DEVELOPMENT OF NEW NETWORK-LEVEL OPTIMIZATION MODEL FOR SALEM DISTRICT PAVEMENT MAINTENANCE PROGRAMMING

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Development of New Network-Level Optimization Model for Salem District

Pavement Maintenance Programming

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(ABSTRACT)

Infrastructure systems are critical to sustaining and improving economical growth. Poor condition of infrastructure systems results in lost productivity and reduces the quality of life. Today's global economy forces governments to sustain and renew infrastructure systems already in place in order to remain competitive and productive (GAO, 2008). Therefore, civil engineers and policymakers have been quite interested in the overall quality of the highways and bridges throughout the US (Miller, 2007). Transportation networks are essential parts of the Nation's infrastructure systems. Deterioration due to age and use is the main threat to the level of service observed in surface transportation networks. Thus, highway agencies throughout the United States strive to maintain, repair and renew transportation systems already in place (Miller, 2007). A recent disaster, the collapse of the Minneapolis I-35 W Bridge, once again revealed the importance of infrastructure preservation programs and resulted in debates as to how state departments of transportation (DOTs) should and can preserve the existing infrastructure systems. Therefore, it is essential to establish effective maintenance programs to preserve aging infrastructure systems.

The major challenge facing the state highway maintenance managers today is to preserve the road networks at an acceptable level of serviceability subject to the stringent yearly maintenance and rehabilitation (M&R) budgets. Maintenance managers must allocate such limited budgets among competing alternatives, which makes the situation even more challenging. Insufficient use of available smart decision-making tools impedes eliciting effective and efficient maintenance programs. Hence, this thesis presents the development and implementation of a network-level pavement maintenance optimization

model which can be used by maintenance managers as a decision-making tool to address the maintenance budget allocation issue.

The network-level optimization model is established with the application of the Linear Programming algorithm and is subject to budget constraints and the agencies' pavement performance goals in terms of total lane-miles in each pavement condition state. This tool is developed with Microsoft Office Excel. The tool can compute the optimal amount of investment for each pavement treatment type in a given funding period. Thus, the model enables maintenance managers in highway agencies to develop alternative network-level pavement maintenance strategies through an automated and optimized process rather than using what-if analysis.

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CHAPTER 1

1. INTRODUCTION AND SIGNIFICANCE OF THE PROBLEM

Infrastructure systems are critical to sustaining and improving economical growth. Poor condition of infrastructure systems results in lost productivity and reduces the quality of life. Today's global economy forces governments to sustain and renew infrastructure systems in order to remain competitive and productive (GAO, 2008). Therefore, civil engineers and policymakers have been quite interested in the overall quality of the highways and bridges throughout the US (Miller, 2007). Transportation networks are essential parts of the Nation's infrastructure systems. Deterioration due to age and use is the main threat to the level of service observed in surface transportation networks. Thus, highway agencies throughout the United States strive to maintain, repair and renew transportation systems already in place (Miller, 2007). The future prosperity of USA and growth in the US economy highly depend on the nation's highways, railways, transit systems, airports and ports (ASCE, 2005). One very encouraging example of how the United States can benefit from setting infrastructure maintenance as a priority is South Korea. South Korea, one of Asia's poorest countries in the 1950s, has seen an outstanding economic growth due to substantial investment in transportation infrastructure systems and, thus, is ranked as the world's 11^{th} largest economy today (Miller, 2007).

Highway agencies in the United States have utilized their resources for the construction of new paved road networks for 40 years starting from 1950s until the late 1980s. Reign of this strategy mainly stemmed from the Traditional Federal Highway Program in that highway agencies could invest the fund provided by The Federal Highway Trust Fund only in construction of new infrastructure systems. Decision-makers in highway agencies viewed M&R costs as "sunk costs" in that there was no mechanism that held them accountable for preserving infrastructures already in place (Dornan, 2002). Hence, highway agencies wanting to benefit from the Federal Highway Trust Fund used their available resources for new capital projects. Disregarding the paramount importance of maintaining existing infrastructure systems in a timely manner and omitting the long term consequences of deferred maintenance resulted in increasing needs for renewal and replacement of highway infrastructure assets (Dornan, 2002).

A report to FHWA dated 1996 shows that investment in new highway construction projects has declined since 1989, while rehabilitation work and preventive maintenance projects started to have the priority in fiscal programs of highway agencies (Hicks et al., 1997). According to the same report, the amount of funding necessary to preserve the existing level of pavement serviceability was $50 Billion while the amount spent was only $25 Billion as of 1996. To aggravate the matter, this ever-lasting gap between required funding to maintain the existing infrastructure systems in the US and available funding has been widening day by day. Infrastructure Card Report released by ASCE in 2005 points out this widening gap. The aforementioned report dated 2005 shows that available funding for highway improvement programs was $59.4 billion, while required funding to improve transportation infrastructure condition nationally was $94 billion (ASCE, 2005). Finally, the gap between required transportation surface program investment and available fund for maintenance and repairs through 2010 is $1.6 trillion (Miller, 2007). These statistics clearly suggest that Federal Highway Funding will continue to be insufficient to maintain and rehabilitate highway infrastructures already in place. The fact that current transportation surface programs fail to consider sound and detailed economic analysis in planning and selecting maintenance projects aggravates the matter.

Consequently, the major challenge facing State DOT managers today is to preserve state road networks at an acceptable level of serviceability under the stringent yearly maintenance and rehabilitation (M&R) budgets. Managers must allocate such limited budgets among competing alternatives, which makes the situation even more challenging. Infrastructure 2007 report published by The Urban Land Institute and Ernst & Young states that "the programs in some areas do not employ the best tools and approaches to ensure effective and efficient investment decisions" (Miller, 2007).

In conclusion, infrastructure systems in USA are in an urgent need of maintenance and rehabilitation and therefore must be treated immediately. Thus, infrastructure maintenance policies need to be established and considered as a priority in spite of never ending budget gaps. Therefore, it is essential to establish effective maintenance programs to preserve aging infrastructure systems already in place in USA. The following sections will first explain different notions inherent in deferred and preventive maintenance; state the importance of timely application of preventive maintenance and then compare preventive maintenance with deferred maintenance. Finally, the MS candidate will justify the motive behind this research by demonstrating the need for effective network-level pavement maintenance programming and propose a network level optimization model through which VDOT and other State DOTs will be able to select the best maintenance program for the road network - that is, what proportion of available budget to spend on which treatment type in each time period so that the network-level maintenance program will yield the most effective use of resources and achieve the best pavement performance throughout the road network. The proposed model will use a network level optimization approach subject to VDOT's annual M&R budget constraints and VDOT's performance targets.

CHAPTER 2

2. LITERATURE REVIEW

2.1. MAINTENANCE STRATEGIES

Infrastructure systems deteriorate due to external effects such as usage, climate and aging. This deterioration unfortunately cannot be eliminated. However, maintenance strategy and its application time affect long term condition and performance of a road network. Therefore, it is essential to know logic behind widely used maintenance strategies such as deferred and preventive maintenance. Figure 1 shows typical pavement life cycle of a pavement section and the significance of the optimal timing of pavement maintenance application in terms of pavement performance and cost. As seen in the Figure 1, the older the pavement is, the more rapidly it deteriorates. Application of preventive maintenance in the first 15 years of pavement life, that is- before pavement condition deteriorates to fair condition, not only cost less, but also extends the life of pavement.

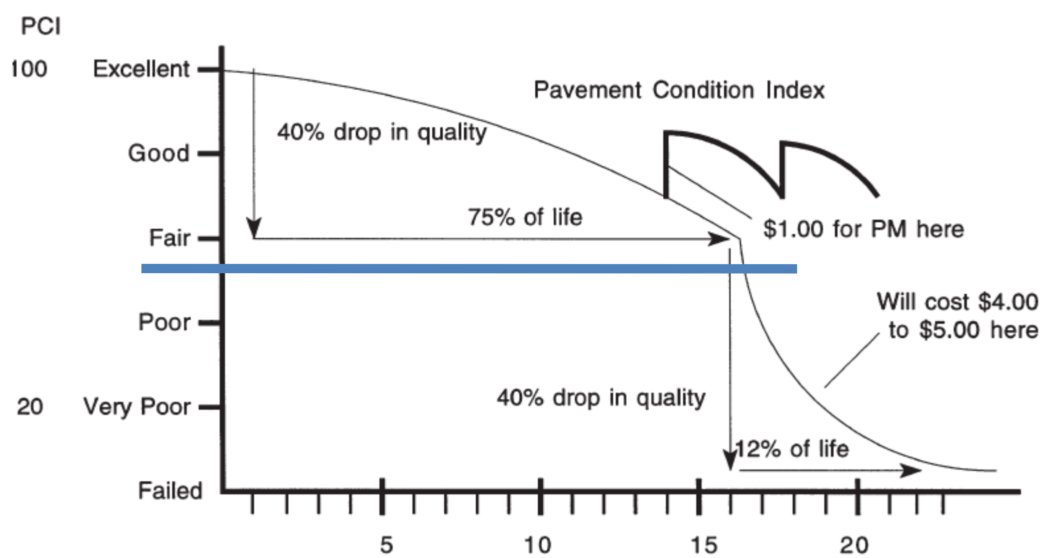

Figure 1: Typical Pavement Life Cycle (Hicks et al., 1997)

Figure 1 also suggests that frequent but small expenditures could result in more cost effective programs in long term than applying costly treatments after Pavement Condition Index, PCI, of a pavement falls below fair condition level[1]. Furthermore, the U.S. Army Corps of Engineers developed the pavement condition index (PCI). PCI is established based on the type and severity of 19 different distresses for hot-mix asphalt (HMA) roads and streets (Zimmerman, K.A. and Peshkin, D. G., 2003). PCI suggests a numerical rating between 0 and 100 (100 represents a pavement in excellent condition).

2.1.1. Deferred Maintenance

Highway agencies reluctantly defer some maintenance actions due to their limited annual M&R budgets. This is known as “Deferred Maintenance”. Deferral of required maintenance actions affects serviceability of pavement significantly, thus deficiencies on pavement become visible. Hence, disturbance on road users increases due to drop in ride quality, while endangering road safety. Considering the foregoing characteristic of deferred maintenance, highway agencies not only fail to provide sufficient level of serviceability to meet public demand for better quality highway services, but also incur high expenditures to correct severe deficiencies (Wei and Tighe, 2004). Consequently, deferred maintenance results in increase in life-cycle cost of a pavement.

2.1.2. Preventive Maintenance

Hicks et al. (1997) define preventive maintenance as “Program strategy intended to arrest light deterioration, retard progressive failures and reduce the need for routine maintenance” (Hicks et al. 1997, pp. 1). An important element of preventive maintenance is timing. Figure 2 and Figure 3 show the impact of properly applied preventive maintenance and delayed preventive maintenance on life cycle of pavement respectively. A distress value between 0 and 50 corresponds to a satisfactory pavement condition, while a distress value greater than 50 illustrates unsatisfactory pavement condition. Diagonal lines in both figures represent accumulating pavement distress over the life of a pavement. Figure 2 illustrates that preventive maintenance application to a pavement section in a satisfactory condition significantly extends the serviceability life of a pavement, while Figure 3 shows that taking no measures to retard the progressive

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[1] Solid blue line in Figure 1 represents the equivalent PCI level for distress point 50 used in Figure 2 and 3

deterioration of a pavement necessitates corrective maintenance. The timely application of preventive maintenance is best illustrated by the comparison of shaded areas in both figures. Shaded areas represent the improvement in the pavement condition due to application of treatments. According to Figures 2 and 3, pavements, which have treatment applied when severity of distress is low, receive substantial benefits in terms of extension in pavement life, whereas pavements that have treatment applied when severe distress is present receive little benefit.

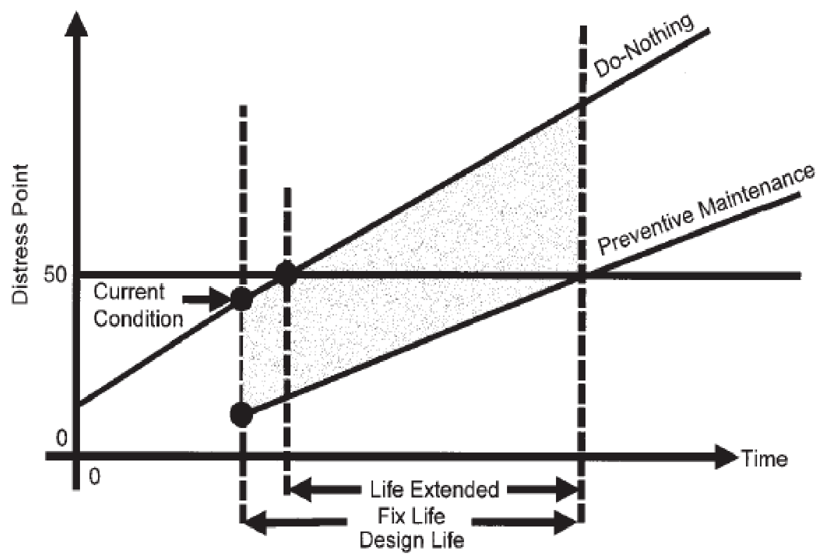


Figure 2: Properly Applied Preventive Maintenance (Galehouse, 1998)

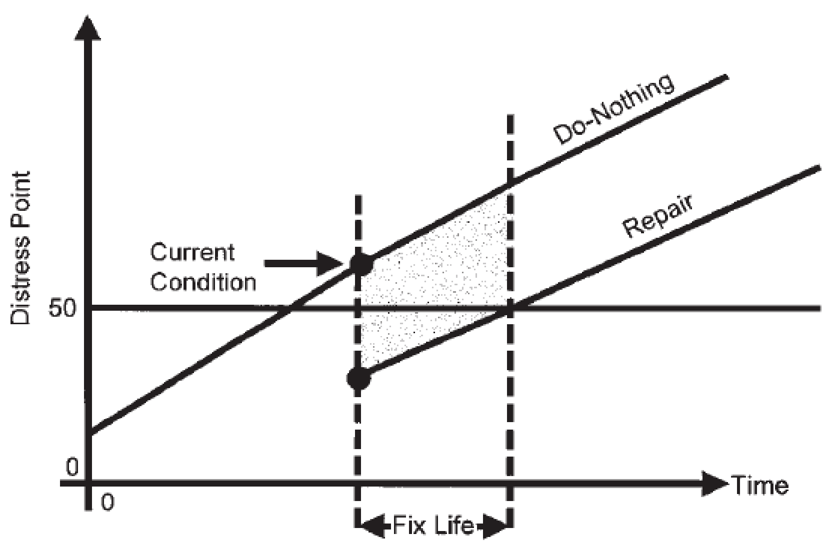


Figure 3: Delayed Preventive Maintenance (Galehouse, 1998)

Furthermore, preventive maintenance programs aid decision-makers in making reliable and accurate forecasts in terms of future road network condition. Consequently, knowing future road performance will enable decision-makers to plan preventive maintenance projects, required work force and budget ahead of time (Galehouse, 1998). This statement reinforces the argument which emphasizes the paramount importance of having a preventive maintenance program based on reliable data and robust decision-making tools.

2.1.3. Deferred Maintenance vs. Preventive Maintenance

Application of preventive maintenance in timely manner is useful in extending pavement life (Hicks et al., 1997). However, it is a challenge to justify the superiority of preventive maintenance over deferred maintenance due to some certain reasons. Table 1 lists advantages and disadvantages inherent in these two widely used maintenance strategies.

Preventive Maintenance	Deferred Maintenance
Slows down the pace of deterioration, extends the life of a pavement	Applied when pavement is seriously deteriorated and distress is visible
Substantial less costs incurred but earlier	Higher costs incurred to correct deficiencies
Life-cycle cost of pavement reduces	Life-Cycle Cost of pavement increases
Improvements are not immediate or visible	Improvements are visible and immediate

Table 1: Preventive Maintenance vs. Deferred Maintenance

2.2. PRIOR RESEARCH IN NETWORK LEVEL OPTIMIZATION

Various approaches for network level optimization of maintenance and rehabilitation programming have been proposed in recent years. Common components of these approaches are as follows:

- Identification of network information system
- Evaluation of Current Needs
- Definition of treatment strategies
- Prediction of Future Condition of Assets
- Development of an optimization algorithm
- Selection of Appropriate Treatments

Previously proposed optimization approaches have, in particular, two essential elements, namely optimization algorithms and pavement performance prediction models. Such elements could vary remarkably depending on researchers' approach to the problem. Investigation of mathematical models in order to predict the future pavement performance is still getting a lot of attention from researchers. Particularly, the Markov prediction model seems to be the most frequently used approach in predicting future pavement condition due to its ability to integrate rehabilitation and pavement deterioration rates in a single transition probability matrix (Abaza and Ashur, 1999). Abaza and Ashur (1999) applied Markov model to predict future pavement performance and developed a nonlinear optimization method to establish optimum pavement condition throughout the network subject to budget constraints. The Markov model used by Abaza and Ashur consisted of three main components.

- Five condition states, namely *a*, *b*, *c*, *d* and *f*, representing excellent, good, fair, poor and bad condition respectively.
- Deterioration transition probabilities, P_{ij}, representing pavement deterioration rate. P_{ij} represents the probabilities that a pavement section will deteriorate from state i to state j in a single time interval
- Maintenance transition probabilities, f_{ij}, representing the probabilities that a pavement section will improve from state i to state j in a single interval as a result of maintenance actions applied in a given interval.

The main objective of the research done by Abaza and Ashur (1999) was to determine the optimum future maintenance and rehabilitation program to be implemented. The model proposed was able to provide decision makers with amount of investment required for each maintenance and rehabilitation treatment strategy in order to achieve most effective M&R program.

Turnquist and Mbwana (1996) described a network level pavement management system using a large scale linear programming algorithm, converted from dynamic programming formulation, in order to achieve network level optimization (Mbwana and Turnquist, 1996). Markov Transition Probabilities, as used in many previous researches in this field such as those by Chen et al. (1996) , Liu and Wang (1996) and Abaza and Ashur (1999), were employed in the model in order to predict future pavement condition. However, Turnquist and Mbwana's formulation of the markov decision process model assigned a specific identity to each individual section defined in the network. Thus, maintaining identities related to each individual section is unique for the problem of network level optimization. Hence, this approach aids in transition from network level planning to project level actions easily since section-specific pavement conditions are available (Turnquist and Mbwana, 1996). The model developed was applied to highway network in Nassau County, New York; solutions produced were observed and were compared with the practices followed in New York State. However, Wang et al. (2003) do not favor this approach due to its complex and disputable assumptions (Wang et al., 2003)

Another approach used in modeling network level optimization problem is goal - programming. Raviarala et al. (1997) favored this approach due to its strength in considering problems encompassing conflicting objectives with different degree of importance. Prior works published by Raviarala and Grivas (1994) show that goal programming is beneficial to attain conflicting objectives simultaneously. However, goal programming sustains a few disadvantages in that it is not easy to integrate Markov Transition Probabilities into optimization procedure. Furthermore, integer programming used in this approach is inapplicable to large scale pavement networks due to high computational requirements (Raviarala et al., 1997). Hence, the model proposed by Raviarala et al. (1997), instead of an integer program, uses a linear program to develop optimal multi-year maintenance program. A set of linear functions of the decision variables is defined in order to create the goal program for pavement network optimization. However, this model entails up-front effort in order to assess network condition and controls specification. Assessment of network condition involves definition of pavement states, inventory and inspection data, while controls specification consists of three processes, namely treatment identification, condition-treatment matching and estimation of pavement state transition times.

Developing a reliable pavement performance prediction model is as essential as the algorithm used in the optimization model (Li et al., 1997). Thus, Li et al. (1997) stresses on the importance of producing a pavement deterioration model which considers the effect of a treatment on pavement deterioration rate after maintenance actions take place. In contrast, homogenous (time-independent) Markov decision process disregards the effect of applying a treatment to a pavement section and assumes that application of a treatment has no effect on the deterioration rate of pavement, regardless of the treatment applied. This assumption conflicts with what occurs in field. Therefore, non-homogenous (Time-related) Markov decision process was introduced by Li et al. (1997). The model developed by Li et al. (1997) assumes that application of a maintenance action to a pavement section will result in a new deterioration rate which is computed based on Ontario Asphalt Deterioration Equation (Li et al., 1997). Furthermore, Li et al. (1997) defined unit cost of each treatment and quantified the effect of each treatment strategy on pavement in terms of a jump in PCI (Li et al., 1997). Thus, cost-effectiveness based priority programming for a network level optimization problem was established. This model adopts integer programming approach in the pursuit of producing the most cost-effective maintenance program for each programming year. The objective of this model is to maximize the total benefit-cost ratio (cost-effectiveness) and to make comparisons among different treatments planned for each programming year as to select best set of maintenance actions, given available budget and other constraints (Li et al., 1997). This comparison is based on unit cost of each treatment strategy as well as the particular effect of each treatment on future pavement performance. The effectiveness of a particular treatment strategy is defined as the product of the area between the predicted performance curve and minimum serviceability level multiplied by the length and traffic volume of the section to which such particular treatment strategy is applied. The comparison made based on the cost effectiveness results in prioritization among treatment strategies, thus, producing a maintenance program for each year.

Another example of network level optimization model was established in Arizona. Arizona Department of Transportation used a network level optimization model whose objective was to minimize the annual M&R cost over the planning period. Liu and Wang (1996) proposed a new network optimization system where available annual budget for maintenance and rehabilitation was introduced as a constraint. The objective of the proposed model was to maximize the pavement network performance by effectively using the available M&R budget. Liu and Wang (1996) used linear programming approach to perform network level optimization. The objective function of the model proposed is as follows;

$$Z = \sum_{l} \sum_{k} \sum_{i} w_{i,k}^{l} * f_i$$

Where $w^{l}_{i,k}$ denotes the proportion of roads that are in condition state *i* at the beginning of l^{th} time of period of planning horizon *T* and to which the preserving action *k* is applied. Here f_i denotes the performance rating for condition state *i*. f_i is used in the model as an utility value to consider the impact of each condition state on overall pavement network performance (Liu and Wang, 1996). The objective function maximizes the total pavement performance over the planning horizon *T*.

The outcome of this network level optimization model was;

- The allocation of the annual budget for different maintenance actions
- Proportions of the pavements expected to be in each condition state at the beginning of each year

Consequently, genetic programming algorithm has been of great interest to researchers striving to improve the current available optimization models used for network level

M&R programming. Tack and Chou (2002) recently showed that a genetic algorithm based optimization proved beneficial in determining multiyear maintenance programs. The objective of the model proposed was to bring about the highest average pavement condition level throughout the road network. Following the investigation for dynamic programming algorithm along with two different genetic algorithm techniques, namely simple (SGA) and preconstrained genetic algorithm (PCGA), Tack and Chou showed that SGA and PCGA techniques yield near optimal solutions. In addition, the degree of flexibility and scalability inherent in genetic algorithm technique is of great advantage in that each pavement type may require different pavement deterioration models and repair types (Tack and J. Chou, 2002). On the other hand, dynamic programming lacks such attributes as flexibility and scalability. Thus, dynamic programming has proved unsuccessful in adjusting to new variables introduced in the model. Therefore, Tack and J. Chou (2002) concluded that dynamic programming was the most difficult to implement in comparison to SGA and PCGA. Furthermore, Cheu et al. (2004) enforces this argument by asserting that genetic algorithm is suitable for problems with substantial number of variables and constraints, since coding objective functions in genetic algorithm is efficient and flexible.

In conclusion, previous research conducted in the subject matter strives for attaining one common goal, that is – identifying the most efficient pavement maintenance program in network level while being effective in addressing the needs of the system. Optimization model developed within this research effort differs from the ones introduced thus far in that it is very practical and easily reproducible since number of components pertaining to the model far less than the models introduced previously. Hence, it is very easy for any decision-maker, regardless of technical background, to study the model and make use of it. Furthermore, the model works with values that have been found deterministically as opposed to probabilistic approach, hence does not require any rigorous probabilistic calculations. Finally, the model developed herein suggests a very broad budget allocation approach and a general view of pavement condition throughout the network resulting from such budget allocation approach. This research adds value to body of knowledge in that simplicity and practicality inherent in the model is likely to appeal to decision-makers in highway agencies since it does not require investing substantial time and resources for doing pavement maintenance analysis through this model.

2.3. HIGHWAY ECONOMIC REQUIREMENT SYSTEM-STATE VERSION (HERS-ST)

Highway Economic Requirement System-State Version (HERS-ST) software is a tool that performs network-level optimization based on the synthesis of engineering knowledge and applied microeconomics (FHWA 2005). Relationship between parameters, such as traffic volumes, road capacity, pavement deterioration rates, speeds, crashes, travel time, curves and grades, and other highway attributes comprise the engineering aspect, while cost-benefit analysis used in HERS-ST is performed based on microeconomic theory. Engineering relationships is used for determining the benefit, such as travel time savings and operating cost reductions. HERS-ST also incorporates discount rate and life-cycle cost analysis in its analyses (FHWA 2005).

Moreover, Federal Highway Administration's (FHWA's) Office of Legislation and Strategic Planning used The Highway Economic Requirement System (HERS-ST) throughout the last decade as a decision-making tool in order to determine the most effective national highway investment level and strategy (FHWA, 2007). This valuable tool aids in estimating the level of investment required to accomplish economically feasible and optimal highway maintenance and rehabilitation programs. HERS-ST provides users with information pertaining to system condition and user cost levels based on a level of investment used in analysis.

As mentioned earlier, the level of expenditure on highway capital investment is an important part of the analysis since this amount must be justified on benefit-cost grounds. Rigorous benefit-cost analysis is done by taking a representative sample of highway sections. HERS-ST determines alternative strategies for each section and selects the best strategy that brings the most beneficial improvements based on various assumptions and constraints. Reductions in user costs, agency maintenance costs due to the improvements are accounted as benefits; while the initial capital costs of the improvements are considered as costs. Finally, the HERS-ST model determines improvements requiring less investment and achieving more benefits. The model can also provide the user cost level resulting from a given level of highway capital expenditure. Thus, the incremental benefit-cost analysis inherent in the HERS-ST program determines the optimal highway investment strategy. Subsequently, the results obtained from analysis are generalized and extrapolated to the highway network. Finally, Congress uses the output of HERS-ST analysis as benchmarks to determine the highway budget (FHWA, 2007).

Furthermore, future pavement and capacity deficiencies can be elicited by including specific parameters in the analysis. Subsequently, HERS-ST can determine a set of alternative improvements to address pavement and capacity deficiencies based on user-specified constraints and performance objectives (FHWA, 2007). Each improvement alternative goes through precise benefit-cost analysis, and ultimately the most economically improvement alternatives are identified (FHWA, 2007). In the end of this process, users are provided with the information related to overall pavement condition throughout the network, treatment alternatives chosen for sections defined and level of investment required to maintain and improve the prevailing pavement condition throughout the network which is divided into sections (FHWA, 2007). The following two sub-sections give more details about information that HERS-ST model is capable of providing.

2.3.1. Objective of the HERS-ST Model

The model is suitable for determining beneficial improvements in selected representative sections at state level. Furthermore, the model can provide projects that are likely to prove cost-efficient for further study, based on the benefit-cost framework implemented in the model. HERS-ST might be able to assign priorities for project funding, depending on functional classes, geographic areas, or types of improvements. However, HERS-ST does not consider the effect of interdependencies between prototype sections. Initial improvement costs include typical capital expenditures. The HERS-ST model can provide users with the following information (FHWA 2007)

- What level of capital expenditure is justified on benefit-cost grounds?
- What user cost level will result from a given stream of investment?

- What investment level is required to maintain user cost levels?
- What are the user cost and fiscal impacts of varying the investment stream (e.g., postponing improvement of backlog deficiencies)?
- What are the tradeoffs between capital investment and the performance of the highway system?
- If total investment is less than the economically efficient level, how much is lost in lower benefits?
- What is the cost, over 20 years, of correcting all existing and accruing highway deficiencies?
- Given a certain investment scenario, what percentage of the vehicle miles traveled will be on roads with conditions below a minimum tolerable standard?
- Given a stream of investment, what is the most effective mix of highway improvements on existing facilities?
- Will performance increase or decrease relative to the base year?
- What would be the effect of higher or lower fuel excise tax rates on VMT and capital needs?

2.3.2. HERS-ST Structure

The HERS-ST model consists of two separate programs, namely pre-processor and the main program. The pre-processor creates the HERS-ST data file based on the section data pertaining to each section. Subsequently, users enter the inputs noted below in order to perform analyses in HERS-ST (FHWA, 2007).

- A set of run specifications
- Tables containing design standards
- Deficiency levels for highways by functional system
- Specifications of the costs of highway improvements considered by HERS-ST
- Emissions cost factors
- The HERS-ST data file

The main HERS-ST program utilizes these inputs to predict possible improvements to the road network. Thus, potential improvements for each funding period are analyzed and compared. Thus, HERS-ST outputs expenditures by functional class and improvement type, for each funding period. It should be noted that this process is subject to the parameters and constraints that users feed into the model. Finally, HERS-ST program gives a set of tables noted below as the primary output (FHWA, 2007).

- The state of the highway system at the start of the run and at the end of each funding period
- The changes occurring during each funding period
- The changes occurring during the overall analysis period
- The benefits and costs of the improvements considered during each funding period
- The benefits and costs of the improvements considering the overall analysis period

2.3.3. Project Evaluation in HERS-ST Model

HERS-ST project evaluation process identifies sections in the network, which need immediate improvements, and selects suitable treatments for each section identified based on engineering and economic aspects. As noted earlier, engineering analyses help identifying the most suitable improvements; whereas economic analyses determines which improvements are most beneficial. All funding periods in the overall analysis are considered in the project evaluation process and the results are provided in tables as noted in section 2.3.2.

Furthermore, HERS-ST consider various combinations of three improvement types, namely pavement, widening, and alignment (FHWA, 2007). HERS-ST follows the following procedure in order to select a project for current funding period.

- Is an improvement necessary for a section in a given period?
- If yes, HERS-ST provides a list of alternative improvements for the section

- Each improvement is evaluated for implementation
- Each improvement brings benefits with some level of expenditure. HERS-ST estimates expenditure pertaining to each improvement
- The best improvement is selected for implementation based on cost-benefit ratio, subject to funding constraints and performance objectives.
- The sum of all beneficial improvements on all improved sections and total costs incurred for all improvements are calculated.

The project evaluation process explained above is summarized in Figure 4.

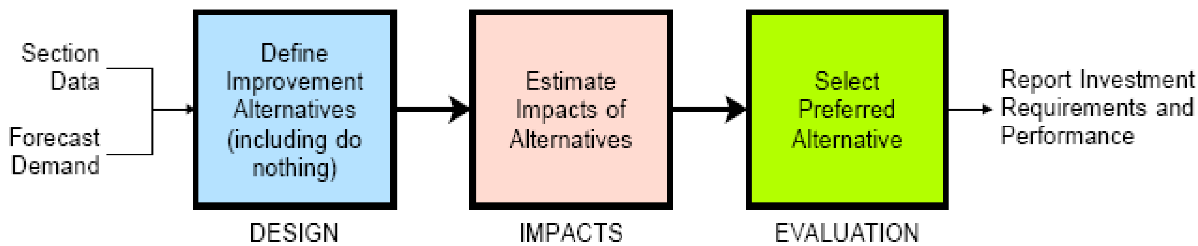


Figure 4: Major Steps in Project Evaluation (FHWA, 2005)

In conclusion, the HERS-ST software is an analysis tool designed to aid transportation agencies in planning and scheduling highway work, as well as determining future highway system needs. It is a well-structured smart decision-making tool, which identifies deficiencies in highway sections by simulating highway condition and performance levels (Focus, 2003). Moreover, the HERS-ST software considers economic criteria, as well as engineering principles, when it simulates the selection of improvements for implementation. In other words, HERS-ST suggests only those projects with benefits exceeding initial costs pertaining to such projects, that is- Benefit-Cost Analysis. 17 states in the United States have been using HERS-ST model for statewide decision-making since 1997 and it has proven to be a very valuable transportation planning tool. However, the HERS-ST model is very data-intensive. It also requires substantial up-front time, effort and trained personnel, which affects the practicality of the HERS-ST model. Therefore, the network-level optimization tool presented herein has been designed to require a few basic parameters, which are introduced in the following sections. Thus, the amount of time and effort needed for running the simulation in the model developed within research is notably less than that of HERS-ST. Furthermore, outputs given by the model presented herein are concise and suggest less details pertaining to the road network, whereas HERS-ST lists improvements selected for each section in the road network with benefits and costs pertaining to each improvement.

CHAPTER 3

3. SPECIFIC OBJECTIVES AND SCOPE OF THE WORK

3.1. SPECIFIC OBJECTIVES

The study presented in this document builds upon the research conducted by de la Garza and Krueger (2007). In their research titled "Simulation of Highway Renewal Asset Management Strategies", de la Garza and Krueger (2007) showed how "what-if" analysis could help highway maintenance managers develop, consider and compare alternative pavement maintenance strategies by changing the amount of available maintenance budget and pavement condition targets. Thus, highway maintenance managers could then determine the most effective pavement maintenance programming strategy among alternative strategies created through "what-if" analysis (de la Garza and Krueger, 2007). Furthermore, "System Dynamics" approach is one of the major elements of the research undertaken by de la Garza et al. (1998) to perform "What-if" analysis (de la Garza et al., 1998). However, "System Dynamics" approach does not report the optimal level of investment to be allocated to each renewal activity such that the most effective pavement maintenance strategy can be identified. Hence, highway maintenance managers must allocate the available budget manually and then observe how this new budget allocation strategy influences the overall network performance. Thus, there was an opportunity to improve on the former research by developing a model which is capable of performing such budget allocation process optimally. Therefore, this research effort strived towards developing a smart decision-making tool to perform network level optimization for pavement maintenance programming problem through application of Linear Programming methodology. The outcome of the research presented herein aids highway maintenance managers in developing alternative network-level pavement maintenance strategies through an automated process. Subsequently, decision-makers are able to compare the impact of each strategy and identify a strategy such that most efficient use of scarce resources will materialize. In other words, the decision making tool developed through this research effort enables decision-makers to have the power of selecting, based on reliable and accurate historical data, most effective maintenance programming strategy that results in the best preserving program possible.

3.2. SCOPE OF THE WORK

The scope of this research consists of the following elements:

1. This research is undertaken to create a network-level optimization model, hence it does not address project-level maintenance programming problem.
2. The research considers the problem of developing a pavement maintenance programming only, maintenance programming for other assets in highway facilities is not covered within the scope of this research.
3. The pavement condition data pertaining to 500 lane-miles of Interstate Road Network (I-81 and I-581) in Salem district are used in the analyses, pavement data pertaining to primary and secondary roads are not considered.
4. Pavement deterioration rates are adopted from former research conducted by de la Garza and Krueger (2007). These deterioration rates are fixed. Therefore, development of a specific deterioration model for Interstate Road Network in Salem District is not addressed within the scope of this research.
5. Particular treatments for each pavement condition state are developed and technical specifications of such particular treatments are given.

CHAPTER 4

4. RESEARCH METHODOLOGY

The methodology which the MS candidate uses in this research consists of the following steps.

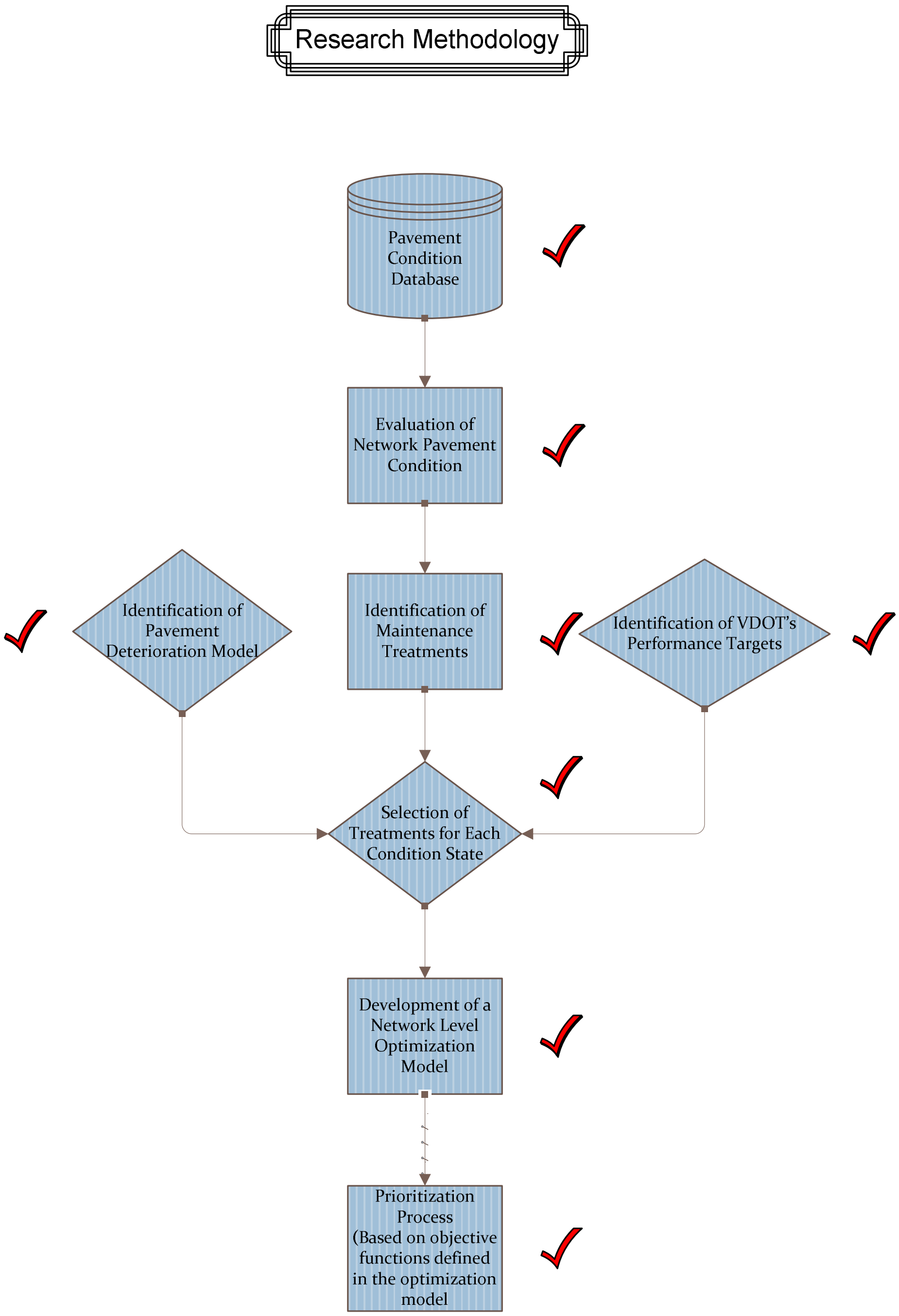


Figure 5: Methodology

4.1. EVALUATION OF NETWORK PAVEMENT CONDITON

Data pertaining to pavement condition of interstate road network (I-81 and I-581) in Salem District has been collected by VDOT regularly for the last 8 years and is currently available to analyze. Furthermore, available data is accurate, reliable and up to date to be used in the analyses.

4.2. EVALUATION OF CURRENT PAVEMENT CONDITION

Data collection efforts performed by VDOT resulted in development of an extensive database. This database is analyzed with a focus on pavement condition ratings. The most recent inspections pertaining to I-81 and I-581 Interstate Road Network in Salem District is the starting point for the process of identifying current pavement condition. The number of lane-miles in each specific condition state is computed based on CCI (Combined Condition Index) values, then used in the optimization model as the baseline pavement condition. Thus, each condition state is assigned a CCI (Combined Condition Index) range so that lane-miles throughout the network could be grouped in 5 condition states defined in this research. Finally, it must be noted that the Linear Programming Model designed within this research is initialized with an arbitrary baseline condition to test the model and then, the actual baseline condition is used in order to have the results presented in the following sections of this document.

4.3. IDENTIFICATION OF VDOT'S PERFORMANCE TARGETS

Pavement performance targets set by VDOT are the essential component of the proposed research, since such performance targets are introduced as either constraints or objectives in the optimization model. Answers to the following question are investigated in this research effort.

- What is the minimum acceptable number of lane-miles in each condition state?
- What are the objectives of Virginia Department of Transportation?
    - Minimize the number of lane-miles in fair. poor and very poor condition
    - Maximize the number of lane-miles in excellent and good condition
    - Meet some predefined performance targets, in terms of lane-miles in each condition state, for certain number of years

The output of the model can be enriched by creating new scenarios and performing sensitivity analysis. There is an interesting research opportunity in investigating cases where available annual highway maintenance budget is not sufficient to meet the prescribed performance targets. In such case, performance targets must either be changed or removed completely. Another interesting case is where Virginia Department of Transportation is to decide how excess pavement maintenance budget should be spent. MS candidate addresses questions related to the former case by loosening some of the constraints pertaining to VDOT's performance targets. In the latter case, the allocation of excess budget into renewal activities and its impact on the performance of the network are investigated through modifications in the objective functions defined for the different network level optimization models developed.

4.4. IDENTIFICATION OF MAINTENANCE TREATMENTS

Figure 5 shows 9 renewal activities which restore the condition of lane-miles from a downstream condition (worse) to an upstream condition (better). Expected performance targets for each condition state can be achieved through balancing upward and downward flows of lane miles, i.e. determining how much money highway agencies to invest in each treatment type (de la Garza and Krueger, 2007). Impact of each treatment type and unit cost of each renewal activity are considered in the optimization model, while prioritizing the treatments selected for a given year.

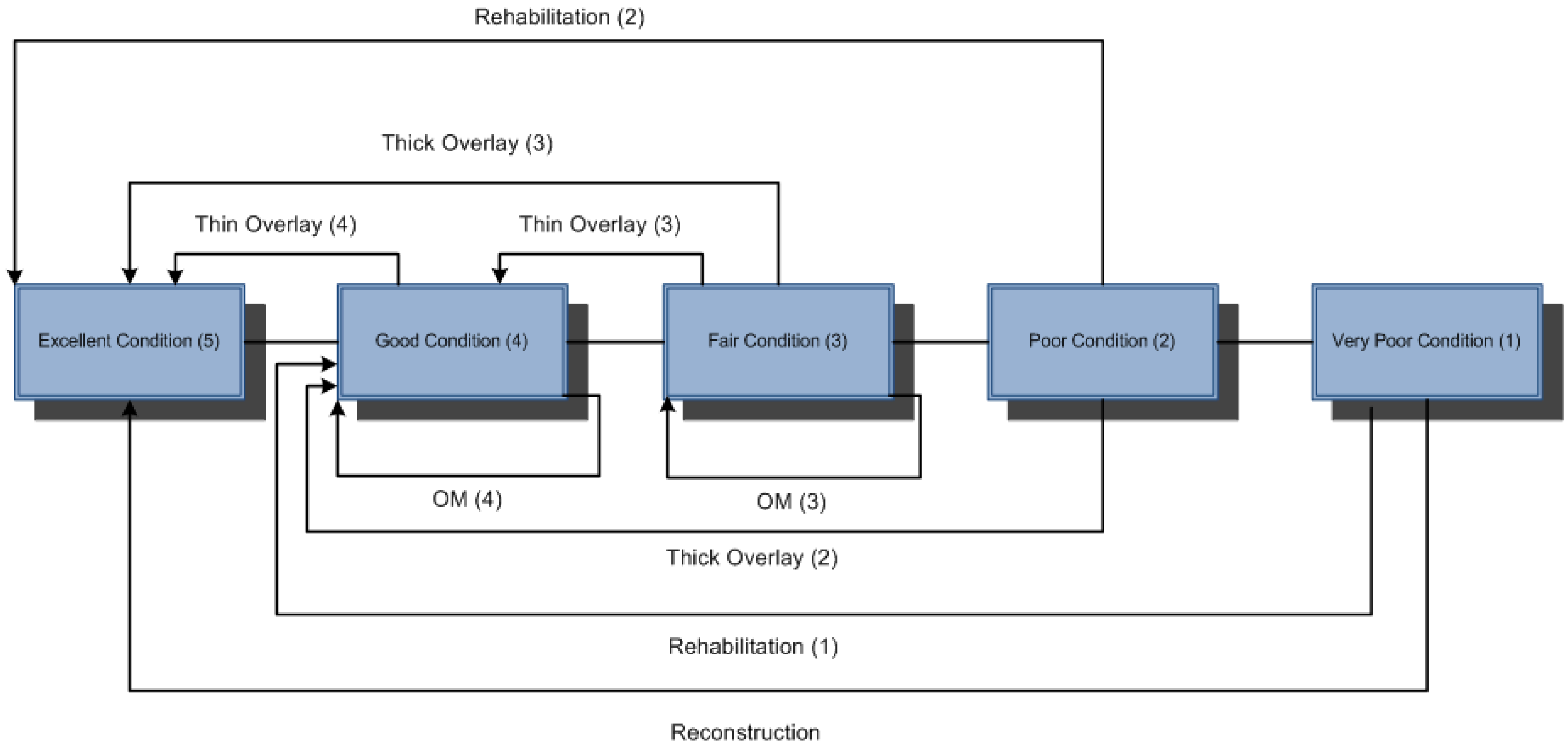


Figure 6: Pavement Condition States & Highway Maintenance Activities (de la Garza and Krueger, 2007)

4.5. IDENTIFICATION OF THE PAVEMENT DETERIORATION PREDICTION MODEL

Reliable pavement deterioration prediction models are beneficial for pavement management systems in that highway agencies can predict the optimal time for applying maintenance and rehabilitation treatments and determine the required long-term financial requirements (Sadek et al., 1996). Thus, highway maintenance managers need accurate pavement deterioration predictions so as to make more accurate decisions pertaining to the planning and cost allocation of maintenance and rehabilitation programs (Suh et al., 2002). Furthermore, Rohde et al. (1997) emphasizes on the essence of predicting the pavement deterioration accurately by stating that it is important to use reliable performance prediction models to see the long-term consequences of various maintenance strategies (Rohde et al., 1997).

Pavement deterioration rates used in this research effort are adopted from the former research conducted by de la Garza and Krueger (2007). The pavement deterioration rates, which were computed deterministically based on historical data, are fixed for each pavement condition state. Liu et al. (1997) favor this assumption by stating that it is reasonable to assume fixed yearly deterioration rates since values of many parameters used in nonlinear deterioration models are not available, hence nonlinear deterioration models are not practical in real problems (Liu et al., 1997). The network-level optimization model developed herein assumes that pavement deterioration materializes in increments of one condition state per year, that is-deterioration from an upstream condition to the next downstream condition only, e.g. pavement in good condition can deteriorate only to fair condition each period.

4.6. SELECTION OF TREATMENTS FOR EACH CONDITION STATE

There are 9 renewal activities defined in this research. Each of these renewal activities is designed for a specific pavement condition state. Hence, 500 lane-miles of road network on I-81 and I-581 are treated with 9 renewal activities as depicted in **Figure 5**. The network-level optimization model established optimally selects the renewal activities into which pavement maintenance budget is to be allocated based on the parameters, decision variables and objective functions used.

CHAPTER 5

5. DEVELOPMENT OF NEW NETWORK-LEVEL OPTIMIZATION MODEL

An objective function and a set of constraints in the form of a system of equations or inequalities form mathematical optimization models. Optimization models facilitate the decision making process and therefore are used very often in almost all areas of engineering (Arsham, 2007). This section of the thesis work presents an overview of a network level optimization model developed through linear programming approach. Thus, the sets, parameters and decision variables are defined in the following sections. The constraints and objective functions are then stated and explained in detail.

5.1. DEFINITION OF SETS

5.1.1. P, a Set of Funding Periods: A set of funding periods corresponds to years that Highway maintenance budget (HMB) is available to use. The length of each funding period is one year.

P: (1, 2, 3, 4, ………, *i*, ………., 15), where **i** represents any one-year long period of the analysis , while 15 represents the last period of the analysis, e.g. 1 represents the first one-year long period of the analysis (between baseline year, 0, and year 1)

5.1.2. S, a Set of Pavement Condition States: This set represents the pavement's condition state. There are 5 predefined pavement condition states available. These condition states are as follows:

S: (1, 2, 3, 4, 5)

1. Very Poor Condition
2. Poor Condition
3. Fair Condition
4. Good Condition
5. Excellent Condition

S_1: First set of pavement condition states

S_1: 1, 2, 3

1. Very Poor Condition
2. Poor Condition
3. Fair Condition

S_2: Second set of pavement condition states

S_2: 4, 5

4. Good Condition
5. Excellent Condition

5.1.3. R, a Set of Treatments: A set of treatments represents the treatment types to be used in the model. There are 9 predefined treatment types available. These treatments and their definitions are as follows:

R: (1, 2, 3, 4, 5, 6, 7, 8, 9)

1. **Reconstruction** applied to pavement in **very poor condition**: This treatment type restores pavement in very poor condition to excellent condition.
2. **Rehabilitation$_2$** applied to pavement in **poor condition**: This treatment type restores pavement in poor condition to excellent condition.
3. **Thick Overlay$_3$** applied to pavement in **fair condition**: This treatment type restores pavement in fair condition to excellent condition.
4. **Thin Overlay$_4$** applied to pavement in **good condition**: This treatment type restores pavement in good condition to excellent condition.
5. **Rehabilitation$_1$** applied to pavement in **very poor condition**: This treatment type restores pavement in very poor condition to good condition.
6. **Thick Overlay$_2$** applied to pavement in **poor condition**: This treatment type restores pavement in poor condition to good condition.

7. **Thin Overlay$_3$** applied to pavement in **fair condition**: This treatment type restores pavement in fair condition to good condition.
8. **Ordinary Maintenance (OM$_3$)** applied to pavement in **fair condition**: This treatment type preserves pavement in fair condition.
9. **Ordinary Maintenance (OM$_4$)** applied to pavement in **good condition**: This treatment type preserves pavement in good condition.

5.2. DEFINITION OF PARAMETERS

Parameters stated below will be used in subsequent sections where sample problems are introduced.

$\boldsymbol{B_i}$: Highway Maintenance Budget available within period $\boldsymbol{i}$, $\forall i \in P$

$\boldsymbol{U_{ij}}$: Unit (Per lane-mile) cost of treatment $\boldsymbol{j}$ within period $\boldsymbol{i}$, $\forall i \in P$ and $\forall j \in R$

$\boldsymbol{N_{k0}}$: Number of lane-miles in condition **k** at time 0

$\boldsymbol{G_{ki}}$: Required number of lane-miles (Target specified by VDOT) in condition $\boldsymbol{k}$ at the end of period $\boldsymbol{i}$, $\forall i \in P$ and $\forall k \in S$

$\boldsymbol{D_{(k+1)\,k}}$: Deterioration Rate from condition state $\boldsymbol{(k+1)}$ to condition state $\boldsymbol{k}$, $\forall k \in S$

5.3. DEFINITION OF VARIABLES

Ultimate goal of the research conducted herein is to determine the optimal values of the decision variables such that the most efficient pavement maintenance programming will materialize. Variables included in the model not only reveal amount of annual investment required for each renewal activity, but also the number of lane-miles in each condition state resulting from such investments. Variables used in the developed models are as follows:

- X_{ij}: Amount of money spent on treatment **j** within period **i**, $\forall i \in P$ and $\forall j \in R$
- N_{ki}: Number of lane-miles in condition **k** at the end of period **i**, $\forall i \in P$ and $\forall k \in S$

It should be noted that X_{ij} represents a decision variable, whereas N_{ki} is a variable which is dependent upon X_{ij}. In other words, the optimization model presented herein determines optimal values of X_{ij}, and optimal N_{ki} values are computed through X_{ij} as an output variable.

5.4. OBJECTIVE FUNCTION

Objective function stated in below is a generic objective function that will be used in problems discussed in the following sections.

$$\text{Minimize} \sum_{i \in P} \left((w_1 * N_{1i}) \pm (w_2 * N_{2i}) \pm (w_3 * N_{3i}) \pm (w_4 * N_{4i}) \pm (w_5 * N_{5i}) \right)$$

The terms with *N* represents the number of actual lane-miles. Furthermore, w_1, w_2, w_3, w_4 and w_5 represent possible weighting coefficients pertaining to each condition state. Such coefficients can be used in problems presented in the following sections in order to do sensitivity analysis.

- N_{1i} is number of lane-miles in very poor condition at the end of period ***i***, $\forall i \in P$
- N_{2i} is number of lane-miles in poor condition at the end of period ***i***, $\forall i \in P$
- N_{3i} is number of lane-miles in fair condition at the end of period ***i***, $\forall i \in P$
- N_{4i} is number of lane-miles in good condition at the end of period ***i***, $\forall i \in P$

- N_{5i} is number of lane-miles in excellent condition at the end of period i, $\forall i \in P$

There are two basic models that this document presents in the following sections.

1. **Basic Model 1** strives to provide the most efficient budget allocation pattern given constraints and maintenance budget
2. **Basic Model 2** strives to determine the minimum budget required to meet performance goals set by Virginia Department of Transportation (VDOT)

Problem Statements 1 through 5 presented in this document pertain to basic model 1 which can be used to determine the most efficient budget allocation pattern given available maintenance budget for 15 funding periods. Each problem statement is assigned a specific model as noted below.

1. Problem statement 1 is solved through Model 1.1
2. Problem statement 2 is solved through Model 1.2
3. Problem statement 3 is solved through Model 1.3
4. Problem statement 4 is solved through Model 1.4
5. Problem statement 5 is solved through Model 1.5

Each problem differs from each other; therefore, parametric analyses are performed in order to see the effect of changing parameters in both objective function and maintenance budget. Furthermore, problem statement 6 and problem statement 7 pertain to basic model 2 which can be used to determine the minimum budget required to meet performance goals set by VDOT. Problem 7 is slightly different from problem 6 in that a new constraint pertaining to maintenance budget is introduced for problem 7. Problem statements 6 and 7 are also assigned specific models as noted below.

1. Problem statement 6 is solved through Model 2.1
2. Problem statement 7 is solved through Model 2.2

In conclusion, sections **5.5** through **5.7** present two basic models developed within this research effort. Furthermore, different problem statements are included for each basic model and parametric analyses are performed.

5.5. PROBLEM STATEMENTS

Problem statements given in this section are included in this document for demonstrating the results of the models developed during this research effort.

5.5.1. PROBLEM PARAMETERS

5.5.1.1.Performance targets set by Virginia Department of Transportation

		P														
Required Number of Lane-Miles in condition k at the end of period i (G_ki)		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
S	1	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0
	2	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0
	3	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	4	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
	5	125.0	125.0	125.0	125.0	125.0	125.0	125.0	125.0	125.0	125.0	125.0	125.0	125.0	125.0	125.0

Table 2: Performance Targets Set by Virginia Department of Transportation

5.5.1.2.Deterioration Rates

Deterioration Rate from Condition State (k+1) to k

		Condition State (k)				
		1	2	3	4	5
Condition State (k)	1		4			
	2			3		
	3				5	
	4					3
	5					

Table 3: Pavement Deterioration Rates (de la Garza and Krueger, 2007)

5.5.1.3. Number of Lane-Miles in Each Condition State – Baseline Condition

Number of Lane-Miles in each condition at the the beginning of year 1 (Baseline Condition)		
Condition State (k)	**CCI Value**	**N_k0**
1	CCI<=49	25
2	49<CCI<=59	75
3	59<CCI<=69	150
4	69<CCI<=89	175
5	CCI>89	75
Total Lane-Miles	500	

Table 4: Baseline Pavement Condition

Baseline condition presented above is real and computed deterministically based on the pavement condition inspections performed by Virginia Department of Transportation.

5.5.1.4. Available Annual Maintenance Budget Profile 1

Annual Highway Maintenance Budget ($) available in Period *i*		
		Budget Amount
P	1	$6,000,000
	2	$8,700,000
	3	$8,700,000
	4	$8,700,000
	5	$8,700,000
	6	$8,700,000
	7	$8,700,000
	8	$9,000,000
	9	$9,000,000
	10	$9,000,000
	11	$9,600,000
	12	$9,600,000
	13	$8,700,000
	14	$8,700,000
	15	$8,700,000

Table 5: Available Annual Maintenance Budget

5.5.1.5.Unit Cost of Each Renewal Activity

Unit Cost of Each Treatment within each Period i *(U_ij)*										
		R								
		Recon	$Rehab_2$	$Thick_3$	$Thin_4$	$Rehab_1$	$Thick_2$	$Thin_3$	OM_3	OM_4
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
P	**0**	**$299,437**	**$138,135**	**$67,805**	**$29,156**	**$188,135**	**$101,808**	**$59,991**	**$19,644**	**$12,268**
	1	**$303,929**	**$140,207**	**$68,822**	**$29,593**	**$190,957**	**$103,336**	**$60,891**	**$19,939**	**$12,452**
	2	**$308,488**	**$142,310**	**$69,855**	**$30,037**	**$193,821**	**$104,886**	**$61,804**	**$20,238**	**$12,639**
	3	**$313,115**	**$144,445**	**$70,902**	**$30,487**	**$196,729**	**$106,459**	**$62,731**	**$20,541**	**$12,829**
	4	**$317,812**	**$146,611**	**$71,966**	**$30,945**	**$199,679**	**$108,056**	**$63,672**	**$20,850**	**$13,021**
	5	**$322,579**	**$148,810**	**$73,045**	**$31,409**	**$202,675**	**$109,677**	**$64,627**	**$21,162**	**$13,216**
	6	**$327,418**	**$151,043**	**$74,141**	**$31,880**	**$205,715**	**$111,322**	**$65,597**	**$21,480**	**$13,415**
	7	**$332,329**	**$153,308**	**$75,253**	**$32,358**	**$208,800**	**$112,992**	**$66,581**	**$21,802**	**$13,616**
	8	**$337,314**	**$155,608**	**$76,382**	**$32,844**	**$211,932**	**$114,686**	**$67,579**	**$22,129**	**$13,820**
	9	**$342,374**	**$157,942**	**$77,528**	**$33,336**	**$215,111**	**$116,407**	**$68,593**	**$22,461**	**$14,027**
	10	**$347,509**	**$160,311**	**$78,691**	**$33,836**	**$218,338**	**$118,153**	**$69,622**	**$22,798**	**$14,238**
	11	**$352,722**	**$162,716**	**$79,871**	**$34,344**	**$221,613**	**$119,925**	**$70,666**	**$23,140**	**$14,451**
	12	**$358,013**	**$165,157**	**$81,069**	**$34,859**	**$224,937**	**$121,724**	**$71,726**	**$23,487**	**$14,668**
	13	**$363,383**	**$167,634**	**$82,285**	**$35,382**	**$228,311**	**$123,550**	**$72,802**	**$23,839**	**$14,888**
	14	**$368,834**	**$170,148**	**$83,519**	**$35,913**	**$231,736**	**$125,403**	**$73,894**	**$24,197**	**$15,111**
	15	**$374,366**	**$172,701**	**$84,772**	**$36,451**	**$235,212**	**$127,284**	**$75,002**	**$24,560**	**$15,338**

Inflation Rate	1.5%

Table 6: Unit Cost of Each Renewal Activity

It should be noted that constant inflation rate, which is 1.5 %, is considered in the calculation of unit prices pertaining to each renewal activity in order to retain the network level optimization model practical.

5.5.2. DECISION VARIABLES

***X_{ij}*:** Amount of money spent on treatment **j** within period **i**, $\forall i \in P$ and $\forall j \in R$

***N_{ki}*:** Number of lane-miles in condition **k** at the end of period **i**, $\forall i \in P$ and $\forall k \in S$

5.5.3. OBJECTIVE FUNCTION

Minimize $\sum_{i \in P} \left((N_{1i} + N_{2i} + N_{3i}) \right)$

This problem will be subject to the constraints listed in the following pages. Most of these constraints, if not all, will apply to the problems stated in this document. The MS candidate will make the necessary notes as to what constraints apply to what problems in the corresponding sections of this document.

5.5.4. CONSTRAINTS

Constraint 1

$$G_{ki} - N_{ki} \geq 0, \forall i \in P, \forall k \in S_1$$

Constraint 2

$$N_{ki} - G_{ki} \geq 0, \forall i \in P, \forall k \in S_2$$

Constraint 1 represents the performance targets being greater than or equal to the number of lane-miles in very poor, poor and fair condition.

Constraint 2 represents the number of lane-miles in good and excellent condition being greater than the performance targets stated by Virginia Department of Transportation (VDOT).

Constraints 1 and 2 guarantee that the model will satisfy VDOT's performance goals if there is any feasible solution to the problem.

Constraint 3

$$\sum_{j=1}^{9} X_{ij} \leq B_i, \forall i \in P$$

Constraint 3 represents the annual highway maintenance **budget constraint**. Money spent on 9 different renewal activities (treatments) within the period *i* must be less than or equal to the budget available for period *i*, which is B_i. This constraint will be denoted as "**Budget Constraint"** throughout this document for avoiding repetition of stating the same inequalities for each problem type.

Constraint 4

$$N_{5i} = N_{5(i-1)} - \frac{N_{5(i-1)}}{D_{54}} + \frac{X_{i1}}{U_{i1}} + \frac{X_{i2}}{U_{i2}} + \frac{X_{i3}}{U_{i3}} + \frac{X_{i4}}{U_{i4}}, \forall i \in P$$

This constraint represents the requirement that the number of lane-miles in excellent condition at the end of period *i* have to be equal to the sum of the following components:

$N_{5(i-1)}$: The number of lane-miles in excellent condition at the end of period *(i-1)* or beginning of the period *i*.

$-\frac{N_{5(i-1)}}{D_{54}}$: The number of lane-miles in excellent condition deteriorating to good condition.

$\frac{X_{i1}}{U_{i1}}$: The number of lane miles restored from very poor condition to excellent condition through the application of **Reconstruction.**

$\frac{X_{i2}}{U_{i2}}$: The number of lane miles restored from poor condition to excellent condition through the application of **Rehabilitation$_2$**.

$\frac{X_{i3}}{U_{i3}}$: The number of lane miles restored from fair condition to excellent condition through the application of **Thick Overlay$_3$**.

$\frac{X_{i4}}{U_{i4}}$: The number of lane miles restored from good condition to excellent condition through the application of **Thin Overlay$_4$**.

Constraints 5 through 8 can be explained and written in the exact same manner. Thus, constraints 4 through 8 will be denoted as "**Lane-mile Equality Constraints"** throughout this document for avoiding repetition of stating the same equations for each problem type.

Constraint 5

$$N_{4i} = N_{4(i-1)} - \frac{N_{4(i-1)}}{D_{43}} + \frac{N_{5(i-1)}}{D_{54}} + \frac{X_{i5}}{U_{i5}} + \frac{X_{i6}}{U_{i6}} + \frac{X_{i7}}{U_{i7}} + \frac{X_{i9}}{U_{i9}} - \frac{X_{i9}}{U_{i9}} - \frac{X_{i4}}{U_{i4}}, \forall i \in P$$

Constraint 6

$$N_{3i} = N_{3(i-1)} - \frac{N_{3(i-1)}}{D_{32}} + \frac{N_{4(i-1)}}{D_{43}} + \frac{X_{i8}}{U_{i8}} - \frac{X_{i8}}{U_{i8}} - \frac{X_{i7}}{U_{i7}} - \frac{X_{i3}}{U_{i3}}, \forall i \in P$$

Constraint 7

$$N_{2i} = N_{2(i-1)} - \frac{N_{2(i-1)}}{D_{21}} + \frac{N_{3(i-1)}}{D_{32}} - \frac{X_{i2}}{U_{i2}} - \frac{X_{i6}}{U_{i6}}, \forall i \in P$$

Constraint 8

$$N_{1i} = N_{1(i-1)} + \frac{N_{2(i-1)}}{D_{21}} - \frac{X_{i1}}{U_{i1}} - \frac{X_{i5}}{U_{i5}}, \forall i \in P$$

Constraint 9

$$N_{ki} \geq 0, \forall i \in P, \forall k \in S$$

$$X_{ij} \geq 0, \forall i \in P, \forall j \in R$$

The inequalities in constraint 9 denote the non-negativity constraints. Thus, these constraints will be represented as “**Non-Negativity Constraints”** for avoiding repetition of stating the same equations for each problem type.

5.6. BASIC MODEL 1

5.6.1. PROBLEM STATEMENT 1

How should VDOT allocate its annual highway maintenance budget for different renewal activities such that number of lane-miles in poor, very poor and fair condition will be minimized?

Model 1.1 is used to address the problem stated above.

Objective Function

Minimize $\sum_{i \in P} \left((N_{1i} + N_{2i} + N_{3i}) \right)$

This problem will be subject to the constraints listed in the previous pages except for **Performance Target** constraints, i.e. Constraint 1 and Constraint 2.

5.6.1.1.Results Obtained from Model 1.1

	Budget Allocated to each Renewal Activity														
Renewal Activity	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**	**Year 6**	**Year 7**	**Year 8**	**Year 9**	**Year 10**	**Year 11**	**Year 12**	**Year 13**	**Year 14**	**Year 15**
Recon	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Rehab2	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Thick Overlay 3	$6,000,000	$4,405,144	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Thin Overlay 4	$0	$0	$0	$0	$0	$1,013,385	$2,968,761	$4,142,545	$5,190,799	$6,304,176	$8,088,317	$5,809,834	$5,896,981	$5,985,436	$0
Rehab1	$0	$0	$1,765,335	$4,670,579	$1,574,172	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Thick Overlay 2	$0	$4,294,856	$4,218,684	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Thin Overlay 3	$0	$0	$2,715,981	$4,029,421	$4,834,597	$5,863,998	$5,731,239	$4,857,455	$3,809,201	$2,695,824	$1,511,683	$0	$0	$0	$0
Ordinary Maintenance 3	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Ordinary Maintenance 4	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Total Budget Spent	$6,000,000	$8,700,000	$8,700,000	$8,700,000	$6,408,769	$6,877,383	$8,700,000	$9,000,000	$9,000,000	$9,000,000	$9,600,000	$5,809,834	$5,896,981	$5,985,436	$0
Available Budget	$6,000,000	$8,700,000	$8,700,000	$8,700,000	$8,700,000	$8,700,000	$8,700,000	$9,000,000	$9,000,000	$9,000,000	$9,600,000	$9,600,000	$8,700,000	$8,700,000	$8,700,000

	Fraction of Maintenance Budget to Renewal Activities - Budget Profile #1														
	Year 1	**Year 2**	**Year 3**	**Year 4**	**Year 5**	**Year 6**	**Year 7**	**Year 8**	**Year 9**	**Year 10**	**Year 11**	**Year 12**	**Year 13**	**Year 14**	**Year 15**
Preventive Maintenance	1.00	1.00	1.00	1.00	0.74	0.79	1.00	1.00	1.00	1.00	1.00	0.61	0.68	0.69	0.00
Reconstruction	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Rehabilitation	0.00	0.00	0.20	0.54	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Rehabilitation 1	0.00	0.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Rehabilitation 2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Thick Overlays	1.00	1.00	0.48	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Thick Overlay 2	0.00	0.49	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Thick Overlay 3	1.00	0.51	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Thin Overlays	0.00	0.00	0.31	0.46	0.75	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00
Thin Overlay 3	0.00	0.00	1.00	1.00	1.00	0.85	0.66	0.54	0.42	0.30	0.16	0.00	0.00	0.00	0.00
Thin Overlay 4	0.00	0.00	0.00	0.00	0.00	0.15	0.34	0.46	0.58	0.70	0.84	1.00	1.00	1.00	0.00
Ordinary Maintenance	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ordinary Maintenance 3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ordinary Maintenance 4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

LEGEND	
Maintenance Type	(grey)
Renewal Type	(orange)
Renewal Activity	(light blue)

Table 7: Budget Allocation that Materializes Based on Model 1.1

	Actual Lane-Miles															
Condition State	**Baseline**	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**	**Year 6**	**Year 7**	**Year 8**	**Year 9**	**Year 10**	**Year 11**	**Year 12**	**Year 13**	**Year 14**	**Year 15**
Very Poor Condition	25.0	43.7	70.3	74.6	50.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Poor Condition	75.0	106.3	53.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Fair Condition	150.0	46.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Good Condition	175.0	165.0	219.7	321.2	379.6	453.7	436.9	364.8	281.8	196.5	108.6	0.0	0.0	0.0	0.0	166.7
Excellent Condition	75.0	138.5	156.3	104.2	69.5	46.3	63.1	135.2	218.2	303.5	391.4	500.0	500.0	500.0	500.0	333.3

Table 8: Number of Lane-Miles in Each Condition State for Every Funding Period

5.6.1.2.Charts Produced Based on the Results Obtained from Model 1.1

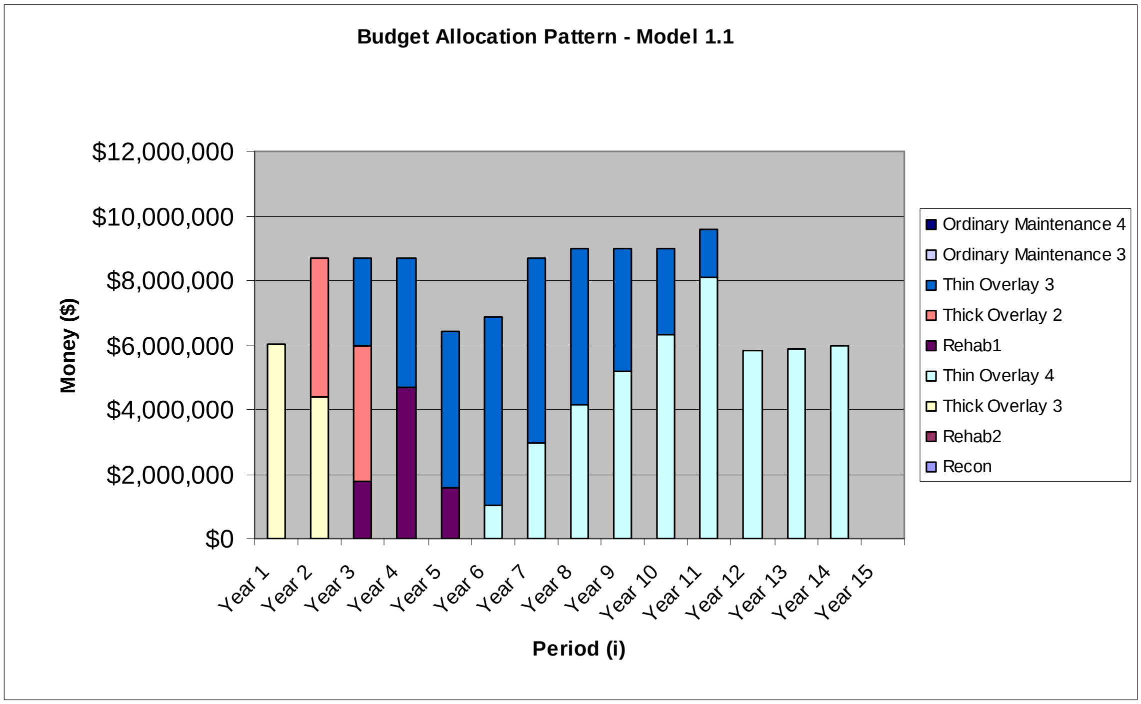


Figure 7: Budget Allocation Pattern Resulted from Model 1.1

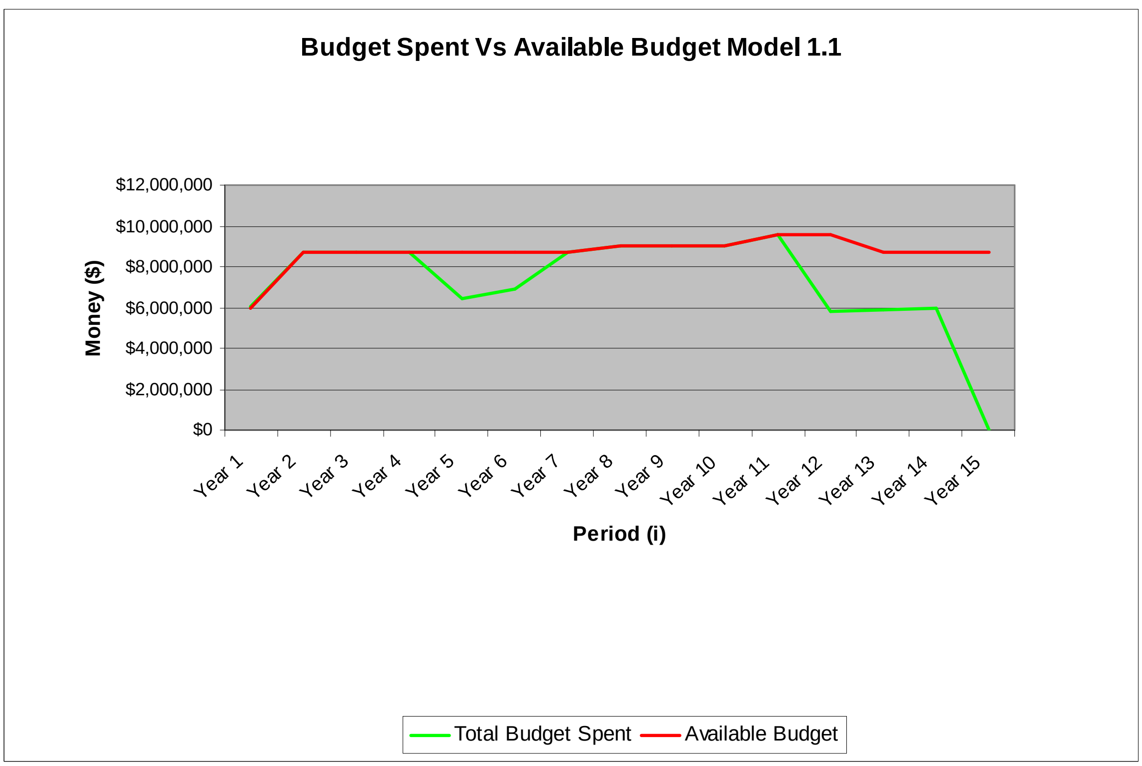


Figure 8: Comparison between Budget Spent and Available Budget in each Period

5.6.1.3.Pavement Condition Trend Analysis

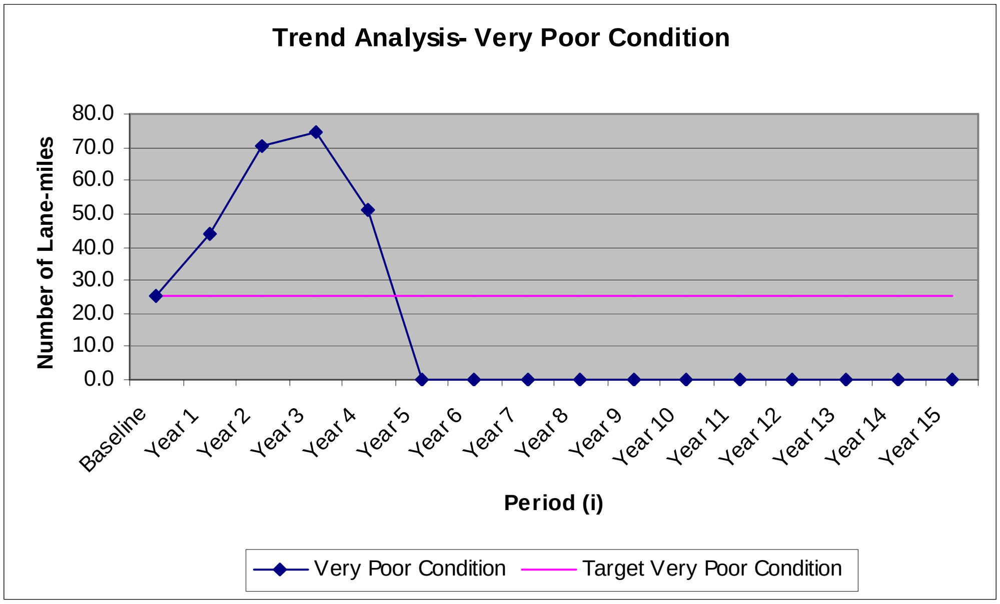


Figure 9: 15 Year Trend Analysis Pertaining to Pavement in Very Poor Condition

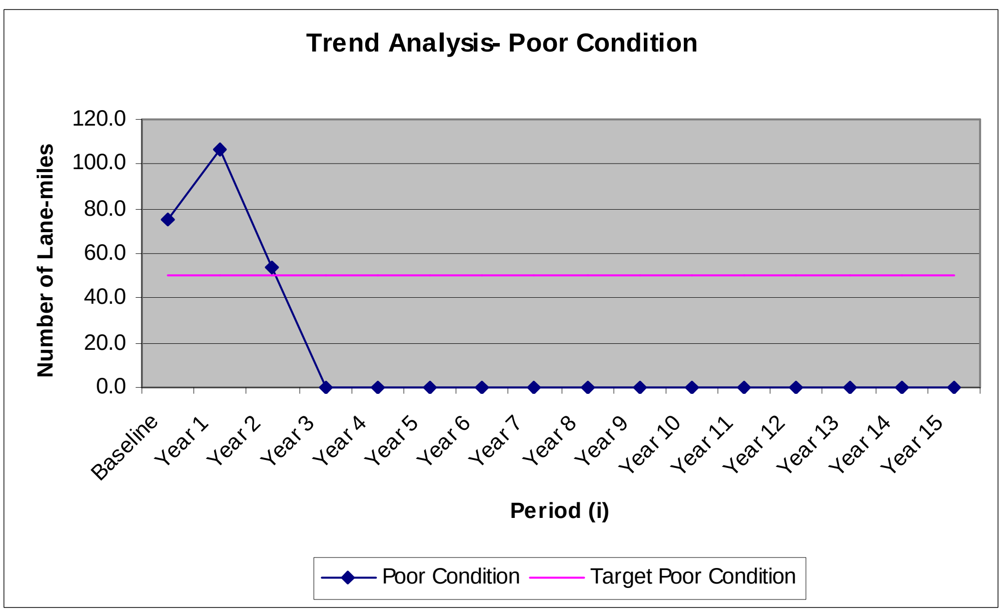


Figure 10: 15 Year Trend Analysis Pertaining to Pavement in Poor Condition

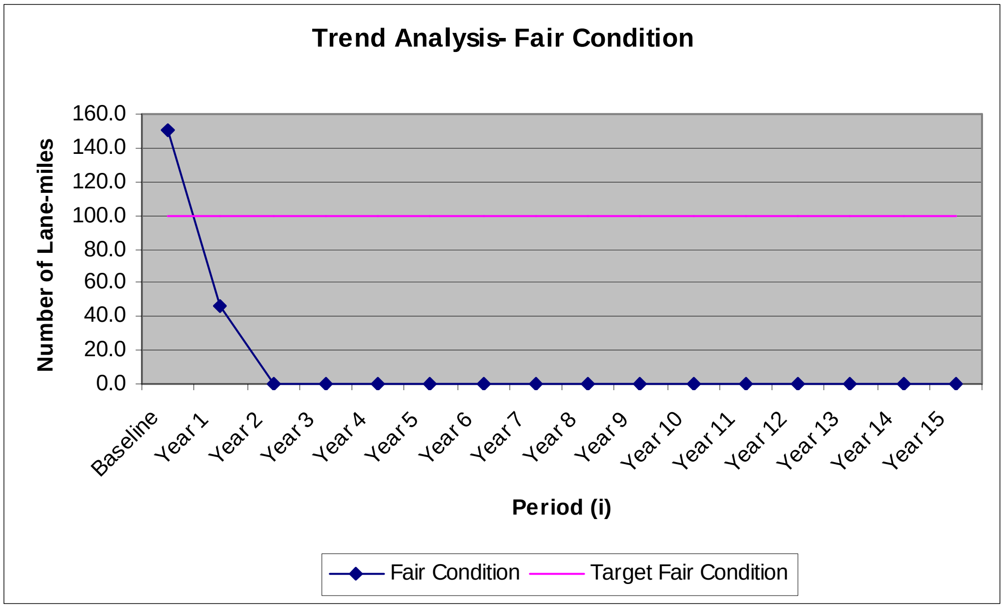


Figure 11: 15 Year Trend Analysis Pertaining to Pavement in Fair Condition

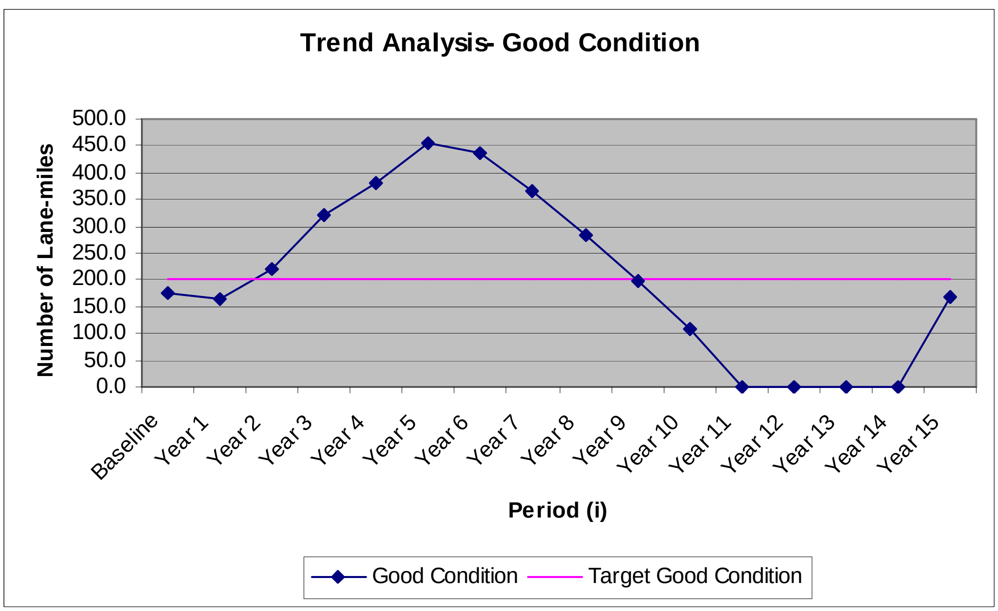


Figure 12: 15 Year Trend Analysis Pertaining to Pavement in Good Condition

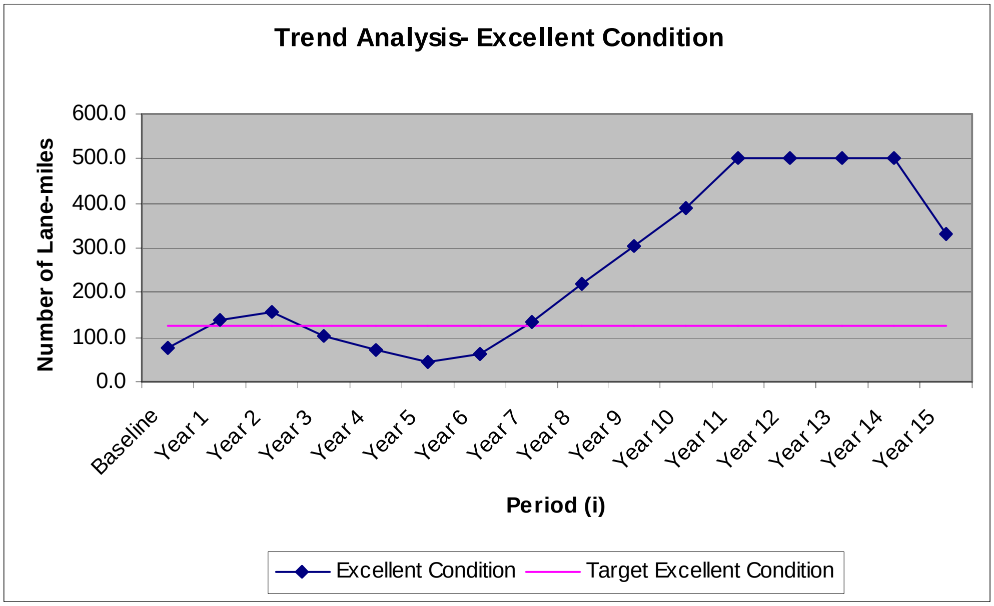


Figure 13: 15 Year Trend Analysis Pertaining to Pavement in Excellent Condition

5.6.1.4.Observations

The goal of the objective function defined in problem 1 is to minimize the lane-miles in very poor, poor and fair condition.

Firstly**, Table 7** and **Table 8** show the budget allocation pattern and the level of service pertaining to each year respectively, which resulted from the parameters and the objective function used in **Model 1.1**. Based on the results shown in **Table 7**, Virginia Department of Transportation should completely consume the available annual highway maintenance budget in the first four periods in order to minimize the lane-miles in very poor, poor and fair condition. The budget allocation materializing in year 1 mainly focuses on **Thick Overlay 3** renewal activity. Thus, available maintenance budget in year 2 is essentially spent on **Thick Overlay 3** and **Thick Overlay 2** renewal activities, which restores lane-miles in fair condition to excellent condition and poor condition to good condition, respectively. Hence, it is essential to note that **Model 1.1** gives priority to restoring lane-miles in fair and poor condition in first 2 periods in order to restore lane-miles in such conditions to good and excellent conditions. Furthermore, it can be observed that the model allocates budget into **Rehabilitation 1** and **Thin Overlay 3** activities for 3 years starting from the third period. Rehabilitation 1 restores pavement in very poor condition to good condition while Thin Overlay 3 restores pavement in fair condition to good condition. This observation results in the conclusion that the model starts to treat pavement in very poor condition and keeps restoring pavement in fair condition to upstream conditions. One interesting fact about the budget allocation pattern period 3 through period 15 is that renewal activities applied to poor condition are not considered in that there are lane-miles neither in fair nor in poor condition.

Secondly, available pavement maintenance budget between years 6 and 11 is allocated into only Thin Overlay 4 and Thin Overlay 3 renewal activities, which restore the pavement in fair condition to good condition and the pavement in good condition to excellent condition, respectively. This budget allocation pattern focusing on **Thin Overlay 3** and **Thin Overlay 4**, can be attributed to the fact that the lane-miles during years 6 through 11 are in good and excellent condition. Hence, application of **Thin Overlay 3** to the lane-miles deteriorating from good condition to fair condition is necessary, while application of **Thin Overlay 4** ensures that lane-miles in good condition deteriorating from excellent condition are restored back to excellent

Another interesting observation, based on the results, is that although there is available budget during years 12 through 15, the model does not allocate such excess budget to renewal activities. The following two reasons result in this case:

- Money available is much more than required to retain lane-miles in either good or excellent condition.
- The objective function defined for Model 1.1 strives only for minimizing the number of lane-miles in very poor, poor and fair condition. Therefore, Model 1.1 should not invest any money into

renewal activities in any period where the expenditure in a given period does not improve the value of the objective function. In other words, if the application of a renewal activity does not reduce the number of lane-miles in very poor, poor or fair condition for any given year, then Model 1.1 does not invest any money for the given period. Thus, Model 1.1 does not incur any cost in year 15, where some of the lane-miles in excellent condition in year 14 deteriorate down to good condition. This behavior results from the fact that the value of the objective function is independent of the number of lane-miles in good and excellent condition. Consequently, even if Model 1.1 had spent some money in order to restore the lane-miles, deteriorating from excellent condition to good condition in year 14, back to excellent condition in year 15, this would not have had affected the value of the objective function, which is essentially to be minimized by Model 1.1.

In conclusion, **Model 1.1** favors renewal activities under preventive maintenance category over ordinary maintenance. Furthermore, one important observation is that **Model 1.1** focuses on restoring the lane-miles in very poor, poor and fair condition first and then maintaining the lane-miles restored back to good and excellent condition to retain the optimal value of the objective function.

5.6.2. PROBLEM STATEMENT 2

How should VDOT allocate its annual highway maintenance budget for different renewal activities such that number of lane-miles in poor, very poor and fair condition will be minimized while excess budget will be used towards maximizing the number of lane-miles in excellent condition?

The only difference between problem statement 1 and problem statement 2 derives from the fact that each model has a different objective function. The objective function defined for problem statement 2 is designed to favor having as many lane-miles in excellent condition as possible through using arbitrary weights, subject to available budget. Thus, MS candidate strives for revealing the significance of using arbitrary weights in the objective function in order to favor one condition state over another.

It should be noted that **Model 1.2** is used to address the problem stated above.

DECISION VARIABLES

X_{ij}: Amount of money spent on treatment **j** within period **i**, $\forall i \in P$ and $\forall j \in R$

N_{ki}: Number of lane-miles in condition **k** at the end of period **i**, $\forall i \in P$ and $\forall k \in S$

OBJECTIVE FUNCTION

Minimize $\sum_{i \in P} \left((N_{1i} + N_{2i} + N_{3i}) - (N_{4i} + 5 * N_{5i}) \right)$

This problem will be subject to the constraints listed in the previous pages except for **Performance Target** constraints, i.e., Constraint 1 and Constraint 2.

5.6.2.1.Results Obtained from Model 1.2

	Budget Allocated to each Renewal Activity														
Renewal Activity	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**	**Year 6**	**Year 7**	**Year 8**	**Year 9**	**Year 10**	**Year 11**	**Year 12**	**Year 13**	**Year 14**	**Year 15**
Recon	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Rehab2	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Thick Overlay 3	$3,642,178	$4,887,469	$0	$0	$0	$510,142	$0	$0	$0	$0	$0	$0	$0	$0	$0
Thin Overlay 4	$2,357,822	$3,812,531	$4,450,095	$4,724,519	$5,858,508	$5,975,430	$5,313,338	$5,393,038	$5,473,934	$5,556,043	$5,639,384	$5,809,834	$5,896,981	$5,985,436	$6,075,218
Rehab1	$0	$0	$0	$816,258	$2,841,492	$2,214,428	$0	$0	$0	$0	$0	$0	$0	$0	$0
Thick Overlay 2	$0	$0	$4,249,905	$3,159,223	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Thin Overlay 3	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Ordinary Maintenance 3	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Ordinary Maintenance 4	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Total Budget Spent	$6,000,000	$8,700,000	$8,700,000	$8,700,000	$8,700,000	$8,700,000	$5,313,338	$5,393,038	$5,473,934	$5,556,043	$5,639,384	$5,809,834	$5,896,981	$5,985,436	$6,075,218
Available Budget	$6,000,000	$8,700,000	$8,700,000	$8,700,000	$8,700,000	$8,700,000	$8,700,000	$9,000,000	$9,000,000	$9,000,000	$9,600,000	$9,600,000	$8,700,000	$8,700,000	$8,700,000

	Fraction of Maintenance Budget to Renewal Activities - Budget Profile #1														
	Year 1	**Year 2**	**Year 3**	**Year 4**	**Year 5**	**Year 6**	**Year 7**	**Year 8**	**Year 9**	**Year 10**	**Year 11**	**Year 12**	**Year 13**	**Year 14**	**Year 15**
Preventive Maintenance	1.00	1.00	1.00	1.00	1.00	1.00	0.61	0.60	0.61	0.62	0.59	0.61	0.68	0.69	0.70
Reconstruction	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Rehabilitation	0.00	0.00	0.00	0.09	0.33	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Rehabilitation 1	0.00	0.00	0.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Rehabilitation 2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Thick Overlays	0.61	0.56	0.49	0.36	0.00	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Thick Overlay 2	0.00	0.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Thick Overlay 3	1.00	1.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Thin Overlays	0.39	0.44	0.51	0.54	0.67	0.69	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Thin Overlay 3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Thin Overlay 4	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Ordinary Maintenance	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ordinary Maintenance 3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ordinary Maintenance 4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

LEGEND	
Maintenance Type	(grey)
Renewal Type	(orange)
Renewal Activity	(light blue)

Table 9: Budget Allocation that Materializes Based on Model 1.2

	Actual Lane-Miles															
Condition State	**Baseline**	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**	**Year 6**	**Year 7**	**Year 8**	**Year 9**	**Year 10**	**Year 11**	**Year 12**	**Year 13**	**Year 14**	**Year 15**
Target Very Poor Condition	25.0	43.8	70.3	97.0	102.8	10.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Target Poor Condition	75.0	106.3	106.8	39.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Target Fair Condition	150.0	81.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Target Good Condition	175.0	84.1	0.0	0.0	0.0	34.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Target Excellent Condition	75.0	184.6	322.9	363.4	397.2	454.2	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0

Table 10: Number of Lane-Miles in Each Condition State for Every Funding Period

5.6.2.2.Charts Produced Based on the Results Obtained from Model 1.2

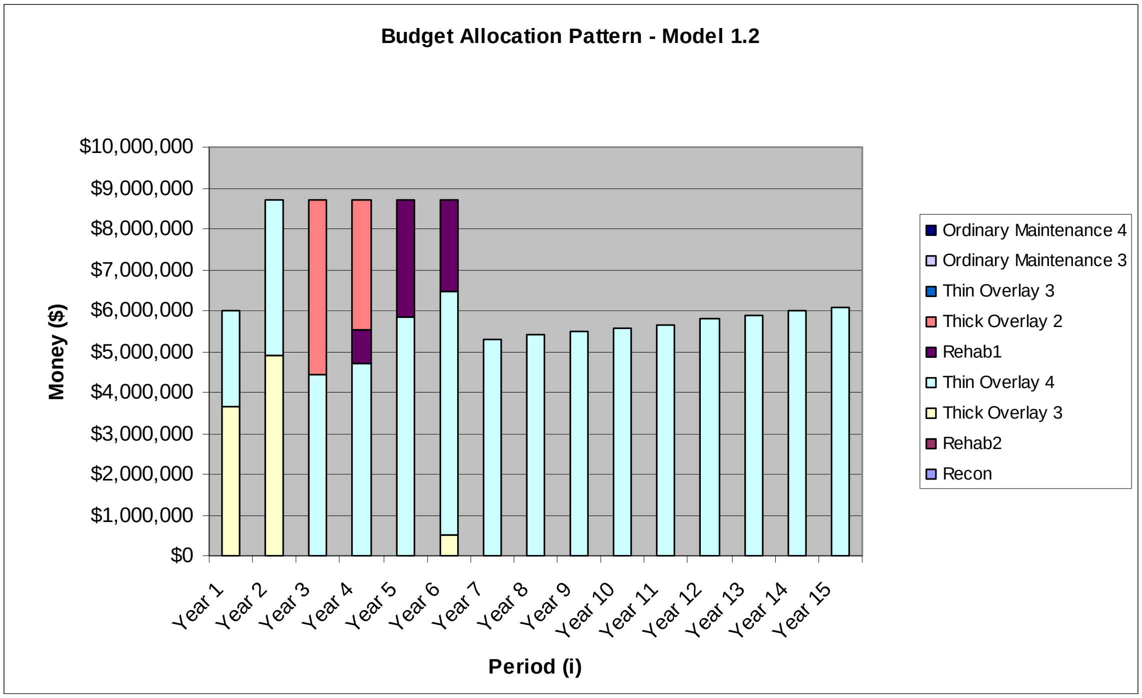


Figure 14: Budget Allocation Pattern Resulted from Model 1.2

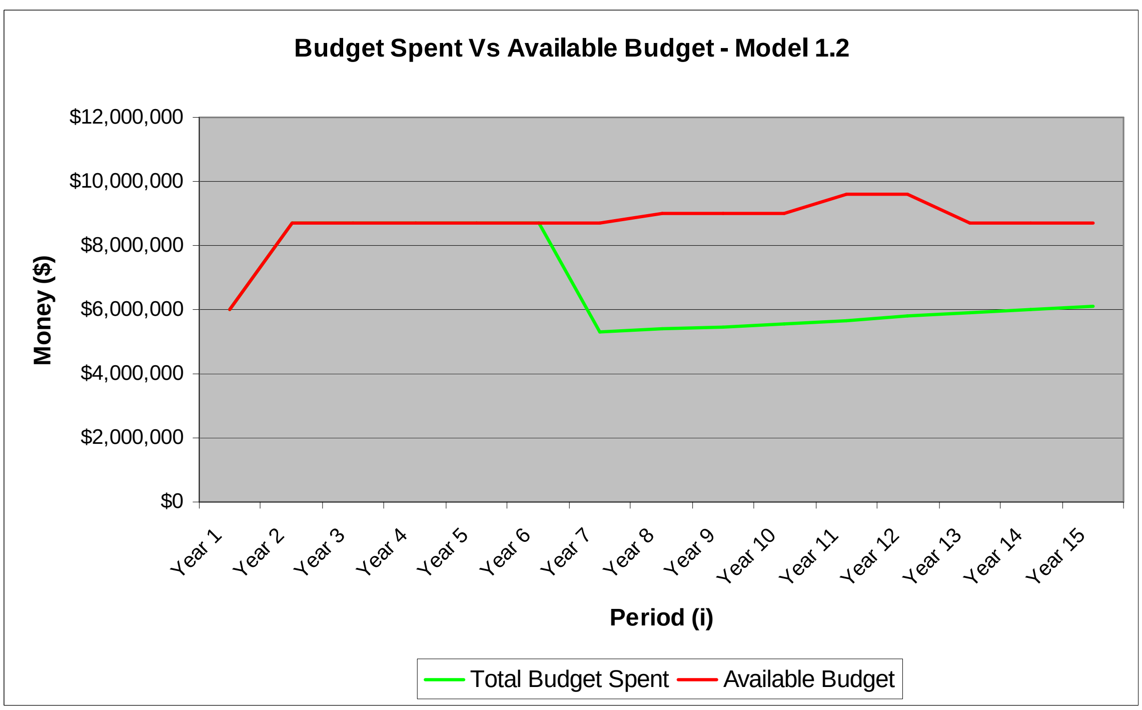


Figure 15: Comparison between Budget Spent and Available Budget in each Period

5.6.2.3.Pavement Condition Trend Analysis

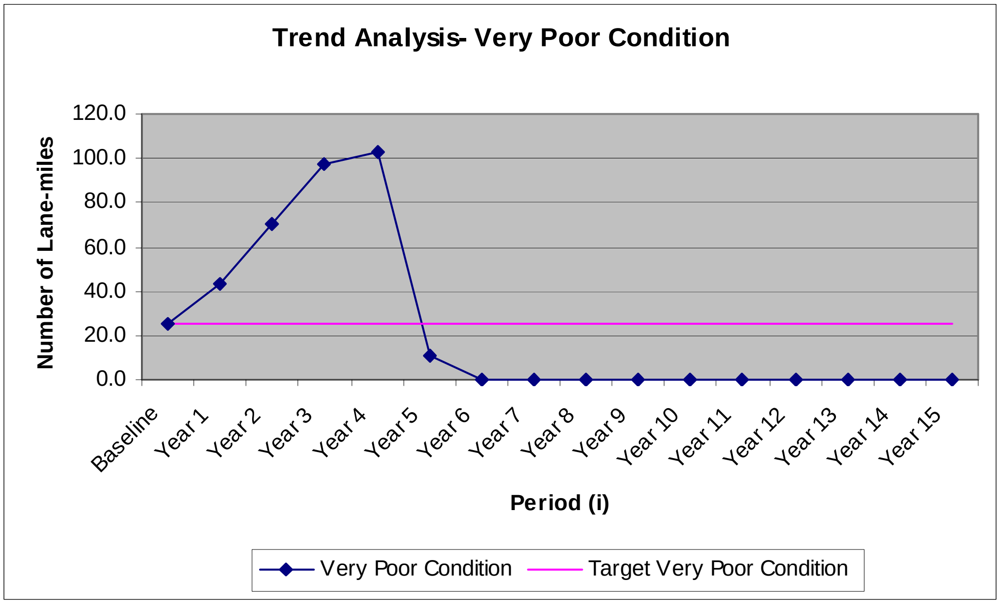


Figure 16: 15 Year Trend Analysis Pertaining to Pavement in Very Poor Condition

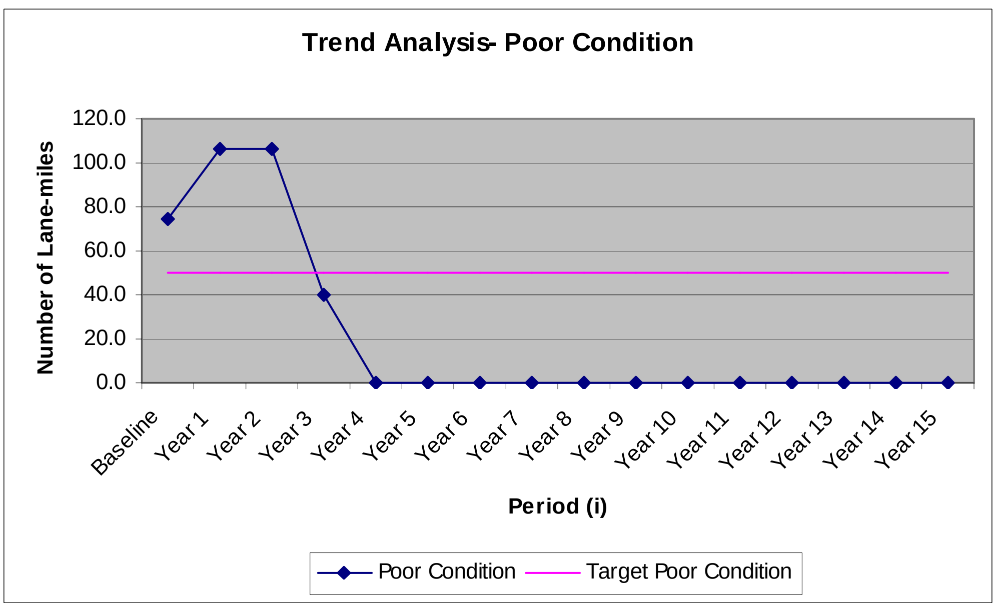


Figure 17: 15 Year Trend Analysis Pertaining to Pavement in Poor Condition

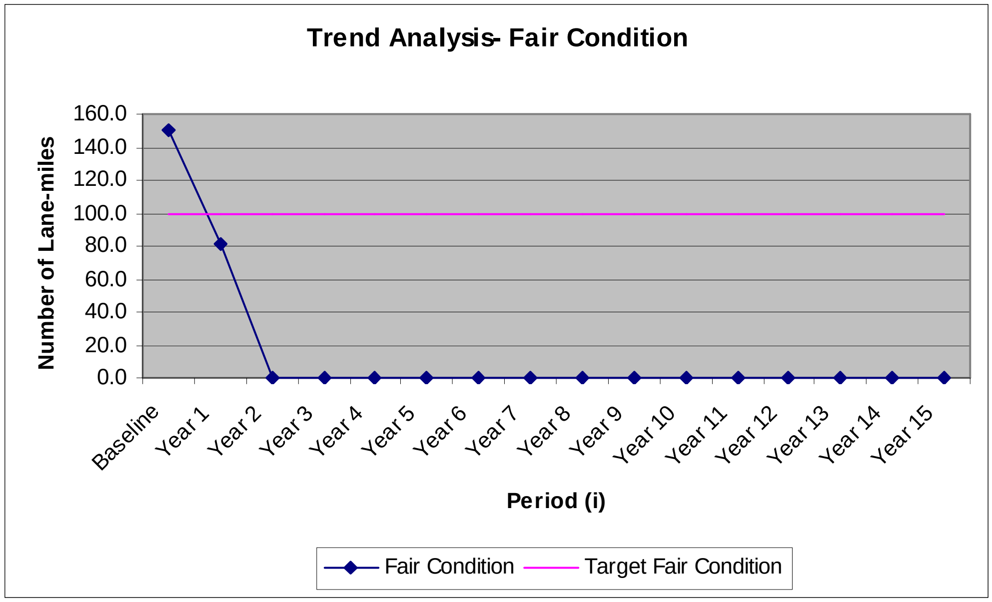


Figure 18: 15 Year Trend Analysis Pertaining to Pavement in Fair Condition

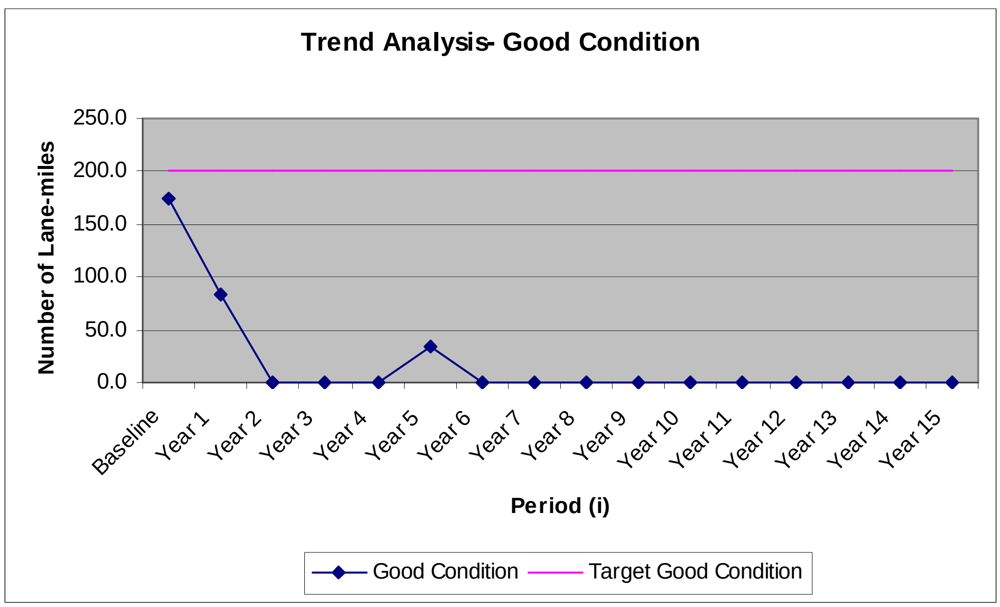


Figure 19: 15 Year Trend Analysis Pertaining to Pavement in Good Condition

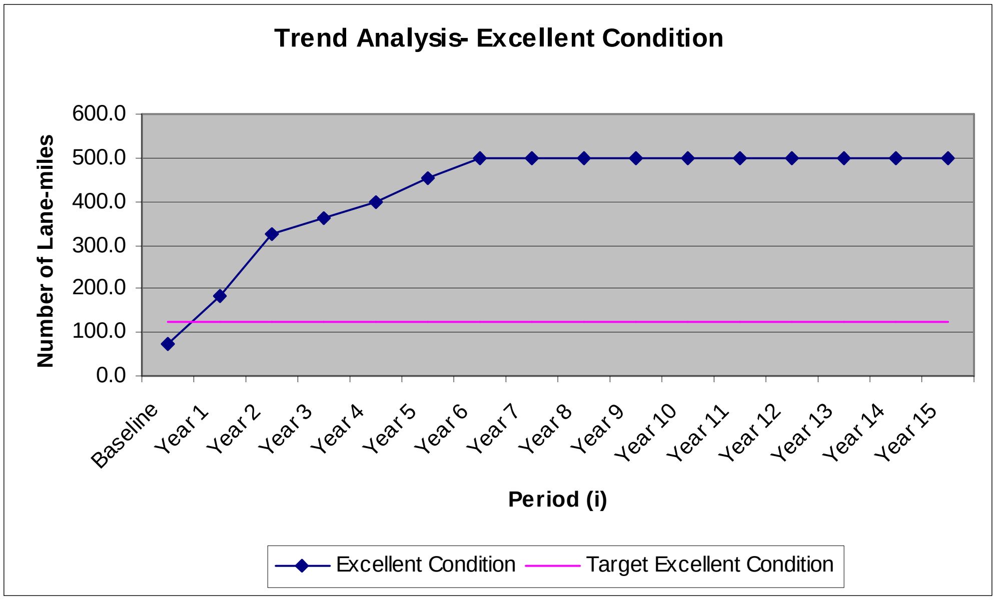


Figure 20: 15 Year Trend Analysis Pertaining to Pavement in Excellent Condition

5.6.2.4. Observations

The goal of the objective function defined in problem 2 is to minimize the lane-miles in very poor, poor and fair condition while excess budget will be used towards maximizing the number of lane-miles in excellent condition.

Firstly**, Table 9** and **Table 10** show the budget allocation pattern and the level of service pertaining to each year respectively, which resulted from the parameters and the objective function used in **Model 1.2**. Based on the results shown in **Table 9**, Virginia Department of Transportation should completely consume the available annual highway maintenance budget in the first 6 periods in order to minimize the lane-miles in very poor, poor and fair condition while maximizing the number of lane-miles in excellent condition. It should be noted that available budget in first 4 periods was fully expended in Model 1.1. This observation clearly shows that the objective function defined for Model 1.2 actually brings about a significant difference between Model 1.1 and Model 1.2 in terms of both budget allocation pattern and pavement level of service.

Secondly, the budget allocation materializing in the first three years mainly focuses on **Thick Overlay 3** and **Thin Overlay 4** renewal activities. **Thick Overlay 3** restores lane-miles in fair condition to excellent condition, while **Thin Overlay 4** restores pavement in good condition to excellent condition. Thus, it is essential to note that **Model 1.2** gives priority to restoring lane-miles in fair and good condition in order to restore lane-miles in such conditions to excellent conditions. This behavior can be attributed to the fact that the objective function defined for Model 1.2 favors having as many lane-miles as possible in excellent condition. Furthermore, it can be observed that the difference between budget allocation pattern obtained from **Model 1.1** and **Model 1.2** for the first two periods results from the fact that **Model 1.2** treats pavement which can be restored to excellent condition with the least cost, i.e. **Thin Overlay 4** and **Thick Overlay 3**,

One interesting fact about the budget allocation pattern period 3 through period 5 is that renewal activities applied to very poor condition and poor condition gain more importance. Thus, all the lane-miles in the network are in excellent condition starting from year 7. Hence, **Thin Overlay 4** is the only renewal activity into which pavement maintenance budget is allocated since **Thin Overlay 4** ensures that lane-miles in good condition deteriorating from excellent condition are restored back to excellent. This observation justifies the use of arbitrary weights included in the objective function pertaining to **Model 1.2**.

Another interesting observation, based on the results, is that although there is available budget during years 7 through 15, the model does not allocate such excess budget to renewal activities since money available for pavement maintenance is much more than required to retain lane-miles in excellent condition

Finally, **Model 1.2**, as **Model 1.1** does, favors renewal activities under preventive maintenance category over ordinary maintenance. Furthermore, one important observation is that **Model 1.2** focuses on restoring the lane-miles in fair and good condition to excellent condition first, then restoring lane-miles in very poor and poor condition to good condition, and then maintaining the lane-miles restored back to excellent condition to retain the optimal value of the objective function. Finally, **Model 1.2** provides better level of service than **Model 1.1** in that all the lane-miles in the network are in excellent condition after year 6 based on the results obtained from **Model 1.2**, while **Model 1.1** achieves the same result at year 11.

In conclusion, it must be noted that **Model 1.2**, as opposed to **Model 1.1**, does allocate some money into **Thin Overlay 4**, which restores the lane-miles in good condition to excellent condition, in year 15. This is due to the last component, $5 * N_{5i}$, of the objective function defined for **Model 1.2**. This component forces **Model 1.2** to maximize the number of lane-miles in excellent condition since having more lane-miles in excellent condition minimizes the value of the objective function, which is essentially the only goal of **Model 1.2**. Consequently, **Model 1.2** results in a different budget allocation strategy in year 15 than **Model 1.1** due to different objective functions pertaining to each model.

5.6.3. PROBLEM STATEMENT 3

How should VDOT allocate its annual highway maintenance budget for different renewal activities such that number of lane-miles in poor, very poor and fair condition will be minimized while excess budget will be used towards maximizing the number of lane-miles in excellent condition?

The only difference between Problem 2 and Problem 3 stems from the fact that the model developed for Problem 3 will be subject to one of the performance target constraints, namely **Constraint 1** starting from year **3**. The reason for enforcing **Constraint 1** starting from year 3 is that the optimization model presented herein does not yield any feasible solution when **Constraint 1** is applied to the model starting from year 1 or year 2.

Constraint 1 pertains to the performance requirements for Very Poor, Poor and Fair condition, being less than the performance targets.

It should be noted that **Model 1.3** is used to address the problem stated above.

DECISION VARIABLES

X_{ij}: Amount of money spent on treatment **j** within period **i**, $\forall i \in P$ and $\forall j \in R$

N_{ki}: Number of lane-miles in condition **k** at the end of period **i**, $\forall i \in P$ and $\forall k \in S$

OBJECTIVE FUNCTION

Minimize $\sum_{i \in P} \left((N_{1i} + N_{2i} + N_{3i}) - (N_{4i} + 5 * N_{5i}) \right)$

Subject to

Constraint 1

$G_{ki} - N_{ki} \geq 0, \forall k \in S_1$, i=3, 4, 5… 15

5.6.3.1.Results Obtained from Model 1.3

	Budget Allocated to each Renewal Activity														
Renewal Activity	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**	**Year 6**	**Year 7**	**Year 8**	**Year 9**	**Year 10**	**Year 11**	**Year 12**	**Year 13**	**Year 14**	**Year 15**
Recon	$0	$0	$0	$0	$0	$0	$0	$0	$0	$2,929,030	$0	$0	$0	$0	$0
Rehab2	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Thick Overlay 3	$6,000,000	$1,414,871	$0	$4,835,845	$2,966,032	$2,267,623	$1,126,779	$0	$0	$0	$0	$0	$0	$0	$0
Thin Overlay 4	$0	$0	$0	$16,870	$4,573,541	$6,432,377	$5,111,811	$5,650,503	$5,719,226	$5,460,978	$5,639,384	$5,809,834	$5,896,981	$5,985,436	$6,075,218
Rehab1	$0	$2,342,038	$8,700,000	$2,459,107	$1,160,427	$0	$0	$1,401,401	$3,280,774	$0	$0	$0	$0	$0	$0
Thick Overlay 2	$0	$4,943,091	$0	$1,388,178	$0	$0	$2,461,410	$1,948,096	$0	$0	$0	$0	$0	$0	$0
Thin Overlay 3	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Ordinary Maintenance 3	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Ordinary Maintenance 4	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Total Budget Spent	$6,000,000	$8,700,000	$8,700,000	$8,700,000	$8,700,000	$8,700,000	$8,700,000	$9,000,000	$9,000,000	$8,390,009	$5,639,384	$5,809,834	$5,896,981	$5,985,436	$6,075,218
Available Budget	$6,000,000	$8,700,000	$8,700,000	$8,700,000	$8,700,000	$8,700,000	$8,700,000	$9,000,000	$9,000,000	$9,000,000	$9,600,000	$9,600,000	$8,700,000	$8,700,000	$8,700,000

	Fraction of Maintenance Budget to Renewal Activities - Budget Profile #1														
	Year 1	**Year 2**	**Year 3**	**Year 4**	**Year 5**	**Year 6**	**Year 7**	**Year 8**	**Year 9**	**Year 10**	**Year 11**	**Year 12**	**Year 13**	**Year 14**	**Year 15**
Preventive Maintenance	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.93	0.59	0.61	0.68	0.69	0.70
Reconstruction	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.33	0.00	0.00	0.00	0.00	0.00
Rehabilitation	0.00	0.27	1.00	0.28	0.13	0.00	0.00	0.16	0.36	0.00	0.00	0.00	0.00	0.00	0.00
Rehabilitation 1	0.00	1.00	1.00	1.00	1.00	0.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
Rehabilitation 2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Thick Overlays	1.00	0.73	0.00	0.72	0.34	0.26	0.41	0.22	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Thick Overlay 2	0.00	0.78	0.00	0.22	0.00	0.00	0.69	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Thick Overlay 3	1.00	0.22	0.00	0.78	1.00	1.00	0.31	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Thin Overlays	0.00	0.00	0.00	0.00	0.53	0.74	0.59	0.63	0.64	0.65	1.00	1.00	1.00	1.00	1.00
Thin Overlay 3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Thin Overlay 4	0.00	0.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Ordinary Maintenance	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ordinary Maintenance 3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ordinary Maintenance 4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

LEGEND	
Maintenance Type	(grey)
Renewal Type	(orange)
Renewal Activity	(cyan)

Table 11: Budget Allocation that Materializes Based on Model 1.3

	Actual Lane-Miles															
Condition State	Baseline	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15
Target Very Poor Condition	25.0	43.7	58.0	25.0	25.0	0.0	12.5	25.0	24.0	8.6	0.0	0.0	0.0	0.0	0.0	0.0
Target Poor Condition	75.0	106.3	47.4	50.0	50.0	50.0	50.0	23.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Target Fair Condition	150.0	46.5	43.4	76.6	37.5	37.5	22.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Target Good Condition	175.0	165.0	238.3	273.1	268.6	144.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Target Excellent Condition	75.0	138.5	112.9	75.3	118.9	268.3	414.7	452.0	476.0	491.4	500.0	500.0	500.0	500.0	500.0	500.0

Table 12: Number of Lane-Miles in Each Condition State for Every Funding Period

5.6.3.2. Charts Produced Based on the Results Obtained from Model 1.3

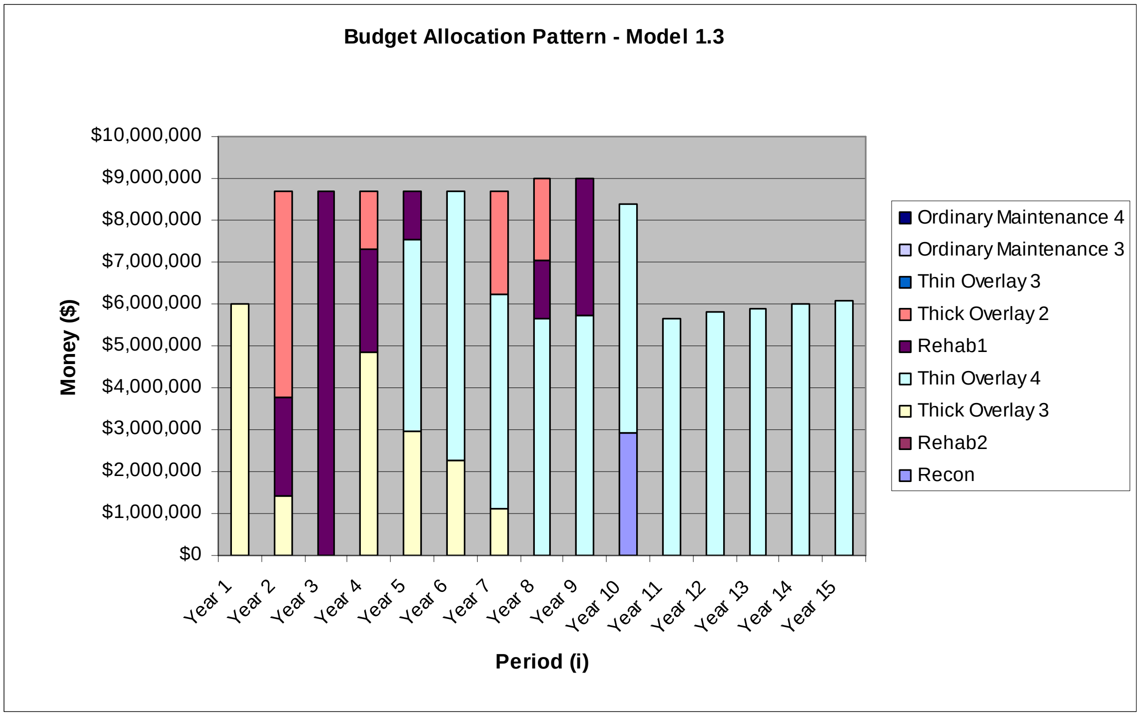


Figure 21: Budget Allocation Pattern Resulted from Model 1.3

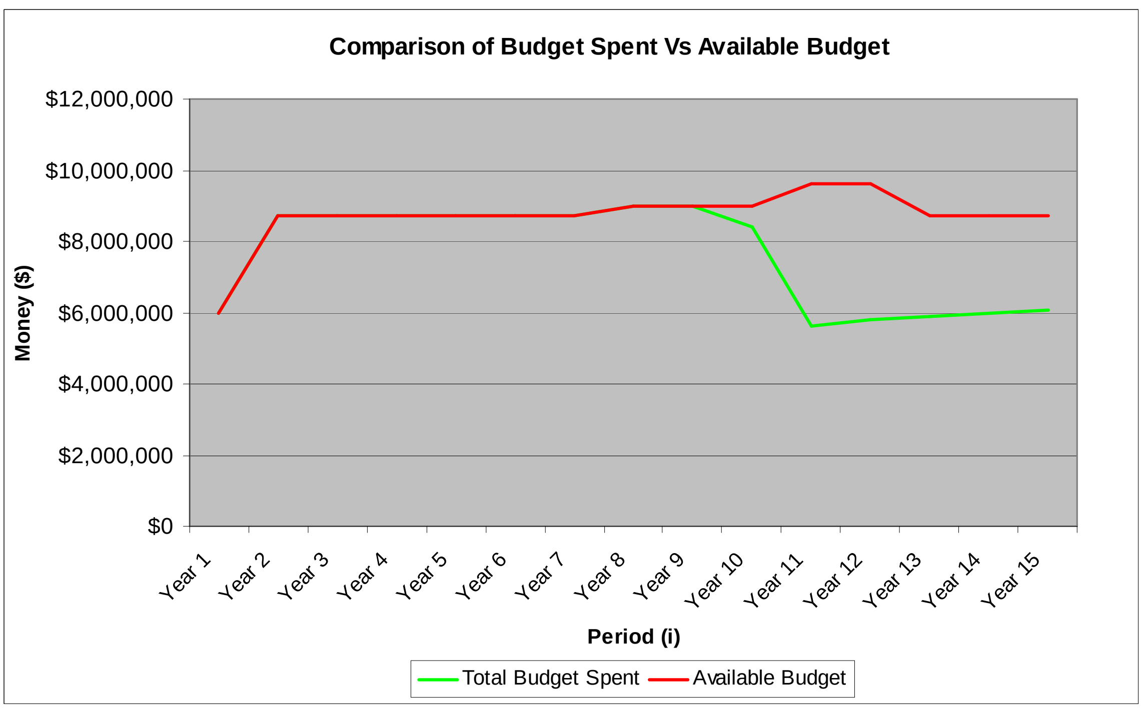


Figure 22: Comparison between Budget Spent and Available Budget in each Period

5.6.3.3.Pavement Condition Trend Analysis

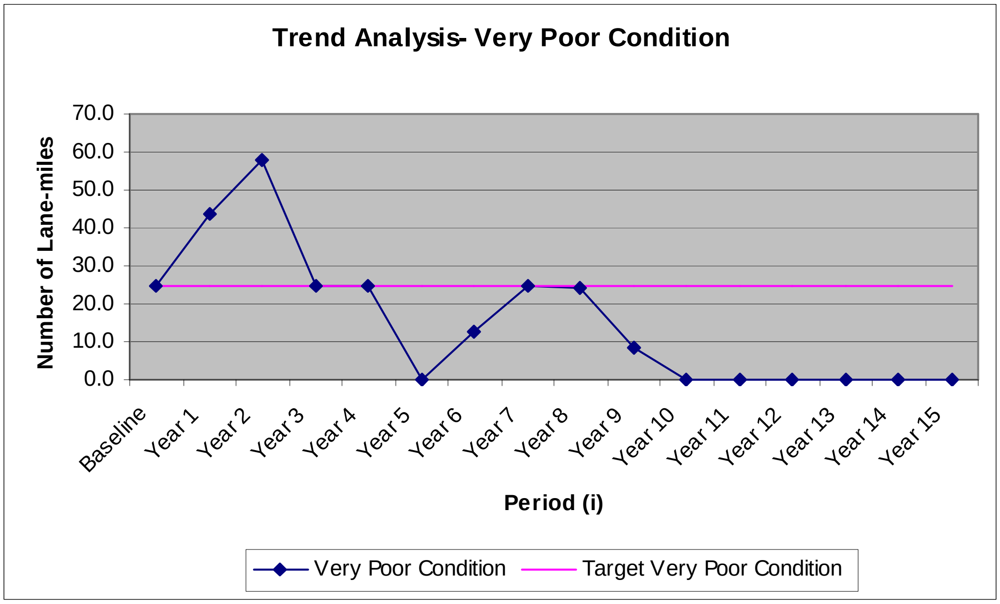


Figure 23: 15 Year Trend Analysis Pertaining to Pavement in Very Poor Condition

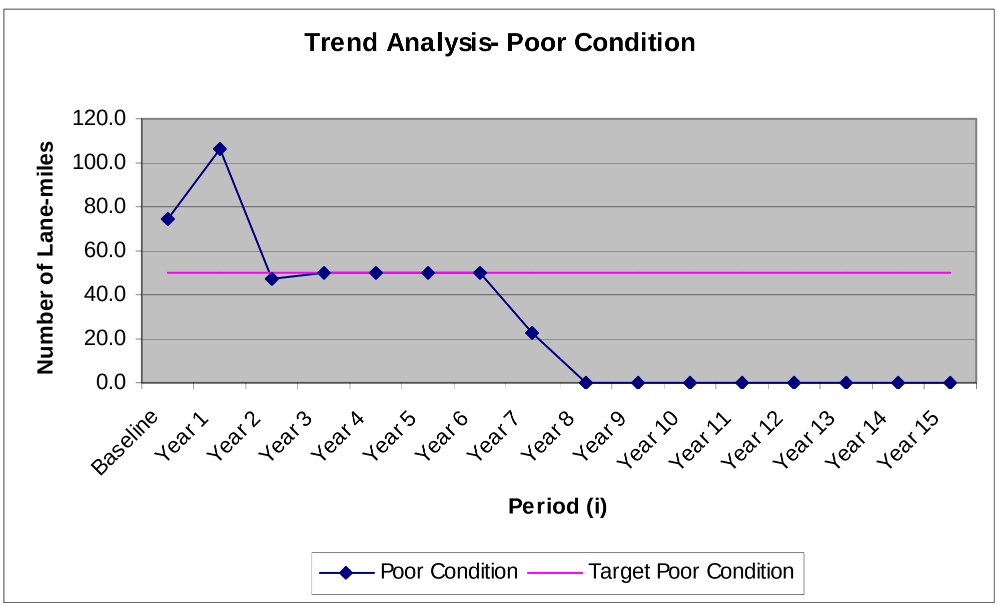


Figure 24: 15 Year Trend Analysis Pertaining to Pavement in Poor Condition

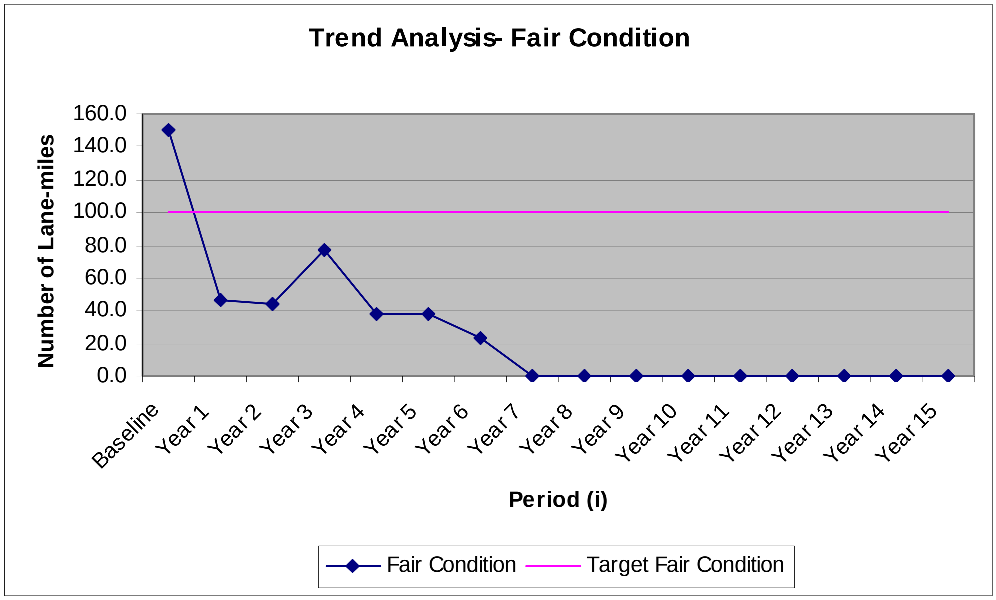


Figure 25: 15 Year Trend Analysis Pertaining to Pavement in Fair Condition

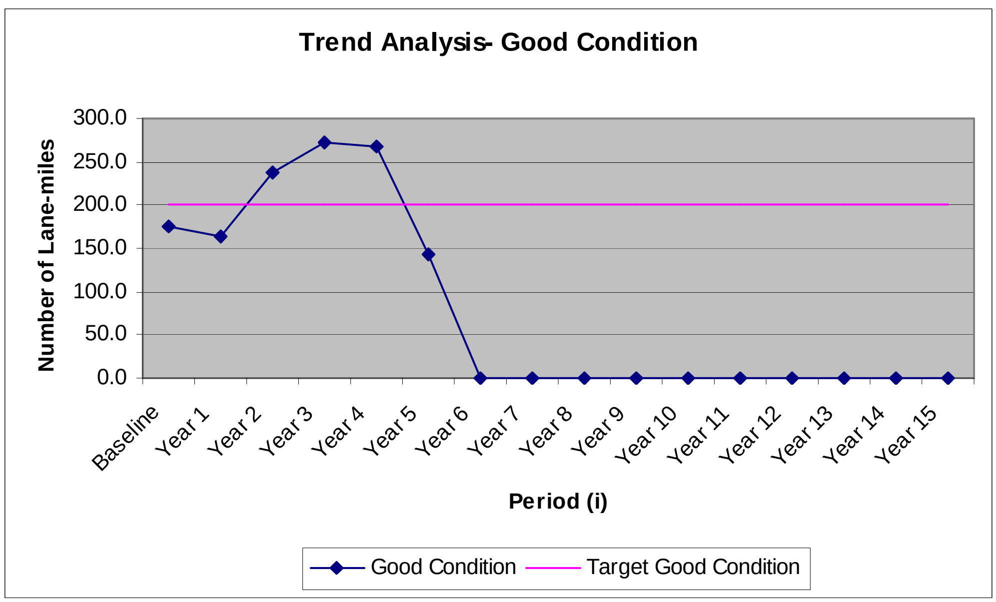


Figure 26: 15 Year Trend Analysis Pertaining to Pavement in Good Condition

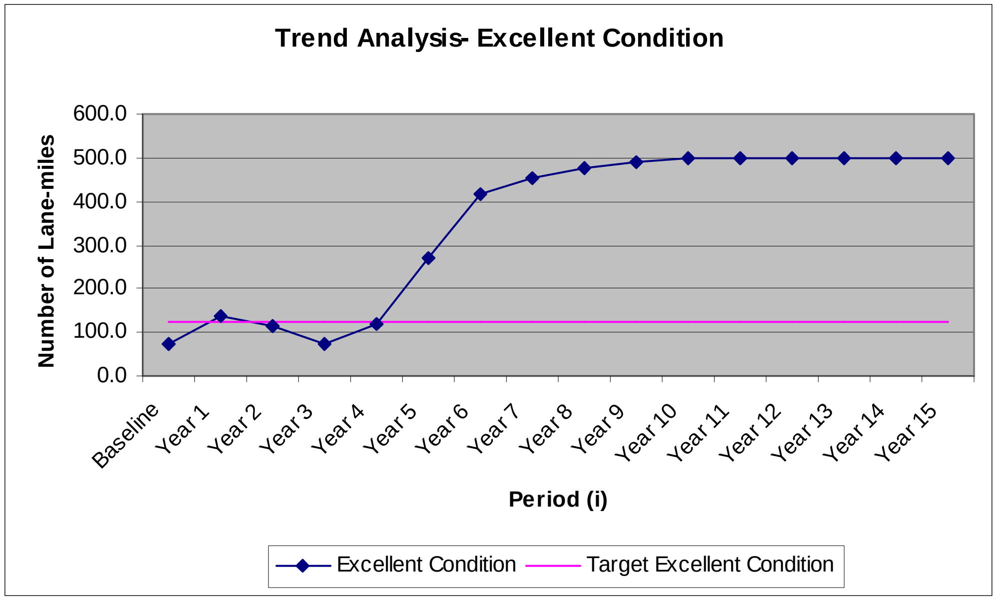


Figure 27: 15 Year Trend Analysis Pertaining to Pavement in Excellent Condition

5.6.3.4.Observations

The goal of the objective function defined in problem 3 is to minimize the lane-miles in very poor, poor and fair condition while excess budget will be used towards maximizing the number of lane-miles in excellent condition. As noted earlier, the only difference between problem statement 2 and problem statement 3 is the performance target constraints pertaining to allowable number of lane-miles in very poor, poor and fair condition starting from year 3 of the analysis.

Firstly**, Table 11** and **Table 12** show the budget allocation pattern and the level of service pertaining to each year respectively, which resulted from the parameters, pavement performance constraints and the objective function used in **Model 1.3**. The results shown in **Table 10** indicates that budget allocation which materialized based on **Model 1.3** significantly differs from that of **Model 1.1** and **Model 1.2** in that **Model 1.3** is designed to meet the performance targets set by Virginia Department of Transportation starting from year 3 of the analysis. Hence, the results show that the available pavement maintenance budget for the first 3 years should be spent on renewal activities which restore lane-miles in very poor, poor and fair to good and excellent condition. Thus, **Model 1.3** allocates the whole budget into Thick Overlay 3 in the first year of the analysis, while available pavement maintenance budget is split between Thick Overlay 3, Rehabilitation 1 and Thick Overlay 2 renewal activities for the following 3 years. Moreover, Rehabilitation 1 consumes the available money in year 3 in an effort to bring number of lane-miles in very poor condition down to an acceptable level. Thus, the budget allocation pattern that materializes in the first three years clearly shows that **Model 1.3** works as expected resulting in a feasible and optimal solution.

Secondly, it should be noted that available budget in first 9 periods was fully expended in **Model 1.3**. One interesting observation is that the level of service resulting from **Model 1.3** is lower than that of **Model 1.2** although the amount of money spent in **Model 1.3** is more than **Model 1.2.** The difference between levels of service pertaining to each model is especially significant for years 5 through 9. This difference results from introducing performance constraints to the model which limits the number of budget allocation patterns that the model could generate. Hence, presence of performance constraints precludes the model from generating more optimal results, which could, otherwise, be obtained in the absence of such constraints.

Finally, **Model 1.3**, as **Models 1.1 and 1.2** do, favors renewal activities under preventive maintenance category over ordinary maintenance. Furthermore, one important observation is that **Model 1.3** first focuses on bring the lane-miles in very poor, poor and fair condition to good and excellent condition in order to meet the pavement performance targets set by Virginia Department of Transportation resulting in less efficient maintenance programming than that of **Model 1.2**, which has the same objective function as **Model 1.3**.

In conclusion, **Model 1.3** is inferior to **Model 1.2** in terms of level of service in that all the lane-miles in the network are in excellent condition after year 6 based on the results obtained from **Model 1.2**, while **Model 1.3** achieves the same result after 10 years of pavement maintenance.

5.6.4. PROBLEM STATEMENT 4

How should VDOT allocate its annual highway maintenance budget for different renewal activities such that number of lane-miles in poor, very poor and fair condition will be minimized?

This problem will be subject to the constraints listed in the previous pages except for **Performance Target** constraints, i.e., Constraint 1 and Constraint 2.

The only difference between Problem Statement 4 and Problem Statements 1 derives from the fact that pavement maintenance budget available in each period is different from that of problem statement 1. **Table 13** shows the pavement maintenance budget profile that pertains to problem statement 4, while **Table 5** from problem statement 1 is placed below next to **Table 13** for easy comparison.

It should be noted that **Model 1.4** is used to address the problem statement 4.

Annual Highway Maintenance Budget ($) available in Period *i*

		Budget Amount
P	1	$6,000,000
	2	$6,480,000
	3	$6,480,000
	4	$6,480,000
	5	$6,480,000
	6	$6,660,000
	7	$6,660,000
	8	$6,960,000
	9	$6,960,000
	10	$6,960,000
	11	$7,200,000
	12	$7,200,000
	13	$7,260,000
	14	$7,380,000
	15	$7,500,000

Table 13: Available Annual Maintenance Budget

Annual Highway Maintenance Budget ($) available in Period *i*

		Budget Amount
P	1	$6,000,000
	2	$8,700,000
	3	$8,700,000
	4	$8,700,000
	5	$8,700,000
	6	$8,700,000
	7	$8,700,000
	8	$9,000,000
	9	$9,000,000
	10	$9,000,000
	11	$9,600,000
	12	$9,600,000
	13	$8,700,000
	14	$8,700,000
	15	$8,700,000

Table 14: Available Annual Maintenance Budget from Model 1.1

5.6.4.1.Results Obtained from Model 1.4

	Budget Allocated to each Renewal Activity														
Renewal Activity	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15
Recon	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Rehab2	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Thick Overlay 3	$4,000,001	$6,155,853	$2,646,282	$3,435,715	$3,501,081	$5,088,587	$4,175,374	$3,350,806	$2,467,514	$1,670,888	$516,049	$298,247	$0	$0	$0
Thin Overlay 4	$0	$0	$0	$631,712	$0	$1,562,008	$2,484,626	$3,609,194	$4,492,486	$5,289,112	$6,683,951	$5,809,834	$5,896,981	$5,985,436	$0
Rehab1	$0	$0	$0	$0	$2,978,919	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Thick Overlay 2	$1,999,999	$324,147	$3,833,718	$2,412,572	$0	$9,405	$0	$0	$0	$0	$0	$223,907	$0	$0	$0
Thin Overlay 3	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Ordinary Maintenance 3	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Ordinary Maintenance 4	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Total Budget Spent	$6,000,000	$6,480,000	$6,480,000	$6,480,000	$6,480,000	$6,660,000	$6,660,000	$6,960,000	$6,960,000	$6,960,000	$7,200,000	$6,331,988	$5,896,981	$5,985,436	$0
Available Budget	$6,000,000	$6,480,000	$6,480,000	$6,480,000	$6,480,000	$6,660,000	$6,660,000	$6,960,000	$6,960,000	$6,960,000	$7,200,000	$7,200,000	$7,260,000	$7,380,000	$7,500,000

	Fraction of Maintenance Budget to Renewal Activities - Budget Profile #1														
	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15
Preventive Maintenance	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.88	0.81	0.81	0.00
Reconstruction	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Rehabilitation	0.00	0.00	0.00	0.00	0.46	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Rehabilitation 1	0.00	0.00	0.00	0.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Rehabilitation 2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Thick Overlays	1.00	1.00	1.00	0.90	0.54	0.77	0.63	0.48	0.35	0.24	0.07	0.08	0.00	0.00	0.00
Thick Overlay 2	0.33	0.05	0.59	0.41	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.43	0.00	0.00	0.00
Thick Overlay 3	0.67	0.95	0.41	0.59	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.57	0.00	0.00	0.00
Thin Overlays	0.00	0.00	0.00	0.10	0.00	0.23	0.37	0.52	0.65	0.76	0.93	0.92	1.00	1.00	0.00
Thin Overlay 3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Thin Overlay 4	0.00	0.00	0.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00
Ordinary Maintenance	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ordinary Maintenance 3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ordinary Maintenance 4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

LEGEND	
Maintenance Type	(grey)
Renewal Type	(orange)
Renewal Activity	(cyan)

Table 15: Budget Allocation that Materializes Based on Model 1.4

	Actual Lane-Miles															
Condition State	**Baseline**	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**	**Year 6**	**Year 7**	**Year 8**	**Year 9**	**Year 10**	**Year 11**	**Year 12**	**Year 13**	**Year 14**	**Year 15**
Target Very Poor Condition	25.0	43.8	65.5	87.4	94.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Target Poor Condition	75.0	86.9	87.7	29.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Target Fair Condition	150.0	76.9	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	5.5	0.0	0.0	0.0	0.0
Target Good Condition	175.0	184.4	186.6	238.7	240.9	342.3	277.4	219.3	159.1	106.2	59.9	0.0	0.0	0.0	0.0	166.7
Target Excellent Condition	75.0	108.1	160.2	144.1	164.2	157.4	222.6	280.7	340.9	393.8	440.1	494.5	500.0	500.0	500.0	333.3

Table 16: Number of Lane-Miles in Each Condition State for Every Funding Period

5.6.4.2.Charts Produced Based on the Results Obtained from Model 1.4

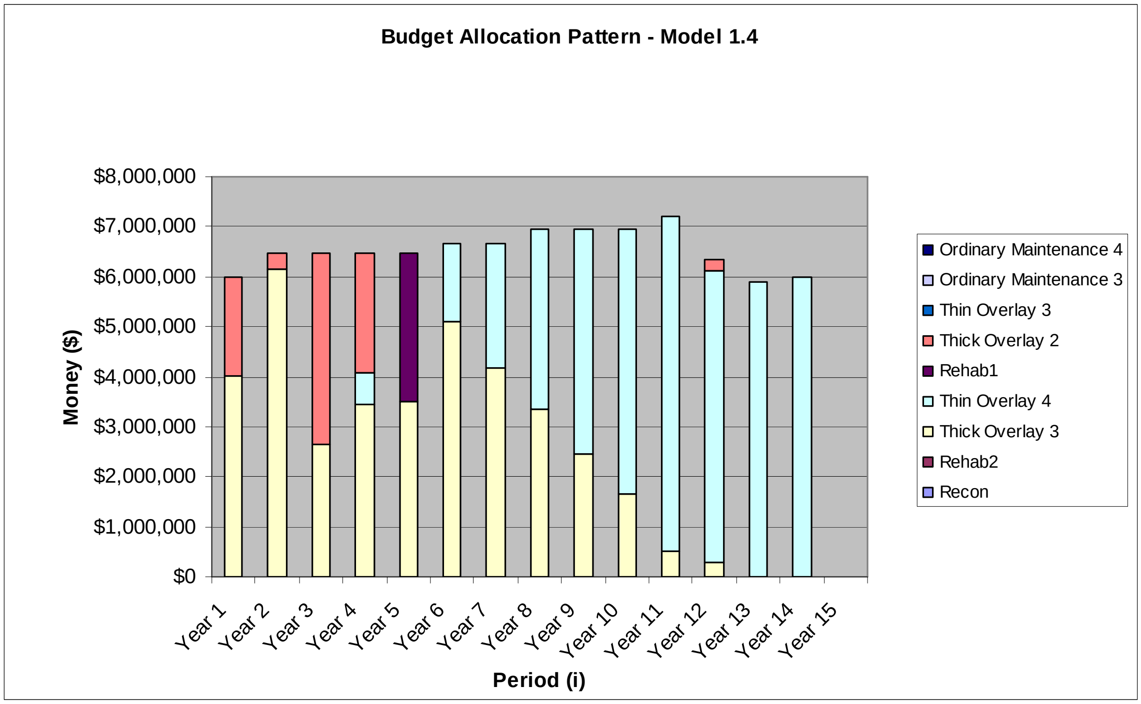


Figure 28: Budget Allocation Pattern Resulted from Model 1.4

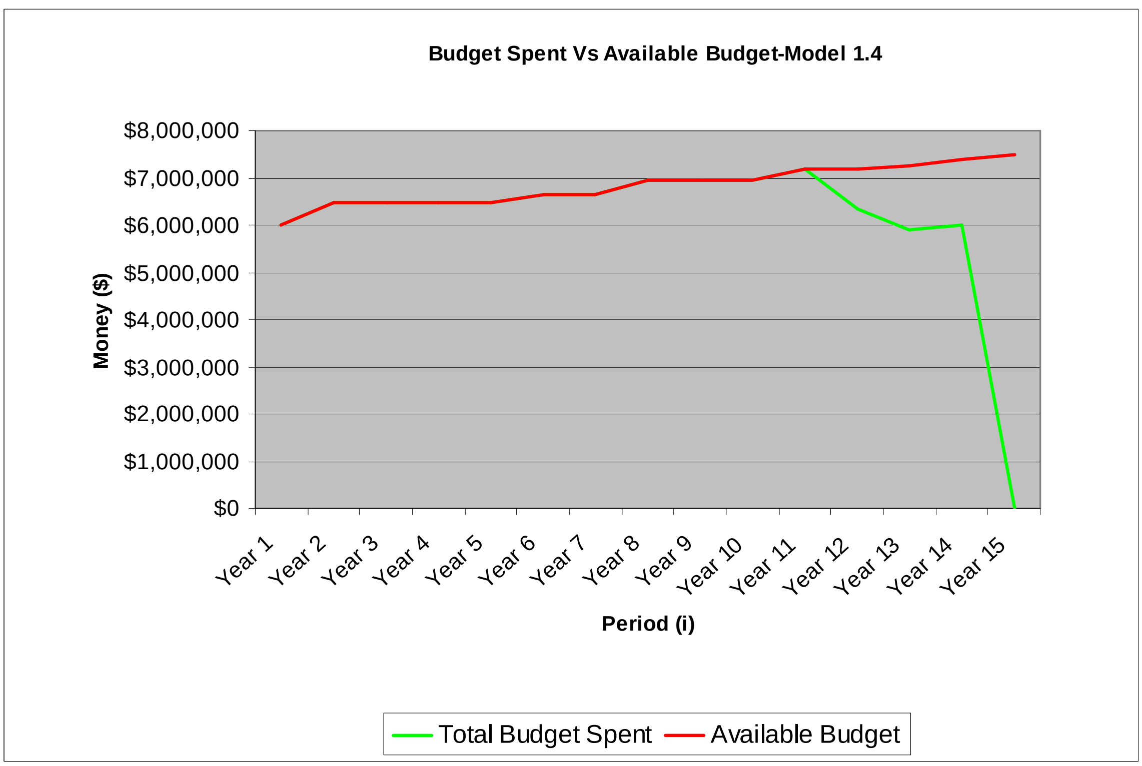


Figure 29: Comparison between Budget Spent and Available Budget

5.6.4.3.Pavement Condition Trend Analysis

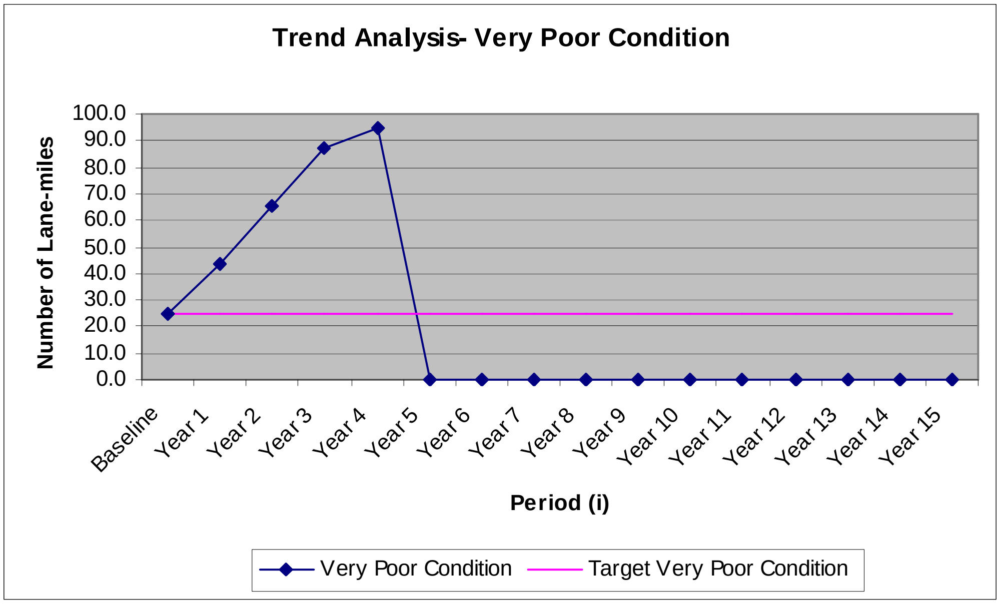


Figure 30: 15 Year Trend Analysis Pertaining to Pavement in Very Poor Condition

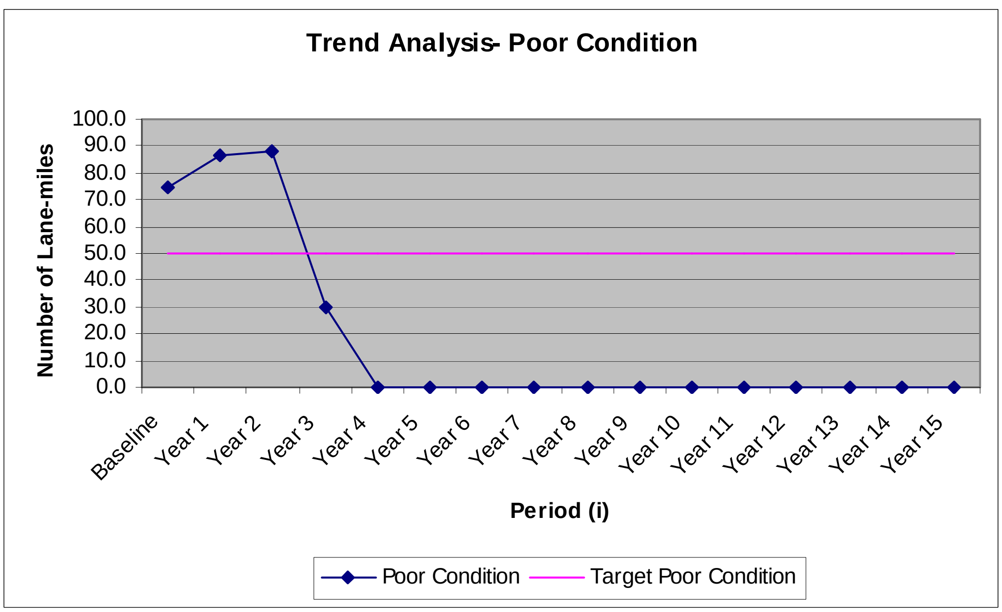


Figure 31: 15 Year Trend Analysis Pertaining to Pavement in Poor Condition

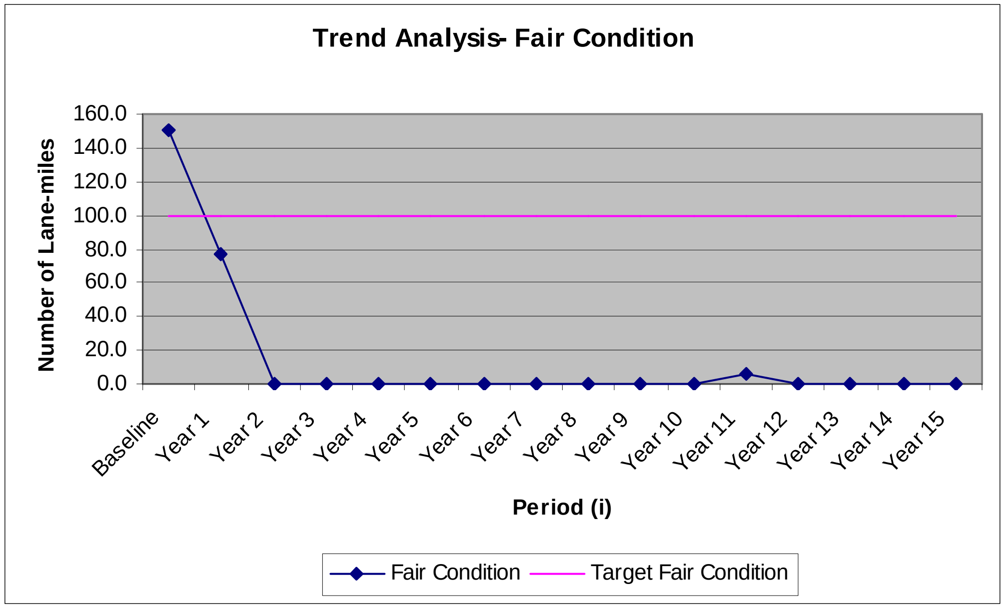


Figure 32: 15 Year Trend Analysis Pertaining to Pavement in Fair Condition

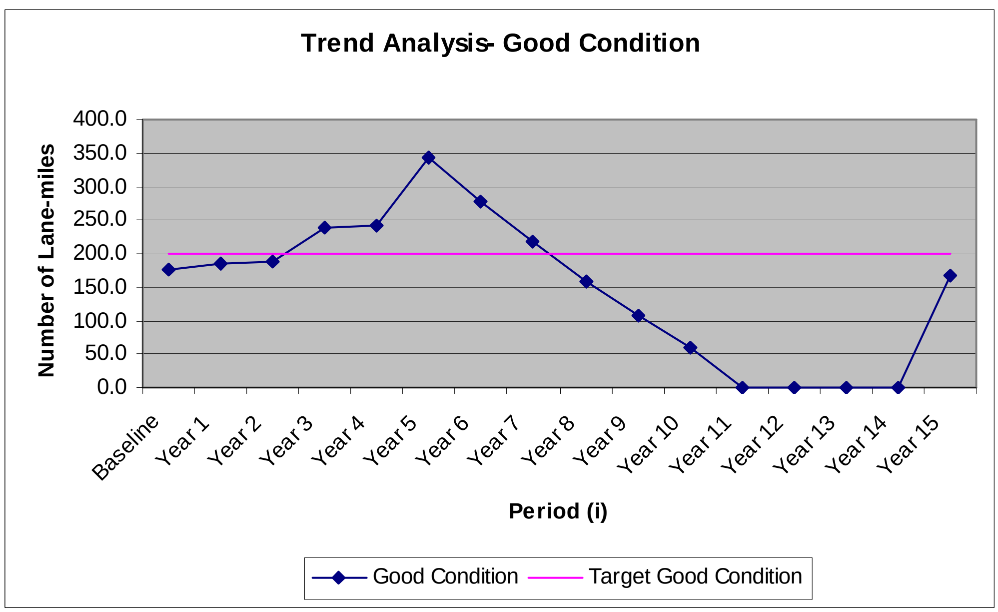


Figure 33: 15 Year Trend Analysis Pertaining to Pavement in Good Condition

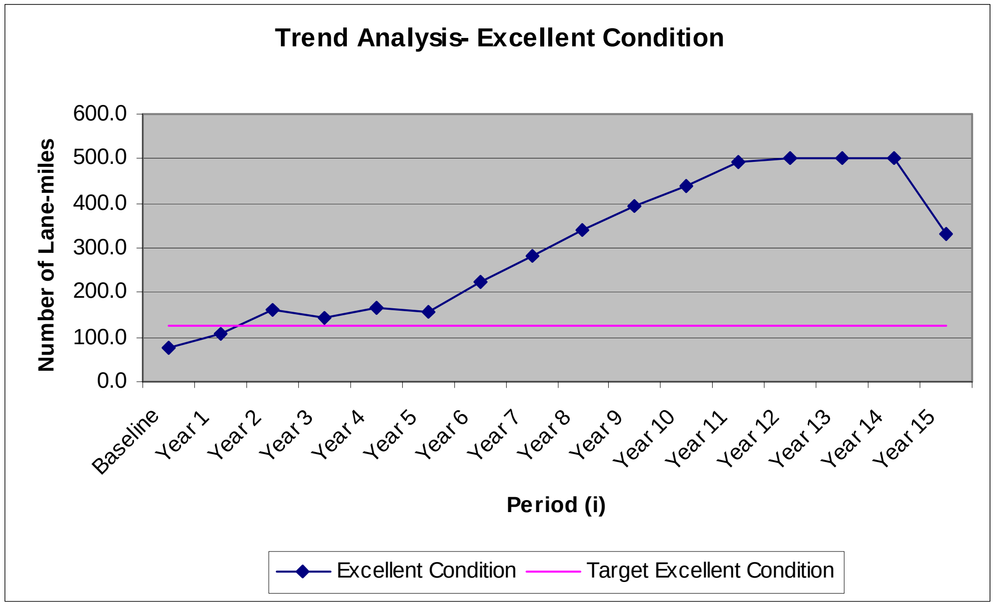


Figure 34: 15 Year Trend Analysis Pertaining to Pavement in Excellent Condition

5.6.4.4.Observations

The goal of the objective function defined in problem 4 is to minimize the lane-miles in very poor, poor and fair condition. The only difference between **Model 1.1** and **Model 1.4** results from the pavement maintenance budget available each period. The main purpose of developing this model is to see the significance of having less amount of money in budget allocation pattern and accordingly its effects on pavement level of service.

Firstly**, Table 14** and **Table 15** show the budget allocation pattern and the level of service pertaining to each year respectively, which resulted from the parameters and the objective function used in **Model 1.4**. Based on the results shown in **Table 14**, Virginia Department of Transportation should completely consume the available annual highway maintenance budget in the first eleven periods in order to minimize the lane-miles in very poor, poor and fair condition. The budget allocation materializing in year 1 focuses on **Thick Overlay 3** and **Thick Overlay 2** renewal activities, which slightly differs from that of **Model 1.1**. Moreover, **Model 1.4** favors **Thick Overlay 3** until year 13, whereas **Model 1.1** stops allocating money into **Thick Overlay 3** after year 2**.** Thus, available maintenance budget in years 6 through 14 is essentially spent on **Thick overlay 3** and **Thin Overlay 4** renewal activities in **Model 1.4**, while the pavement maintenance budget available in the same period in **Model 1.1** is allocated into **Thin Overlay 3** and **Thin Overlay 4**, ignoring **Thick Overlay 3** renewal activity.

Another interesting observation, based on the results, is that although there is available budget during years 13 through 15, the model does not allocate such excess budget to renewal activities. Following two reasons that result in this case:

- Money available between years 13 and 15 is much more than required to retain lane-miles in either good or excellent condition and there is no need to apply treatment to very poor, poor or fair condition since all the lane-miles are in excellent condition between years 13 and 15.

- The objective function defined for Model 1.4 strives only for minimizing the number of lane-miles in very poor, poor and fair condition. Therefore, Model 1.4, as Model 1.1, should not invest any money into renewal activities in any period where the expenditure in a given period does not improve the value of the objective function. In other words, if the application of a renewal activity does not reduce the number of lane-miles in very poor, poor or fair condition for any given year, then Model 1.4 does not invest any money for the given period. Thus, Model 1.4 does not spend any money in year 15, where some of the lane-miles in excellent condition in year 14 deteriorate down to good condition. This behavior results from the fact that the value of the objective function is independent of the number of lane-miles in good and excellent condition. Consequently, even if Model 1.4 had spent some money in order to restore the lane-miles, deteriorating from excellent condition to good condition in year 14, back to excellent condition in year 15, this would not have had affected the value of the objective function, which is essentially to be minimized by Model 1.4.

In conclusion, **Model 1.4**, as **Model 1.1** does, favors renewal activities under preventive maintenance category. Furthermore, **Model 1.4** focuses on restoring the lane-miles in poor and fair condition first and then maintaining the lane-miles restored back to good and excellent condition to retain the optimal value of the objective function.

Moreover, **Model 1.4** and **Model 1.1** differ in terms of both budget allocation strategy and pavement level of service. This difference can be attributed to the more stringent pavement maintenance budget pertaining to **Model 1.4** in that although **Model 1.4** allocates the available budget completely between years 1 and 11, it can not achieve the level of service which **Model 1.1** provides. Finally, the difference between **Model 1.4** and **Model 1.1,** in terms of level of service, results mostly from the number of lane-miles that each model have in excellent condition throughout 15 years of analysis.

5.6.5. PROBLEM STATEMENT 5

How should VDOT allocate its annual highway maintenance budget for different renewal activities such that number of lane-miles in poor, very poor and fair condition will be minimized while excess budget will be used towards maximizing the number of lane-miles in excellent condition?

The only difference between Problem Statement 5 and Problem Statement 2 derives from the fact that pavement maintenance budget available in each period for problem statement 5 is different from that of problem statement 2. **Table 13** shows the pavement maintenance budget profile that pertains to problem statement 5.

It should be noted that Model 1.5 is used to address the problem statement 5.

Annual Highway Maintenance Budget ($) available in Period *i*

		Budget Amount
P	1	$6,000,000
	2	$6,480,000
	3	$6,480,000
	4	$6,480,000
	5	$6,480,000
	6	$6,660,000
	7	$6,660,000
	8	$6,960,000
	9	$6,960,000
	10	$6,960,000
	11	$7,200,000
	12	$7,200,000
	13	$7,260,000
	14	$7,380,000
	15	$7,500,000

Table 17: Available Annual Maintenance Budget

Annual Highway Maintenance Budget ($) available in Period *i*

		Budget Amount
P	1	$6,000,000
	2	$8,700,000
	3	$8,700,000
	4	$8,700,000
	5	$8,700,000
	6	$8,700,000
	7	$8,700,000
	8	$9,000,000
	9	$9,000,000
	10	$9,000,000
	11	$9,600,000
	12	$9,600,000
	13	$8,700,000
	14	$8,700,000
	15	$8,700,000

Table 18: Available Annual Maintenance Budget from Model 1.1

DECISION VARIABLES

X_{ij}: Amount of money spent on treatment **j** within period **i**, $\forall i \in P$ and $\forall j \in R$

N_{ki}: Number of lane-miles in condition **k** at the end of period **i**, $\forall i \in P$ and $\forall k \in S$

OBJECTIVE FUNCTION

Minimize $\sum_{i \in P} \left((N_{1i} + N_{2i} + N_{3i}) - (N_{4i} + 5 * N_{5i}) \right)$

This problem will be subject to the constraints listed in the previous pages except for **Performance Target** constraints, i.e. Constraint 1 and Constraint 2.

5.6.5.1.Results Obtained from Model 1.5

	Budget Allocated to each Renewal Activity														
Renewal Activity	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**	**Year 6**	**Year 7**	**Year 8**	**Year 9**	**Year 10**	**Year 11**	**Year 12**	**Year 13**	**Year 14**	**Year 15**
Recon	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$727,461	$0	$0
Rehab2	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Thick Overlay 3	$0	$6,480,000	$1,767,603	$0	$0	$0	$1,618,723	$187,834	$0	$0	$0	$0	$0	$0	$0
Thin Overlay 4	$3,999,996	$0	$4,673,500	$4,027,481	$2,573,853	$6,660,000	$5,041,277	$5,382,004	$5,552,186	$5,618,966	$5,782,324	$5,918,926	$5,873,371	$5,985,436	$6,075,218
Rehab1	$0	$0	$0	$0	$3,906,147	$0	$0	$0	$545,274	$1,341,034	$1,417,676	$1,281,074	$0	$0	$0
Thick Overlay 2	$2,000,004	$0	$38,897	$2,452,519	$0	$0	$0	$1,390,162	$862,540	$0	$0	$0	$0	$0	$0
Thin Overlay 3	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Ordinary Maintenance 3	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Ordinary Maintenance 4	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Total Budget Spent	$6,000,000	$6,480,000	$6,480,000	$6,480,000	$6,480,000	$6,660,000	$6,660,000	$6,960,000	$6,960,000	$6,960,000	$7,200,000	$7,200,000	$6,600,832	$5,985,436	$6,075,218
Available Budget	$6,000,000	$6,480,000	$6,480,000	$6,480,000	$6,480,000	$6,660,000	$6,660,000	$6,960,000	$6,960,000	$6,960,000	$7,200,000	$7,200,000	$7,260,000	$7,380,000	$7,500,000

	Fraction of Maintenance Budget to Renewal Activities - Budget Profile #1														
	Year 1	**Year 2**	**Year 3**	**Year 4**	**Year 5**	**Year 6**	**Year 7**	**Year 8**	**Year 9**	**Year 10**	**Year 11**	**Year 12**	**Year 13**	**Year 14**	**Year 15**
Preventive Maintenance	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.91	0.81	0.81
Reconstruction	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.00	0.00
Rehabilitation	0.00	0.00	0.00	0.00	0.60	0.00	0.00	0.00	0.08	0.19	0.20	0.18	0.00	0.00	0.00
Rehabilitation 1	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	0.00	0.00	0.00
Rehabilitation 2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Thick Overlays	0.33	1.00	0.28	0.38	0.00	0.00	0.24	0.23	0.12	0.00	0.00	0.00	0.00	0.00	0.00
Thick Overlay 2	1.00	0.00	0.02	1.00	0.00	0.00	0.00	0.88	1.00	0.00	0.00	0.00	0.00	0.00	0.00
Thick Overlay 3	0.00	1.00	0.98	0.00	0.00	0.00	1.00	0.12	0.00	0.00	0.00	1.00	0.00	0.00	0.00
Thin Overlays	0.67	0.00	0.72	0.62	0.40	1.00	0.76	0.77	0.80	0.81	0.80	0.82	0.89	1.00	1.00
Thin Overlay 3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Thin Overlay 4	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Ordinary Maintenance	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ordinary Maintenance 3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ordinary Maintenance 4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

LEGEND	
Maintenance Type	(grey)
Renewal Type	(orange)
Renewal Activity	(cyan)

Table 19: Budget Allocation that Materializes Based on Model 1.5

	Actual Lane-Miles															
Condition State	**Baseline**	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**	**Year 6**	**Year 7**	**Year 8**	**Year 9**	**Year 10**	**Year 11**	**Year 12**	**Year 13**	**Year 14**	**Year 15**
Target Very Poor Condition	25.0	43.8	65.5	93.0	114.2	0.0	7.6	13.4	20.3	20.2	14.1	7.7	2.0	0.0	0.0	0.0
Target Poor Condition	75.0	86.9	110.2	84.6	40.8	30.6	22.9	27.7	9.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Target Fair Condition	150.0	135.0	7.1	0.0	0.0	0.0	31.5	3.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Target Good Condition	175.0	49.2	101.1	0.0	0.0	157.4	21.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Target Excellent Condition	75.0	185.2	216.2	322.4	345.1	312.0	416.9	455.2	469.8	479.8	485.9	492.3	498.0	500.0	500.0	500.0

Table 20: Number of Lane-Miles in Each Condition State for Every Funding Period

5.6.5.2. Charts Produced Based on the Results Obtained from Model 1.5

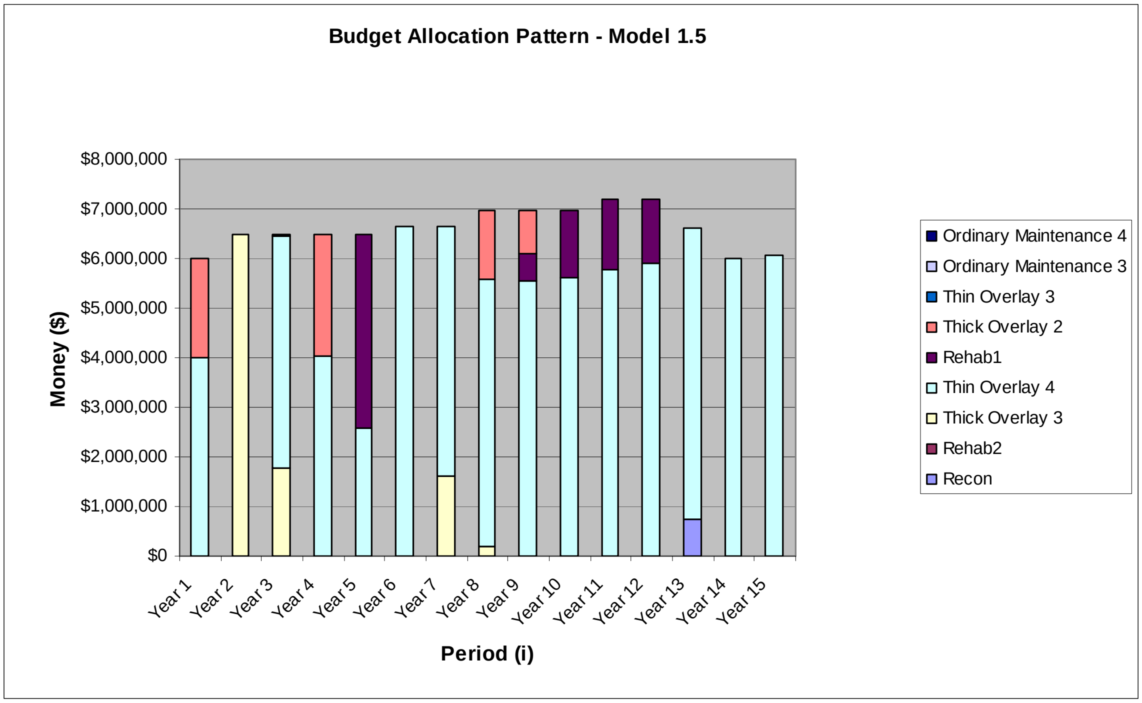


Figure 35: Budget Allocation Pattern Resulted from Model 1.5

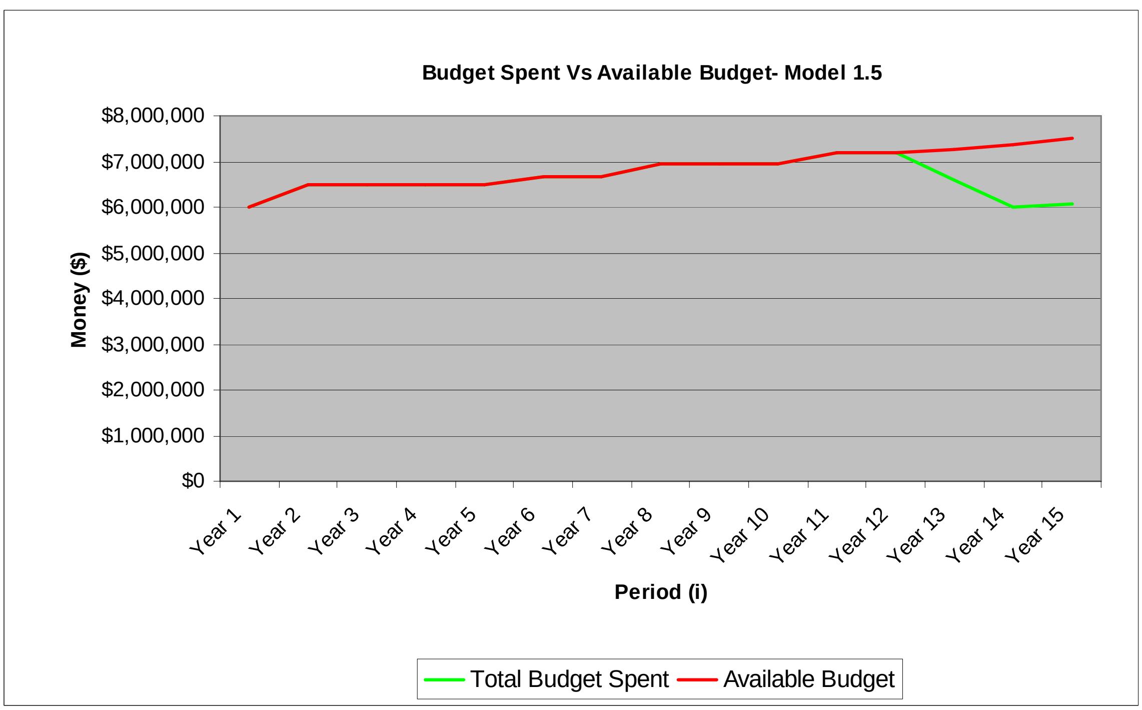


Figure 36: Comparison between Budget Spent and Available Budget

5.6.5.3.Pavement Condition Trend Analysis

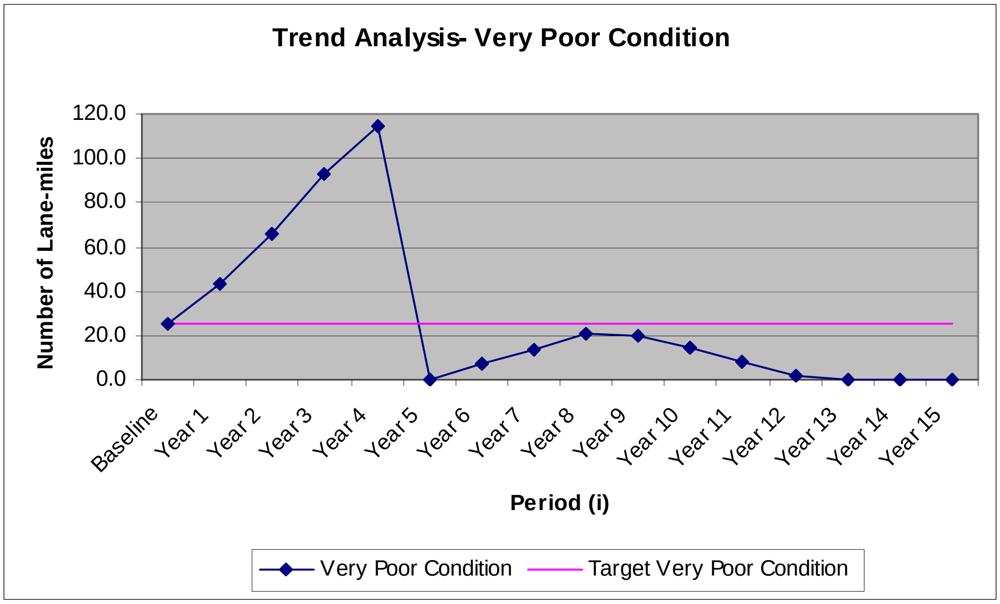


Figure 37: 15 Year Trend Analysis Pertaining to Pavement in Very Poor Condition

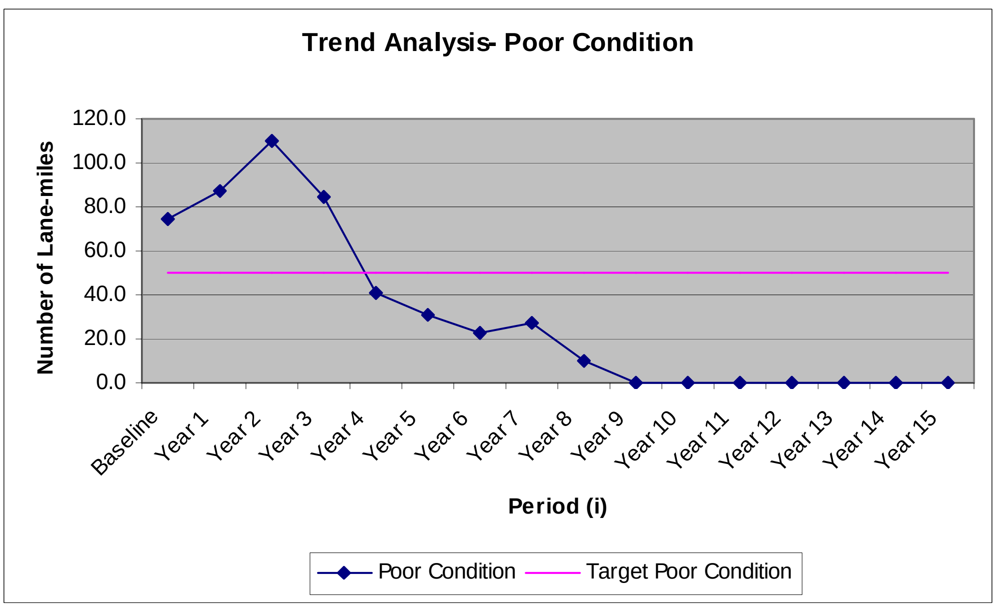


Figure 38: 15 Year Trend Analysis Pertaining to Pavement in Poor Condition

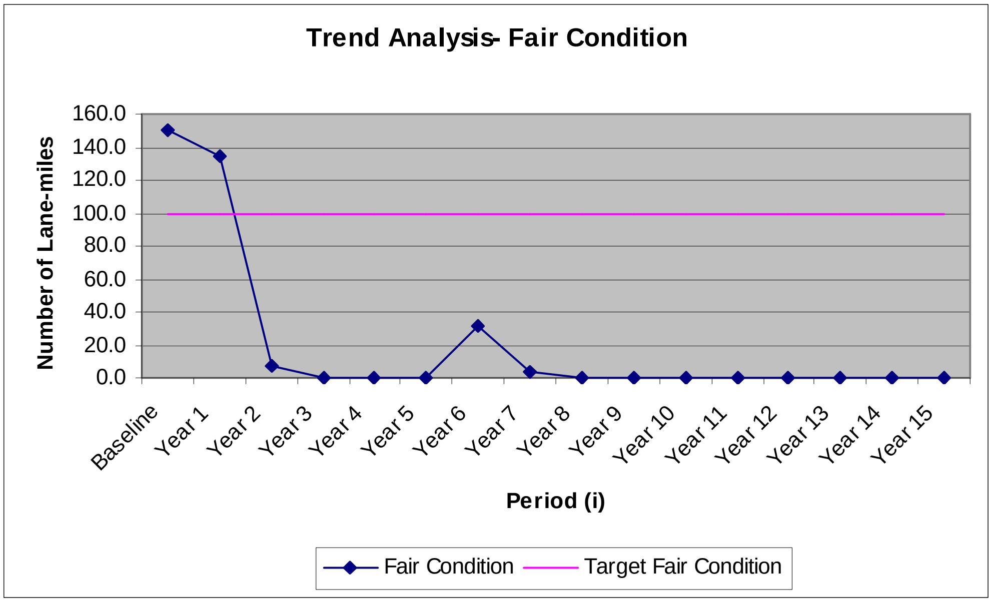


Figure 39: 15 Year Trend Analysis Pertaining to Pavement in Fair Condition

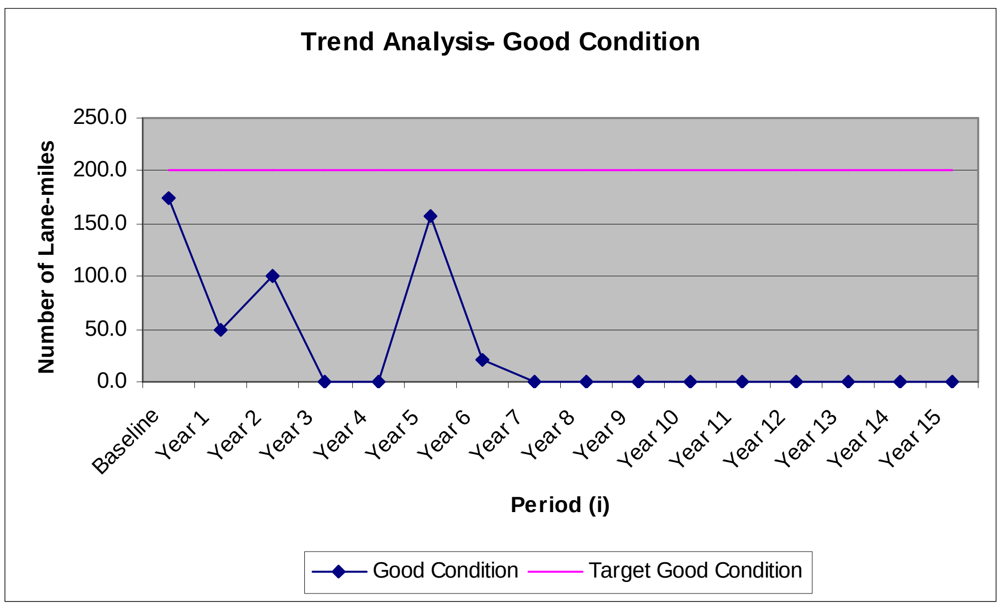


Figure 40: 15 Year Trend Analysis Pertaining to Pavement in Good Condition

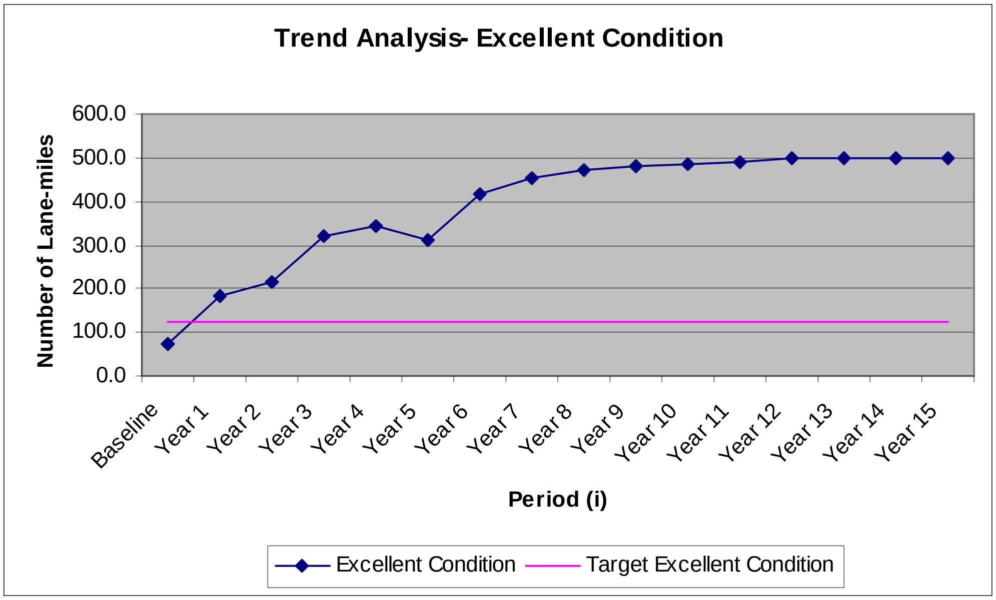


Figure 41: 15 Year Trend Analysis Pertaining to Pavement in Excellent Condition

5.6.5.4.Observations

The goal of the objective function defined in problem 5 is to minimize the lane-miles in very poor, poor and fair condition while excess budget will be used towards maximizing the number of lane-miles in excellent condition. As noted earlier, the only difference between Problem Statement 5 and Problem Statement 2 derives from the fact that pavement maintenance budget available in each period for problem statement 5 is different from that of problem statement 2.

Firstly**, Table 16** and **Table 17** show the budget allocation pattern and the level of service pertaining to each year respectively, which resulted from the parameters and the objective function used in **Model 1.5**. Based on the results shown in **Table 16**, Virginia Department of Transportation should completely consume the available annual highway maintenance budget in the first 12 periods in order to minimize the lane-miles in very poor, poor and fair condition while maximizing the number of lane-miles in excellent condition.

It should also be noted that **Model 1.5** spends the pavement maintenance budget available in first 2 periods in a different manner than **Model 1.2**. Furthermore, both **Model 1.2** and **Model 1.5** favors the application of **Thin Overlay 4** renewal activity in long term, while expenditure pattern pertaining to each model differs in magnitude until year 14. This observation shows that change in the magnitude of pavement maintenance budget available for each model could result in significant differences in terms of both budget allocation pattern and pavement level of service.

Secondly, all the lane-miles in the network are in excellent condition starting from year 14, therefore, **Thin Overlay 4** is the only renewal activity into which pavement maintenance budget is allocated in that **Thin Overlay 4** ensures that lane-miles deteriorating from excellent condition are restored back to excellent. This observation justifies the use of arbitrary weights included in the objective function pertaining to **Model 1.5,** as it was for **Model 1.2**.

In conclusion, **Model 1.5** yields poorer level of service than **Model 1.2** in that all the lane-miles in the network are in excellent condition after year 6 based on the results obtained from **Model 1.2**, while **Model 1.5** achieves the same result at year 14. This result does not come as a surprise in that the difference in the available pavement maintenance budget pertaining to each model affects the level of service achieved. Finally, all the parameters, constraints and variables defined for each model are the same except for the available pavement maintenance budget. Hence, the comparison made between **Model 1.5** and **Model 1.2** reveals the importance of the available pavement maintenance budget, as well as the need for an optimized budget allocation process.

5.7. BASIC MODEL 2

5.7.1. PROBLEM STATEMENT 6

What is the minimum budget that VDOT needs to spend in order to meet the performance targets pertaining to very poor, poor and fair condition for 15 years?

There are 3 main differences between Problem 6 and problems introduced so far.

1. Model developed for Problem 6 will not be subject to the Budget Constraint presented earlier since the goal of problem statement 6 is to determine the minimum budget that VDOT is to spend in order to meet the performance targets pertaining to very poor, poor and fair condition.

2. Model developed for Problem 6 will be subject to one of the performance target constraints, namely **Constraint 1** starting from year **1**. Constraint 1 pertains to the performance requirements for Very Poor, Poor and Fair condition.

3. Objective Function defined for problem statement 6 is different from that of problems introduced thus far.

It should be noted that Model 2.1 is used to address the problem statement 6.

DECISION VARIABLES

X_{ij}: Amount of money spent on treatment **j** within period **i**, $\forall i \in P$ and $\forall j \in R$

N_{ki}: Number of lane-miles in condition **k** at the end of period **i**, $\forall i \in P$ and $\forall k \in S$

OBJECTIVE FUNCTION

Minimize $\sum_{i \in P} \sum_{j \in R} X_{ij}$

Subject to

Constraint 1

$$G_{ki} - N_{ki} \geq 0, \forall i \in P, \forall k \in S_1$$

5.7.1.1.Results Obtained from Model 2.1

	Budget Allocated to each Renewal Activity														
Renewal Activity	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**	**Year 6**	**Year 7**	**Year 8**	**Year 9**	**Year 10**	**Year 11**	**Year 12**	**Year 13**	**Year 14**	**Year 15**
Recon	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Rehab2	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Thick Overlay 3	$9,153,706	$3,991,694	$4,102,796	$4,188,602	$4,262,925	$4,697,540	$4,696,441	$4,732,990	$4,787,930	$1,821,932	$0	$0	$0	$0	$0
Thin Overlay 4	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$10,136,171	$4,628,979	$4,698,414	$4,782,341	$0
Rehab1	$3,527,528	$0	$0	$0	$773,618	$0	$0	$0	$0	$0	$0	$0	$0	$86,798	$2,940,152
Thick Overlay 2	$10,817,146	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Thin Overlay 3	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Ordinary Maintenance 3	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Ordinary Maintenance 4	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Total Budget Spent	$23,498,380	$3,991,694	$4,102,796	$4,188,602	$5,036,543	$4,697,540	$4,696,441	$4,732,990	$4,787,930	$1,821,932	$10,136,171	$4,628,979	$4,698,414	$4,869,139	$2,940,152
Available Budget	$6,000,000	$8,700,000	$8,700,000	$8,700,000	$8,700,000	$8,700,000	$8,700,000	$9,000,000	$9,000,000	$9,000,000	$9,600,000	$9,600,000	$8,700,000	$8,700,000	$8,700,000

Table 21: Budget Allocation that Materializes Based on Model 2.1

	Actual Lane-Miles															
Condition State	**Baseline**	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**	**Year 6**	**Year 7**	**Year 8**	**Year 9**	**Year 10**	**Year 11**	**Year 12**	**Year 13**	**Year 14**	**Year 15**
Very Poor Condition	25.0	25.0	25.0	25.0	25.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.3	13.1	25.0	25.0
Poor Condition	75.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13.0	39.3	49.2	50.0	46.3
Fair Condition	150.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	39.1	88.6	59.1	39.4	26.3	17.5
Good Condition	175.0	290.0	293.7	295.4	296.2	321.5	316.7	314.5	313.4	312.9	312.7	0.0	0.0	0.0	0.0	145.4
Excellent Condition	75.0	185.0	181.3	179.6	178.8	178.5	183.3	185.5	186.6	187.1	148.2	398.4	398.4	398.4	398.7	265.8

Table 22: Number of Lane-Miles in Each Condition State for Every Funding Period

5.7.1.2.Charts Produced Based on the Results Obtained from Model 2.1

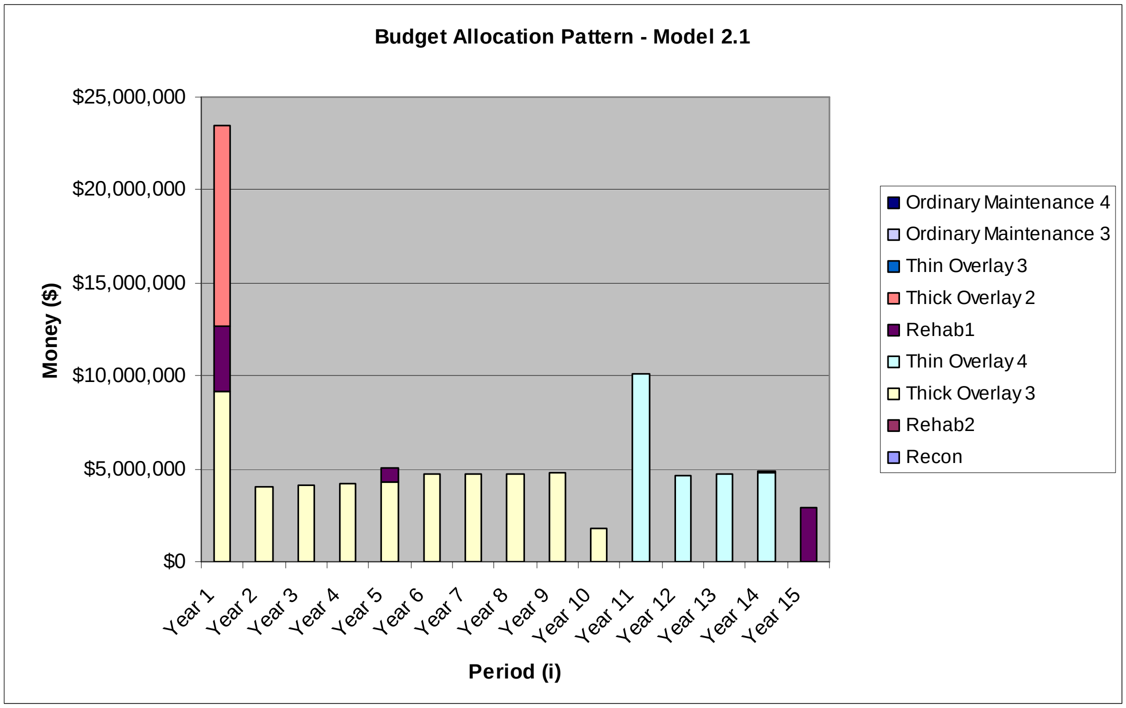


Figure 42: Budget Allocation Pattern Resulted from Model 2.1

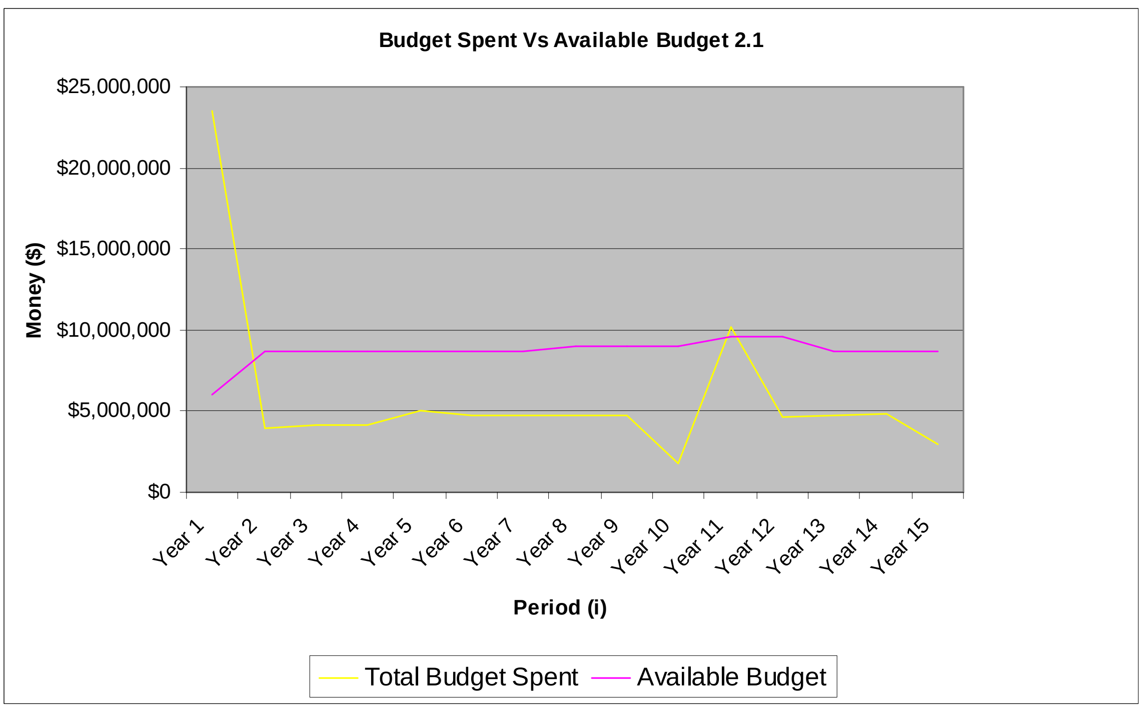


Figure 43: Comparison between Budget Spent and Available Budget in each Period

5.7.1.3.Pavement Condition Trend Analysis

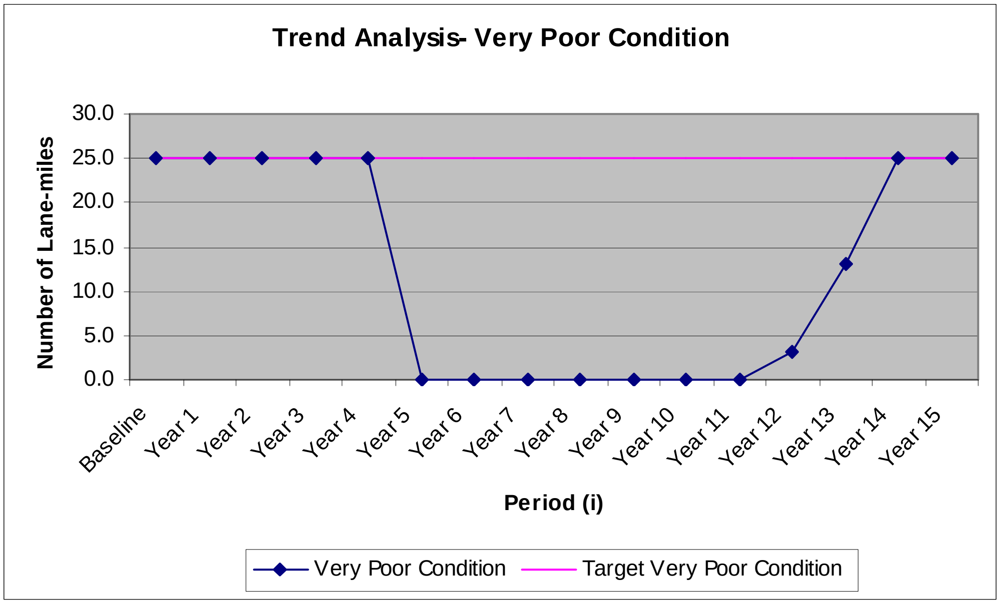


Figure 44: 15 Year Trend Analysis Pertaining to Pavement in Very Poor Condition

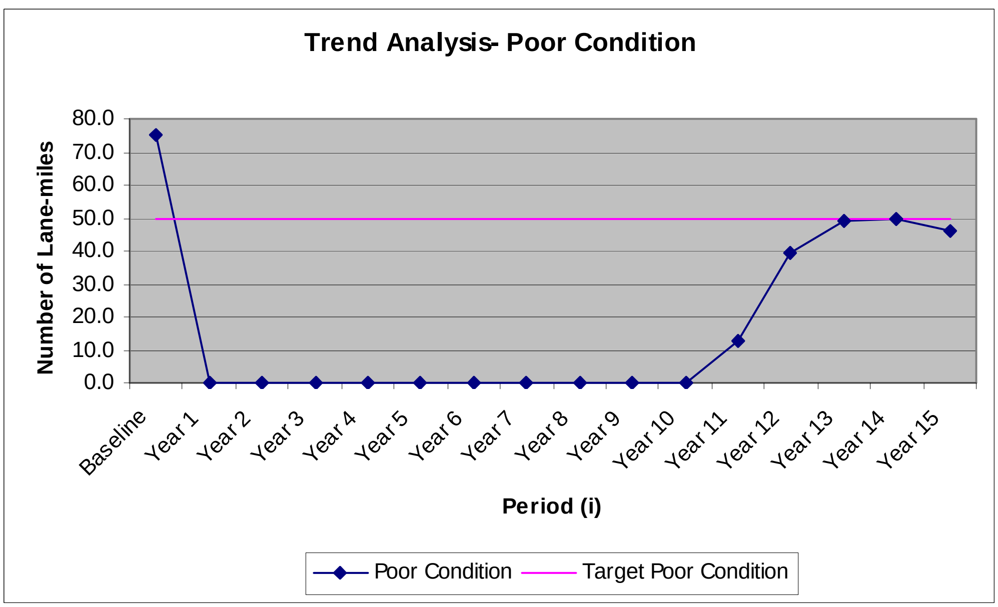


Figure 45: 15 Year Trend Analysis Pertaining to Pavement in Poor Condition

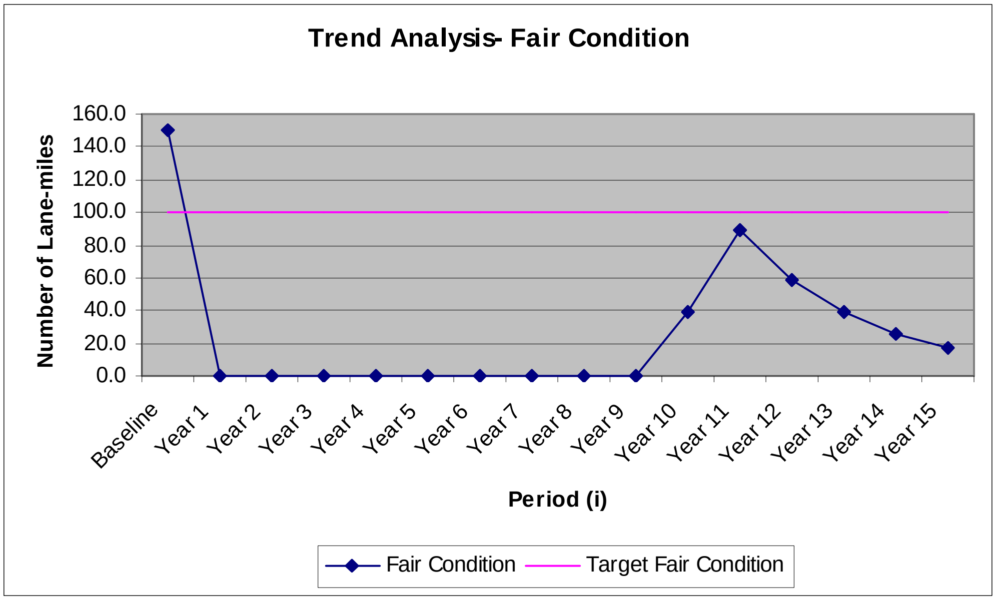


Figure 46: 15 Year Trend Analysis Pertaining to Pavement in Fair Condition

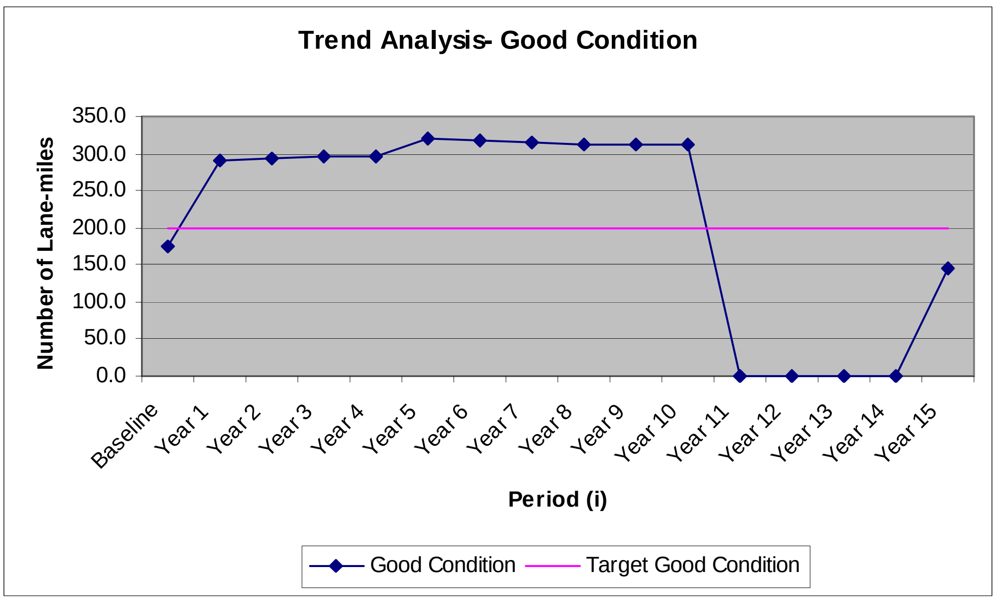


Figure 47: 15 Year Trend Analysis Pertaining to Pavement in Good Condition

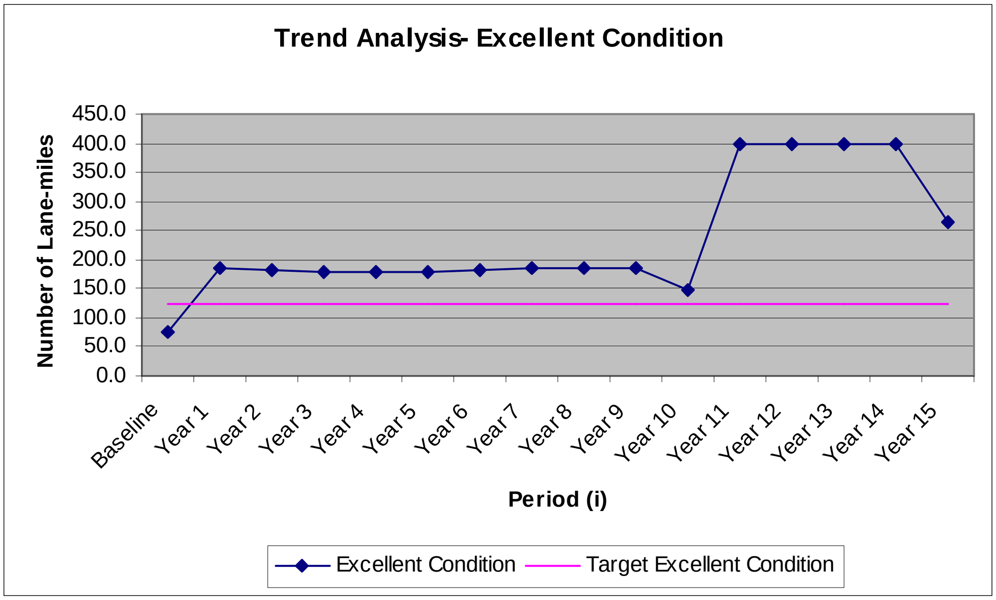


Figure 48: 15 Year Trend Analysis Pertaining to Pavement in Excellent Condition

5.7.1.4.Observations

The goal of the objective function defined in problem 6 is to minimize the total budget spent over the 15 year analysis period. Firstly**, Table 18** and **Table 19** show the budget allocation pattern and the level of service pertaining to each year respectively, which resulted from the parameters, pavement performance constraints and the objective function used in **Model 2.1**.

The results shown in **Table 18** indicates that budget allocation which materialized based on **Model 2.1** significantly differs from that of the models presented earlier due to the following reasons:

1. **Model 2.1** is designed to meet the performance targets for very poor, poor and fair condition, which are set by Virginia Department of Transportation, starting from year 1 of the analysis

2. There are not any budget constraints in **Model 2.1**

Hence, the results show that money to be spent in year 1 is extremely more than following 14 years. This budget allocation pattern results from the fact that **Model 2.1** restores lane-miles in fair and poor condition immediately in first year of analysis. Thus, trend analysis charts, figures 44 through 48, clearly show that **Model 2.1** minimizes the lane-miles in fair and poor condition in order to meet the performance targets introduced as constraints in **Problem 6** given that there is no limit in the amount of money available at any given period. Moreover, **Thick Overlay 2 and Thick Overlay 3** renewal activities receive more than 80% of budget spent, while only 20% is allocated to **Rehabilitation 1** in the first year of analysis resulting in significant improvements in pavement condition.

Another interesting observation is that starting from year 2; money spent on renewal activities decreases rapidly and focuses mainly on **Thick Overlay 3,** which restores pavement in fair condition to excellent condition, between years 2 and 10. This budget allocation pattern stems from the fact that **Model 2.1** strives for restoring the lane-miles deteriorating from good condition to fair condition.

Finally, it is important to note that **Model 2.1** and **Model 1.4** use almost the same amount of money over 15 years. Thus, comparison between level of service obtained based on these two models are essential. Hence, **Table 15** and **Table 19** indicate that **Model 1.4** yields better level of service in long term, while **Model 2.1** is superior to **Model 1.4** in the first 5 years of the analysis. This result stems from the fact that **Model 2.1** invests almost 4 times more money in maintenance activities than **Model 1.4** in the first 5 years of the analysis**.**

In conclusion, **Model 2.1** is designed to determine the minimum budget required in order to meet the performance targets pertaining to very poor, poor and fair condition over 15 years of analysis. Highway agencies aiming to restore lane-miles in very poor, poor and fair condition in the first a few years of the analysis can use this model not only to determine the minimum budget required to meet the performance targets, but also to realize visible and rapid improvements in terms of pavement performance throughout the network. However, the drawbacks of this model are as follows:

- Substantial costs in the first a few years of pavement maintenance programming
- Lower pavement level of service starting from 6^{th} year of analysis

5.7.2. PROBLEM STATEMENT 7

What is the minimum budget that VDOT needs to spend in order to meet the performance targets pertaining to very poor, poor and fair condition starting from year 2?

There are 2 main differences between Problem 7 and Problem 6.

1. Model developed for Problem 7 will be subject to the Budget Constraint presented earlier in order to limit the maximum amount of money which can be available at a given year – that is $ 9,600,000 in this problem.

2. Model developed for Problem 7 will be subject to one of the performance target constraints, namely **Constraint 1** starting from year **2**, as opposed to Problem 6 where Constraint 1 pertains to the performance requirements for Very Poor, Poor and Fair condition applies starting from year **1**

The reason for presenting Problem 7 stems from the fact that highway agencies usually do not have substantial amount of money for maintenance at one year. The budget allocation pattern demonstrated in Model 2.1 indicates that Virginia Department of Transportation should spend almost $ 24,000,000 in one year in order to meet the performance targets and to minimize the cost for the 15 year analysis period. However, this budget allocation pattern is not very likely to materialize in practice. Hence, maximum amount of money, which can be allocated in one year, is capped through introducing a budget constraint in Problem 7. Thus, deviation between budgets pertaining to each period decreases and **problem statement 7** yields more practical results than that of **problem statement 6**.

It should be noted that Model 2.2 is used to address the problem statement 7.

DECISION VARIABLES

X_{ij}: Amount of money spent on treatment **j** within period **i**, $\forall i \in P$ and $\forall j \in R$

N_{ki}: Number of lane-miles in condition **k** at the end of period **i**, $\forall i \in P$ and $\forall k \in S$

OBJECTIVE FUNCTION

Minimize $\sum_{i \in P} \sum_{j \in R} X_{ij}$

Subject to

Constraint 1

$G_{ki} - N_{ki} \geq 0, \forall k \in S_1$, i=2, 3… 15

Constraint 3

$$\sum_{j=1}^{9} X_{ij} \leq B_i, \forall i \in P$$

Constraint 3 represents the annual highway maintenance **budget constraint**. Money spent on 9 different renewal activities (treatments) within the period *i* must be less than or equal to the budget available for period *i*, which is $ 9,600,000 each year.

5.7.2.1.Results Obtained from Model 2.2

	Budget Allocated to each Renewal Activity														
Renewal Activity	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15
Recon	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Rehab2	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Thick Overlay 3	$6,977,606	$0	$6,406,423	$3,785,364	$3,993,183	$4,937,241	$4,809,979	$4,786,770	$4,813,403	$1,350,736	$0	$0	$0	$0	$0
Thin Overlay 4	$0	$0	$0	$0	$0	$0	$0	$0	$0	$995,636	$9,600,000	$4,625,113	$4,694,489	$4,808,876	$0
Rehab1	$0	$7,423,060	$2,422,765	$2,459,107	$1,065,505	$0	$0	$0	$0	$0	$0	$0	$0	$283,726	$2,940,152
Thick Overlay 2	$2,622,394	$2,176,940	$770,812	$0	$3,057,718	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Thin Overlay 3	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Ordinary Maintenance 3	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Ordinary Maintenance 4	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Total Budget Spent	$9,600,000	$9,600,000	$9,600,000	$6,244,471	$8,116,407	$4,937,241	$4,809,979	$4,786,770	$4,813,403	$2,346,372	$9,600,000	$4,625,113	$4,694,489	$5,092,602	$2,940,152
Available Budget	$9,600,000	$9,600,000	$9,600,000	$9,600,000	$9,600,000	$9,600,000	$9,600,000	$9,600,000	$9,600,000	$9,600,000	$9,600,000	$9,600,000	$9,600,000	$9,600,000	$9,600,000

Table 23: Budget Allocation that Materializes Based on Model 2.2

	Actual Lane-Miles															
Condition State	Baseline	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15
Very Poor Condition	25.0	43.8	25.0	25.0	25.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.8	13.8	25.0	25.0
Poor Condition	75.0	80.5	50.0	50.0	37.7	0.0	0.0	0.0	0.0	0.0	0.0	15.1	40.3	49.5	50.0	46.1
Fair Condition	150.0	32.1	59.5	0.7	0.0	0.0	0.0	0.0	0.0	0.0	45.3	86.9	57.9	38.6	25.7	17.2
Good Condition	175.0	190.8	263.5	264.6	277.4	338.0	324.4	318.0	315.1	313.7	283.2	0.0	0.0	0.0	0.0	145.6
Excellent Condition	75.0	152.9	101.9	159.7	159.8	162.0	175.6	182.0	184.9	186.3	171.5	398.0	398.0	398.0	399.3	266.2

Table 24: Number of Lane-Miles in Each Condition State for Every Funding Period

5.7.2.2.Charts Produced Based on the Results Obtained from Model 2.2

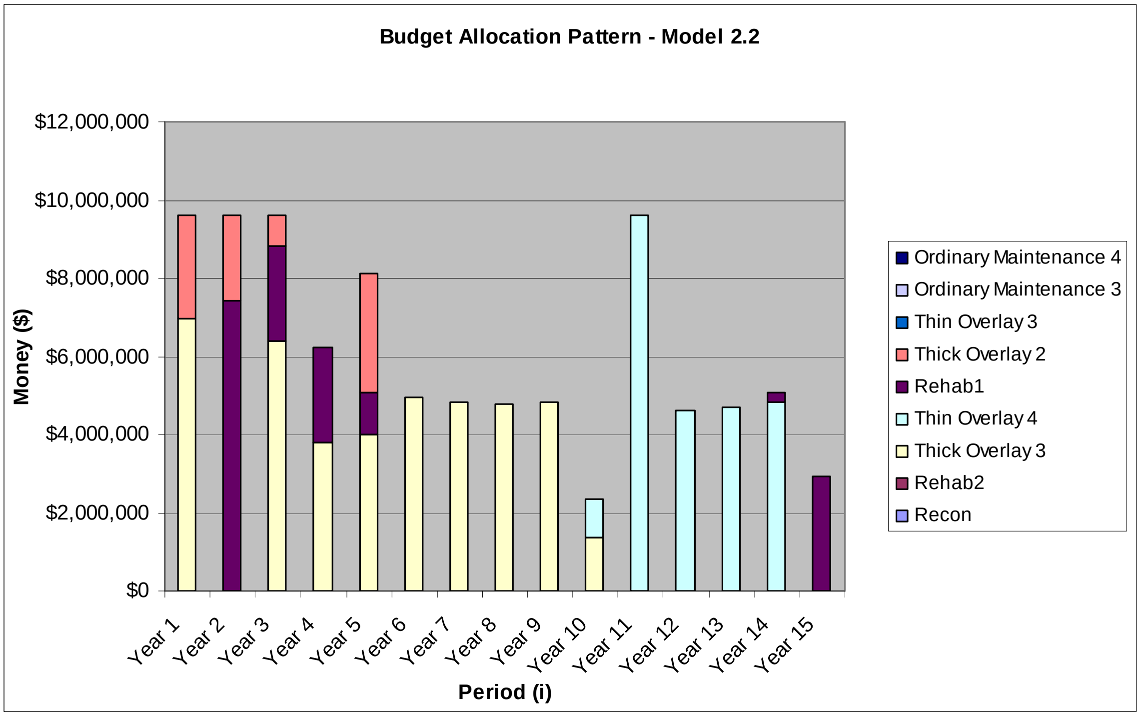


Figure 49: Budget Allocation Pattern Resulted from Model 2.2

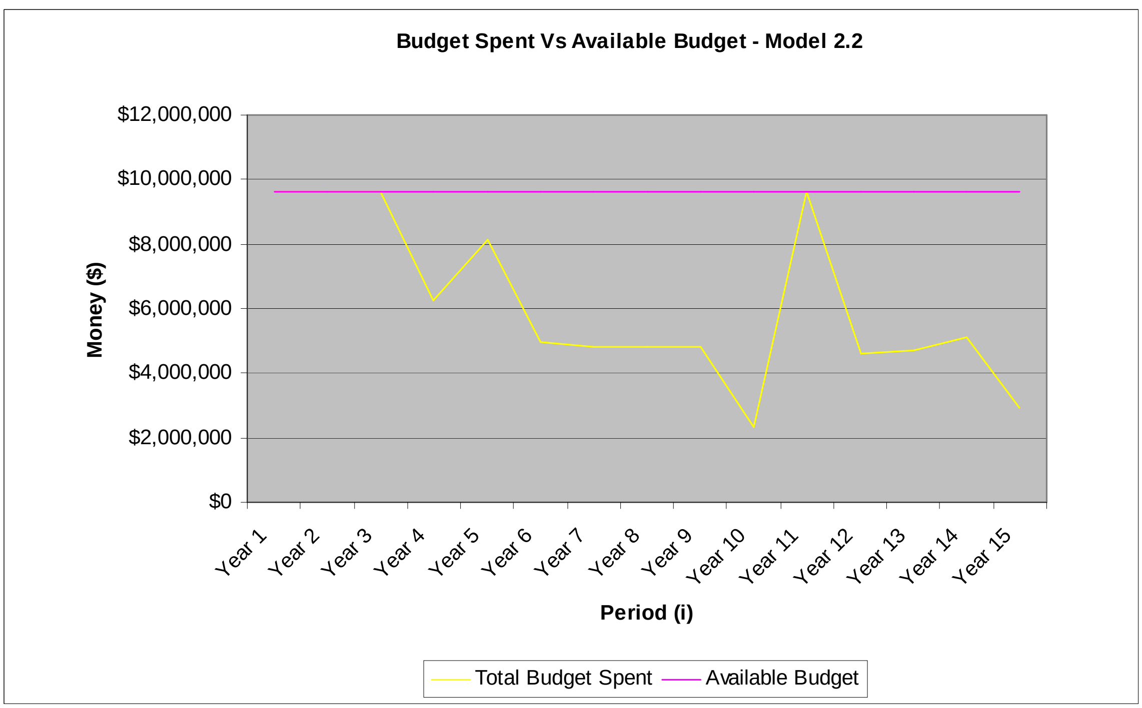


Figure 50: Comparison between Budget Spent and Available Budget in each Period

5.7.2.3.Pavement Condition Trend Analysis

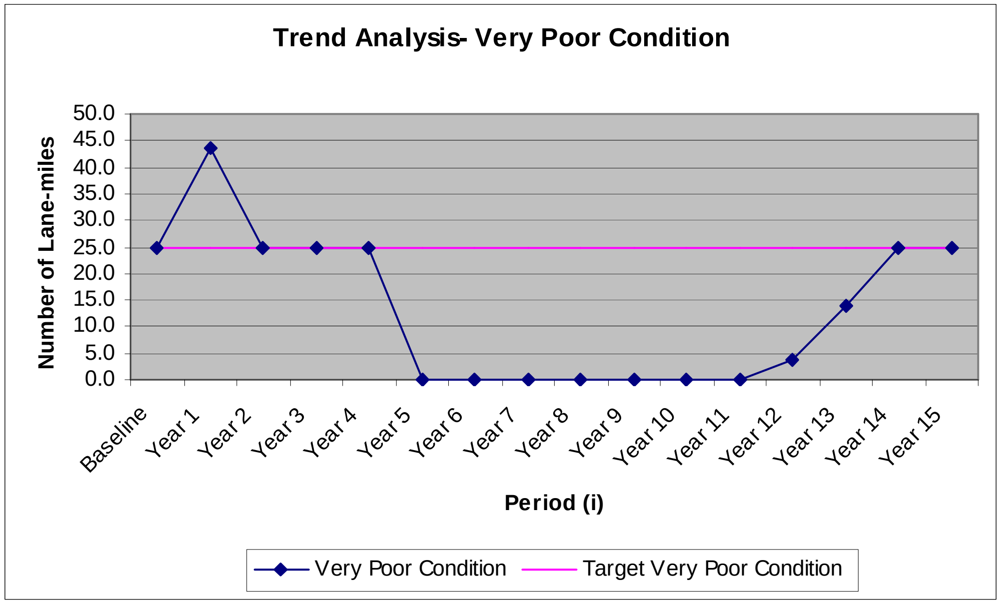


Figure 51: 15 Year Trend Analysis Pertaining to Pavement in Very Poor Condition

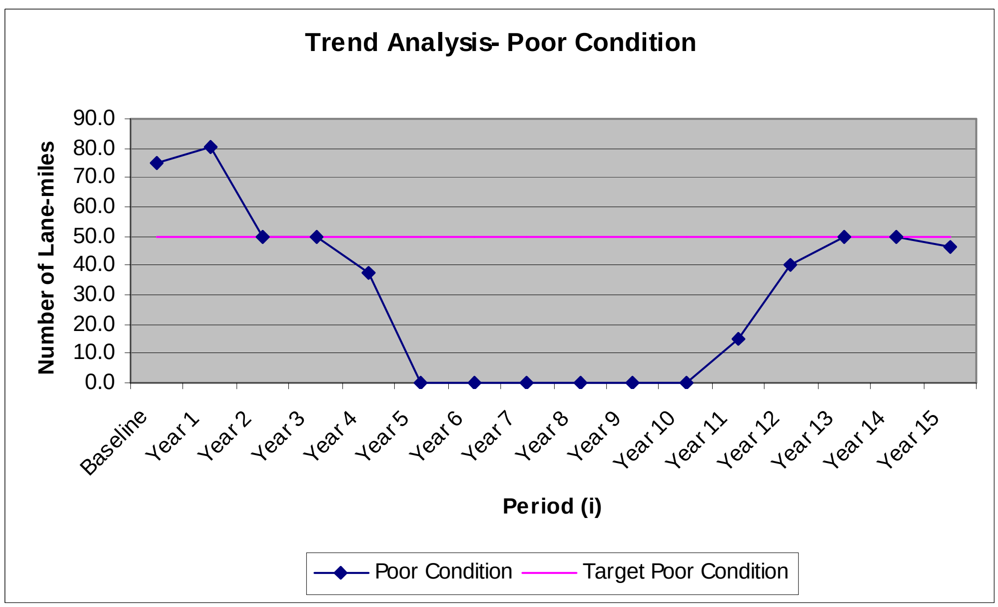


Figure 52: 15 Year Trend Analysis Pertaining to Pavement in Poor Condition

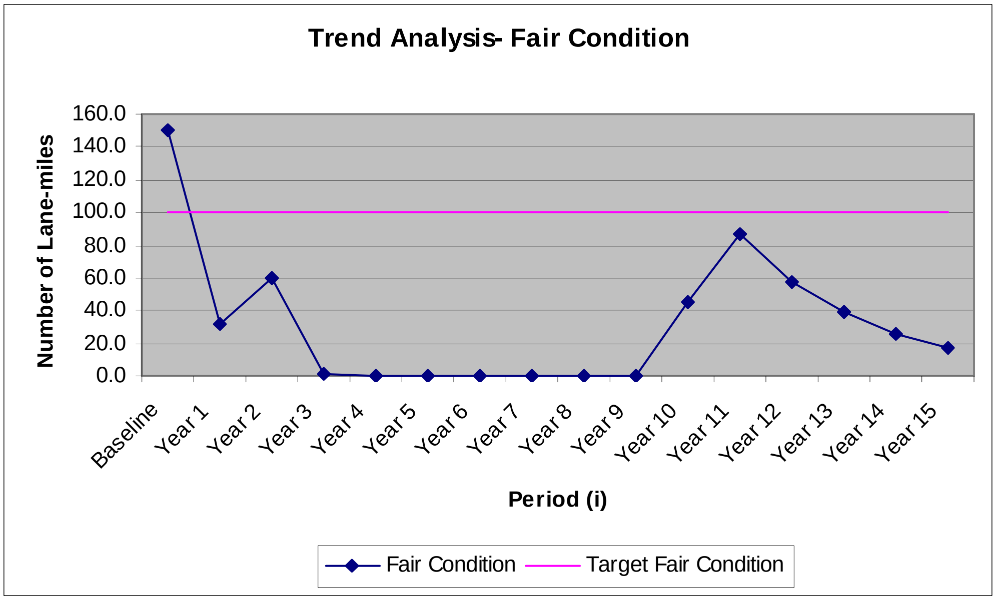


Figure 53: 15 Year Trend Analysis Pertaining to Pavement in Fair Condition

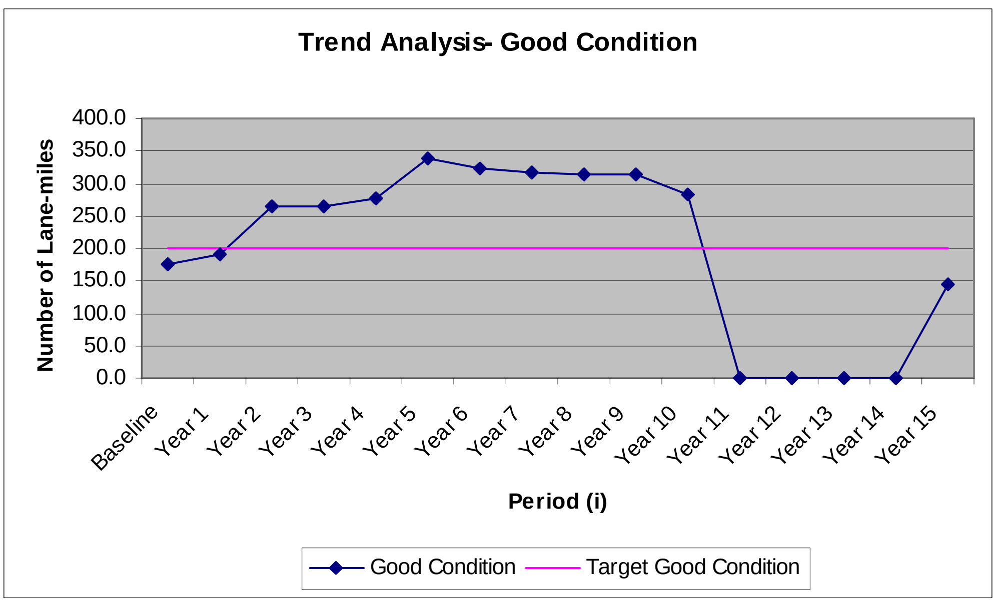


Figure 54: 15 Year Trend Analysis Pertaining to Pavement in Good Condition

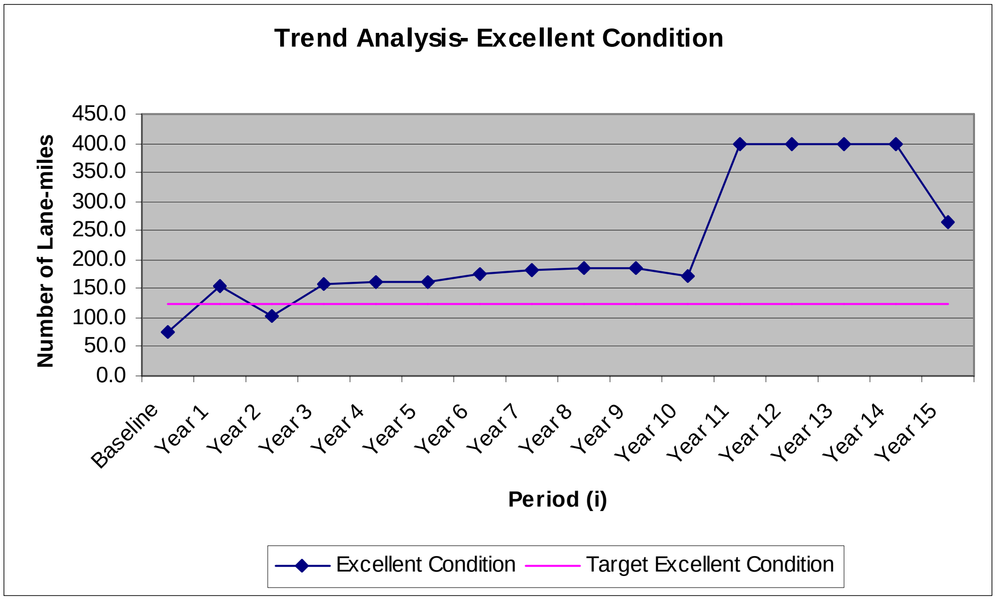


Figure 55: 15 Year Trend Analysis Pertaining to Pavement in Excellent Condition

5.7.2.4.Observations

The goal of the objective function defined in problem 7 is to minimize the total budget spent over the 15 year analysis period as it is in problem 6. Firstly**, Table 20** and **Table 21** show the budget allocation pattern and the level of service pertaining to each year respectively, which resulted from the parameters, pavement performance constraints and the objective function used in **Model 2.2**.

The results shown in **Table 20** indicates that budget allocation which materialized based on **Model 2.2** significantly differs from that of **Model 2.1** presented earlier due to the fact that **Model 2.2** is subject to budget constraints. Thus, the results show that money to be spent in year 1 in **Model 2.2** is less than half of what is spent in **Model 2.1** during the same period. The trend analysis charts, figures 51 through 55, clearly show that **Model 2.2** restores some of the lane-miles in fair, poor and very poor condition for the first 4 years in order to meet the performance targets introduced as constraints in **Problem 7** given that there is now a limit in the amount of money available at each period. Furthermore, **Model 2.2** minimizes the lane-miles in very poor, poor and fair condition between years 5 and 10. Moreover, budget allocated to renewal activities between years 10 and 15 decreases rapidly since **Model 2.2** already meets the performance targets and strives for minimizing the budget which is essentially the objective of this model.

One important observation is that **Thick Overlay 2 and Thick Overlay 3** renewal activities receive 100% of budget spent in the very first year, while **Rehabilitation 1** gains more importance in the following years of analysis resulting in significant improvements in pavement condition.

Another interesting observation is that money spent on renewal activities until year 10 is, in particular, invested in 3 renewal activities, namely **Thick Overlay 2, Thick Overlay 3** and **Rehabilitation 1**. Moreover, **Model 2.2** invests money in **Thin Overlay 4** mainly in order to restore the lane-miles deteriorating from excellent to good starting from year 10. This can be attributed to fact that **Model 2.2** prefers to minimize the lane-miles in good condition in an endeavor to prevent deterioration of lane-miles from good to fair condition since performance constraints introduced herein limits the number of lane-miles that can be present in fair condition at any given year.

Finally, it is important to note that **Model 2.1** and **Model 2.2** use almost the same amount of money over 15 years. Thus, comparison between level of service obtained based on these two models are essential. Hence, **Table 19** and **Table 21** indicate that **Model 2.1** and **Model 2.2** yield almost the same level of service in long term, while **Model 2.1** is superior to **Model 2.2** in the first 5 years of the analysis. This result stems from the fact that **Model 2.1** invests more than twice as much money as **Model 2.2** does in the very first year of the analysis**.** Hence, substantial amount of money spent upfront makes the difference between two models compared here.

In conclusion, **Model 2.2** is designed to determine the minimum budget required in order to meet the performance targets pertaining to very poor, poor and fair condition over 15 years of analysis. Highway agencies aiming to restore lane-miles in very poor, poor and fair condition in long term can use this model not only to determine the minimum budget required to meet the performance targets, but also to obtain more practical investment strategy over 15 years of analysis.

CHAPTER 6

6. COMPARISON OF MANUAL AND AUTOMATIC BUDGET ALLOCATION PROCESSES

This chapter compares and discusses the budget allocation pattern and pavement performance level obtained from manual budget allocation process (Krueger and de la Garza, 2008) and automatic budget allocation process for 15 year analysis period. Manual budget allocation process refers to decision-making process based on system dynamics approach used by Krueger and de la Garza (2008), while automatic budget allocation process refers to network-level optimization tool developed within research based on linear programming algorithm. Parameters used in both manual and automatic budget allocation process are listed below.

Available Annual Highway Maintenance Budget:

Annual Highway Maintenance Budget ($) available in Period *i*

		Budget Amount
P	1	$6,000,000
	2	$8,700,000
	3	$8,700,000
	4	$8,700,000
	5	$8,700,000
	6	$8,700,000
	7	$8,700,000
	8	$9,000,000
	9	$9,000,000
	10	$9,000,000
	11	$9,600,000
	12	$9,600,000
	13	$8,700,000
	14	$8,700,000
	15	$8,700,000

Unit Cost of Each Treatment:

Unit Cost of Each Treatment within each Period i *(U_ij)*

	R								
	Recon	$Rehab_2$	$Thick_3$	$Thin_4$	$Rehab_1$	$Thick_2$	$Thin_3$	OM_3	OM_4
p	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
0	$299,437	$138,135	$67,805	$29,156	$188,135	$101,808	$59,991	$19,644	$12,268
1	$303,929	$140,207	$68,822	$29,593	$190,957	$103,336	$60,891	$19,939	$12,452
2	$308,488	$142,310	$69,855	$30,037	$193,821	$104,886	$61,804	$20,238	$12,639
3	$313,115	$144,445	$70,902	$30,487	$196,729	$106,459	$62,731	$20,541	$12,829
4	$317,812	$146,611	$71,966	$30,945	$199,679	$108,056	$63,672	$20,850	$13,021
5	$322,579	$148,810	$73,045	$31,409	$202,675	$109,677	$64,627	$21,162	$13,216
6	$327,418	$151,043	$74,141	$31,880	$205,715	$111,322	$65,597	$21,480	$13,415
7	$332,329	$153,308	$75,253	$32,358	$208,800	$112,992	$66,581	$21,802	$13,616
8	$337,314	$155,608	$76,382	$32,844	$211,932	$114,686	$67,579	$22,129	$13,820
9	$342,374	$157,942	$77,528	$33,336	$215,111	$116,407	$68,593	$22,461	$14,027
10	$347,509	$160,311	$78,691	$33,836	$218,338	$118,153	$69,622	$22,798	$14,238
11	$352,722	$162,716	$79,871	$34,344	$221,613	$119,925	$70,666	$23,140	$14,451
12	$358,013	$165,157	$81,069	$34,859	$224,937	$121,724	$71,726	$23,487	$14,668
13	$363,383	$167,634	$82,285	$35,382	$228,311	$123,550	$72,802	$23,839	$14,888
14	$368,834	$170,148	$83,519	$35,913	$231,736	$125,403	$73,894	$24,197	$15,111
15	$374,366	$172,701	$84,772	$36,451	$235,212	$127,284	$75,002	$24,560	$15,338

Inflation Rate	1.5%

Deterioration Rates:

Deterioration Rate from Condition State (k+1) to k

Condition State (k)	Condition State (k) 1	2	3	4	5
1		4			
2			3		
3				5	
4					3
5					

Baseline Condition:

Number of Lane-Miles in each condition at year 0 (Baseline Condition)

Condition State (k)	CCI Value	N_k0
1 (Very Poor)	CCI<=49	25
2 (Poor)	49<CCI<=59	75
3 (Fair)	59<CCI<=69	150
4 (Good)	69<CCI<=89	175
5 (Excellent)	CCI>89	75

Total Lane-Miles	500

6.1. COMPARISON AND DISCUSSION OF RESULTS

This section shows the comparison of results obtained from manual and automatic budget allocation process based on the parameters listed in section 6. It must be noted that the MS Candidate runs two different scenarios in the automatic budget allocation process, that is - network level optimization model presented herein. The reason for running two scenarios is to see the significance of changing the objective function in the network level optimization model and its effect on budget allocation process and pavement performance. Objective functions used in each run are stated and pavement performance trend analysis charts are located side by side for easy comparison of the results.

I. **Scenario 1:** How should VDOT allocate its annual highway maintenance budget for different renewal activities such that number of lane-miles in poor, very poor and fair condition will be minimized for the next 15 funding periods?

It should be noted that **Model 1.1** is used to run **Scenario 1**.

DECISION VARIABLES

X_{ij}: Amount of money spent on treatment **j** within period **i**, $\forall i \in P$ and $\forall j \in R$

N_{ki}: Number of lane-miles in condition **k** at the end of period **i**, $\forall i \in P$ and $\forall k \in S$

OBJECTIVE FUNCTION

$$\text{Minimize} \sum_{i \in P} \left((N_{1i} + N_{2i} + N_{3i}) \right)$$

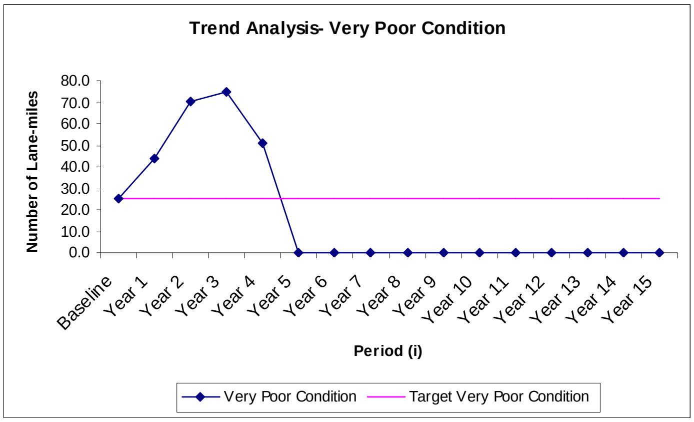
This problem will be subject to all the constraints listed in Problem Statement 1 except for **Performance Target** constraints, i.e. Constraint 1 and Constraint 2.

Results, which are obtained from the network-level optimization tool developed within this research and the manual budget allocation process, are compared and discussed next.

Pavement Performance Trend Analysis Comparison

Automatic Budget Allocation Process- **Model 1.1**

System Dynamics Approach



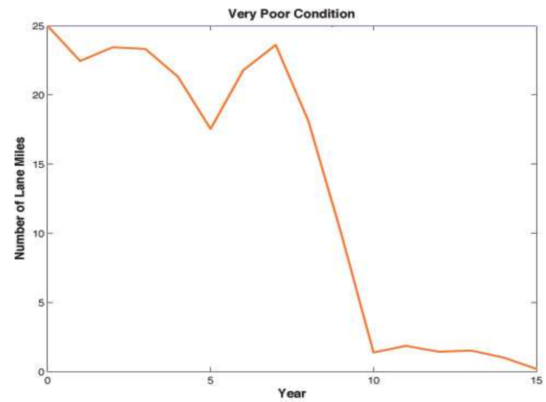
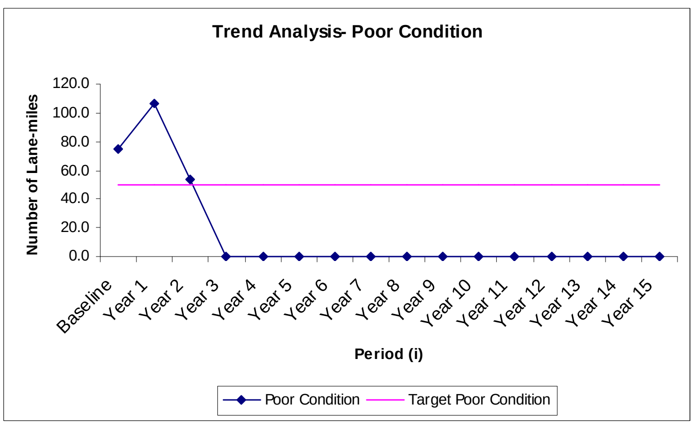


Figure 56: Krueger and de la Garza (2008) – Very Poor



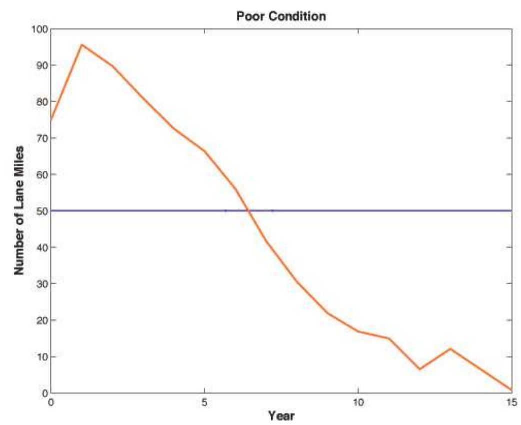
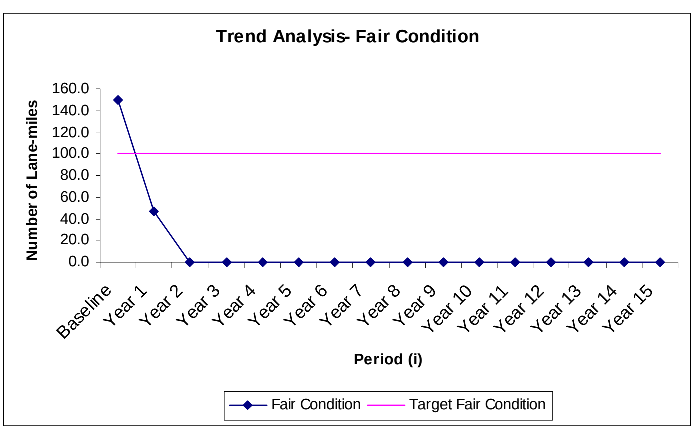


Figure 57: Krueger and de la Garza (2008) – Poor



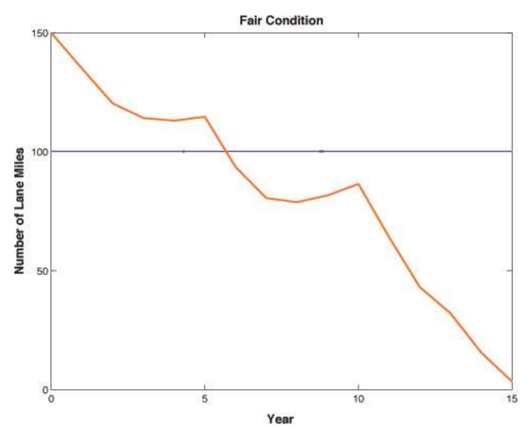
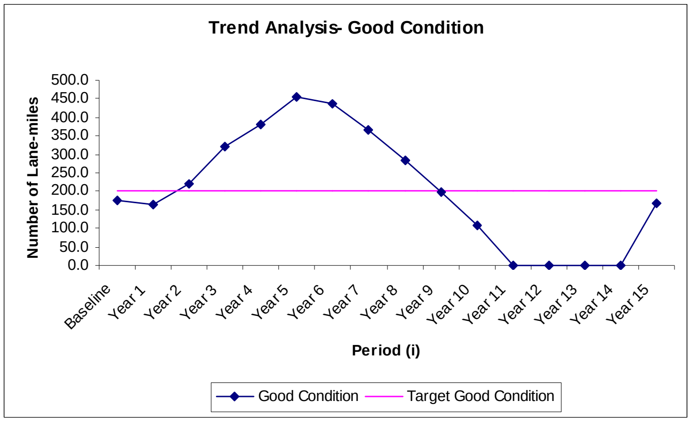


Figure 58: Krueger and de la Garza (2008) - Fair



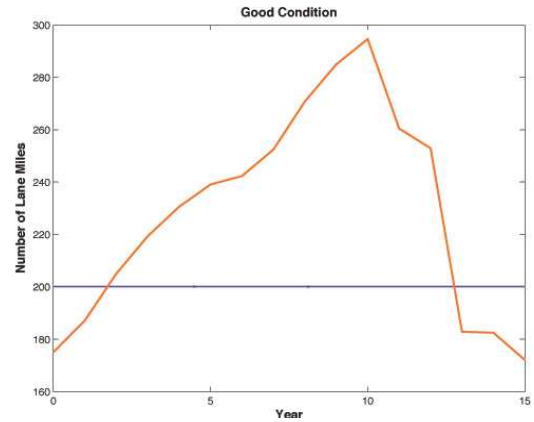
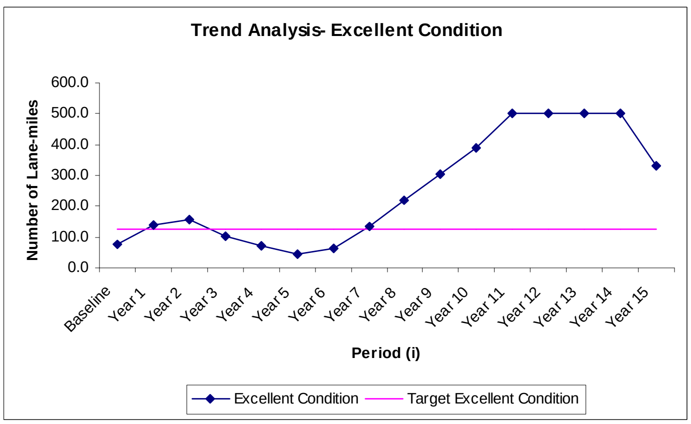


Figure 59: Krueger and de la Garza (2008) -Good



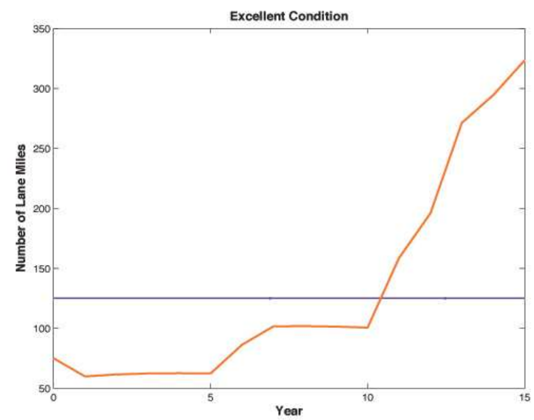


Figure 60: Krueger and de la Garza (2008) - Excellent

	Condition State				
	Very Poor Condition	Poor Condition	Fair Condition	Good Condition	Excellent Condition
Baseline	25.0	75.0	150.0	175.0	75.0
Year 1	43.7	106.3	46.5	165.0	138.5
Year 2	70.3	53.6	0.0	219.7	156.3
Year 3	74.6	0.0	0.0	321.2	104.2
Year 4	50.9	0.0	0.0	379.6	69.5
Year 5	0.0	0.0	0.0	453.7	46.3
Year 6	0.0	0.0	0.0	436.9	63.1
Year 7	0.0	0.0	0.0	364.8	135.2
Year 8	0.0	0.0	0.0	281.8	218.2
Year 9	0.0	0.0	0.0	196.5	303.5
Year 10	0.0	0.0	0.0	108.6	391.4
Year 11	0.0	0.0	0.0	0.0	500.0
Year 12	0.0	0.0	0.0	0.0	500.0
Year 13	0.0	0.0	0.0	0.0	500.0
Year 14	0.0	0.0	0.0	0.0	500.0
Year 15	0.0	0.0	0.0	166.7	333.3

Figure 61: Actual Lane-Miles in Each Condition State Resulted From Scenario 1

Results shown in page 104 and 105 indicate that system dynamics approach and automatic budget allocation process yield similar pavement performance levels in the end of 15 funding periods, although the magnitude of change in pavement performance is different from each other throughout 15 years. Furthermore, automatic budget allocation process minimizes the number of lane-miles in very poor, poor and fair condition , that is – 0, within first 3 funding periods, whereas budget allocation materialized based on system dynamics approach cannot achieve the same level of performance even until the last funding period. Moreover, system dynamics approach aims at having as many lane-miles in excellent condition as possible. Therefore, it yields approximately 320 lane-miles at the end of funding period 15, while automatic budget allocation process is at 333 lane-miles.

In conclusion, automatic budget allocation process yields better results than system dynamics approach if a decision-maker's goal is to minimize the number of lane-miles in very poor, poor and fair condition within the first a few years of the analysis. This conclusion can be easily reinforced by comparison of charts pertaining to very poor, poor and fair condition shown in previous pages. The network level optimization model, **Model 1.1**, presented herein also suggests that all of the lane-miles in the road network will be in either good or excellent condition at the end of funding period 15, whereas results given by system dynamics approach indicates that the total number of lane-miles in very poor, poor and fair condition will be between 50 and 100 at the end of period 15. Observations noted here encourages the MS candidate to run another scenario to see the significance of favoring excellent condition in the objective function and observe if the network level optimization developed within this research is still superior to system dynamics approach utilized by Krueger and de la Garza (2008) in terms of overall pavement performance throughout 15 years of analysis. Hence, results given by **Model 1.2**, which is already presented in **Section 5.6**, will be compared with results suggested by system dynamics approach presented by Krueger and de la Garza (2008).

II. Scenario 2: How should VDOT allocate its annual highway maintenance budget for different renewal activities such that number of lane-miles in very poor, poor and fair condition will be minimized while excess budget will be used towards maximizing the number of lane-miles in excellent condition for the next 15 funding periods?

The objective function defined in scenario 2 is designed to favor having as many lane-miles in excellent condition as possible through using arbitrary weights, subject to available budget.

It should be noted that **Model 1.2** is used to run **Scenario 2**.

DECISION VARIABLES

X_{ij}: Amount of money spent on treatment **j** within period **i**, $\forall i \in P$ and $\forall j \in R$

N_{ki}: Number of lane-miles in condition **k** at the end of period **i**, $\forall i \in P$ and $\forall k \in S$

OBJECTIVE FUNCTION

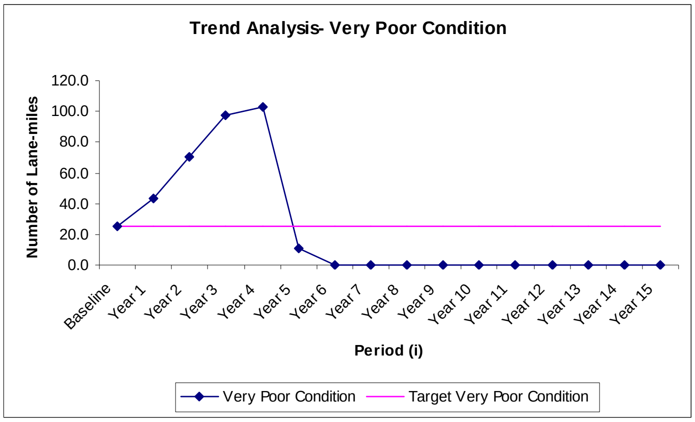
Minimize $\sum_{i \in P} \left((N_{1i} + N_{2i} + N_{3i}) - (N_{4i} + 5 * N_{5i}) \right)$

This problem will be subject to all the constraints listed in scenario 1.

Pavement Performance Trend Analysis Comparison

Automatic Budget Allocation Process-**Model 1.2**

System Dynamics Approach



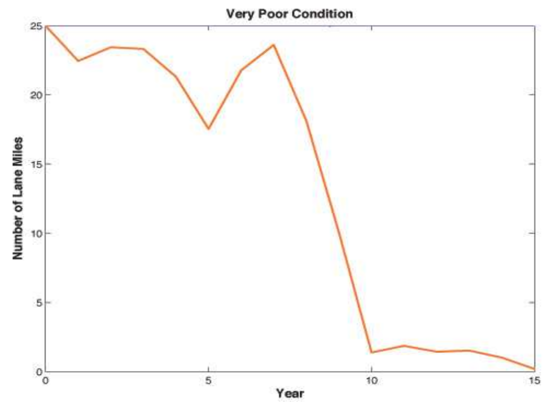
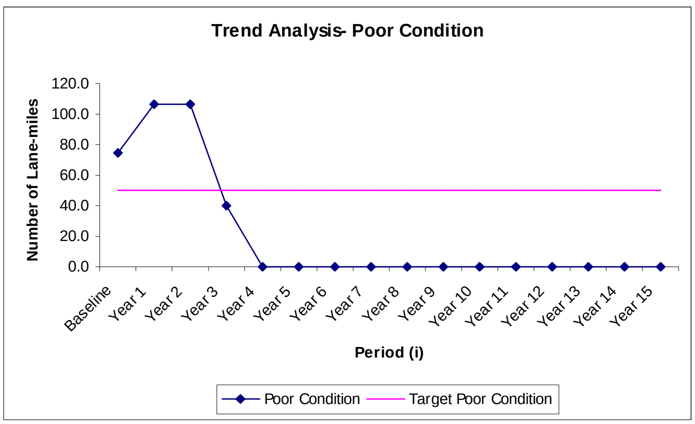


Figure 62: Krueger and de la Garza (2008) -Very Poor



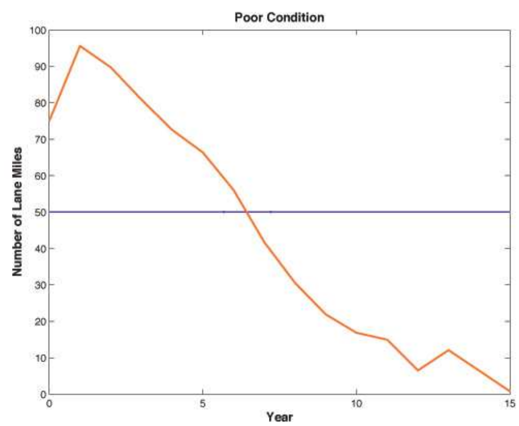
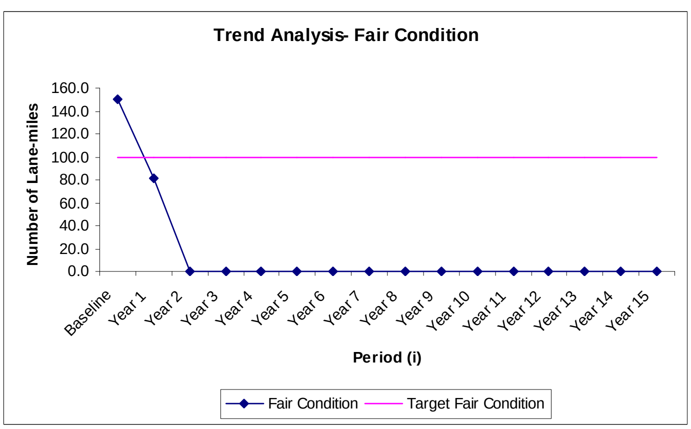


Figure 63: Krueger and de la Garza (2008) - Poor



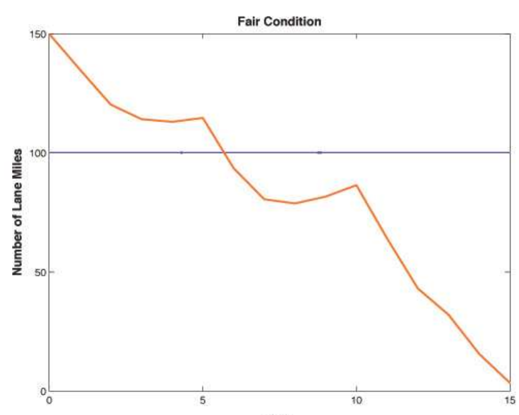
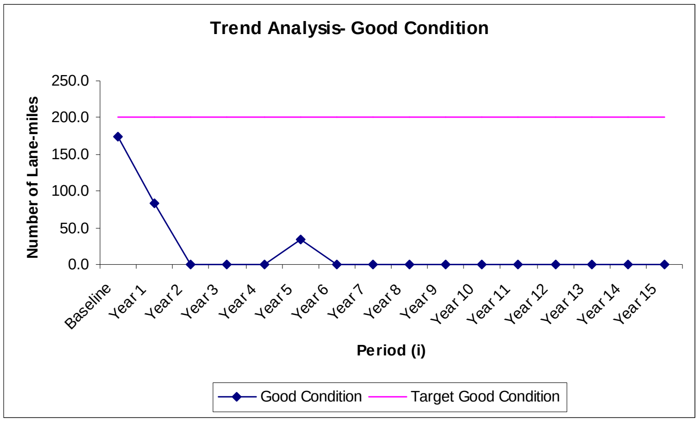


Figure 64: Krueger and de la Garza (2008) - Fair



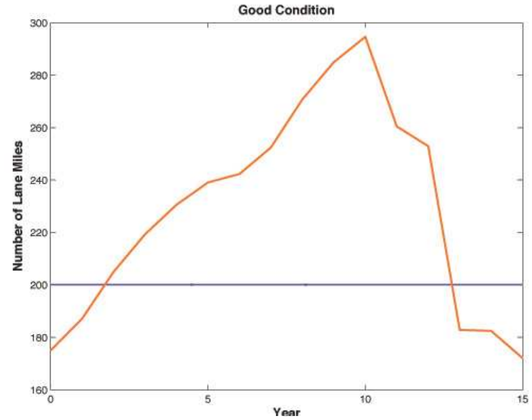
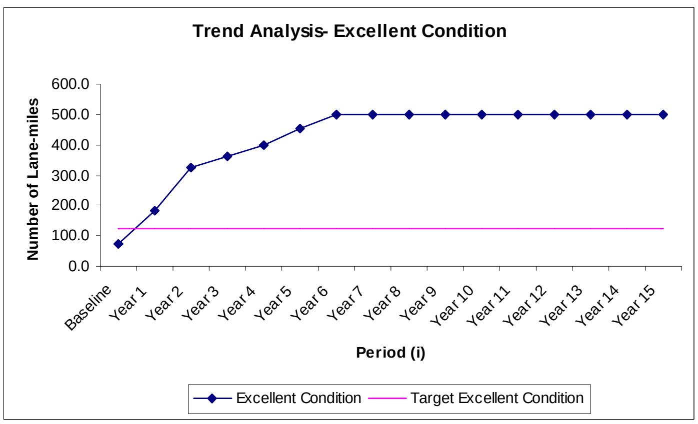


Figure 65: Krueger and de la Garza (2008) - Good



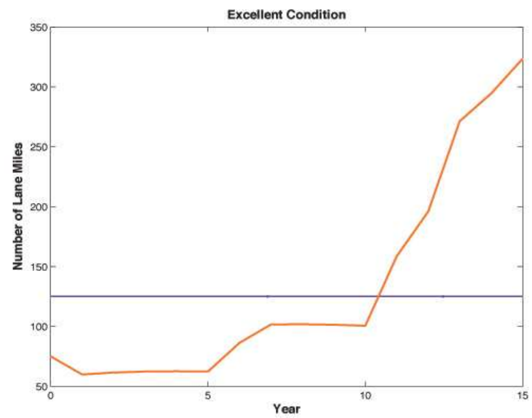


Figure 66: Krueger and de la Garza (2008) - Excellent

	Condition State				
	Very Poor Condition	Poor Condition	Fair Condition	Good Condition	Excellent Condition
Baseline	25.0	75.0	150.0	175.0	75.0
Year 1	43.8	106.3	81.3	84.1	184.6
Year 2	70.3	106.8	0.0	0.0	322.9
Year 3	97.0	39.6	0.0	0.0	363.4
Year 4	102.8	0.0	0.0	0.0	397.2
Year 5	10.9	0.0	0.0	34.9	454.2
Year 6	0.0	0.0	0.0	0.0	500.0
Year 7	0.0	0.0	0.0	0.0	500.0
Year 8	0.0	0.0	0.0	0.0	500.0
Year 9	0.0	0.0	0.0	0.0	500.0
Year 10	0.0	0.0	0.0	0.0	500.0
Year 11	0.0	0.0	0.0	0.0	500.0
Year 12	0.0	0.0	0.0	0.0	500.0
Year 13	0.0	0.0	0.0	0.0	500.0
Year 14	0.0	0.0	0.0	0.0	500.0
Year 15	0.0	0.0	0.0	0.0	500.0

Figure 67: Actual Lane-Miles in Each Condition State Resulted From Scenario 2

System dynamics approach and **Model 1.2** differ substantially in terms of both short and long term pavement performance based on the results shown in page 108 and 109. **Model 1.2** minimizes the number of lane-miles in poor and fair condition, that is – 0, until funding period 4 as opposed to period 3 observed in scenario 1. Moreover, **Model 1.2** favors having as many lane-miles in excellent condition as possible due to the change in the objective function. Therefore, it suggests that all the lane-miles in the road network, that is – 500, will be in excellent condition after funding period 5. However, system dynamics approach cannot achieve the same level of service even at the end of funding period 15, where the number of lane-miles in excellent condition is at approximately 320. These observations clearly indicate that results given by the network level optimization tool developed within this research effort is highly dependant upon objectives, which a decision-maker using this tool defines.

In conclusion, the network level optimization tool presented herein yields better results than system dynamics approach suggested by Krueger and de la Garza (2008), if decision-maker's goal is to minimize the number of lane-miles in very poor, poor and fair condition, while maximizing the number of lane-miles in excellent condition. This conclusion can be easily reinforced by comparison of charts pertaining to very poor, poor and fair condition shown in previous pages. The tool developed within this research also tops system dynamics approach in terms of maximizing the number of lane-miles in excellent condition. Comparison performed here also suggests that 100% of the lane-miles in the road network will be in excellent condition at the end of funding period 5 based on the network level optimization tool; whereas results given by system dynamics approach indicate that the total number of lane-miles in excellent condition will be around 70% of the road network.

CHAPTER 7

7.1. CONCLUSIONS

Observations made regarding the models 1, 2 and 3 discussed in previous chapters show that **Model 1.2** yields more desirable results than that of **Model 1.1** and **Model 1.3**. Different results obtained from each model can be attributed to the fact that the objective function defined for each model and the constraints to which each model is subject are different and therefore each model yields significantly different outcomes in terms of both budget allocation pattern and pavement level of service. It must be noted that the models discussed above can be customized based on the decision-maker's needs and sensitivity analysis can easily be made through changing the problem parameters and constraints.

Moreover, it should also be noted that **Model 1.5** and **Model 1.2** can be compared since the only difference between these two models stem from the annual maintenance budget used in such models. Thus, after analyzing both models, it is evident that **Model 1.5** yields poorer level of service than **Model 1.2** in that all the lane-miles in the network are in excellent condition after year 6 based on the results obtained from **Model 1.2**, while **Model 1.5** achieves the same result at year 14. This result does not come as a surprise in that the difference in the available pavement maintenance budget pertaining to each model affects the level of service achieved. Furthermore, the parameters, constraints and variables defined for each model are the same except for the available pavement maintenance budget. Hence, the comparison made between **Model 1.5** and **Model 1.2** reveals the importance of the available pavement maintenance budget, as well as the need for an optimized budget allocation process. Consequently, this observation shows that change in the magnitude of pavement maintenance budget available for each model could result in significant differences in terms of both budget allocation pattern and pavement level of service.

It is also important to note that **Model 2.1** and **Model 1.4** use almost the same amount of money over 15 years. Thus, comparison between the levels of service obtained based on these two models show that **Model 1.4** yields better level of service in long term, while

Model 2.1 is superior to **Model 1.4** in the first 5 years of the analysis in that **Model 2.1** favors incurring upfront cost so that rapid improvement in pavement performance can be achieved. Hence, number of lane-miles in poor and fair condition decreases down to 0 after the application of renewal activities in the very first year of the analysis.

Another interesting observation is that **Model 2.1** and **Model 2.2** yield almost the same level of service in long term, while **Model 2.1** is superior to **Model 2.2** in the first 5 years of the analysis. Moreover, **Model 2.2** interestingly spends more money than **Model 2.1,** although the level of service provided by both models is almost the same. However, highway agencies aiming to restore lane-miles in very poor, poor and fair condition in long term should use **Model 2.2** not only to determine the minimum budget required to meet the performance targets, but also to obtain more practical investment strategy over 15 years of analysis.

It is important to note that Constraint 2, which represents the number of lane-miles in good and excellent condition being greater than the performance targets stated by Virginia Department of Transportation (VDOT), is never used in any of the models presented in this research. Constraint 2 actually have been enforced in a few models, however, the optimization model developed within this research did not yield any feasible solution based on the performance targets set for excellent and good condition. Furthermore, parameters, such as baseline pavement condition and available highway maintenance budget, used in this research affected the infeasibility noted above since performance targets set for excellent and good condition could not be met with available highway maintenance budget and the baseline condition stated in this document.

In conclusion, it is important to emphasize on the fact that results obtained based on manual budget allocation are inferior to what is obtained from the network level optimization tool presented herein. The tool searches for the optimal pavement maintenance programming considering multiple years of analysis, whereas manual budget allocation process takes every funding period separately and develop a strategy at the beginning of the next funding period. This process omits the effect of maintenance investment made today on the following years. Therefore, it has been shown that manual budget allocation process yields less desirable results in terms of effectiveness and cost-efficiency in comparison to automatic budget allocation process. Hence, this drawback results in the conclusion that the network-level optimization tool developed herein yields more desirable pavement maintenance programming than manual budget allocation process.

7.2. CONTRIBUTIONS to BODY OF KNOWLEDGE

The network level optimization model presented in this document contribute to the problem area in that previous research and optimization models that have been reviewed in Chapter 2 of this document used probabilistic deterioration models, whereas the network-level optimization model designed in this research use a deterministic deterioration model developed based on 8 years of real pavement condition data collected in the last 8 years. Models using probabilistic models, those by Turnquist and Mbwana (1996) and Abaza and Ashur (1999), have been criticized due to the following three aspects inherent in each model:

1. Probabilistic models are complex and difficult to understand
2. Probabilistic models are time-consuming and require quite up-front effort to put the current pavement data in the format that can be used in the model
3. Disputable assumptions regarding probabilistic approach undermine the strength of the models proposed

Moreover, integer programming approach proposed by Raviarala et al. (1997) is not applicable to large scale programming problems due to high computational requirements, whereas the network level optimization problem presented herein works on Linear Programming approach and can handle high computational requirements. Furthermore, the Highway Economic Requirements System/State Model, which is also introduced in Chapter 2 of this document, searches for possible improvements on individual sections of highways and evaluate them. This evaluation is performed on each section of highway for a single funding period. Subsequently, HERS-ST repeats the process for the following funding periods. Finally, after the analysis is completed for all the funding periods, the results are gathered and printed to several output files.

Results shown in this document reinforce the idea that incorporating a smart decision-making tool is beneficial in determining an effective and efficient pavement maintenance programming. Thus, **Chapter 6** of this thesis shows that system dynamics approach presented by Krueger and de la Garza (2008) yields less desirable results than what is presented in this research since the network-level optimization model developed herein searches for the optimal pavement maintenance programming considering multiple years of analysis, whereas a decision-maker arbitrarily allocates money into renewal activities in first year, and then go through the same process for the following years in system dynamics approach. Thus, the system dynamics approach does not consider the effect of the budget allocation performed in a given year on the following periods. Hence, this drawback results in the conclusion that the network-level optimization tool developed herein yields more desirable pavement maintenance programming than manual budget allocation process, which essentially elicits the contribution of this thesis work to body of knowledge.

It should also be noted that the network-level optimization model developed in this research is flexible in terms of adjusting the parameters and objective functions within the excel tool complementing this document. There is no need to divide the road network into sections, as required in models reviewed in Chapter 2 of this document, in order to create new models in the model developed within this research. Thus, decision-makers in highway agencies do not need to allocate substantial up-front time, effort and money in order to create models that are suitable for problems which they have at hand. Furthermore, optimization model developed within this research effort differs from the ones introduced thus far in that it is very practical and easily reproducible since number of components pertaining to the model far less than the models introduced previously. Hence, it is very easy for any decision-maker, regardless of technical background, to study the model and make use of it. Furthermore, the model works with values that have been found deterministically as opposed to probabilistic approach, hence does not require any rigorous probabilistic or economic calculations.

In conclusion, the model developed herein suggests a broad budget allocation strategy and a potential pavement condition trend throughout the network. Therefore, this research adds value to body of knowledge, not only because simplicity and practicality inherent in the network level optimization model is likely to appeal to decision-makers in highway agencies since it does not require investing substantial time and resources for doing pavement maintenance analysis, but also the optimization tool yields better results than that of suggested by system dynamics approach as shown in Chapter 6 of this thesis.

CHAPTER 8

8. FUTURE RESEARCH

Optimization models 1.1, 1.2, 1.4 and 1.5 presented thus far do not consider the pavement performance targets as constraints, resulting in negative deviations between the actual pavement performance and the pavement performance targets set by Virginia Department of Transportation. Hence, a mechanism, as models presented within this research, must be developed to measure the efficiency of budget allocation pattern so that efficiency of being effective in budget allocation process can be determined (Krueger and de la Garza, 2008). Components of a mechanism, required for measuring the efficiency of being effective, discussed and presented in the following section of this document.

Measuring the Efficiency of Budget Allocation Process- Cost/Benefit Ratio

The following components must be considered in the process of developing a mechanism, which measures the "efficiency of being effective" in budget allocation process (Krueger and de la Garza, 2008).

1. **Level of Service Index (LOS)**
2. **Weighted Level of Service Index**
3. **Available Annual Maintenance Budget**
4. **The Objective Function**

LOS (Level of Service Index)

The level of service index (LOS index) can be found through using N_{ki} and G_{ki}, explained below. Based on the positive/negative difference between these two values, LOS index can be determined.

- Number of lane-miles in each condition state at the end of each period, N_{ki}, is not known so these are decision variables as always.
- Number of lane-miles required in each condition state at the end of each period, G_{ki}, is set by Virginia Department of Transportation and is known.

Furthermore, Krueger and de la Garza (2008) defined a LOS index in a scale that ranges from 0 to 2. When the number of lane-miles in either of 5 condition states is at its target level, its LOS Index is 1. For Excellent and Good condition, when the number of lane-miles goes above the targets set, then the LOS Index grows from 1 to 2. For Fair, Poor and Very Poor condition, when the number of lane-miles goes below the targets set, then the LOS Index grows from 1 to 2. LOS index numbers can be found through a mechanism, namely **Effectiveness Curves**, designed in Microsoft Excel, which has been developed by Krueger and de la Garza (2008). The mechanism developed assigns each condition state LOS index numbers based on the actual performance and the targeted performance. The performance mentioned herein is represented in terms of lane-miles. Thus, users need to enter only the actual and targeted number of lane-miles in each condition state. The difference between these two numbers determines the LOS index pertaining to each condition state.

Weighted Level of Service Index

This index is defined in terms of Level of Service Index (LOS Index) which measures how far a given condition state is from its specified target (Krueger and de la Garza, 2008). Weighted level of Service index can be found through multiplying LOS index for each condition state in a given year by the number of lane-miles in each state in a given year and divide the result by the total lane-miles in the network:

$$WeightedLOSindex(i) = \frac{I_5(i) * N_{5i} + I_4(i) * N_{4i} + I_3(i) * N_{3i} + I_2(i) * N_{2i} + I_1(i) * N_{1i}}{\sum_{k \in S} \sum_{i \in P} N_{ki}}$$

Where,

$I_5(i)$ is the effectiveness (Level of Service) index for the number of lane-miles in excellent condition at year *i*, $i \in P$

N_{ki} is the number of lane-miles in condition state *k* at the end of year *i*, $k \in S$, $i \in P$

Available Annual Maintenance Budget

Another component of this problem is Annual Maintenance Budget, B_i. Moreover, there is no rollover if the available annual maintenance budget for a given year is not spent completely, thus leaving unspent money. In the case where there is unspent money for a given period, this money disappears next year, therefore this must be penalized. The gap between the available annual maintenance budget and the actual yearly expenditures will adversely impact the cost/benefit ratio which will be the objective function of this problem.

Objective Function

The objective function of the problem is to minimize the Cost/ Benefit Ratio which is defined as “efficiency of being effective” (Krueger and de la Garza, 2008).

$$Cost/Benefit(i) = \frac{TotalExpenditures(i)}{WeightedLOSIndex(i)} \times \frac{B_i}{TotalExpenditures(i)}$$

Objective Function: $Min \sum_{i \in P} Cost/Benefit(i)$

The objective function defined above is more complex than the objective functions presented within this document since Weighted LOS Index is in the second order polynomial form. Thus, more detailed investigation is required to address this problem. Therefore, it is of paramount importance to develop a new optimization tool, which is capable of solving the objective function above. Furthermore, depending on the nature of the objective function, linearization can also be investigated. Linearization of non-linear functions can be useful since some optimization tools, such as the network level optimization tool developed within this research, can analyze and solve only linear systems.

Finally, present value of the actual expenditures pertaining to each model presented herein can be calculated and compared in terms of actual cost incurred over 15 years of maintenance. Present value is the value of future expenditure discounted to reflect the time value of money (Wikipedia, 2008). In other words, present value reflects how much a dollar today is worth in 15 years. Hence, comparison suggested here could result in more accurate cost analysis as inflation rate and discount rate are considered in present value calculations for 15 years of maintenance expenditures.

APPENDIX A

Creating a New Model in Excel Premium Solver

Excel Premium Solver is a powerful tool that is capable of solving optimization problems with hundreds of variables and constraints. It works with the same logic as Excel Solver add-in that Microsoft Excel contains. However, Excel Premium Solver is more powerful and more user-friendly than default excel solver add-in. Thus, Excel Premium Solver is more suitable for the network-level pavement maintenance programming optimization problem in that it involves more variables than a default excel solver add-in can solve. Therefore, Excel Premium Solver has been used to facilitate this research and results obtained have been presented.

Furthermore, the problem of network-level optimization for pavement maintenance programming consists of 3 major elements:

1. **The Objective Function:** The objective function defined in a network-level optimization model reflects what the decision-maker aims to attain

2. **Decision Variables:** The decision-maker strives for determining the value of decision variables, e.g. fraction of budget to be allocated to each renewal activity at a given year

3. **Constraints:** Every optimization problem is subject to constraints. Pavement performance targets set by Virginia Department of Transportation (VDOT) and available highway maintenance budget are examples of constraints.

Network-Level optimization models can be designed and elements noted above can be defined in Excel Premium Solver. Hence, Appendix A gives insight as to how the network-level optimization model presented here has been created. Thus, a visual tool, a movie, has been developed to aid users in using the network-level optimization models and Excel Premium Solver. Following pages will give more insight about the excel sheets ,where the models are presented, and how users can define the objective function, decision variables and constraints pertaining to the problem in Excel Premium Solver.

Introduction to Excel Sheets

1. **Annual Maintenance Budget:** This excel sheet contains two tables:

    a. Budget Amount

    b. Budget Multiplier

Users should only enter the budget amount pertaining to year 1, which corresponds to cell **D8** in this sheet. Furthermore, budget multipliers determine how much money will be available to spend at each year starting from year 2 since budget multipliers pertaining to each period are multiplied by first year's budget. Therefore, the budget multiplier pertaining to year 1 is always 1, while users manually enter the budget multipliers which belong to years between 2 and 15.

The process explained above is of paramount importance in that each year's maintenance budget computed here is an input in the main model. Users can see how this process materializes by watching the movie created exclusively for this research.

2. **Unit Price Calculation:** This excel sheet contains three tables:

    a. Unit price of each material comprising 9 renewal activities

    b. Co-efficient numbers

    c. The tables computing unit cost of each renewal activity

Users should only enter the unit prices pertaining to each material, which correspond to the cells between **D2:D15**. The unit cost of each renewal activity is computed based on the values entered by the user manually and is carried over to the excel sheet "**Unit Cost of Each Treatment"**, which is explained next.

3. **Unit Cost of Each Treatment:** This excel sheet contains only one table which presents the unit cost of each treatment in each period for 15 years. It must be noted that fixed inflation rate is considered in the calculations. Users can change inflation rate as needed.

4. **Deterioration Rates:** This excel sheet contains only one table which lists the deterioration rates pertaining to each condition state. Users do not need to change any value in this table.

5. **Baseline Condition:** This excel sheet contains only one table which lists the number of lane-miles in each condition state at the beginning of the analysis – that is year 0. Users can change the number of lane-miles in each condition state as needed if sensitivity analyses are to be performed.

6. **Performance Targets:** This excel sheet contains only one table listing the performance targets aimed in each year in terms of lane-miles in each condition state. User can change the performance targets pertaining to each condition state in each period as needed.

6 excel sheets explained thus far provide inputs into the network-level optimization models developed within this research. Thus, the network-level optimization of pavement maintenance programming can be performed by using such inputs in excel premium solver. Hence, users need to define the objective function, decision variables and constraints pertaining to each model by using excel premium solver. This process is explained in detail in the following sections of this document. Users should also watch the video provided with this research in order to see how one can define the objective function, decision variables and constraints in the excel premium software. Subsequently, users can solve the problem and see the outputs, e.g. tables and charts, pertaining to the model created.

Defining the Objective Function in Excel Premium Solver

Users should follow the steps below in order to define a new objective function in excel premium solver. Furthermore, watching the video provided with this research document would be helpful and facilitate the process significantly.

1. Open the excel file **“Thesis Work Demonstration”**
2. Go to the tab “ **Model 1.1**”
3. Click on **D7** and define the objective function. The objective function is always either to minimize or maximize sum of the variables[2], value of which the model is set to determine.
4. After defining the objective function, go to “**Tools**” menu in Microsoft Excel 2003 – **Add-ins** in Microsoft Excel 2007. It must be noted that the instructions given here apply to Microsoft 2003.
5. Select “**Excel Premium Solver**”
6. Select “**Start Using Premium Solver**” in the window that opens
7. Select “**Objective**” text
8. Click “**Add**”
9. Select the cell where your objective function is located- **D7** is in the video created within this research.
10. Select “**Min**” or “**Max**” depending on the problem objective – that is either maximizing or minimizing the value of the objective function.
11. Select “**OK**” and this concludes the process of defining the objective function.

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[2] Decision variables are always the amount of money allocated to each renewal activity at each period and number of lane-miles in each condition state at each period. These variables are located in **D** and **I** column starting from cell 13 to cell 153. The video provided with this thesis work will aid users in locating these variables

Adding Variables in Excel Premium Solver

Users should follow the steps below in order to add variables in Excel Premium Solver. There are two types of variables.

- **Budget Variables:** These variables correspond to the amount of money allocated to each renewal activity at each period.
- **Pavement Performance Variables:** These variables correspond to the number of lane-miles in each condition state at the end of each period.

Furthermore, it should be noted that watching the video provided with this research document would be helpful and facilitate the process significantly.

Adding Budget Variables

1. Presuming that Excel Premium Solver window is still open, select "**Decision Variables**" text
2. Click on "**Add**" button
3. Select the cells between **D13**: **D21** in the "**add variables window**" that opens after selecting add button. These cells pertain to the amount of money allocated to each activity in year 1. Thus, the model will determine the value of these variables after the optimization problem is solved
4. Click "**OK**"

The process explained above should be replicated for each year- that is until year 15. The last cell range to be selected is **D143**: **D151**, which corresponds to the budget variables pertaining to year 15.

Adding Pavement Performance Variables

1. Presuming that Excel Premium Solver window is still open, select "**Decision Variables**" text

2. Click on "**Add**" button

3. Select the cells between **I13**: **I17** in the "**add variables window**" that opens after selecting add button. These cells pertain to the number of lane-miles in each condition state at the end of period 1. Thus, the model will determine the value of these variables after the optimization problem is solved

4. Click "**OK**"

The process explained above should be replicated for each year- that is until year 15. The last cell range to be selected is **I143**: **D147**, which corresponds to the pavement performance variables pertaining to year 15.

Adding Constraints in Excel Premium Solver

Users should follow the steps below in order to add constraints in Excel Premium Solver. There are 4 types of constraints:

- **Performance Constraints:** These constraints correspond to the performance goals- that is how many lane-miles must be in a specific condition state at the end of each period, which are set by Virginia Department of Transportation.

- **Budget Constraints:** These constraints correspond to the upper limit of annual highway maintenance budget available in each period- that is the sum of the amount of money spent on each renewal activity in each period must be less than or equal to what is available in each period.

- **Lane-Mile Constraints:** These constraints result from the fact that the balance between upstream and downstream transfer of lane-miles – that is moving up or down from one condition state to another condition state, must be established. The details of this constraint type can be found in Section **4.5.4** of this document.

- **Total Lane-Mile Constraints:** These constraints result from the fact that the sum of the number of lane-miles in each condition state must be equal to 500, which is the total number of lane-miles in the road network at the beginning of the analysis.

Furthermore, it should be noted that watching the video provided with this research document would be helpful and facilitate the process significantly.

Adding Performance Constraints

1. Presuming that Excel Premium Solver window is still open, select "**Constraints**" text
2. Click on "**Add**" button
3. Select the cells between **N13**: **N17** in the "**add constraint window**" that opens after selecting add button. These cells pertain to the difference between the performance targets set by Virginia Department of Transportation and actual lane-miles that will be obtained after the model is run. More detail about this constraint can be found in **Section 4.5.4** of this document.
4. Select "≤"
5. Select the cells between **O13**: **O17**
6. Click "**OK**"

The process explained above should be replicated for each year- that is until year 15, if performance constraints are to be exercised.

Adding Budget Constraints

1. Presuming that Excel Premium Solver window is still open, select "**Constraints**" text
2. Click on "**Add**" button
3. Select the cell **Q13** in the "**add constraint window**" that opens after selecting add button. This cell pertains to the budget spent in year 1. The value of this cell will be obtained after the model is run.
4. Select "≤"
5. Select the cell **R13**
6. Click "**OK**"

The process explained above should be replicated for each year- that is until year 15, if budget constraints are to be exercised.

Adding Lane-Mile Constraints

1. Presuming that Excel Premium Solver window is still open, select "**Constraints**" text
2. Click on "**Add**" button
3. Select the cells between **T13:T17** in the "**add constraint window**" that opens after selecting add button. The value of this cell will be obtained after the model is run and must be "0".
4. Select "="
5. Select the cell **U13:U17**
6. Click "**OK**"

The process explained above should be replicated for each year- that is until year 15.

Adding Budget Constraints

1. Presuming that Excel Premium Solver window is still open, select "**Constraints**" text
2. Click on "**Add**" button
3. Select the cell **Y18** in the "**add constraint window**" that opens after selecting add button. This cell pertains to the sum of the lane-miles in that year. The value of this cell will be obtained after the model is run and must be "500".
4. Select "="
5. Select the cell **Z18**
6. Click "**OK**"

The process explained above should be replicated for each year- that is until year 15.

The objective function, decision variables and constraints have been defined in Excel Premium Solver thus far. Subsequently, select "**Standard LP Simplex**" from the drop-down menu, and then click on "**Solve**" in order to see if a feasible solution to the problem exists. Moreover, if there is a feasible solution to the problem, tables and charts pertaining to the model are created automatically in the following excel sheets.

1. **Tables:** This excel sheet contains the tables listed below

    - Budget Allocated to Each Renewal Activity
    - Fraction of Maintenance Budget to Renewal Activities
    - Actual Lane-Miles in each Condition State

    Values that tables above contain are used as inputs in order to create trend analysis and budget allocation charts

2. **Trend Analysis:** This excel sheet contains the following charts"

    - Trend analysis for lane-miles in very poor condition
    - Trend analysis for lane-miles in poor condition
    - Trend analysis for lane-miles in fair condition
    - Trend analysis for lane-miles in good condition
    - Trend analysis for lane-miles in excellent condition

3. **Budget Allocation:** This excel sheet contains the following charts:

    - Budget Allocation Pattern
    - Budget Spent Vs. Available Budget

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