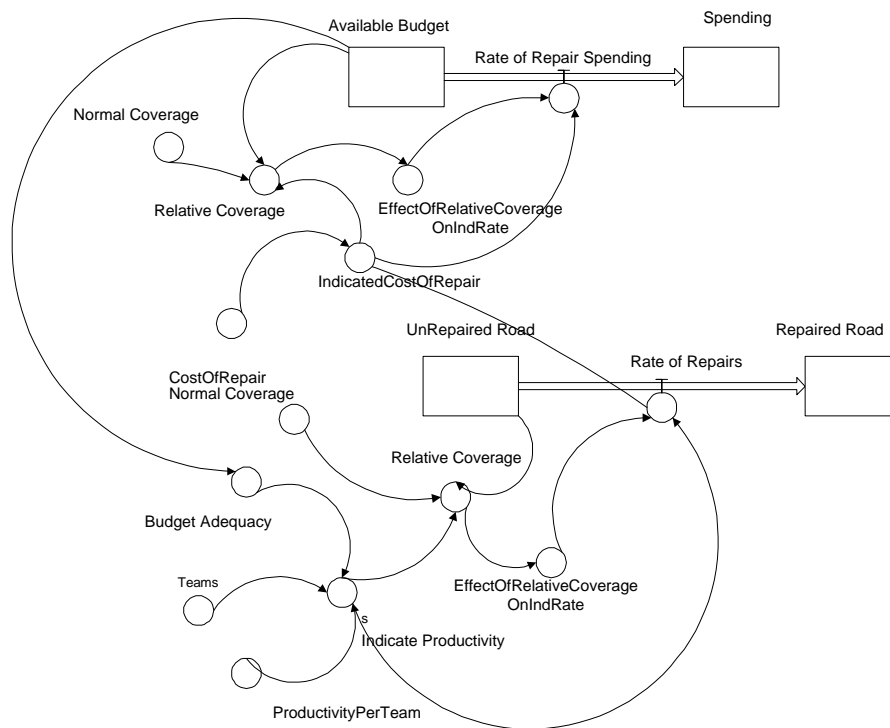


Fig. 4N1

First Order Control of Spending and Repairs

6 Base Run Control Switch Values:

HR Policy Selector=1 HR Policy Teams =1 Poor road Paving Control=0 Budget Mode Fin=0 CVP=2.5 RSL=.5 PSIChoicePolicySwitchPSI =1 Delay Category Corr=0 Percent Correct=0 Winter Control Switch=1 Correct Quality=1

Policy Parameter Values

#### Policy 1

HR Policy Selector=1 HR Policy Teams =1 Poor road Paving Control=1 Budget  
Mode Fin=0 CVP=2.3 RSL=.85 PSICoicePolicySwitchPSI=0

Delay Category Corr=1 Percent Correct=.35 and Winter Control Switch=0  
Correct Quality =0

This mix may lead to earlier paving and lower PSI in the long run. In addition, the mix might create too much Overlay repair work.

#### Policy 2

HR Policy Selector=1 HR Policy Teams =1 Poor road Paving Control=1 Budget  
Mode Fin=0 CVP=2 RSL=.75 PSICoicePolicySwitchPSI=0

Delay Category Corr=1 Percent Correct=.60 Winter Control Switch=0

By reducing the CVP the amount of Overlay performed is reduced, which allows for increased Paving below the CVP.

Policy 3 All same as Policy 2 except RSL=.85-still too much Overlay

Policy 4 same as 3 except Percent Correct .75

For all Policy choices the process of choice was driven by the desire to reduce the amount of Overlay relative to Paving, even if this meant classifying road incorrectly, which has the effect of reducing Overlay (as described in the section dealing with Correct Road Classification).

7. KaleidaGraph From Sysnergy Software, Reading, PA.

## **Chapter 7**

### **Additions to the Knowledge Base**

Additions to the base will be discussed under three categories:

- 7.1 Practical Management
- 7.2 Pavement Management Education
- 7.3 Academic

#### **7.1 Practical Applications**

GASB 34 [see Section 3.2 of dissertation] provides a general guideline for pavement management. It allows state and local governments to report on the condition of their infrastructure assets and the effectiveness of ongoing efforts to preserve these assets as an alternative to traditional depreciation. (In other words, managers can expense the asset rather than depreciate it). The purpose is to discourage deferred maintenance of critical assets. Managers indicate that it is the deferring of repairs that causes long-term cost to increase. Managers were also clear that cheaper short-term repairs were not the correct solution.

Section 4e of the Modified Approach allows, in lieu of depreciation, that a process has the following components.

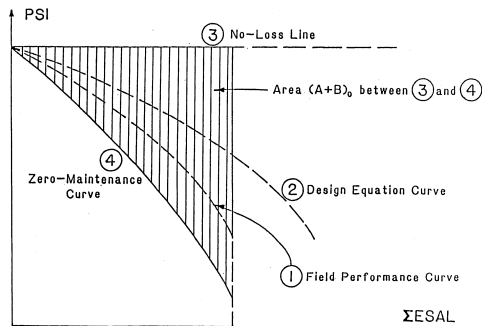
- Maintains an up-to-date inventory of eligible infrastructure
- Performs condition assessment of eligible infrastructure assets at least every three years
- Summarize the results, noting any factors that may influence trends in the information reported
- Estimate each year the annual amount to maintain and preserve the eligible infrastructure at or above a prescribed level. (McNamee, P., Dorman, D., Bajadeck, D. and Chait, E 1999).

- 

What was discovered is the lack of information available to implement the guidelines that have been suggested. Currently, managers make decisions based on pressures of the system. Pressures include the need to spend down the total allocated yearly budget or

lose it, not to allow any deaths, to respond to political pressures, and appear to maintain the road at best quality possible for the budget available. To accomplish this decisions are made to repair roads in the winter, categorize roads at better quality after repairs, and plan budgets that downplay the damage classification of the roads. In addition, there is a lack of information available for the correct management of the roads they are responsible for. Inventories of roads at town levels proved to be unavailable. At the state level there was no record kept of the amount of road repaired by type, and how much was allocated for its maintenance. The lack of such data makes good decision making difficult. In fact benefit to cost analysis is made impossible. Therefore, the allocation of resources based on pressure tends to create the high possibility that resources are wasted. The simulation reveals that improved operational decisions can improve the road without great increases in demand for resources.

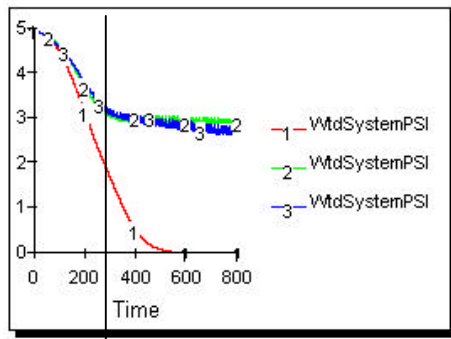
Fwa and Shina (1985) have suggest the use of the PSI curve should be related to costs to allow the generation of benefit to cost data, Figure 7.1. The model generates similar behavior patterns for different maintenance costs that can be used for a benefit-cost analysis.



Total Pavement Damage Defined by Zero Maintenance  
Pavement Performance Curve  
From Fwa and Shinha (1985 :44)

Fig. 7.1a Total Pavement Damage vs. Costs Expenditure Curve

(continued next page)



Comparative -PSI

b

Curve 1= No Maintenance

Curve 2 =Base Run

Curve 3= Unconstrained Budget and Assumptions Corrected

Fig 7.1 Comparative Maintenance -DamageCurves

By comparing the cost of repairs against the condition of the system, at a given time, managers can improve their decisions on expenditures as suggested by Fwa and Shina (1985). The data from the model has been collected on spreadsheets as well as the benefit to cost ratios generated by the model.

Several practices require correction as applied to road pavement management. These are:

- No paving in winter, except where a situation is so dangerous as to endanger life.
- Managers must assign both correct quality and correct categorizations to roads that are repaired.
- The Critical Value Point and RSL relationship need to be evaluated before decisions are made about either one alone.
- Managers need to collect and evaluate the following statistics if they are to gain control over road capacity in an area: Accident rates and related road conditions and spending allocations as related to types of road repairs. They must also develop a benefit to cost relationship between costs and final condition of the road.
- Managers should be involved with regional planning to prevent incorrect allocations to roadway development. In many cases road designers did not communicate with managers responsible for the maintenance of the system.

## 7.2 Engineering Education

Textbooks of engineering and articles written about pavement management represent the PSI curve as a smooth curve as seen in Fig. 7.2.

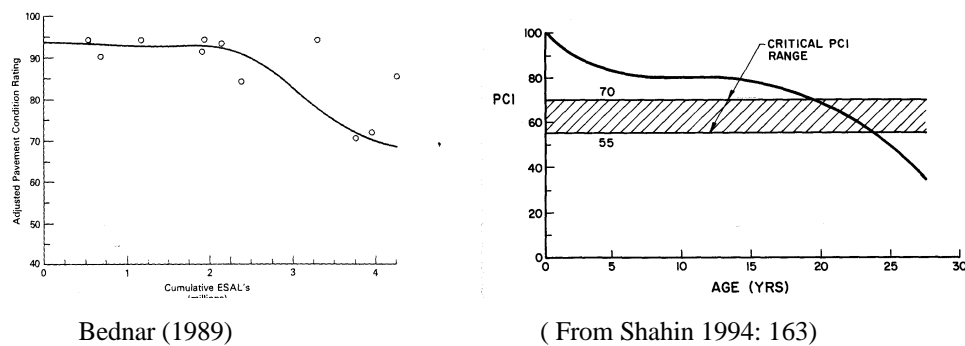


Fig. 7.2 PSI Curves from Literature

During a presentation to a group of system dynamists the same question arose as to why the curve is not smooth. The answer lies in what Fwa and Shinah (1985) have written in relation to the curve.

It should be noted that the PSI curves, which are used as measures, are not totally accurate as given. The loss represented by traditional studies does not represent the true total pavement damage. This is because a certain level of routine maintenance is always present in practice. Some of the damages have already been recovered by maintenance work when a condition survey is made.

In fact a curve provide by Price Waterhouse (1999), Figure 7.3, is much more informative

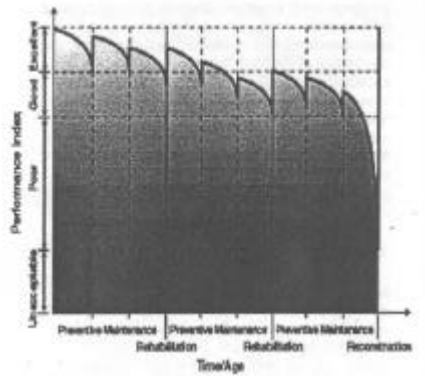
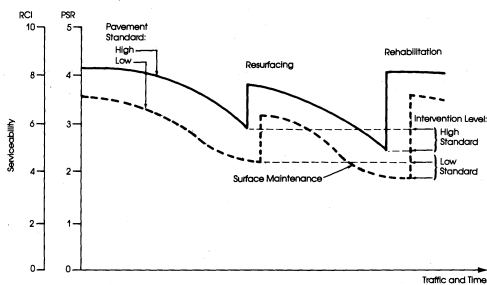


Fig. 7.3 Life Cycle Asset Management Approach  
(Price Waterhouse Coopers :3)

The curve follows what a single repair process repeated several times would look like. Such a repair process is seen in Figure 7.4



From Paterson (1987 :114 fig4.1)  
Fig. 7.4 Performance defined as the trend of serviceability with time

A close evaluation of the PSI curve generated in the simulation reveals that the curve represents small oscillations between repair and deterioration, Figure 7.4.



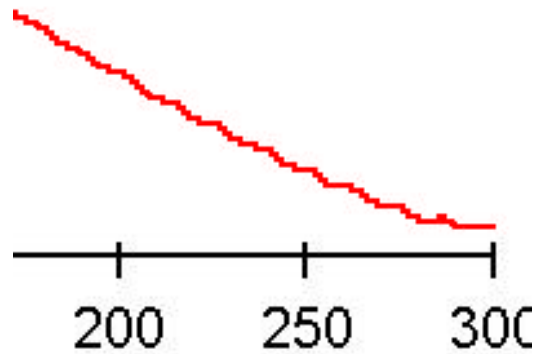


Fig. 7.5 PSI Curve Magnification

Engineers in training should be made more familiar with an improved representation of the curve.

### 7.3 Academic Conflict

#### Mental Models

Many authors have discussed the problems created by weak mental models. We have been warned of “cognitive illusions” (Edwards and vonWinterhead 1986), the inability to deal with complex issues due to misperceptions of feedback, and limitations to our information processing (Serman 1998), but some choose to ignore the warnings altogether. Even recommendations that policy makers should decide whether they wish to make decisions based on results obtained from their unaided mental models, or from results obtained from some combination of formal and mental models” (Radzicki 1998 :8) are not heeded.

Mass (1991) states

-a system dynamics model is intended to yield operational insights about feedback relations that can produce or contribute to problems, can counteract policy interventions, or can reinforce benefits of policy action aimed at high leverage points (:68).

### **7.31 Problem Creation**

During the development of this model a decision-making process based on a set of weak mental models was discovered. These decisions centered on repair policies initiated by managers, whose intent was to save lives by reducing accidents.

It should be noted that managers do not make repair decisions based on user costs or rehabilitation costs alone. From a pragmatic point of view, managers allocate resources based on risk assessment. Their drive is to not only to keep roads in usable condition, but to also keep the rate of accidents, and their associated costs, to a minimum.

One consequence of regional development appears to be increases in accident rates. This due to the fact that along with,“ the higher traffic volume, particularly large trucks, has come an increase in traffic accidents. Unfortunately, this trend shows no sign of abating (Los Angeles Times 1996). In the New England Region, is the example of Route 128 also known as Interstate 95. In 1992, there were 421 crashes, while in 1997 the number reported was 491. In 1990 there were 120,426 cars a day at the I-93 interchange in Woburn, Massachusetts, but in 1997, this number had reached 144,992 cars a day. In Alabama, “take a two-lane road, add some newly sprouted subdivision feeding motorists into congested traffic flow, mix an equal part impatience, speed and tailgating, and, police say that’s a thoroughfare that needs attention” (Montgomery 1997).

However, the attention that is paid to accident prevention may lead to unintended consequences due to poor decision-making. In system dynamics, we often find behavior

based on weak models and untested assumptions. In this case, Pavement System Managers have expressed the following comments:

“We do the most used roads to keep user costs and complaints down. I’ll do I91 before I do a secondary road. We try to do these roads before they go bad. (CT).

The reasoning behind such decisions is given as, “higher volume roads have more accidents. With higher volumes of use, you have a greater chance of a problem. It’s risk that leads to repairs. “With high volumes you have a 70% chance of accidents, with low volumes you have a 30% chance. That’s my risk, that’s when I will do it” (INL).

Research suggests that during periods of what appears to be high sustained volumes on a facility, there will exist periods of turbulence or apparent instability in traffic performance. This may not be apparent from a system level view, but can give rise to local conditions that increases the probability of a crash. One can infer that, correlated with changes in volume, there will also be changes in vehicle speeds (Hughes 1999).

When this information came to light, a review of traffic accidents was performed. What was found was a situation that did not confirm what managers believe or why they commit resources as they do. Reports that were reviewed indicated that most accidents occur when the road conditions are better. The information revealed that there were:

- 1,492 accidents on a set of two lane highways
- Average speed was 87.2 mile per hour
- Surface conditions were dry in 61.3% of accidents
- 1,395 accidents occurred when the road had no defects (only 4.3% occurring with ruts, holes, bumps or other defects)
- 1,080 occurred in daylight
- 1,039 occurred with clear weather.
- 502 were associated with moving violations.

The majority of accidents occur under the best of conditions. An article in the Boston Globe, implied that, highways (sic: are) stuck in loop of more cars, more crashes (Brown 1999).

What could cause this contradiction in the apparent cause and action taken to prevent accidents?

### **7.32 Basis of Decisions**

Research in highway design conducted by McFarland (1972), and the graphs used to represent pavement conditions, seem to be contributing to the process. Managers make their decisions based on their education, experiential learning from other managers, and past practice

### **McFarland Set of Assumption**

McFarland's (1972) research is based on several assumptions and a static view of accident causes. Among the stated assumptions in the publication are:

- It is assumed, in effect, that the pavement serviceability index and coefficient of friction decrease over time such that both can be taken into account by simply relating accident rates to the pavement serviceability index.

(However, he goes on to state that this is an oversimplification and future research is needed in the area to derive more complete relationships (:33).

- Based on this information it seems reasonable to use ...the corresponding assumed levels of serviceability index as multipliers (:34)
- It is assumed that the accident rates on urban roads are the same at all levels of the serviceability index (:36)
- McFarland relates accidents to a constant 50 MPH speed (:35)

Based on this information, and an analysis of the engineering literature, inputs that effect accidents were included in this system dynamics model of a pavement system.

### **7.33 Causes of Accidents**

Skid resistance is defined as the force that resists the sliding of tires on a pavement when the tires are prevented from rotating (Shahin 1994: 90). Hydroplaning occurs when water or contaminants separate tire and pavement surfaces. Under heavy traffic the pavement surface becomes polished. In general, skid resistance deteriorates in heavy traffic until it reaches equilibrium. There is no specific value at which skid resistance levels off and due to the seasonal variation of skid resistance there is only a mean equilibrium value. The research has shown that skid resistance has a higher correlation between the number of trucks, than with the total number of vehicles. The friction coefficient also decreases with increases in speed. Figures 7.6 through 7.9, taken from engineering research, are presented to show the relationships that exist between these variables. Figure 7.6 indicates the relationship between road serviceability and speed.

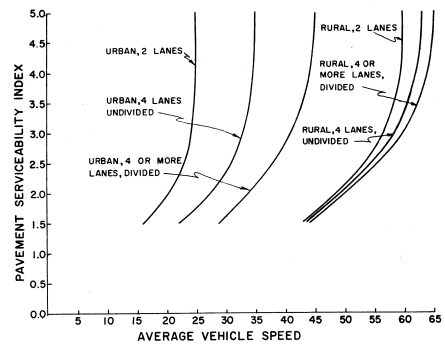


Figure 7.6 Average Vehicle Speed Related to Pavement Serviceability by Type of Road (From McFarland 1972 :10)

Figure 7.7 relates the impact of speed on the frictional coefficient, defined as, “the ratio between frictional force in the plane interface and the force normal to the plane.

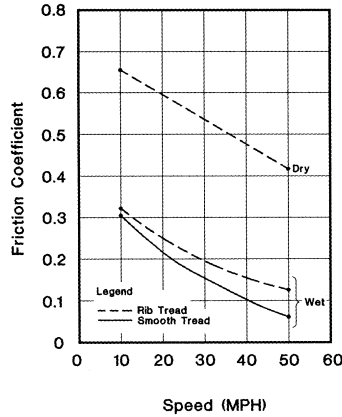


Fig. 7.7 Friction values on asphalt seal-coat surface related to speed  
From (Shahin 1994 :96)

[The frictional coefficient is a measure of skid resistance. As the frictional coefficient or skid number, (SN) declines, there is a greater probability of skidding and accident occurrence. The term skid number and frictional coefficient refer to the same process measured with different scale. For ease of understanding, the value of the SN=100 x friction factor (Shahin 1994 : 98).]

Figure 7.8 relates the impacts of volume to skid number. As volume, measured in 100 million vehicle miles, increases the road becomes polished, reducing the SN.

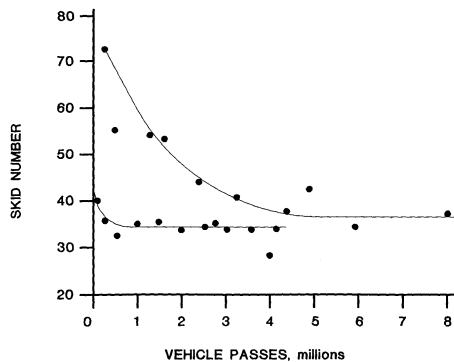


Fig. 7.8 Skid resistance as a function of traffic exposure  
Shahin (1994 :93)

Hass (1978) wrote that considerations of time/traffic/climate based changes in skid resistance require periodic measurements, preferably on a mass-inventory basis, for investment program purposes. On a short-term basis, skid resistance changes can occur rapidly, usually because of rainfall. However, in the long run, due to seasonal effects combined with several million vehicle passes most pavement shows a continual decrease in skid resistance (:12). Figure 7.9 represents the seasonal impacts on skid resistance.

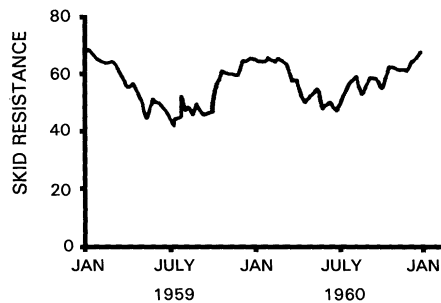


Fig. 7.9 Seasonal Change vs. Skid Resistance  
(From Shahin (1994 :91))

To test these findings, a formulation for accident rates, controlled by PSI and effected by speed and changing seasons was created. In addition, speed was adjusted for volume using the formulas provided by de la Garza (1998). The findings of the simulation are counter to McFarland's work and support the policy of lowering improvement in pavement conditions to decrease the rate of accidents, not increasing spending and improving conditions.

Table functions were created for each of the inputs shown in Figures 7.6 through 7.9. The resulting dynamics, of tests, run on the simulation model, are discussed in the next section.

### 7.34 Simulation Findings

It was during the development of the reference mode that the issue of allocating more funds to road repairs as a means of preventing accidents came to light.

Rates were developed using the inputs created from table functions based on the Figures 7.6-7.9. These functions then impacted on a normalized SN. The developed SN was then related to accident generation.

A set of conditions was input to the model that allowed improvement in the PSI curve after an initial phase of deterioration, Figure 7.10.

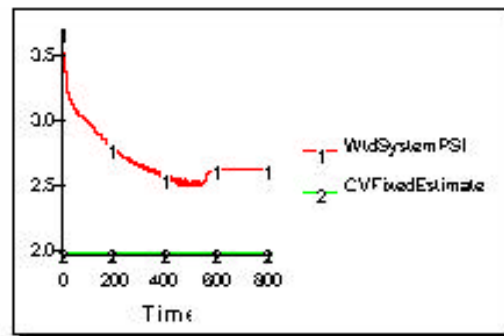


Fig. 7.10 PSI Curve

A set of experiments to determine if a change in policy could effect the rates of accidents was conducted on the model. Figure 7.6 shows a set of accident rates labeled  $SN_{CombinedAccRate}$  and  $PSI_{AdjSimAccRate}$ . The rate  $PSI_{AdjSimAccRate}$  (PSAR) is used as a surrogate measure of the rate  $SN_{CombinedAccRate}$ . (SNAR) The reason for this choice is made on appearance only. Both rates are used in the model, however, in order to make the graphs, used in this paper more readable, the SNAR is used. The PSAR rate is a rate generated by the effect of the PSI on speed. The SNAR compounds the effect seasonally and creates an oscillation that makes the graphic more difficult to read when run as a comparison. However, both rates respond to a change in the road condition (PSI) in the same manner. The SNAR is given a ripple effect due to seasonal changes (seen in Figure 7.9).



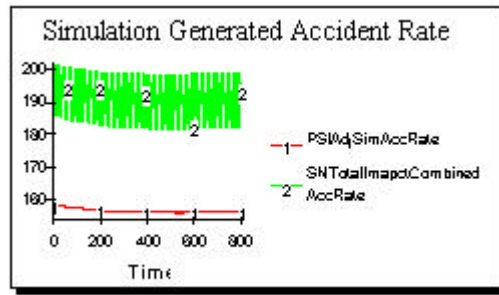


Fig. 7.11 Simulated Accident Rates

A base run under an unconstrained budget was made. The PSI effect as determined by McFarland is compared to that generated by the simulation, Figure 7.12. McFarland recommends repairs and increased spending to reduce accidents based on the research described above. McFarland's findings assume that as the PSI deteriorates accidents increase. In fact, in the real system, as stated earlier, managers spend more on improvement to prevent accidents. However, this tends to increase the PSI, as indicated in Figure 7.12 and with it the accident rate.

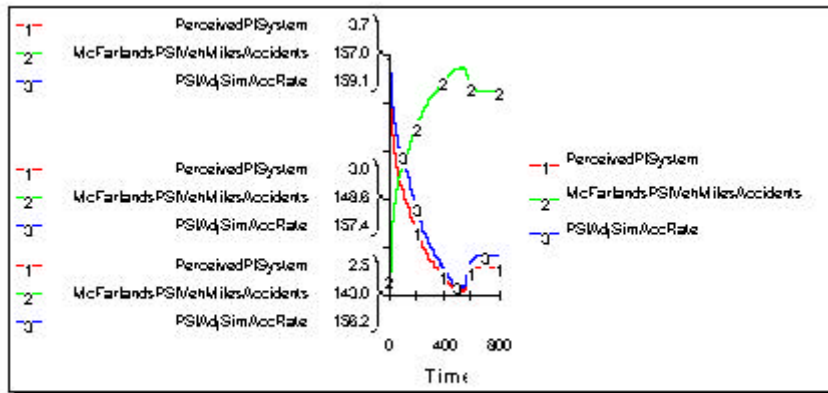


Fig. 7.12 PSI and Comparative Accident Rates: Simulation Vs. McFarland

When managers receive a more funding, we expect to see better PSI conditions and higher rates. With an unconstrained budget not only does the system not collapse, but note that with the increase in the PSI, accidents also increase. As we cannot allow our infrastructures to collapse, as indicated by the continuation of a constrained budget, we can expect increases in expenditures to create increases in accident rates.

A policy to counter the effect practiced by managers is recommended. The original formulation described in Chapter 4 was designed so that as accident rates either go up or down, the model turns on and off the rates of paving. A counter policy of selecting lower levels of maintenance and paving was developed. The impact of the policy is to lower the available miles for paving and maintenance, which then effects the allocation of resources needed. This brings down the rates of repair for paving and maintenance and creates a lowered PSI accompanied by lower accident rates.

Figure 7.13 shows the impact of an improving PSI on the accident rate.

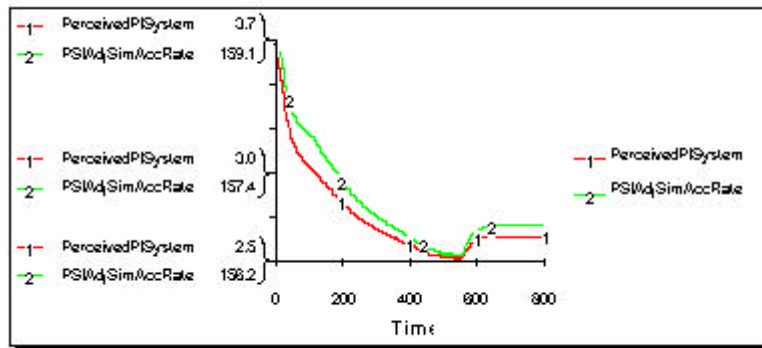


Fig. 7.13 PSI and Related Accident Rates

The effect of spending less when accident rates increase are seen in Figure 7.14.

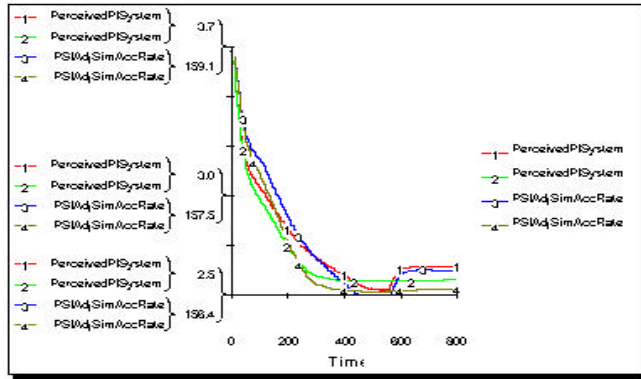


Fig. 7.14 PSI and Accident Rate Counter Policy Recommendations

Note that after the policy is enacted the PSI comes down, curve 2 along with the accident rate, curve 4. The effect on industry is as expected, Figure 7.14. However, no collapse is evident.

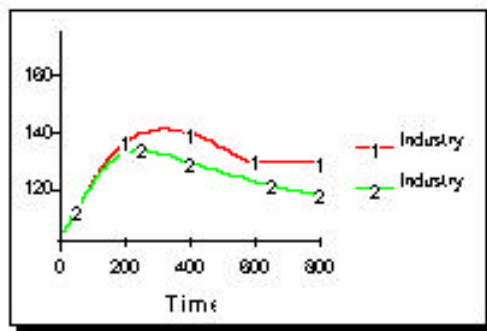
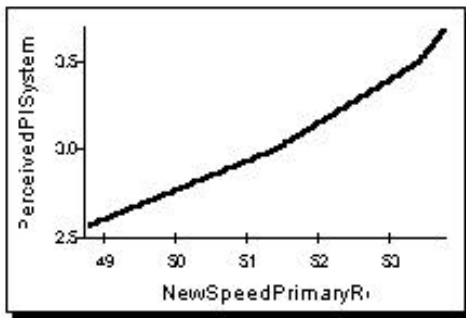
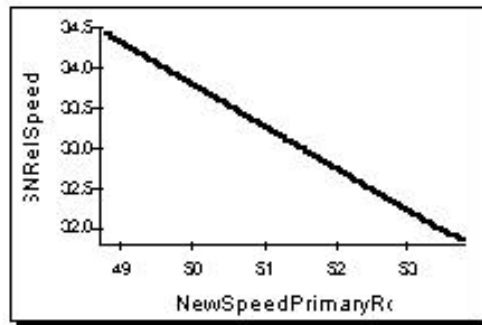


Fig. 7.15 Industry

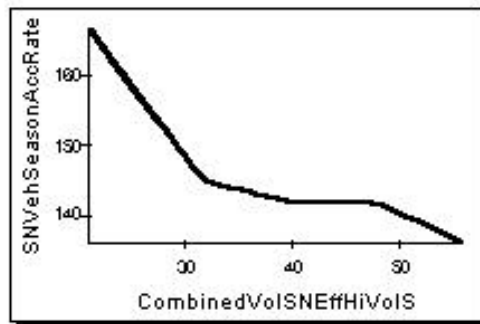
McFarland's analysis is flawed. The increase in volume of traffic decreases the SN number, this is reinforced by changes in speed and seasonal variation. McFarland, by keeping his assumed test speed constant and assuming that the volume effect could be subsumed into the PSI, and neglecting seasonal effects creates a static analysis of a dynamic process, fails to incorporate the change in speed and volume effects on the accident rates. Figure 7.15 a-c, show the relationships between the variables as they effect each other. Note as the PSI increases so does speed. The speed increase reduces the SN. As the SN value decreases accident rates go up.



a Speed/PSI Relation



b. Speed vs. SN



c. Seasonal, Speed and PSI Effects on SN and Accident Rates

Fig. 7.16 Cause of Accidents- Variable Relationships

The problem with the work done by McFarland is that it is based on a static (constant) speed, with no adjustment for volume, etc. (Note1). The mental model that managers carry are creating both over-spending and an increase in accidents.

The important question seems to be-Why do managers persist in spending money that may be causing more accidents? An understanding of what causes this decision process falls into the work on escalation to commitment (Shaw and Ross 1989), attribution theory (Kelly cited in Martinko 1995) and perseverance of belief (Curtis 1989). At the time of this writing, managers have not been confronted with this issue. However, it is an issue that demands close attention.

#### Limitations of Accident Simulation:

There are multiple variables unaccounted for that can also increase the accident rate. Such variables include time of day, drug or alcohol use by drivers, direction of travel as related to solar glare, geometric design of the road, wetness of pavement etc. Before attempting to implement the suggested policy, research is needed to evaluate highway accident rates by classification of cause and the sequence of such accidents (i.e. before or after type of pavement improvement).

#### **Concluding Remarks**

Observations:

It is apparent that pavement managers do not have a complete understanding of the road capacity that they are responsible for managing. During research, to develop this dissertation, the following areas of management concern were raised:

- Small town pavement systems do not keep an inventory of roads as required by FASB.
- At both the small town and state level, record keeping of the amount of funds allocated for a specific type of repair, and tracking the deterioration for the work performed, leaves system managers without the ability to conduct benefit to cost analysis.

- Continuation of a set of policies that prevent the use of Pave repairs, with replacement of short-term maintenance, leads to lower current costs but increases in future spending and tax burdens.
- The addition of resources without change in the policies that control those resources is wasteful and does not improve system characteristics. In fact, these characteristics may sometimes be diminished.
- 

Quotes from newspaper articles verify much of the work discussed in this paper. As examples please note:

As related to misclassification or roads:

“Some of the projects were more costly than expected because... roads deteriorated in the time between completion of the design and the start of construction. Delaying the repairs and going to bidding would inconvenience drivers and could have allowed more deterioration to become more costly and dangerous.” The total extra cost to the state-almost \$11.8 million in one year. (Hartford Courant, 1/28/02)

In terms of the impact of road systems on development:

“Spaulding said it would not go forward without a commitment from the state to spend up to \$30 million for a ‘flyover’ connector to I-84.”( Hartford Courant 9/9/2002)

In terms of projects:

“I tell the software I have \$500,000 a year to make road improvements. Then I ask it, which roads should I fix first? It will print it out and tell me that at this rate it’s going to take 105 years to correct all the road problems I have because I don’t have enough money”. New York Times 1/27/02)

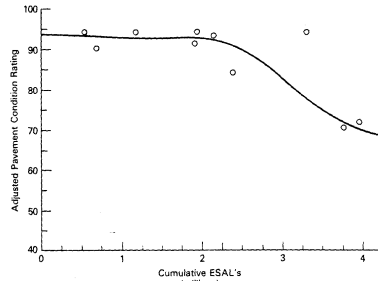
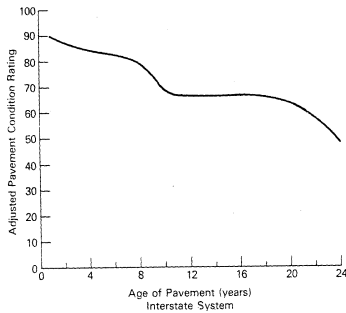
In Connecticut, the town of Manchester and Vernon are fighting over additional development. If the development occurs in Vernon, Manchester still gets hit with more traffic and no benefit., and of course the opposite effect can occur.

### **Future Research**

One area that needs further research is the effect on tax policy as it impacts both road development and regional planning. The other area is the effect that the pressure to spend, and at the same time not be the cause of deaths, has on managers in making incorrect decisions and allocations. These allocations can exacerbate problems rather than allow effective solutions.

## Appendix A Graphics and Related Formulas

### PSI Curves



### Arkansas

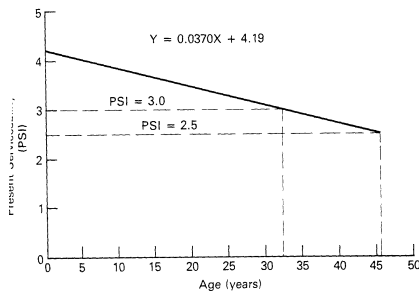
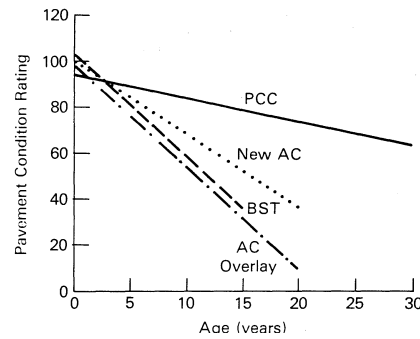


Figure 7.—Serviceability-performance curve for PSI versus age.

### Iowa



### Pennsylvania

### Washington

Bednar (1989)

### Damage Types

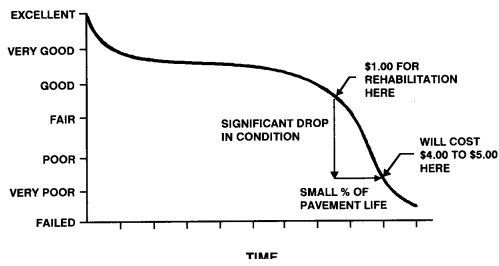
Classification of Observable Distresses in AC Surfaced Pavement							
Classification by Possible Causes				Classification by Possible Effects			
Load	Climate/Durability	Moisture/Drainage	Others	Roughness	Skid/Hydroplaning Potential	FOD Potential	Rate of Deterioration and Maintenance Requirements
Alligator Cracking	Bleeding	Alligator Cracking	Oil Spillage	Corrugation	Bleeding	Block Cracking	All Distresses
Corrugation	Block Cracking	Depression	Jet Blast Erosion	Depression	Depression	Joint Reflection Cracking	
Depression	Joint Reflection Cracking	Patching of Moisture Caused Distress	Polished Aggregate	Rutting	Polished Aggregate	Long./Trans. Cracking	
Patching of Load-Caused Distress	Long./Trans. Cracking	Swelling		Shoving of Asphalt Pavement	Rutting	Slippage Cracking	
Polished Aggregate	Patching of Climate/Durability-Caused Distress	Ravelling/Weathering		Swelling		Ravelling/Weathering	
Rutting	Shoving from PCC					Jet Blast Erosion	
Slippage Cracking	Raveling/Weathering					Oil Spillage	
	Swelling						

From Shahin (1994: 199)

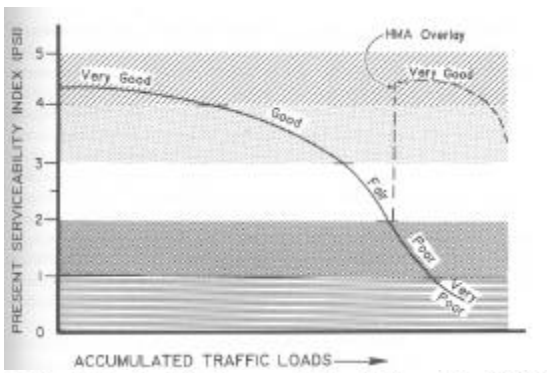


# Road Classification

PAVEMENT CONDITION RATING



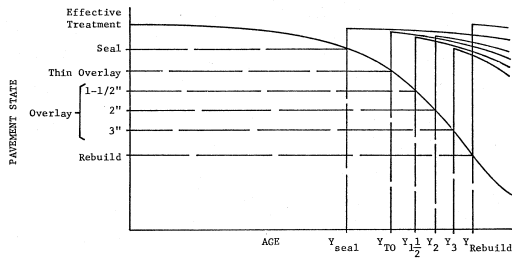
Shahin (1994: 2 )



Typical Relationship Between PSI and Cumulative Traffic

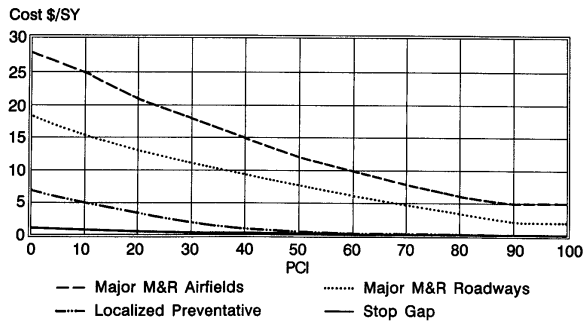
Roberts and Kendall (1991: 479)

16



University of Ct. School Of Engineering( Stephesn et.al, 1983: 16)

## Repair Costs



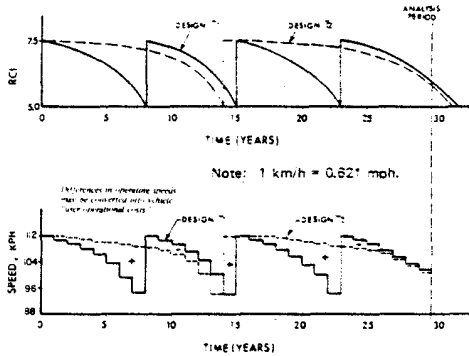
Shahin (1994 :168)

## Psychographic Measures

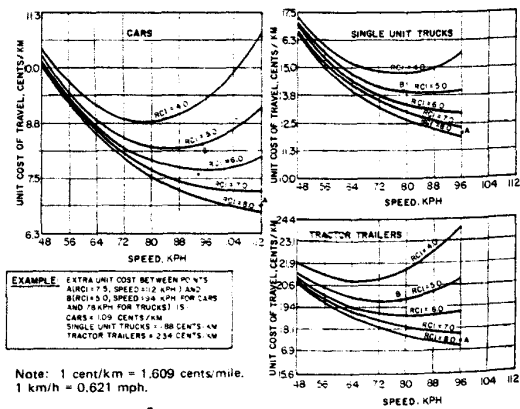
INDIVIDUAL JUDGMENT OF TEST SECTION PAVEMENT QUALITY AT TEST SPEED	
RATER NAME	<b>PERFECT</b> — 5 VERY GOOD 4 GOOD 3 FAIR 2 POOR 1 VERY POOR 0 <b>IMPASSABLE</b>
RATER ID NO. DATE	
SEAT POSITION <input type="checkbox"/> RF <input type="checkbox"/> RR <input type="checkbox"/> LR	
TEST SECTION NUMBER	
PAV'T TYPE <input type="checkbox"/> RIGID <input type="checkbox"/> FLEX <input type="checkbox"/> F/R	
RATING TRAVEL SPEED	
TIME	
AVOID DISTRACTIONS. KEEP YOUR JUDGEMENTS CONFIDENTIAL.	
OFFICE USE ONLY	

Weaver (New York State DOT: 40)

## Vehicle Operating Costs



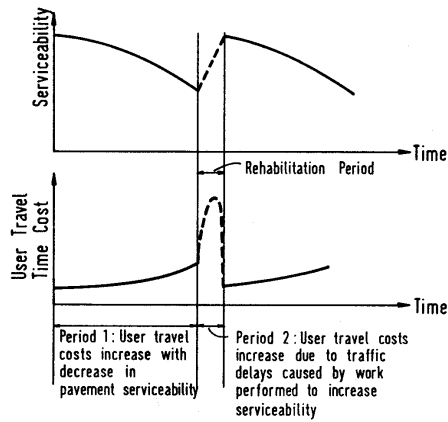
Karan:and Hass (University of Waterloo 126 Speed Profiles –Roughness and Speed over time)



Karan and Hass-Comparative Costs (University of Waterloo)

Vehicle type (1)	PCI = 100 (dollars/ vehicle/km) (2)	PCI = 100 (dollars/ vehicle/mi) (3)	PCI = 30 (dollars/ vehicle/km) (4)	PCI = 30 (dollars/ vehicle/mi) (5)
Passenger car	0.153	0.245	0.221	0.354
Bus	0.285	0.456	0.375	0.600
Truck	0.443	0.709	0.685	1.096

Berger and Greenstein (1981: 382)

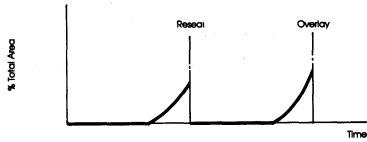


(Fwa and Sinha 1991)

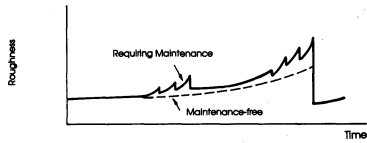
# Long Term Life Cycle Costs

Time-profiles of pavement condition, maintenance and costs over life-cycle of a paved road

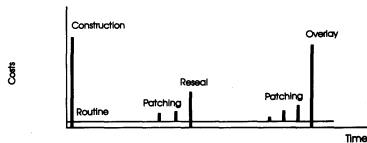
(a) Surfacing Distress



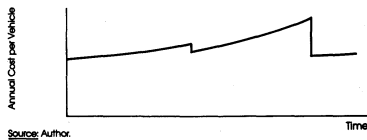
(b) Road Roughness



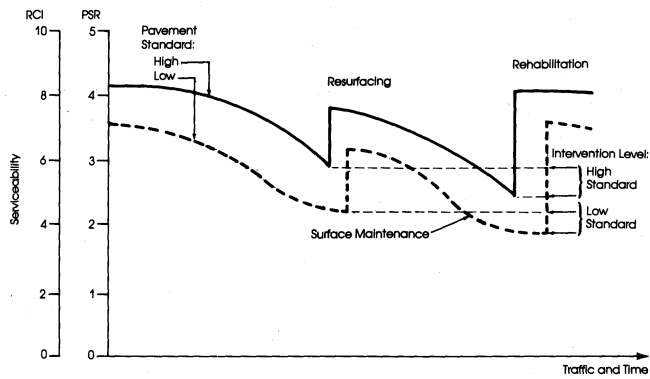
(c) Road Costs



(d) Vehicle Operating Costs



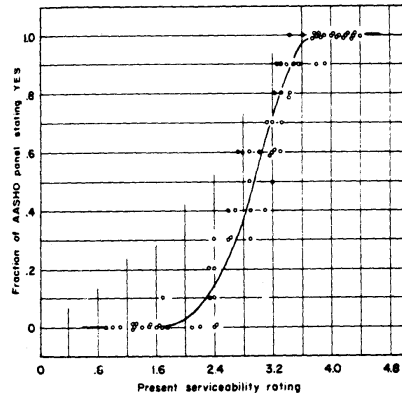
Source: Author.



Performance defined as the trend of serviceability with time  
Paterson (1987: 114)

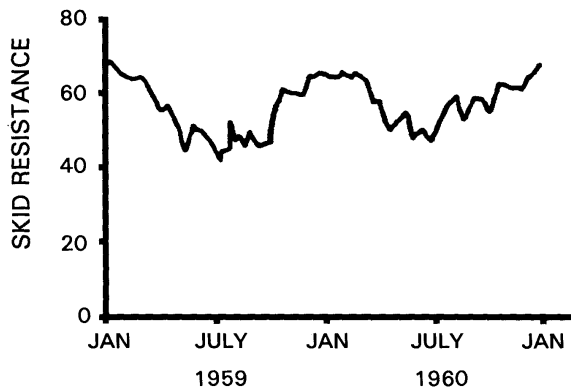
## Dissatisfaction Curves

Acceptability of serviceability by subjective assessment

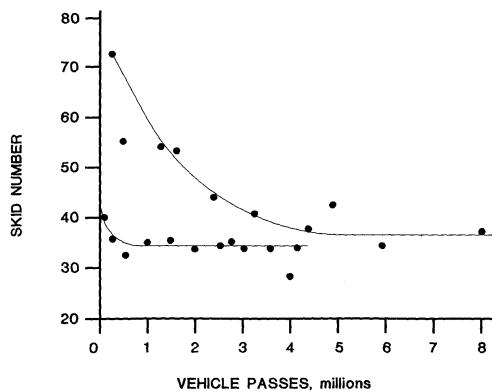


(Highway Serviceability and PSI)  
Paterson (1987:12)

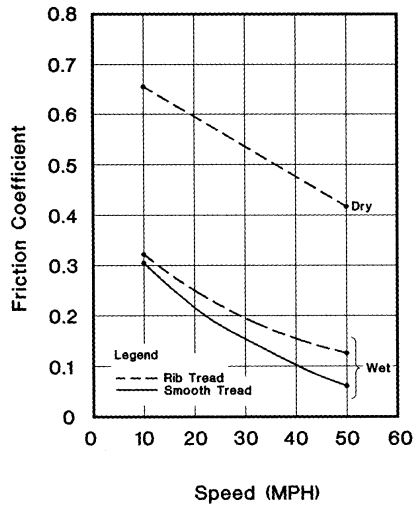
## Accident Related Curves-Skid and Speed Effects



(Seasonal Change Skid Resistance)  
Shahin (1994: 91)

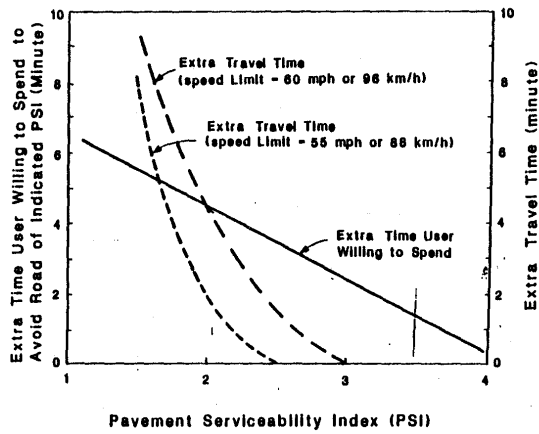


Loss of skid resistance as a function of traffic exposure  
Shahin (1994: 93)



Friction values on asphalt seal-coat surface  
Shahin (1994: 96)

### Road Speed and Waiting Time



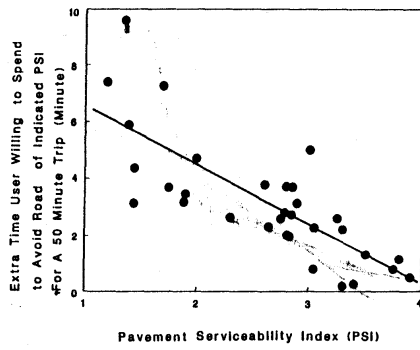
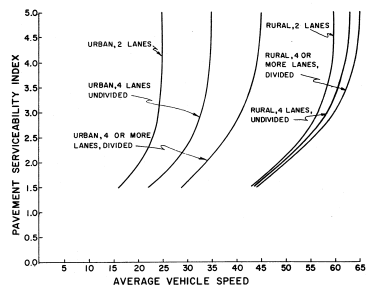


FIG. 7. Relationship between Pavement PSI and Extra Time User is Willing to Spend to Avoid a Given Road for 50-min Trip (after Garg and Horowitz 1987)

(Berger and Greenstein (1991))



Average Vehicle Speed Related To Pavement Serviceability Index by Type of Road (McFarland 1972)

### ESAL Formulation

$$E = 182.5 \text{ APT} [1.15 - 0.083 \ln(A/2)]$$

E= ESAL's/Year/Lane

A= Average Annual Daily Traffic(AADT) in two directions

P= Percent Trucks-100

T= Truck Factor(Rigid=1.15, Flexible=.76

(Bednar :.93)

Notes:

1. All curves, Tables, Figures and formulas used or quoted from the literature are available in Appendix A of this dissertation. The information has been added to 1) allow any reader of this dissertation to see the how and why certain formulations were incorporated in the model 2) to conserve space needed for the presentation of the core of the model
  
2. By definition- The ESAL factor of an axle load is the ratio of the number of load applications of the 18-kip datum load to cause a given level of damage to the number of load applications of the axle load under consideration to cause the same level of damage. . (If the standard damage by 2 applications is 10 cracks, and the damage to cause the same 10 cracks by the load under question is 1, then the load under question has a value of 2 ESAL (Fwa and Sinha, 1980: .33).



## **Appendix B**

### **Interviews**

#### **Interview Process**

In the development of a systems dynamics model, a key element is the acquisition of tacit knowledge. Tacit knowledge is the knowledge that has been internalized by members of an organization, which is usually known to the member at a level of unconscious awareness. A key task for a model builder is to devise some way to obtain this information for use in the formulation of a system dynamics model. The interview process may be looked at as a qualitative approach, as compared to a more quantitative method of collecting numerical information. This does not mean that numerical information will not be forthcoming, but the focus is on a description, which may be an interpretation of events and processes, rather than a formal set of values to be used in statistical analysis.

“Qualitative interviewing is appropriate when the purpose of the research is to unravel complicated relationships and slowly evolving events. It is also suitable when you want to learn how present situations resulted from past decision incidents.”(Rubin, 1995: 51)

One type of interview is the unstructured interview, where very little guidance is offered by the interviewer, and the information gathered is that of interest to the client. A second type of interview is a structured, open-ended interview. In this case, there are predetermined questions, but the interviewee is unconstrained in their answer (Note 1). How do you know if things are going well? A third type is a structured, fixed response interview. Here the answers to questions are constrained by choice of answer. For example “Is, is your job satisfying?, with answers ranging from satisfying to dissatisfied. (Nadler, 1977).

Patton (cited in Erlandson (1993: 88), delineates six basic types of questions:

1. Experience/behavior questions are aimed at eliciting descriptions of experience, behaviors and actions.

2. Opinion/value questions try to find out what people think.
3. Feeling questions are aimed at understanding emotional responses.
4. Knowledge questions are aimed at gathering factual information.
5. Sensory questions-what sensory stimuli respondents are sensitive to.
6. Background/demographic questions are aimed at understanding the respondents education, previous experience, etc.

In the case of system dynamics, the modeler is attempting to develop a story that identifies what problem(s) the system may be facing. In this dissertation, the first set of interviews was conducted to get a general understanding on how resource allocations were managed by road pavement managers. The advantage of the open-ended interview is the ability to develop a rich source of general knowledge of a problem, as seen by those who live in the system under discussion. Respondents can describe how and why they act in certain ways. (In the case of the managers interviewed for this dissertation, questions concerning how they made decisions were asked. Responses to these questions were the source of decision rules used in the model). In addition, as the response is collected, secondary areas of concern may develop, which allows a new set of questions to be formulated for additional interviews with the same person or with new respondents.

Rubin (1995) has described several types of interviews (based on their focus), among these is the topical interview (:27). Topical interviews seek out the explanation of events and description of processes

According to Erlandson (1993) interviews allow the researcher and respondent to move back and forth in time; reconstruct the past, interpret the present and predict the future (:85). This especially applies to a system dynamics model in which we are attempting to develop the behavior, over time, of a problem of interest. Cunningham (1993) has pointed out that information about the past can provide a valuable reference point on predicting the future (:97) He enumerates three corollaries:

1. Intuitive information and creativity is a powerful source of information on the future.

2. Examples of past behavior provide the best example of what might happen in the future if they are based on similar circumstances and if they are consistent measures of behavior.

3. Information collected in this manner is only one perspective on the future, other perspectives are appropriate.

In order to gain completeness and find similarities and dissimilarities interviews were conducted with participants who were chosen based on what the researcher desired to know and from whose perspective the information is desired (Erlandson 1993: 91). In the case of this dissertation, the perspectives might have been those of private road maintenance companies, civil leaders, etc. The owner of this model chose the perspective of the road pavement manager, who makes the final allocation decision.

While a traditional research design might require those selected for interviewing be specified by type of education, years of work experience, etc., a pragmatic problem often arises in field research. Those that you would desire to participate cannot or will not. Unlike controlled experiments, the time allotted by those in the real system is controlled by external factors, not under the control of the researcher. In this dissertation, participants were first chosen by job titles. Managers with backgrounds ranging from engineers to cost estimators to one who had worked his way through the system from repair crew to director of public works were among those willing to participate. Participants worked for state or town agencies and within different roles. For example, participants worked in the areas of road research, data analysis, road pavement management and regional design and evaluation. Therefore alternative perspectives based on scale of problem and differences or resource control and availability were obtained.

Several sets of interviews were conducted. Initial interviews focused on the determination of problems that managers tended to face in their decision making. The first set of interviews led to new questions that were either added to new interviews or feedback to those who had already participated. Questions were often asked of

respondents in terms of their opinions of what other participants had indicated. Areas of disagreement were identified as possible weaknesses in assumptions, caused by differences in mental models, of the participants. These differences were used in determining some of the formulations in the model. The story that developed from these interviews were built into a reference mode and then presented to managers, who had participated (Note 2) in the interview process, for verification (Note 3). The reference mode was used to identify areas that required research in the literature to support the formulation of the systems dynamics model.

Further, new questions were developed for a second set of interviews after consideration of information about pavement systems that was gathered from a search of the literature about the field. A second layer of participants was sought to help in the development of the development sector of the model. Information was obtained from town planning boards, through interviews and copies of data from the boards. When information was sought that could not be obtained at this level, the search was expanded. For example, when information about tax impacts on development was needed town and state planners had no idea as to the impacts. Calls were then made to both state and national business associations and commercial real estate developers. Professionals involved with commercial real estate had the best idea of the impacts under question. The process was akin to detective work, where one follows down leads and clues. Interviews were stopped when repetition of the same types of information appeared to indicate that little new information was being generated. This followed the recommendation by Rubin (1995) that, “ you interview until you gain confidence that you are learning little that is new from subsequent interviews.” (73). ( Note 4).

#### **Auburn MA.**

A few years ago central ‘Mass,’ regional came in and gave us a budget for inspection. The inspection passed off information to the town. They classified road as 1-4 in need of care and gave it to the town engineer. The final decision was left up to him. We get together and discuss what needs to be done.

Major repair is done during the summer and is dependent on money. We try to schedule around high use times.

Major problems with the roads are due to town development-. If its a major problem but development is occurring we do temporary repairs. We do it because the final repair is up to the developer. They are responsible for the roads around the development. This wait we save money. If an area requires new sewers, etc. we wait until it done. The problem is that sometimes an area needs minor rehab and the waiting turns it into a more major job.

Complaints:

We respond to complaints. The complaints are due to floods, etc. When you hear it enough you do something. We don't keep count. Safety takes precedence. If we get complaints from the fire or police department we do it right away.

We will do temporary repairs for complaints and stop gap repairs for safety issues.

Parameter: If we get 40 normal complaints per month we will respond.  
It only takes 10 safety related complaints to get the same response.  
[Effect Ratio:- 10 to 40 with total complaints of 70].

Politics of allocation:

We have a budget that we don't want to exceed.  
If you need to exceed it you need to defend your request. No one will vote against a safety expense. They don't want to be responsible for an injury. On the other hand, normal issues are sometimes based on who knows who!

Rate of political complaints: We get about: 5-7 per month(warm weather)-1-2 in cold weather(CW)  
[Rate of complaints normal-rate is about: 30 per month(WW);20(CW)  
Rate of complaints safety: 2 per month (WW);5-7(CW)]

Accidents go up in winter  
Political complaints vs. normal-

One complaint by someone up high vs. 2 complaints from a citizen.

[Ratio of 1:2 of 10:20  
Re: Safety complaints was 10:40  
One safety is worth 4 normal  
One political is worth 2 normal?]

Why do we respond to political faster than safety-We respond to political complaints because most of the time they have Figured out a means of getting us the money for doing it./

Even for safety, we have to go through a way of getting more resources if needed.

[Rate: If a politician gets 6-7 calls they respond.

They get 5-7 political calls per month, times 6-7 is about 35-49 citizen complaints. The ratio I was given was about 30 citizen complaints per month].

Potholes:

Fixed within 24 hours otherwise we have no insurance coverage.

The biggest causes of accidents is water accumulation and leaves. We get flooding etc. due to poor drainage,

We would many time prefer to do major rehab, but do stop gaps etc, because of the budget.

The roads have been very neglected in this area. We are playing catch up. Money was not allocated in order to stay within the budget, now full repairs are need for what might have been a less expensive way.

People forget too, that development ahs a major effect on the highways.

We had a lot of development with no inspection for proper drainage.

Some of the system was also old, about 50 years old. With development, the old system could not manage the drainage

If you put up 20 houses you need better drainage.

[Parameter?

60% of the drainage problem is due to poor inspection

40% is due to the old system]

### **Development and effect on highway**

Parameter

When 30% of undeveloped land becomes developed, you get an effect on the system. You need to replace the drainage system. When it wasn't done, we had damage to the highway system.

Traffic:

Its not the cars so much. When we talk about development, we mean industrial too. It means more 18 wheelers, etc.. We get corner damage. The trucks make wide sings and damage the edges of the roads. The roads were not designed for large trucks.

We get about 4-5 damages per month from trucks.

Town growth means school buses, fire trucks, police cars.

Communications:

There is little communication between us and the design people.

We do mostly repairs. Major work is subcontracted out.

A repair or minor work can get me 10 years of use, In the short-term contractors save us money. In the long term it would be cheaper for me to buy the equipment and do it myself. We have a short-term focus because of the budget constraints.

Treatments:

We sand the road during the winter that causes damage too.

During a normal winter

We have 8 trucks they carry 1.5 –2 tons of sand and dirt each.

12-16 tons per outing at 2 times =24-32 tons normal

We might send out 12 tons per week for 15 weeks.

During a bad winter, we increase that to 4 times a week, 48-64 tons during bad times.

:

Resources

The state gives us money. We try to use it on major work near state roads or access roads to the state system. The state may give us 300k the town comes up with 200K.

The state gives you so much they tell you can't have more. So, we try to do the major jobs using state money. Anything left over we can use elsewhere.

In the short-term its beneficial. Given equal conditions on a road you do the overlay work and get away with it. You then use the money saved to do work elsewhere.

You try to take into account the overall picture and balance the short-term spending against the long- term life. We discuss (sic-engineer and I)the road and cost implications, of the engineer might do it himself.

### **Rhode Island DOT**

Municipalities use the PCI index, but too labor intensive for network management. It is usually tied to Micropaver Software.

At the state level we use a car that uses lasers to take measurements of the road condition. We then develop a regression for every treatment we perform.

Our rating system goes from 0 to 100. We apply a weighting formula that creates a composite scale of impacts. (Much like a deduct scale and PCI index).

I developed a regression that weighs several deterioration factors and gives me a score.

We use Block Cracking  
 Patching  
 Alligator Cracking  
 Longitudinal Cracking  
 Transverse Cracking  
 Bleeding  
 Edge Cracks

We measure a given length of road, lets say 5000 meters.  
 We then inspect it an record the number of low. Moderate and high severity distresses.  
 For example we enter the number of times we find a low severity area and size.  
 Then calculate density.

They take a measure of all distress.  
 They classify it as to low, medium and high as Shahin does.  
 They then record the size of the area-  
 EX.

LOW	MED	HIGH
0-20 Meter Sq, 21-37 Meter Sq.		

This is done for each category  
 For each strip  
 The severity is determined by the width of the crack from the national highway research reports., 6mm low, 6-19 med., > 20 severe.

Avg. Sq. meters of AC/.1km  
 Depending in the number of sq. meters a score is developed.

(This was done by taking the range of the measures for each severity, then dividing it into 10 groups and applying a score of 10 per each group). Such that if the higher severity in sq. meters was 270 sq. meters. 10 groups with approx. 27 meters per group were created. Each group was then given a score of -10

270-0=Range 270/10=27	
Sq. meters	Score
0-27	-10
28-55	-20
56-83	
so on until 10 groups	-100

Each column is added to the next. When they are all added, the total is subtracted from a 100, which represents a good road surface.



If the total is greater than 100, 100 is subtracted.

This score for alligator cracking is placed in a regression model and effected by the marginal impact.

Total composite score = x(bleeding) +x1(alligators)

This score is sent to a committee for evaluation of treatment.

[Issues:

The PCI score is determined by using past experience of what the road condition was and what repair was made. “PSI-based on ride quality and look”, in my mind.. Mostly it’s from a persons knowledge of when a road is really at zero.”

The scores are feed into a GIS and it tells me how much in percentage of roads are fair  
Good  
Poor  
Excellent.

This is graded on a score of 0-100.  
A score of 65 is passing-we based it on grades in college.

Once we have a road over 65, it is looked at by the GIS and roads between 100 and 65 are then placed in each 25% category.

Then a second software package, TINS, which we have programmed, triggers an appropriate allocation. For example a road that is below 56 in alligator cracking, and below a 50 in bleeding and also has a score of greater than 65 gets one type of rehab, each combination has been determined by a committee,.

The highway assessment committee using past experience of what roads looked like and when they were repaired put the combinations together. The years of experience caught on PC).

We don’t use ESALS-we collect the ESAL data by sensors in the road and give it to the design guys and that’s the last we see of it.  
(Communications between designers and maintenance would improve the process.  
Feedback of how long a road really lasts vs. design would be of help).

The biggest cause of deterioration in the New England is weather-hot to cold. It’s not consistent.

“Budgets are allocated based on predictions of road conditions. But, how much is really allocated is based on political negotiations. Once we have a budget, we put all the

current data into the software. It creates a list of projects, which are prioritized in terms of Life Cycle Costs and Benefits, also optimized..”

As long as the money is available we can do repairs, when it's gone we stop, and wait for next year,

The information we have is part of a recommendation process. It's our info, the assessment committee's recommendations and the politicians inputs. “Sometimes we should do a road for maintenance and repair, but if we run short it could wind up that another year pushes it into full rehab, which costs more than the original repairs.”

### **Boston MA. DOT**

We use a PSI scale of 1-5 at the state level. Our critical value is set at 2.5. However, it is the most heavily used roads that get rehabilitation first. We try to do the roads that have the most traffic. Our resource allocation is based on usage not condition.

In general some roads in need of repair have to wait as the most used roads get priority.(preventive repair), The worse condition roads may need total re-pavement.

Towns do heavy use areas too, dependent on safety, etc.

Second Interviewee:

Statewide we don't have a real allocation process. Cities and towns are responsible themselves. They try to get more of the state funding by making routine maintenance the capital project. They try to shift cost to the state. The project becomes blown up because each town is trying to maximize their share.

Our inspection process is dictated by the Federal Highway Payment Management System. If the federal cost which is on the two your cycle. The problem is it's not feasible to have all different testing cycles.

### **Backlog**

We have none advertised designs, which are designed that construction. These are giveaways to consultants. They design a project for, which no money is available. There's no real logical reason for doing it.

Advertise work: we have work that is advertised and put out for a bid and we don't have the money to pay for it. Many times, we get design work that need to be corrected for size.

We have a regional process were everyone puts the requested in a hat and picked out by politics

## Connecticut State DOT

We do the most used roads to keep user costs and complaints down. I'll do I91 before I do a secondary road. We try to do these roads before they go bad.

Our total costs for a road like I91 are higher. We need to do them at night, so as not to stop traffic. A secondary road is more workable, we can do it day or night. Usually we do it during the day and it costs less.

Our vehicles can cover 100-300 miles per day on highways. At the district level we do windshield inspections and cover about 50-75 miles per day.

We look for drainage, ride, deterioration etc..

We use an IRI (international roughness index).  
We cover a total of 4800 miles (both ways included).

We have a budget of about 54 million dollars. \$27 million for interstate maintenance. \$267 million National Highway money, that's the 80% of TIP Money, then we put in another 20% for matching funds. This is available to towns.  
We resurface by contract work (separate from maintenance).

For an Interstate the process takes 4-5 years from inspection to finish.  
The cost is scoped out in today's dollars. (is the scope in today's dollars estimated at tomorrow's costs or just today's value. A project that costs \$1 million, does it stay at \$1 million for 5 years?)

### Secondary roadways:

We use vendors in place paving program, which is all state money.  
Work is usually bid by town not by project. The work is priced by dollars per ton. No matter what it is, so no matter how many projects there are this is what we pay.  
Drainage work is priced separately.  
These are maintenance contracts as needed.

### Costs:

[Drainage \$325 per hour  
Reclaiming \$1.50 per square meter  
Sweeping-\$350 per square mile]

Towns get money for town roads and can do what they want with it. They have separate vendors they deal with.

### Interstate work-

General maintenance- we do it, state crews.  
Resurfacing:-we hire a private vendor.

We give contractors guidelines.  
Rehabilitation goes from overlays to major reconstruction. An overlay can last 10-12 years. We try to keep the road going with crack sealing etc.

Local level

For state roads other than the Interstate we use a maintenance-VIP work at town level.

Our index goes from 1-9.

When it reaches between 5-9 we do maintenance.

Below 5 we schedule a resurfacing.

Maintenance lasts 3-4 years

Chip seals last 3-4 years-we use it where the average daily traffic is less than 3000.

Above 3000, we do a VIP resurfacing.

Resurfacing lasts about 12 years and costs me \$175,000 per mile.

Full depth reconstruction lasts 19-27 years

A road repair can get put off due to bridge construction, etc, and could then get put back far enough to require a rebuild rather than a resurface or repair. It's a matter of depth between the two.

We determine road needs based on

Ride serviceability 67% and

PCI value 33

Complaints can get things fast tracked.

A call from the Governor's office for example. The town of x did their entire area based on complaints.

Chip seal is cheap, but politicians complain because of kick back from the pavement, etc.

It lasts 3-4 years a major resurface lasts 7-12 years.

I see a lot the work that's supposed to be 7-12 years being redone, two to three times.

Now we are comparing apples (3 short-terms ) to one long term.

Increase in traffic, undersurface is aging,

Lack of quality of the asphalt we get.

Work in winter

Lack of skilled workers

We have a "sloos " list to identify high accident areas.

Federal money:

When Walmart comes in they get permits for all their work. They are responsible for drainage at the site. Town roads are still the town's problem(intersections, small streets).

### **District 3 Highway Dept. MA.**

Consultants have a big impact on what goes on. They inspect the roads and knock on the doors of the town offices-Hey, you got x miles of roads that can get federal funds. Federal funding is available for arterioles, collectors in urban areas and rural major collectors,

Some towns know and others don't.

The consultant wants to make the project big , to get a bigger commission.

The knowledge of the process makes some towns aggressive in going after money.

There are two ways to get money.

L. Chapter 90 –these are state funds that a town get to rehabilitate local roads.

The allocation is based on miles of highway a town has, population and average incomes.

- a. The town submits what it wants to resurface.
- b. It comes to District 3 , they apply for approval, it takes about 3-4 weeks to either approve or reject the application.

3-5% (of the 1%) of roads (rejected) are for resurfacing, maintenance, incorrect specifications, do not meet specification criteria (design does not meet District requirements).

As a rule of thumb if you resurface with 4.5 inches, based on the investment, if you resurface it benefits the town. If it's a rehab the town need to meet specifications of today. To avoid a total re-pavement they can do maintenance, get the work paid for and not hassle with the specs.

So, Chapter 90 pays for consultants, equipment etc.

Sometimes we reject because a town is applying for a TIP project funding, They want a temporary resurfacing. We won't allow it, since the same work will be done when the Tip money comes in. Sometimes other work prevents it, About 1% of the time.

If accepted we do it.

In general, we review the request for TIP money.

We can accept it, reject it or Table it.

If a road is good, we can reject the application.(The application rate has decreased- since everyone knows the funding is less and its harder to get, unless you are aggressive its too much work. People realize they will not get it. Rather than redesign, we repair it.

We advise towns to hold a meeting, to see if there is support for a project. It may involve getting approval to affect the esthetics of an area. We may agree it needs repair, but the public does not.

The Boston area is where project review PRC (Project Review Committee), occurs, the town then needs to get it programmed for TIP.

Have to remember that the towns are applying and sending info to the regional area as well . About 75% of the apps come to region and about 25% go straight to Boston. Then we can schedule after approvals.

When these are programmed, they sometimes get put off. It's up to the towns to keep in touch to make sure they get rescheduled. Sometimes the squeaky wheel gets it, but you can only go so far.

Even safety projects take 2-3 years from time to start to be built. Sometimes the Tip money is constrained and it's a real problem. Even safety projects, about 80% are done and about 10% get backlogged to 5 years.

TIP money is about \$3 million for 50 towns-that's not a lot. One project can eat it all!

We get about 200 apps for chapter 90 per year. There are five districts  
We get about 20 TIPS projects a year

This all started a few years ago when the state was getting about \$400 million per year from the Feds. They were looking for projects, we got used to it. Last few years its been about \$200 million, and next year \$150 and then 100.

When a Tip is applied for its 80% 'Feds'and 10% state matching money.  
Then there is non federal aid which is 100% state money and not Chapter 90 money.  
HPP high priority projects-some congressman wants to earmark money for special projects.  
PWED Public Works and Economic Development through the Department of Transportation and Construction.

### **Manchester, CT.**

We get allocated money based on a percentage of road miles. We have 215 miles and got \$384, 354 dollars.  $384584/215=1789/\text{mile}$ .

Re: Towns-miles per town

Dollars per mile

We can use it for contracts, materials overlays, anything we need.

For maintenance When the state puts in a bid, the town has the option of going with the state bid vendor or getting its own bid out. For pavement overlays, etc.

For re-construction the town bids itself.

For our bids we go by the town of material in place-its about \$40.10 per ton of material, Labor is usually in the unit cost of materials.

Town aid-get it for road materials or contracting from the state.

If we need more we can bond issue for the money.

Operating budget-we get it from the town and it comes out of the general funds.

The state roads in town are the states.

Then there is ICTEA (TIP of MA)

20% is state and 80% is the Feds.

If you apply for ICTEA and don't meet the requirements, you get rejected. You can get it back if its just a matter of form and re-file. But, by then you are almost two years out. By the time the state gets it and responds from the time you started to plan it might be three years.

We do (state) a worse job of it-its due to politics, lack of knowledge, working in the winter.

The problem with the ICTEA is that it takes so long. You bid it at 1995 dollars and in 2000, you get 1995 dollars. Then you need to make up the difference. Or you modify the work and it might effect longevity. But there is always a way to get some money to do the work. You can do incredible things if you know the roads.

With windshield inspections I can do 24 mile a day.

Then there is clams due to damage-we can get 5 to 30 per month,

When you allocate the work its 80% of main roads and 20% of less used roads. Keep people's complaints down. We do maintenance, we haven't got the equipment to pave.

### **Development**

Normally we get 10 years of wear from a road. With development, you still get 10 years but the cost of maintenance goes up.

Before the Mall I used 2 trucks at \$30 per hour each, now I need 6 trucks at \$65 per truck per hour.

Not including materials, it cost me \$4,000 last year,

[Note''

For development 2 trucks

On a scale of 0-10

5 is 3 trucks and

10 is 6 trucks]

There are two development issues:

Residential where we get more cars and industrial where we get more trucks.

With the Mall we got more trucks and they do more damage.

Roads normally need redoing every 15 years (pavement rehab). The question is; if you do a band-aid, how much does the maintenance really cost you when you compare that to doing a rehab first.

You do a major rehab it costs you \$5 per square yard. Maintenance then runs you less than \$1 per square yard. If you redo the road it costs about \$2.50 per square yard at the end of 15 years.

If you don't rehab-, then maintenance goes up to \$3-5 per square yard and you are doing it three times.

10 yards at \$5 =50

10yds at 1=10

10 yards at year 15 \$2.50=25

No rehab

10 yards at \$3.50 =35x3=\$105

For each Sq.Yd. it costs you \$20 more due to maintenance.

But we do a band-aid on it because we have constraints.

Worse then that when you keep repeating maintenance you have to allocate HR from other sources. Then they don't get done and it's a backlog and worsening of the other roads.

You really need to be doing 15 miles of rehab a year. With 215 miles, that's 14.3 years. When you do a road, you want to do it right.. But funding won't allow it. But, you do something to keep overall costs down, You want to reduce claims and complaints. So constraints make us more selective

We look at different techniques and experiment to see which is better.



We (CT) used to be better but quality control is gone. We use cheaper techniques. We get un-funded federal mandates. You can't sit back and depend on the state. Your roads are an asset-to let them deteriorate based on hoping for federal funds is crazy.

But, the squeaky wheel sometimes gets the money-we has education, etc.

If I do 15 miles a year of rehab it might cost me \$2 million..  
Maintenance would be about \$100,000.

Or I can do 15 miles with stop-gap at \$750,000. Or \$1.5 million  
But maintenance, is going to cost me \$500,00 per year. So by doing the rehab I save \$400,000 per year for 15 years or about \$6 million.  
But we can't do it because we don't have the money.

Guess what, even if we did there is another constraint. There are not enough contractors.

We schedule in April for June, July and August

### **Grafton, MA.**

We get Chapter 90 money from the state. We used to get 150 million in 1999.  
This year and next year we will only get 100Million(due to cuts and the big pig).  
We get it by the state dividing the money based on our road miles.(In MA there are 363 towns-we get a percentage of the money based on % of miles in our town).

Sometimes the towns don't use all the money and we save it for a rainy day. IT makes those that don't save look bad. Since the money is free, we should use it all up.

We also get money from the Transportation Improvement Programs (TIP). The state asks for bigger programs of improvement, new lights, etc. This is separate from Chap. 90.  
With chapter 90 its we trust you to do what you think best. But we know there are extras too, Traffic bottlenecks, hazards, congestion, traffic flow improvements.

We send the requests for TIP to District 3(there are five districts in MA. This is regional there is also the CMRP-Central Mass. Regional Planning. There are 11 in the state.  
There is also the CMRPC-planning commission.  
District 3 reviews the project to see if it is warranted.  
The request can then go to the state and sometimes to the Feds.  
If its goes to the state it goes to the MPO. There a vote is taken to determine which of the projects will be sent to the Feds.

Are there delays in the process? How long does it take?

We need to get our apps in Jan to the MPO,. Then in Mar. it goes to the state-3 months.  
From MPO to state  
From the MPO it goes to the state, the state sends it to the Feds in July, -It stays at the state for 5 months  
Then the Feds make a decision in Sept.-2 months for decisions.  
Then it takes 5 –6 years before we get the money.  
The estimate is not allowed to include inflation.

The state gets about \$400 million per year for TIP money. The state can decide not to send to the 'Feds', and still fund it themselves.

### **Politics**

The process can be moved along by politicians. We deal with selectman. One third of my time is dealing with politicians. The squeaky wheel gets the cheese.  
A politician can cut the delays by 50%, 3 years.(

We have a \$21 million business and we try to tun it that way. The towns are not used to running the town as a business. It's a town mind set. The small towns don't have the processes in place.

The board of selectman should not micro manage. On occasion, they create a problem. We have a five year plan. We know that some work needs to be done and some not. But we are being asked to do more with less.

Growth is putting a tax on the services that we can provide. We need human resources, we need to ad personnel. Hr is part of the operating budget. It comes out of the same budget as for roads, so either we take from the roads or add to the budget.

For example in Massachusetts road repair requires a police officer. You can't use a flagman. The officer on overtime costs me \$28 per hour, a flagman costs \$15 per hour. The officer costs me \$8000 last year out of a \$100K operating budget- that's 8%, a lot.

There are also unfunded mandates.

( The biggest problem is drainage.

Development is to hit certain guidelines. We are limited by law. We must leave the property in the same condition we found it. Therefore we develop catch basins, But the basins require tremendous maintenance. It's a maintenance nightmare. I t comes out of our road budget. Development is not good for us. We get \$4000 in taxes from a house and it costs use \$5300 a year to maintain.

We do roads that are supposed to last 20-30 years and they last 16. We can do repairs that last 7 to 10 years to keep the roads up to par.

With older roads, the cracks allow water to get in. We want to repair, but people don't want it., or we need more catch basins. In addition new roads lead t0 more problems as we develop the area.

New Road

1 mile per month-costs is 300-350 per foot or about \$1 million per mile  
Replacement of existing roads-3-4 miles per day costs about 600k per mile

Repairs 5-6 miles per day costs 300k per mile

Inspections for road work done 150 miles per day  
For road condition exams-7-8 miles per day

I get into a prevent modes. I'll do work that lasts 7-10 years.

How do I decide.  
We use a scale of 100.

If its 70-100 we do preventive  
50-70 we take out more asphalt and deepen the repair.  
Less than 50 and we do full restoration.  
Multiple years gives me more bang for the buck.  
We use first hand knowledge.

We are being forced into accounting for infrastructure costs for the first time.- 34.  
It tells us what we have to do to maintain the asset infrastructure.  
If you set it too high then costs can go up-if you don't repair it then why didn't you do it?  
If you set it too low-anyone can get there,

We have 83 mile of road. At \$1 million=\$83 million. We are supposed to have a maintenance program that uses 2-4% of the asset value, at a minimum that's about \$1.6 million. We have \$100 thousand.  
In the public sector we would rather spend big money then maintain it over time. We let things go.  
We do maintenance because we feel its more beneficial. You can never catch up with rehabilitation..  
The Feds and State want out of the program.

Most of the work we do lasts 10 years before it ahs to be redone. Stop gaps last 4, 7-8 years,  
Estimate

7 years cost 600k-what are the last 3 years of costs?  
10 years cost?

Summary:

A computer program has analyzed the road inventory using a method similar to that described in Shahin (1994).  
It has given them picture of what roads fall into what categories and then tells them what the costs benefits are. But is does not include the politics, etc.

## **Regional Planning Worcester MA.**

There are 13 regional agencies.

We do five-year planning and scheduling.

The town works with us and we work with Boston.

We coordinate the TIP development process.

We sit with the districts and towns, and discuss design considerations and if they are feasible program them.

The dollars are competitive. The states have an equation to determine regional planning of TIP money,

Typically priority projects take 3-5 years for scheduling, others longer than 5 years,

About 33 % of the projects are priority and take 3-5 years to schedule.

About 66% are non- priority but take greater than 5 years.

Priority projects can get put off depending on the amount of money available.

Sometime they are delayed because of issues such as right of ways, legal processes, width issues, land taking, etc.

We do windshield inspections, a crew can cover 1.4 miles per hour. We do about 11 miles a day.

If a project gets put off 1,2,3 years, the road work doesn't change. Costs go up, but that's inflation. The work that they need does not change

## **Groton CT.**

A lot of times you want to resurface before it gets bad. You want to catch it before it deteriorates.

Most roads are on a 20 year cycle.

You get about 12 years with a seal, you can add about 5 more years with a patch and 7 years with a resurface.

When it becomes too rough, you need to do it.

High volume roads are kept up because of the risk of accidents. With high volume roads you have a greater chance of a problems. It's the risk that leads to repairs.

I guess I have a 70% chance of accidents. With a low volume road, it's about 30%. That's when you do it.

Patching takes about 2 people.

I have 2-3 crews.

My miles are about

Patching -10%

Overlays-5%

Rehab-2%

[A crew can patch 5 miles per day (100 miles per month of work) at a cost of \$1800 per week or about \$7200 per month., or about \$350 per crew per day. (about \$72/mile-mines)

Overlay –4-5 miles per year are done. But, we can do 1 mile a day at about \$122,000 per mile.(30 miles a month if necessary-mine)

Rehabilitation- .5 miles a week or .1 miles per day or about 2 miles per month. At a costs of \$95 per foot ( \$501,680 per miles-mine)].

#### Development

During construction of a major site we can have problems. If it's a Mall we always will require more trucks.

**Second Round of Interviews** (Done after first cut of the model to clarify questions that came to light during the modeling process and after literature search.)

#### **Grafton MA.**

Generally, we get about 30% of what we ask for in budgeting. We have a single budget for all allocations.

Question: How do you determine how much and how many miles you will do?  
For example if you have 8 miles needing full rehab, 17 miles need overlay and 3 miles need patch; tell me how many of each you will do if your budget is 1 million dollars?

Answer: I would do about  $\frac{3}{4}$  a mile of full rehab, 7 miles of overlay and 3 miles of patch. I would do the rehab first then allocate the rest though the system.  
The process indicates a mental calculation based on the costs per mile and needs of the entire system.

Costs are about Full(.75 times \$500,000=380,000  
Overlay=\$800,000  
Patch= 250

How about complaints-

We get a total of about 60 per year at a cost of \$15,000 (Re: Auburn was 5 per month)  
Cost per complaint on average is \$250.

We can each do about 5 complaints a day (150 per person per month).

We can deal with about 90% of incoming complaints-(4.5/month).

15% of the complaints are safety in nature (.15 times 5-.75/month)

We get to do about 50% of the complaints that come in

I can only hire 1 person per 1650 population in the area,  
See Grafton Master Plan Sheets Used for Development

## **CT. DOT**

When it comes to roads we normally allocate 80% of the budget to high volume roads and 20% to low volume roads. That's as long as the high volume road PSI is above 3. If it goes below that we will take money that is left and give it back to the high volume road repairs.

## **Other sources:**

Commercial Real Estate Brokers-  
Amadon Associates

Factual interviews lead to the ability to estimate the use of acreage and the number of commercial sites in an area.

“You can Figure 10K/ acre for each business”.

## Town of Grafton (MA)

Planning Director-data available on geographic size and growth projections concerning: residential and commercial development, use of town lands and population growth..

## Business Associations

Connecticut Retail Merchants Association-no information available

Connecticut Public Expenditure Council-no information available

Connecticut Retail Merchants Association

Small Business Administration (both state and federal levels)-no information available

## Notes to the Appendix

1. This interview may also be considered a semi-structured interview, where there are basic questions whose order is not predetermined and in which answers are open-ended.
2. There were originally 12 request for participants. The final number ho were active in the process of interviewing was 10. Interviews were conducted between during the spring and fall of 2001. As the model progressed follow up interviews were conducted on an as needed basis to clarify parameter values.
3. The interview method that seemed most appropriate for this dissertation was a topical interview. In this process I was looking or the explanation of events and descriptions of processes. (Rubin :79).

4. State, and town and local agencies have been identified. However, participants requested anonymity for fear of reprisal.

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## Appendix C

### Surveys

Pavement managers make resource allocation decisions about road repairs. The literature and interviews indicated that the following areas are the drivers of concern-

#### Criteria

Complaints-public satisfaction

Accidents-public concern and safety

Road conditions-engineer's perspective

Resources- budget constraint and work force

Controls of resource allocation, from the engineering literature are: Critical Value and Residual Life.

Please answer as best you can-

What types of report you receive that might effect your decisions about the critical points of repairs that you make?

How often do you receive these reports?

How long is the delay between the development of the data and the time you receive it?

Which information do finds is the most used, upon which you base your decisions?

1. How much weight do you give to each of the criteria when you determine what the CV will be set at ?

Type	Wt.	Receive Reports	Frequency	Delay Time	Use	Priority
Complaints-	_____	_____	_____	_____	_____	_____
Accidents-	_____	_____	_____	_____	_____	_____
Road conditions-PSI/PCI	_____	_____	_____	_____	_____	_____
Resources- Budgets	_____	_____	_____	_____	_____	_____
Work Force	_____	_____	_____	_____	_____	_____
Total	_____	_____	_____	_____	_____	_____100%

Please make any comment on the type of information, how you get it, how you use it, that you feel is important.

Each decision we make is based on some assumptions. Some of these we are not always aware of, due to our experience level. To your knowledge how do the following affect your thinking about your decisions? (Did you develop these based on your experience or reading the literature related to pavement management education



What assumptions about conditions and complaints do you base your weight on?

What assumptions about conditions and accident rates do you base your weight on?

What assumptions about road conditions and budget resources do you base your weight on?

What assumptions about road conditions and work force do you base your weight on?

2. To what level of condition do you think a road should deteriorate to before you apply full rehabilitation and full re-paving. (Record as a percentage of original road as newly paved-.i.e. -15% of original conditions, etc).

15\_\_\_\_\_

25\_\_\_\_\_

50\_\_\_\_\_

Other\_\_\_\_\_

3. When you do repairs, what quality do you want the road to be brought to?

On a scale(please circle)

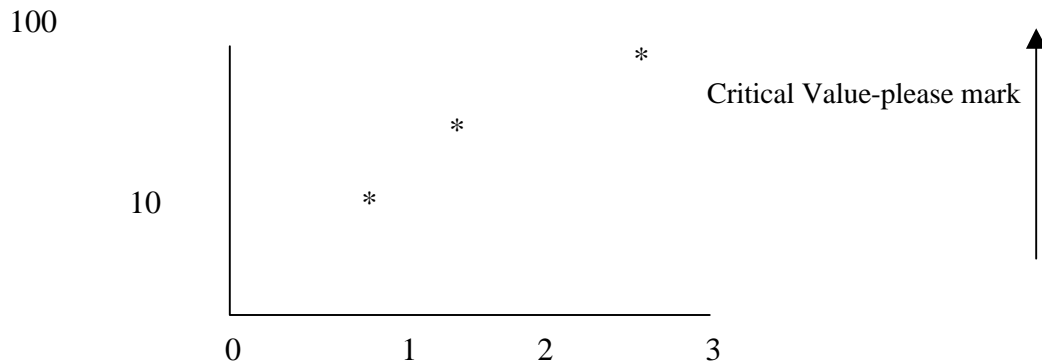
PSI=5 4 3 2 1 Other\_\_\_\_\_

PCI=100- 75- 50 Other\_\_\_\_\_

4, As conditions change we often adjust our decision making. In order to capture the process-on the following graphs please fill in a drawing relating your weighting to a normal value.

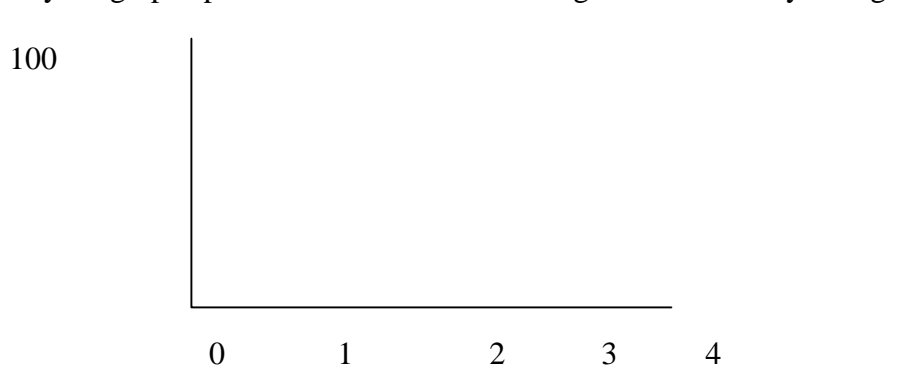
- a) Assuming the normal rate equals one and that the rate of change can be above or below normal. For example, my original answer to number 3 might have been 10%, at a normal rate. As the rate changes my weighting may change to-x%,
- b) B) If a graph represents the only criteria for selecting a critical pavement repair point, please indicate on the right what the pavement serviceability level would be that you would select and how it changes as the graph changes.

EXAMPLE



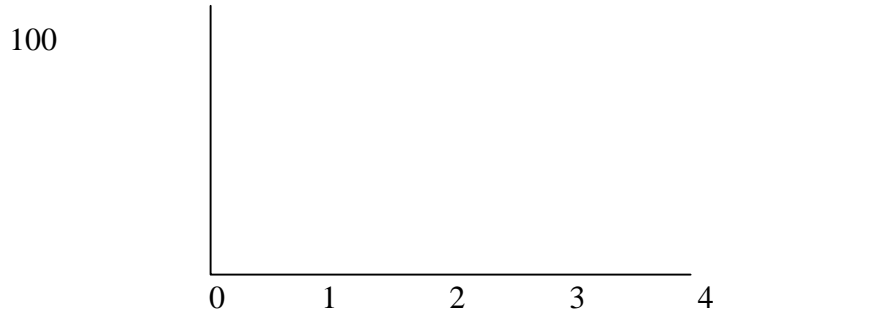
Accidents-multiplier of normal  
 Initial answer to number 3=10%, therefore at normal I am at 1, 10  
 As the rate increases I move up the scale

Accidents  
 In your graphs please fill in the rate and weight values as they change-if they do.



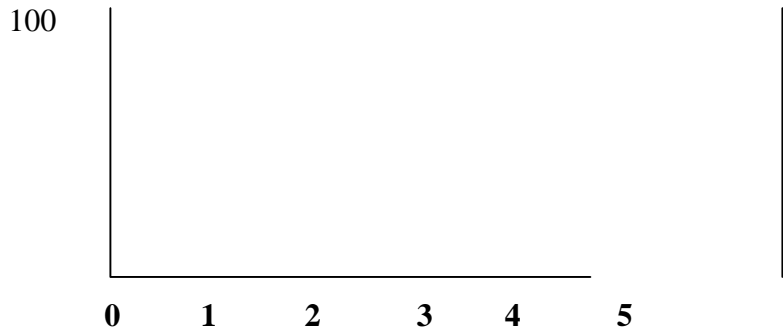
Normal accident rates are reported as 138 per 100 Million Vehicle Miles. If 1 represents normal on this scale and 2 , twice as much, how do you rate its weight in your decision on the percentage scale?

**Road Conditions**

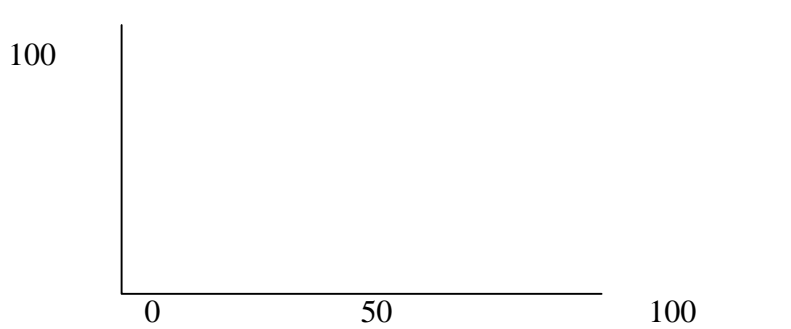


**PSI**

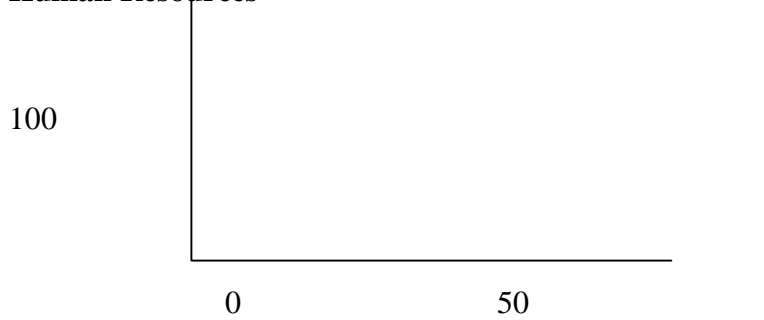
(As the PSI changes how does it effect your weighting)



**Percent left of budget**



**Human Resources**



Maximum I can hire Based on having 100% of those you think you can hire

**Complaints**

100



If complaints were 7-10 per month and normal was 1, i.e. (7-10 complaints/month), how does an increase impact your weighting?

NOTE: If any value along the horizontal scale is too small please fill in a value that makes you feel more comfortable with your decision.

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