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Development of Pavement Network Optimization System

(Development of Pavement Performance Analysis and Procedures)

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DEVELOPMENT OF PAVEMENT NETWORK OPTIMIZATION SYSTEM (DEVELOPMENT OF PERFORMANCE ANALYSIS AND PROCEDURES)

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16. Abstract

A computerized method has been develop to conduct network optimization analysis. The analysis uses performance models along with life-cycle cost analysis to identify the most effective treatment to be applied for a specific pavement section. Performance models were developed for the most common maintenance treatments: sand and chip seals, and rehabilitation treatments: overlay, roadbed modification, and mill and overlay. The models were developed using actual pavement management data collected on field sections for the past 15 years. The life-cycle cost analysis uses the present worth approach along with actual cost figures for initial and annual construction activities.

The individual treatments are used to create alternatives that can provide the acceptable performance level for a given pavement section over the entire analysis period of 20 years. The annual performance of pavement sections is modeled in terms of the present serviceability index (PSI). The most effective treatment alternative is selected based on the highest benefit cost ratio which is defined as the ratio of area under the PSI vs. time curve divided by the total cost of the alternative. Once the most effective alternative is selected for each pavement section, a summary of the annual expenditures is provided for the group of pavement sections that have been selected for analysis. The group of projects can be the entire network or a group of pavement sections that have been selected by the engineer.

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I. INTRODUCTION

Since 1917, the Nevada Department of Transportation (NDOT) has built and currently maintains 5,429 miles of highways and streets (1). There are an additional 46,458 miles of public roads in Nevada (33,010 miles of unimproved roads, and 13,448 miles of paved roads) which are maintained by county, city, and other governmental agencies. NDOT only maintains 12 percent of the highways and streets in the state. However, the condition of this 12 percent is extremely critical to the state and the national highway system since it carries 72 percent of all traffic and almost ninety percent of all heavy truck traffic (2).

NDOT spent $120 million during fiscal year 1998 for resurfacing, restoration, rehabilitation and reconstruction of 532 miles of highways. Another $12 million was spent on maintaining (pavement surface patching and sealing) highway pavements.

Construction costs have increased substantially in recent years. The Construction Price Index has increased eighty percent since 1977 (1). As a result, construction costs have almost doubled in the last 20 years. For example, one ton of bituminous concrete surfacing that cost $15.47 in 1977 cost $25.52 in 1991. The cost of replacing the pavement surface on the 5,429 miles of roadway built and maintained by NDOT alone would be in excess of $2.7 billion (2).

As noted above, Nevada has several thousands of miles of highways and streets which must be continually maintained in spite of the ever increasing construction costs. NDOT has established the preservation of the existing highway system as its number one priority.

In 1991, the U.S. Congress passed the Intermodal Surface Transportation Efficiency Act (ISTEA). Under this Act, State Highway Agencies (SHA) are required to develop and implement a Pavement Management System (PMS). In addition, SHA's are required to conduct several analyses on the PMS data, including the following:

1. Condition Analysis. This includes ride, distress, rutting, and surface friction.
2. Performance Analysis. This includes pavement performance analysis and an estimate of the remaining service life.
3. Investment Analysis. This includes an estimate of network-level and project-level investment strategies.
4. Engineering Analysis. This includes the evaluation of design, construction, rehabilitation, materials, mix designs, and maintenance as they relate to the performance of pavements.
5. Feedback Analysis. This includes the use of the annual evaluation data to update the performance models.

NDOT implemented of a statewide PMS in 1980, which closely follows the ISTEA guidelines and satisfies requirement number 1 above. The NDOT experience with PMS has been very successful. Currently, NDOT is among the very few SHA's that have an implemented PMS. It has created the essential elements of a PMS and implemented the various tasks of data collection, data analysis, and decision-making processes.

In 1992-1993, NDOT sponsored a research project which developed performance models for pavement rehabilitation and maintenance treatments most commonly used in Nevada (3). The products of this research project satisfied requirements 2 and 4 of the ISTEA Act. In 1994, NDOT started a research project to develop analyses and procedures to satisfy requirements 3 and 5 of the ISTEA Act. This report summarizes the findings and recommendations of this research project.

I.1 Objectives

The overall objective of this study is to incorporate various data analysis procedures and decision-making processes into the NDOT pavement management system. The overall process must include the following critical steps:

$ Pavement performance models

$ Life-cycle cost analysis

$ Optimization analysis

The pavement performance models represent the foundation for the entire effort. The life- cycle cost analysis combines the predicted pavement performance with the associated cost. Finally, the optimization analysis uses the results of the pavement performance prediction with those of the life-cycle cost analysis to recommend the most beneficial maintenance and rehabilitation action.

I.2 Results

The products resulted from this research effort include the following:

$ Performance Models

$ Life-cycle cost models

$ Multi-year prioritization (network optimization)

$ Analysis software

II. BACKGROUND

II.1 Pavement Performance Modeling

The increasing interest in pavement performance studies is a result of their representing the final link between theory and practice. As the pavement engineering profession strives for better design procedures and more enduring materials, the evaluation of the long-term pavement performance becomes a critical step for every agency. Predicting the actual performance of specific pavement sections under the combined action of traffic loading and environmental factors can provide valuable data to the various departments of a highway agency.

The pavement design engineer can use such data to check the validity of the design procedure and the appropriateness of the various assumptions that are made during the design process. The materials engineer can verify whether a given type of material is appropriate for the expected level of load and anticipated environmental conditions. As a result, design and construction practices may be altered in order to produce longer lasting pavements.

Pavement management engineers tend to gain the most from such studies. They are usually responsible for recommending various maintenance alternatives for specific applications. This is becoming an increasingly critical task since highway agencies at all levels (city, county and state) are generally operating under a limited budget which requires effective prioritization to provide the highest level of public service. Pavement management engineers are also responsible for setting up a Pavement Management System (PMS) and managing the collected data. Long-term pavement performance studies which develop performance models will help the engineers to evaluate the effectiveness of the PMS and determine the usefulness of the collected data.

The most common method of monitoring pavement performance is through field testing and surveys of actual road sections on a periodic basis. Pavement management systems are usually implemented for this purpose. Highway agencies have also been implementing highly effective quality control/assurance programs to measure materials properties considered to be critical to the long-term performance of the pavement. Development of pavement performance models which can tie the PMS data with materials properties is by far the most effective approach.

Attempts have been made over the last 30 years to develop models that can accurately predict the deterioration of highway pavements over time. In most cases the deterioration has been predicted by theoretical modeling and actual in-service pavement data were not used. In the cases where modeling was performed on in-service data, models were generally developed as a function of the pavement conditions alone - and environmental, materials and structural data were not included. Many of the pavement performance models that exist in the literature are very simple and include only some explanatory variables. The models generally do not account for common maintenance procedures and their effect on the pavement's rate of deterioration (4).

Theoretical modeling may produce deterioration rates which appear reasonable and can be extrapolated over a large range with few constraints. However, theoretical modeling suffers the major constraint of being dependent upon the expected theoretical behavior of the materials and the environment. This is acceptable when modeling materials with known properties and small expected deviations. Since pavement materials are much more variable than most other engineered materials, theoretical modeling has the tendency to produce unreasonable results. This method has been used primarily in the development of models focusing on individual damage or distress types. This is because individual distress modes can generally be simulated in the laboratory.

The most accurate method for developing pavement performance models is the use of a large number of test sections under tightly controlled conditions. The problem with this method is that it can be very costly and may not always allow for exact duplication of field data. This method has been successfully used for modeling a single type of rehabilitation procedure in a specific geographic location (5).

Therefore the most reasonable method for developing pavement performance models is the use of actual field performance data. Statistical modeling eliminates most of the before-mentioned problems but does add one major limitation. The model can only be used within the constraints of the in-service data from which it was developed.

II.1.a Pavement Performance Modeling in Arkansas, Iowa, Pennsylvania, and Washington

Four states (Arkansas, Iowa, Pennsylvania, and Washington) have developed pavement performance models based on information in their existing data bases (6). All four of these states have chosen to use functional performance indicators. This is partially because functional performance indicators allow the states to establish and incorporate life-cycle cost analysis into the models using their currently available data bases and existing PMS programs.

Arkansas used performance data to estimate a pavement's condition rating for the current year based on previous years' data. Components for pavement distress and ride are adjusted for traffic volumes. The pavement-s condition rating is plotted against its age, on a yearly basis. From Arkansas' limited analysis it was concluded that even though the curves fit the data reasonably well, they would have to be revised to account for the effects of cumulative ESAL's.

Iowa considered a more elaborate model which addressed some of the more obvious factors that could affect the performance of the overlay, such as thickness, aggregate durability, base and subgrade characteristics. Sites were selected and divided by service levels and pavement type (rigid and composite). The model did allow Iowa DOT to make some generalizations regarding material selection, but it also had several shortcomings. These included no allowance for maintenance and rehabilitation techniques, limited distribution of data points for loading and age, initial PSI's were all assumed to be constant, and only a few obvious variables that could affect the pavement performance were considered.

Pennsylvania generated performance curves from the roughness and traffic data for each of 22 monitored sites. The curves considered only rigid and composite pavement sections and while they do allow a reasonable prediction of PSI, the data considered were very limited.

Washington developed their curves based on the 5 years of data available in their data base. They considered a larger number of variables than the other three states which led their models to have good statistical correlations (R^2>.70). In all of their models, age was determined to be the most significant independent variable. Other variables such as overlay type showed generalized trends, but were not as significant.

Aside from the individual limitations of each model, all four state=s models shared the common limitation of being very generalized. In most cases this is because very few variables have been included in the final models. The model limitations can be attributed to the original data sets from which the models were developed; in most cases the data set included only a few specific test sections believed to be representative of the entire system.

The validity of the four state=s models depend on the degree to which the pavement sections used in developing the regression equations are representative of the entire system. Another limiting factor that most states have encountered is the limited amount of available data. Few states have enough data to develop models that can represent the entire life of the pavement. Five years of data may be adequate for developing equations for minor maintenance techniques, but falls short when considering a model for the life of a reconstruction job or a major overlay. Except Washington, the four states considered only one model, typically an overlay model. Washington's model accounted for any type of maintenance work. Most other models tend to ignore any maintenance work.

II.2 Life-Cycle Cost Analysis

The ISTEA act has forced all state highway agencies (SHA) to develop pavement management systems. The stage of development and degree of sophistication vary among the individual states. Several SHAs have the ability to perform LCCA, however, it is most commonly performed only at the project level for new construction to compare flexible versus rigid pavements. Pavement performance models are rarely available, and engineering judgement coupled with some historical data is typically used to predict performance and/or set rehabilitation and maintenance schedules. Maintenance cost data are available on a limited basis with questionable accuracy. User costs are not typically incorporated and salvage value may or may not be incorporated. Brief summaries are given below for the procedures used by some state DOTs.

II.2.a. Colorado DOT

The Colorado DOT uses LCCA at the stage of new construction to compare flexible versus rigid pavements and major rehabilitation projects. Pavement performance models are not used. Treatment performance lives are based on historical data and average daily traffic (ADT). For example if the ADT is less than 750 vehicles per day, a seal coat is said to last 3-7 years, and if the ADT is greater than 750 vehicles per day, it is said to last 1-4 years. The actual life used in the LCCA is up to the engineer. Fixed rehabilitation and maintenance schedules and costs are assigned based on the type of pavement. For example, a flexible pavement must receive a 2-inch overlay every 10 years and $600/lane-mile of maintenance each year, while a rigid pavement must receive a 2-inch flexible overlay at 20 years with joint sealing and 1 percent slab replacement, and $300/lane-mile of maintenance each year. User costs and salvage value are not incorporated into the analysis. The actual analysis is performed using computer software, either AASHTO's Darwin 2.0 or an in-house LCCA program. The LCCA employs the present worth economic method.

II.2.b. Wyoming DOT

The Wyoming DOT uses LCCA to compare projects after a committee in the Materials Division discusses and establishes alternatives. Typically two or three alternatives are selected for comparison. Pavement performance models are not used and performance lives are assumed based on recent experience. Fixed Aoccasional@ maintenance schedules and costs are used in the analysis along with user costs and salvage value. The present worth economic method is employed.

Colorado and Wyoming are typical examples of SHA's which do not have pavement performance models, use fixed rehabilitation and maintenance schedules, and have limited historical maintenance cost information.

II.2.c. Oregon DOT

A probabilistic approach of LCCA is used by the Oregon DOT as a basis for economic comparison of "large scale" construction projects (7). For each project alternative, initial designs are established along with their associated initial costs. Several rehabilitation strategies and costs are then developed for each initial design and each strategy is assigned a probability of occurrence in specific years. Figure 1 illustrates the concept for one initial design. A AP@ in the figure represents the probability of selecting a possible rehabilitation strategy. At year i (node i), consideration is given to performing rehabilitation work. The probability of performing rehabilitation in year i is P_2 and the probability of not rehabilitating is P_l.

Additionally, at year i (node k), three rehabilitation strategies are considered with probabilities P_{21}, P_{22}, and P_{23}. In year j (node j), two rehabilitation strategies are considered with probabilities of P_{ll}, and P_{12}. The final probability for each strategy is obtained by multiplying the probabilities at relevant nodes. As an example, the final probability for strategy 1 is P_l times P_{ll}. The sum of the probabilities for the alternative must equal unity.

Annual costs are computed for each strategy and multiplied by the corresponding probability in order to obtain weighted annual costs, expressed as:

$$WACi = Pi * ACosti$$

Where:

WACi = weighted annual cost for strategy i

Pi = probability for strategy i

ACosti = annual cost for strategy i

Weighted annual costs are then cumulated to obtain an expressed equivalent annual cost (EEAC) for the alternative evaluated. The EEAC is computed as follows:

$$EEAC = Sum(WACi) \text{ for } i = 1 \text{ to } m$$

where:

m = total strategies in the analysis

The alternative with the lowest EEAC is selected as the most economical. Similar concepts can be applied if the present worth method of economic analysis is desired.

II.2.d. Alaska, Arizona, and Kansas DOT

Alaska, Arizona, and Kansas have all retained Woodward-Clyde Consultants to assist in the development of their pavement management systems, including LCCA. All three states have models used to predict pavement performance (statistical/mechanistic). Alaska has two models to estimate pavement performance and will be used as an example (8). There were four steps used in pavement performance predictions for Alaska:

1. To predict pavement performance as a function of traffic, material and environment,
2. To predict pavement performance in permafrost areas as a result of thaw settlement,
3. To integrate effects of traffic and thaw settlement to produce an estimate of their combined effects and,
4. To estimate the dispersion around the expected values of performance based on the reliability of prediction models.

Step 1

The following regression models were developed for areas where permafrost was insignificant:

1) transverse cracking as a function of: age and freezing index.

2) fatigue cracking as a function of: ESAL=s and Benkelman Beam deflection.

3) roughness (Mays Road Meter data in inches per mile) as a function of: age, freezing index, number of transverse cracks, ESAL=s, Benkelman Beam deflection, and percent fatigue cracking.

The basic approach in developing the traffic and environmental related performance factors was to first develop models for fatigue (alligator) and transverse cracking and then to combine those forms of distress to predict roughness. As can be seen from a, b, and c above, performance as a function of traffic, materials, and environment is characterized in terms of alligator cracking, transverse cracking, and finally roughness.

Step 2

A model was developed to predict roughness (Mays Meter Data) as a function of differential settlement due to thawing in areas where permafrost is significant.

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Step 3

Roughness due to traffic and thaw settlement are added together to obtain a total expected roughness. If not in a permafrost area, the total roughness is simply due to traffic. At this point, both maintenance costs and user costs are estimated as a function of total roughness.

Step 4

Woodward-Clyde feels that exact prediction of future pavement performance is not possible, and that the dispersion around the best estimates of future performance is characterized by a coeficient of variation (COV). COV is the ratio of standard deviation to the mean. When regression modeling is performed, the coefficient of variation for each performance variable can be estimated from the standard error of estimate resulting from the lack-of-fit of data points from the mean value equation. COV=s of 0.39 and 0.45 were obtained for the alligator cracking and roughness models, respectively. The thaw settlement model was not developed using regression analysis and therefore no COV was obtained for it. A constant COV of 0.45 was assumed for the total roughness based on the above discussion.

Attempts were made to model maintenance costs as a function of fatigue cracking, roughness and thaw settlement. Regression analysis was used to develop a relationship between roughness and maintenance costs and is represented in Figure 2. The R^2 was 0.20 for the model. Although the R^2 is poor, the model was still used. Fatigue cracking and thaw settlement could not be correlated to maintenance cost using regression analysis. A Ageneral trend@ was established to relate fatigue cracking to maintenance costs and Aengineering judgement@ was used to relate thaw settlement to maintenance cost. Based on the relationships just described, it was decided that maintenance costs would be estimated using the roughness model.

Road user costs are incorporated in Alaska=s LCCA procedure. Both driver cost and vehicle operating costs are combined and termed excess road user costs. A relationship was developed to estimate excess road user costs as a function of Mays Meter data.

At this point models exist to predict roughness, fatigue cracking, maintenance costs, and road user costs. The coefficient of determination for the maintenance cost model is 0.20, and is not reported for any of the other models. It should be noted that only three to five years of data from a limited number of roadway sections were available/used to develop these models. There are obviously some uncertainties in using these prediction models, therefore the probabilistic theory is introduced into the modeling. One can estimate the probability that roughness or fatigue cracking would be equal to a specific value. Then for given values of fatigue cracking and roughness, maintenance and excess user costs could be estimated.

Continuous probability distributions of fatigue cracking and roughness at any given time were discretized into ten intervals, each having a probability of 0.10, and the median value for that interval was assumed to represent the interval. For a given variable X, the ten intervals and their representative values (medians) were as displayed in Table 1. X_p denotes the value of X such that the probability of being less than or equal to X_p is p. If X is normally distributed with mean = • and standard deviation = σ, therefore COV = (σ/•), then X_p may be calculated as:

$$X_p = \bullet + k_p \sigma$$

where:

k_p = a value from normal probability tables corresponding to the cumulative probability of p.

The assumption was made that if a pavement performs better or worse than the average at one time, it would continue to perform in the same manner at any other time. This is an arguable assumption. Based on this assumption, the performance values X_p at different time periods were connected to obtain a performance curve such that the probability of being less than or equal to the value on this curve at any given time would be p. A total of 10 different performance curves were thus defined, corresponding to ten values of p, for fatigue cracking and total roughness. The curves are shown schematically in Figure 3.

Maintenance cost and excess road user cost were then calculated for each performance curve, resulting in 10 cost figures for fatigue cracking and ten for total roughness. Averaging the ten values of cost for each distress at time t results in the expected cost at that time due to that distress. Therefore maintenance costs and user costs are established at each time t. Standard deviations of the costs are also calculated.

Figure 4 shows the maintenance policy used to estimate costs for fatigue cracking. The fatigue cracking model is used to estimate, with some uncertainty, that the amount of fatigue cracking will first reach 10 percent in the year t_1. Maintenance will then be performed theoretically reducing the amount of fatigue cracking to zero percent. At this point the fatigue cracking will continue to develop according to the initial prediction model (note the slope of the curve). When 10 percent cracking is reached again, in year t_2, maintenance will be performed theoretically reducing the amount of cracking to zero again. Maintenance cost is estimated as a function of the percent fatigue cracking in the year of maintenance. This process is repeated until time T, for which the comparisons of alternate designs are to be made (typically 15 to 20 years).

Expected maintenance cost due to fatigue cracking in the i^{th} year (EMCF(i)) is given by:

$$EMCF(i) = \Sigma \{MCF(iFC_p)*P(FC_p)\}/10$$

where:

$MCF(iFC_p)$ = maintenance cost for fatigue cracking in the i^{th} year if the performance FC_p is followed.

$P(FC_p)$ = probability of the performance curve FC_p.

Note the 10 in the denominator due to the 10 performance curves.

The present worth value of the total expected maintenance cost due to fatigue cracking (TMCF) for an analysis period of T years is calculated as:

$$TMCF = \Sigma\, \alpha_i\, EMCF(i) \quad \text{for } i=1 \text{ to } T$$

where:

α_i= present worth factor as a function of interest and inflation rates.

Expected maintenance cost due to total roughness is determined in a manner similar to that described for fatigue cracking. A limiting value of roughness is assumed to initiate maintenance and a reduction in roughness due to the maintenance is assumed. The required maintenance cost is a function of the percent reduction in roughness in the year when maintenance is performed.

Expected maintenance cost due to total roughness in the i^{th} year (EMCR(i)) is given by:

$$EMCR(i) = \Sigma \{MCR(i,R_p) * P(R_p)\}/10$$

where:

$MCR(i,R_p)$ = maintenance cost for total roughness in the i^{th} year if the performance R_p is followed.

$P(R_p)$ = probability of the performance curve R_p.

Note the 10 in the denominator due to the 10 performance curves.

The present worth value of the total expected maintenance cost due to total roughness (TMCR) for an analysis period of T years is calculated as:

$TMCR = \Sigma\ \alpha_i\ EMRC(i)$ for i=1 to T

where:

α_i = present worth factor as a function of interest and inflation rates.

Expected user costs in the i^{th} year (EUC(i)) are determined as a function of unit user cost in units of $/inch of roughness/ESAL, total estimated roughness in a given year and the number of ESAL=s for that year. An ESAL is an 18 kip equivalent single axle load. Expected user cost in the i^{th} year (EUC(i)) is given by:

$EUC(i) = \Sigma\ \{UC(i,R_p) * ESAL(i)\}/10$

where:

$UC(i,R_p)$ = user cost in $/ESAL in the i^{th} year if the total roughness performance R_p is followed.

ESAL(i) = number of ESAL=s in the i^{th} year.

Note the 10 in the denominator due to the 10 performance curves.

The present worth value of the total expected user cost (TUC) for an analysis period of T years is calculated as:

$TUC = \Sigma\ \alpha_i\ EUC(i)$ for i=1 to T

where:

α_i = present worth factor as a function of interest and inflation rates.

The present worth of the total expected costs (TEC) for a period of T years is the sum of the individual costs during the T year period and is expressed as:

$$TEC = I_0 + TMCF + TMCR + TUC + SV_T$$

where:

I_0 = initial construction cost in year zero.

SV_T = salvage value in year T.

The Woodward-Clyde Consultants methodology is very complex and it is doubtful that many of the personnel in the pavement community could thoroughly understand it, forcing the agencies to continuously rely on consultants to edit and update the system. Additionally it would be very difficult to explain at the legislative level. It seems as though the probabilistic theory is introduced due to a lack of confidence in pavement performance prediction models and maintenance cost information.

II.3 NDOT Pavement Management System (PMS)

Over the past 18 years, NDOT has implemented a Pavement Management System (PMS) in accordance with the ISTEA which monitors pavement conditions with time (9). The system was initiated in 1980 and provides yearly pavement condition data. The condition surveys are conducted on a mile-by-mile basis for the entire state-maintained system. Data are collected on cracking, rut depth, patching, surface condition, and ride. Additional data on traffic and accidents are collected for informational purposes only.

All these data are merged into a pavement conditions master file. Further analyses are conducted which generate seven performance indicators that are used to classify the pavement sections into one of four repair categories. These indicators include ride, rut depth, cracking, patching, bleeding, raveling, and the present serviceability index (PSI). The PSI used in NDOT's PMS between 1980 and 1994 was based on the PSI relationship that was developed during the AASHO Road Test experiment as follows:

$$PSI = 5.03 - 1.91 \log(1+SV) - 1.38\, RD^2 - 0.01\, (C+P)^{0.5}$$

Where:

SV= Slope variance (10^{-6})

RD= rut depth (in)

C= cracking area ($ft^2/1000ft^2$)

P= patching area ($ft^2/1000ft^2$)

In 1995, NDOT modified the PSI equation using the following relationship:

$$PSI = 5*e^{-0.0041*IRI} - 1.38RD^2 - 0.01(C+P)^{0.5}$$

Where:

IRI= international roughness index (in/mile)

RD= rut depth (in)

C= cracking area ($ft^2/1000ft^2$)

P= patching area ($ft^2/1000ft^2$)

The four repair categories are as follows:

a. Do Nothing

b. Maintenance

c. Overlay

d. Reconstruction

Distinctions among the categories are based on specific distress indicators and their severity. Points are assigned based on the severity and extent of each distress indicator and friction number (see Figure 5). The total summation of the points dictates the general repair category for a section of road. Figure 6 shows the breakdown of the point assignment system and respective repair categories.

The data analysis portion of the PMS produces a total of six reports. The DS-1 and DS-2 reports provide a distress summary by route, county, and milepost and a summary by district, route county, and milepost, respectively. The PD-1, PD-2, and PD-3 reports classify information on roadway miles which require maintenance, overlay, and reconstruction activities, respectively. The MS-4 report provides information on roadway miles requiring maintenance only, and it indicates a recommended repair strategy for each roadway mile. These reports provide information for: a) developing a periodic statewide status report indicating the effort necessary to maintain the entire state roadway system at a prescribed minimum service level; b) a database used to compare predicted and historic performance so strategies can be optimized; c) project prioritization; d) projecting costs and corrective actions and; e) aiding communications between districts, headquarters, and the Federal Highway Administration (FHWA).

III. DEVELOPMENT OF PAVEMENT PERFORMANCE MODELS

Routine maintenance and rehabilitation activities must be conducted in a timely manner to maintain an acceptable level of the present serviceability index (PSI) for a given pavement section. The major difference between maintenance and rehabilitation activities is that maintenance does not show an initial increase in the current level of PSI and only helps in slowing down the rate of deterioration while rehabilitation does show an initial increase in the PSI level and may completely change the rate of deterioration. Figure 7 shows the difference between the two techniques.

For example, when applying a chip seal, which is a maintenance treatment, a significant immediate increase in PSI is not noticed because a chip seal does not reduce roughness, a major component of the PSI equation. However, applying a chip seal, reduces or eliminates water penetration through the surface, thereby slowing further deterioration of the entire pavement structure. On the other hand, applying a thick overlay, which is a rehabilitation technique, immediately increases the current PSI of the road as well as slowing the rate of deterioration.

Usually the cost of a maintenance alternative is less than the cost of a rehabilitation technique. Therefore, in order to optimize the available budget and satisfy the needs of the entire system, highway agencies including NDOT strive to determine a balance between the maintenance and rehabilitation activities.

NDOT uses several maintenance treatments as well as various rehabilitation techniques. The objective of this task was to identify the various maintenance treatments and rehabilitation techniques most commonly used by NDOT and develop performance models for these techniques. The performance data of the selected projects will constitute the data base for the development of the performance models.

III.1 Selection of Maintenance and Rehabilitation Techniques

The primary goal of the selection process was to assure that the techniques to be modeled had been used often enough that they would provide a useful final product for NDOT. If a technique was used only on a limited basis, then the available performance data would be very limited and the developed model would not be extremely useful.

The initial selections were made based on several working meetings between the researchers and NDOT engineers from the Materials and Operations Analysis Divisions. These initial selections were then presented to the pavement management working committee, which has representatives from NDOT, FHWA, and the research team for final approval. The final list included two maintenance treatments and three rehabilitation techniques which NDOT uses on a regular basis.

Maintenance Techniques	Rehabilitation Techniques
	Flexible Overlays
Sand Seals	Roadbed Modifications
Chip Seals	Mill and Overlays

Several other techniques were proposed such as flexible overlays over rigid pavements, rigid overlays over rigid pavements, rigid overlays over flexible pavements, and recycling of flexible pavements. After reviewing these techniques with NDOT personnel, it was decided that these techniques have not been used often enough to develop a sufficient data base for analysis.

III.2 Selection of Projects

Once the final list of maintenance and rehabilitation techniques was established, the research concentrated on establishing guidelines for the selection of projects within each technique. In establishing the project selection guidelines, one must keep in mind the overall objective of the research. As mentioned earlier, the developed models should be used to predict the future performance of the selected techniques. These models will use statistical analyses of actual PMS, environmental, and materials data. Therefore, several minimum requirements must be satisfied to make the statistical analysis appropriate. The following criteria were selected as guidelines for project selection:

1. **Minimum Number of Replicates:** Since the models will be based on statistical analyses, there must be multiple sets of data which share a common basis. For example, there must be multiple projects which share the same geographical location for the same treatment type. For this purpose, the existing NDOT districts were used as various regions and replicate projects were selected within each district.
2. **Minimum Site Length:** When using actual field data, it is very important to select sites that are representative of the entire pavement section. Short projects may suffer from atypical data especially toward the beginning and end of a project. In addition, short sections may have been constructed in response to a localized condition and not as a normal construction project. Therefore, it was decided that a minimum site length of two miles must be maintained to eliminate any unusual or localized conditions.
3. **Availability of Traffic History:** Traffic loads are the most important factors influencing the long-term performance of pavements. The traffic data can be expressed in many different formats, including vehicles per day, percent trucks, equivalent 18,000-pound single axle loads (ESAL), etc. It was decided that each project must have traffic loading data. Since any type of traffic data can be converted to the required format providing that the appropriate conversion factors exist, the criterion for traffic data consisted of the availability of both traffic volumes and the appropriate conversion factors.
4. **Availability of Materials Data:** The unique feature of this study is the inclusion of materials data into the performance models. Therefore, the availability of materials data was considered as a criterion for the selection of any project. It was anticipated that in some cases elaborate materials data would exist while in other cases the data would be limited.
5. **Availability of Structural Information:** It is well known that the performance of a treatment will depend on the quality of the supporting structure. For example, a flexible overlay will perform better on a structurally strong pavement than on a weak pavement. Therefore, the structural information criterion included the availability of information on the thickness and type of the supporting layers.
6. **Availability of PMS Data:** As mentioned earlier, the actual field performance data represent the backbone of this study. Such data are summarized in a PMS data base. Therefore, the availability of the PMS data for the selected project is a very important criterion and must always be satisfied, otherwise the project can not be selected for analysis.

The existing NDOT districts lines were used as regional boundaries. Projects were selected for maintenance and rehabilitation techniques within each district. The projects selection criteria were strictly followed with very few exceptions; some projects that were just under 2 miles long were accepted due to the limited number of available projects. The selected projects are summarized in Tables 2 through 6.

III.3 Data Collection

Three categories of data were of interest: Structural, environmental , and PMS. From each of these general categories, a list of factors that could possibly affect the performance life of the pavement system was derived. In order to be unbiased, the lists of factors were developed before any of the actual data sources were examined.

The lists were organized into standard data collection forms to expedite the collection process. The forms became known as "wish lists," as they contained all of the information the researchers hoped they could obtain. The forms were divided into four primary sections:

1. Project identification and information;
2. Specific material and construction information on the technique of interest;
3. Information desired from the PMS data base, including environmental data;
4. Information on any past construction techniques and materials used within the bounds of the current project.

Standardizing the data collection forms created more efficient collection and reduction of the large amount of information. Figure 8 is an example of the form used for the overlay activity; standard forms used for other techniques may be found in Appendix A.

In summary, the following data were collected and used in the development of performance models:

2) **Materials data of activity being modeled:** These data include the types and percentages of asphalt binder and aggregates used in the maintenance or rehabilitation activity for which the performance model is being developed.

3) **Materials data of existing pavement layers:** These data include the types and percentages of asphalt binder and aggregates used in the layers underlaying the maintenance or rehabilitation activity for which the performance model is being developed.

4) **Structural data:** These data include the thickness of the various layers in the pavement structure including the thickness of the maintenance or rehabilitation activity that is being modeled. The structural number (SN) as defined by the AASHTO design guide was used to normalize the structural data among all of the pavement section. Reference 3 describes the method used to convert the layer thicknesses into SN values.

5) **Pavement performance data:** These data include the PSI, percent cracking, and average rut depth values as obtained from the NDOT PMS data base.

6) **Traffic data:** The equivalent single axle load (ESAL) was used as the traffic element. The average daily ESAL figures were obtained from the PMS data base and used to obtain the cumulative ESALs over the life of the maintenance or rehabilitation activity.

7) **Environmental data:** These data include maximum and minimum temperatures, number of freeze/thaw cycles, number of wet days, and annual precipitation.

The process of obtaining and standardizing all of the necessary data elements has been extensively described in reference 3.

III.4 Model Development

The model development task was a multifaceted operation that involved a great deal of testing as well as regression analysis. The purpose of the model development was to provide a conceptually simple method for examining the functional relationships among variables. The task was divided into the following processes: data review, regression analysis, equation review and tests of reasonableness, equation modification, additional regression analysis, and final model selection.

All of the statistical and regression analyses were performed using the SAS Programming Language. The SAS software is a combination of programs originally designed to perform statistical analyses of data, complex data management and provide a high-level programming language.

III.4.a. Data Review

As discussed earlier, numerous projects were selected under each of the maintenance and rehabilitation treatments. Each project encompasses several miles of a roadway. The NDOT=s PMS measures pavement performance at individual mileposts. Therefore, the performance data of each project includes multiple measurements depending on the number of mileposts within each project. The most appropriate way would be to average the data and use the mean value as representative measure of the project=s performance. However, prior to averaging the data, it was necessary to identify data points which do not fit the general trend. These points are referred to as Aoutliers@. The presence of these Aoutliers@ has the tendency of influencing the evaluated average and therefore provide a skewed measure of the projects performance.

The Inter Quartile Range (IQR) analysis was used to identify the outliers which would then be deleted from the data set prior to the calculation of the average. This analysis consists of identifying the first and third quartiles which are defined as follow:

Q1 = the value below which 25 percent of the data falls

Q3 = the value below which 75 percent of the data falls

The IQR is then defined as:

IQR = Q3 - Q1

Using the Q1, Q3, and IQR, the upper and lower limits of acceptable data can be calculated as follows:

Lower Limit (LL) = Q1-1.5*IQR

Upper Limit (UL) = Q3+1.5*IQR

Outliers are identified as data points that do not fit within the LL and UL limits.

Using the IQR analysis all of the PMS data were reviewed and outliers were eliminated prior to the use of the data in the development of performance models.

III.4.b. Regression Analysis and Model Selection

Linear regression analyses were used to develop relationships between pavement performance indicators and project properties. As indicated earlier, the project properties include structural, materials, environmental, and traffic data which are specific to each project section. The following performance indicators were identified as possibilities for modeling puproses:

8) Surface cracking

9) Permanent deformation or rutting (RD)

10) Surface roughness (IRI)

11) Present serviceability index (PSI)

Several forms of performance models were considered for each of the four performance indicators. The models forms included the followings:

12) Models for each individual district

13) Models for all districts combined

14) Models including materials properties

15) Models excluding materials properties

Sixteen models were developed for each maintenance and rehabilitation treatment which makes the overall number of models that were evaluated close to 50. The following criteria were used to identify the models that will be included in the system analysis process.

1. Reasonable fit of the data as described by the R-squared value.

2. Minimum error in the estimated performance as described by the root mean square error (RMSE)

3. Good stability of the model as described by the ability of the model to predict performance over a wide range of parameters.

The application of the first and second criteria have shown serious limitations of the models developed for cracking and rutting performance. The R-squared values for such models were always below 0.25 and the RMSE were very large which made the prediction ability of these models very poor. The models for roughness and PSI showed good prediction abilities as described by high R-squared values and low RMSE. However it was decided that the PSI models would be used since the PSI is largely dependent on ride and includes some effects of the rut depth and surface cracking. The next step was to assess the need for individual district models and whether or not material properties should be included in the models.

Appendix B shows all the performance models for the various combinations of individual districts, combined districts, and with/without materials properties. By looking at the models parameters and implementing the three criteria identified above, it was concluded that the models based on the combined districts with materials properties should be used. The inclusion of materials properties greatly improved the prediction capability of the models and reduced the error associated with the estimated performance. The combined districts models offer slightly better prediction capabilities but significantly improved the stability of the models over a wide range of input variables. The selected models are presented in Tables 7 through 11.

III.4.c. Definition of Variables

As can be seen from Tables 7 through 11, the models include a large number of variables which must be provided in order for the models to be executed. In order to keep track of these variables, the following list describes the individual parameters, their source, and their corresponding units.

AC: Type of binder used in first the structural layer below the flush, sand and chip seal projects, located in as-built plans, identified as a type.

AGGRATE: Aggregate spread rate for chip and sand seal projects, found in maintenance records, lbs/yd^2.

AGGSIZE: Maximum nominal aggregate size used in chip seal projects, found in maintenance records, 3/8" or 1/2".

BINDRATE: Binder application rate for flush, sand and chip seal projects, found in maintenance records, gal/yd^2.

Binder: Type of binder used in maintenance or rehabilitation projects, found in maintenance records or as built plans, identified as a type. This variable is not part of the actual equation but it is used to select the binder constant which is part of the actual equation.

THICK: Depth or thickness of overlay used in rehabilitation projects, located in as-built plans, inches.

ESAL: Cumulative value of annual Equivalent 18,000-pound Single Axle Loads. The ESAL value fro year zero of a road segment is the product of 365 times the daily equivalent 18,000-pound single axle loads shown in the D18-kip field of the PMS database. For subsequent years, a growth factor is applied to the previous year=s value. The cumulative value is the sum of the values from year zero through the year of interest.

FRZ: The total number of freeze/thaw cycles that a pavement may experience over the course of one year, obtained from the weather section of the PMS data base, cycles per year (one freeze and one thaw are counted as one cyle).

RBDEPTH: Depth of road bed modification in inches. Located in the as built plans.

MAXTEMP: Maximum average yearly temperature that a pavement section may experience, obtained from the weather section of the PMS data base, degrees Fahrenheit.

MINTEMP: Minimum average yearly temperature that a pavement section may experience, obtained from the weather section of the PMS data base, degrees Fahrenheit.

SN: Structural number prior to application of any rehabilitation or maintenance technique. For roadbed modification (RBM), this structural number is calculated at the top of the cement treated base (CTB).

WETDAY: The total number of wet days. Days that moisture was recorded, over the course of one year, obtained from the weather section of PMS data base, days per year.

YEAR: Service year of the project. The year of construction is represented by year zero.

S5,S10, S15: Indicate the application of surface treatments at 5, 10, or 15 years after initial construction, respectively.

III.4.d. Model Limitations

One major drawback of the use of statistical analysis in developing pavement performance models is that the PMS data base does not include a full factorial experiment. In other words, some unrealistic combinations which are needed to complete the factorial design may not exist in the actual PMS. For example the combination of a structurally weak pavement and high ESAL's may never exist in reality. However, it is still needed to complete the factorial design.

Since complete factorial designs do not exist in actual PMS data bases, the statistical relationships will be limited to applications which lie within the boundaries of realistic combinations of variables. Therefore, the statistically based models should only be used with realistic variables and combinations of variables. If unrealistic values or combinations are used in the models, the output of the models may prove to be highly unreliable. For example, if the model is used to predict the performance of a pavement section with a low structural number that is subjected to very high ESAL's, the output of the model may be very unrealistic. This results from the fact that pavements with low structural numbers are not built to carry high ESAL's and vice versa.

IV. DEVELOPMENT OF LIFE-CYCLE COST ANALYSIS

The objective of this task was to develop a life-cycle analysis for each maintenance and rehabilitation technique, using performance histories developed by the performance models. These specific life-cycle cost analyses were combined together to develop a network optimization system.

The completion of this task required the performance of the following four individual subtasks:

1) Selection of Analyses and Parameters
2) Establishment of Performance Periods
3) Selection of Cost Factors
4) State Highway Agencies Survey

IV.1 Selection of Analyses and Parameters

Life-cycle cost analysis (LCCA) can be defined as the economic assessment over the useful life, expressed in terms of discounted dollars. In pavement engineering, life-cycle cost refers to all costs involved with the construction, maintenance, rehabilitation and user impacts of a pavement over a given analysis period. A LCCA enables the pavement engineer to optimize expenditures of available funds by providing an economic assessment of alternate design/rehabilitation/maintenance strategies. When future rehabilitation alternatives coincide with anticipated needs during the pavement service life, pavement maintenance and rehabilitation costs are minimized. A LCCA will distinguish the most economical alternative over time.

LCCA involves the following five steps:

1. Any and all initial treatment alternatives must be identified.
2. An analysis period and treatment scheme for each alternative must be determined.
3. The cost of each alternative and annual maintenance must be determined.
4. The treatment alternatives must be compared on an economic basis.

5. The best treatment scheme must be selected based on the LCCA.

IV.1.a. Economic Analysis Method

AASHTO prescribes that one of two methods of economic analysis be used; Present Worth (PW) or Equivalent Uniform Annual Cost (EUAC), with preference given to the PW method (10). The Present Worth method involves the conversion of any present and future expenses to the basis of today's dollar. The present worth of a future expenditure is equivalent to the amount of money that would need to be invested now at a given compound interest rate for the original investment plus interest to equal the expected cost at the time it is required. The summation of present worth costs are then compared for each alternative. The present worth equation is expressed as:

$$PW = F(1/(1+i)^n)$$

where:

F = A future sum of money at the end of n years

i = Discount rate

n = Number of years

The Equivalent Uniform Annual Cost method requires the conversion of all present and future expenditures to a uniform annual cost (11). EUAC reduces all costs to a common basis of a uniform annual cost for comparison. Recurring costs, such as annual maintenance, are already expressed as annual costs and need not be discounted. The equivalent uniform annual cost equation is expressed as:

$$EUAC = PW(i(1+i)^n)/((1+i)^n-1)$$

where:

PW = Present worth

i = Discount rate

n = Number of years

It was recommended that this research project uses the PW method of economic analysis since it is the method recommended by AASHTO and the most commonly used state highway agencies.

IV.1.b. Discount Rate

When performing a life-cycle cost analysis, a discount rate is required to compare costs occurring at different points in time. A discount rate reduces the impact of future costs on the analysis, reflecting the fact that there is a time value to money. Discount rate can be defined as the difference between the market interest rate and inflation, using constant dollars. Constant dollars refers to an expression of costs stated at price levels prevailing at a particular (constant) date in time, whereas current dollars is an expression of costs stated at price levels prevailing at the time the costs are incurred. AASHTO recommends the constant dollar approach, rather than the use of inflated or current dollars for economic analysis, because it avoids the need for speculation about future inflation in arriving at the economic merit of the alternative.

Discount rate may affect the outcome of a LCCA because certain alternatives may be favored by higher or lower discount rates. Using a low discount rate will favor alternatives with high initial costs because future costs are included at little more than face value. When high discount rates are used, alternatives which span costs over a long period of time will be favored because future costs are discounted in relation to the initial cost. If alternatives require similar rehabilitation and maintenance costs, the discount rate will have little effect on the analysis and initial costs will have the greatest effect.

Choosing an appropriate discount rate is not always simple, because the difference between interest and inflation rates is not constant over time. This makes it impossible to select a unique discount rate that will always be appropriate over time. Because we cannot predict discount rates for extended periods of time, it would be conservative to select a discount rate between 3.5 and 5 percent, as the discount rate has been within this range for many years (12). A discount rate of 4 percent has been most commonly employed in pavement LCCA. Discount rate must always be kept constant when comparing alternatives.

It was recommended that this research project employs the discount rate into the LCCA as a variable which would allow the flexibility of changing it in the future.

IV.1.c. Analysis Period

In order to conduct network optimization, an analysis period must be selected. An analysis period may contain several rehabilitation and maintenance treatments with each treatment having a unique performance period. Therefore, the combination of multiple rehabilitation and maintenance treatments along with their corresponding performance periods should cover the entire analysis period. Figure 11 shows a 20-year analysis period which includes an AC overlay followed by two sand seals and then followed by a second AC overlay.

In the past, pavements were typically designed and analyzed for a 20-year performance period, since the original Interstate Highway Act of 1956 required that traffic be considered through 1976. It is now recommended that consideration be given to 20 year or longer analysis periods, since these may be better suited to the evaluation of alternative long-term strategies based on LCCA. It is also emphasized that the analysis period should be extended to include at least one rehabilitation treatment. The 1986 AASHTO Guide for the Design of Pavement Structures gives the following general guidelines for analysis periods for new construction:

Highway Class	Analysis Period (years)
High-Volume Urban	30 - 50
High-Volume Rural	20 - 50
Low-Volume Paved	15 - 25
Low-Volume Aggregate Surface	10 - 20

An analysis period of 25-40 years is recommended for NDOT's flexible pavements for new construction and 20 years maximum for rehabilitation.

When recommending the length of the analysis period, the following two issues should be considered: 1) Selecting an analysis period which represents the realistic life of asphalt mixtures, and 2) selecting an analysis period which ensures that one or two rehabilitation activities can be included within the period. A 20-year analysis period would satisfy both issues: a) asphalt mixtures could experience severe aging and disintegration problems after 20 years and b) with the 20-year period at least one or maybe two overlay may be implemented.

IV.2 Establishment of Performance Periods

The performance period of a maintenance or a rehabilitation technique represents the length of time that the treatment would last prior to reaching an unacceptable level of service. In this case the PSI is used as the performance indicator. Therefore, the performance period will be the length of time between the time the treatment is applied and when the PSI reaches an unacceptable level on a scale of 0 to 5.0. This unacceptable serviceability is commonly referred to as the terminal PSI. NDOT uses the following critical values:

	Flexible Pavements	Terminal PSI
Interstate, national highway system, and other routes with		
	average daily traffic (ADT)>750	2.5
	All other routes with ADT< 750	2.0

The most important step in this analysis is to define the performance period for each maintenance and rehabilitation technique. The performance models will be used for this purpose. These models will generate a performance curve similar to the one shown in Figure 9 for each maintenance or rehabilitation technique used in Nevada (2 maintenance and 3 rehabilitation techniques can be modeled).

In addition to using the performance models, this task will perform a reality check for the recommended performance periods. These reality checks are necessary because the actual performance period of the pavement would normally include other factors which can not be considered through the performance models. These factors include traffic accidents, high maintenance costs, specific site failures, etc. In addition, some roads sections were not maintained or rehabilitated at the time when their level of service dropped to the critical level due to budget constraints. Therefore, the reality checks were developed to provide guidance to the engineer in interpreting all the external factors which could not be handled through the performance models. These checks consisted of normal performance period for each maintenance and rehabilitation technique. Table 12 summarizes the performance periods used in the NDOT system. An extensive review of the process by which these performance periods were established has been presented in reference 13.

IV.3 Selection of Cost Factors

Cost factors are the costs associated with the LCCA that cover the full life cycle from initial design through the end of a performance period. There are several costs which must be considered in a life-cycle cost analysis for the comparison of rehabilitation and maintenance treatments. These costs include: first costs, annual maintenance costs, road user costs, and salvage value. The objective of this subtask was to identify these costs for use in the LCCA.

IV.3.a. First Costs

First costs include both the initial and construction costs which are related to the design and construction of the rehabilitation or maintenance treatment. Initial costs include the costs of site investigation, traffic analysis, pavement and material design, and preparation of the final plans and specifications for the project.

First costs for the five common rehabilitation and maintenance (the same treatments that performance models were developed for) were obtained from NDOT's Operations Analysis Division. The first costs were given in units of dollars per square yard. All unit costs are on a statewide basis, in other words there is one price for each treatment for all districts. Table 13 summarize the rehabilitation and maintenance first costs as obtained from NDOT.

IV.3.b. Annual Maintenance Costs

The cost of annual maintenance after the application of a rehabilitation or maintenance treatment may significantly affect the life-cycle cost of that treatment. A treatment may appear inexpensive based on initial cost, but if excessive annual maintenance costs are required after placement of the treatment, the life cycle-cost of the treatment will not be favorable. NDOT's Maintenance Manual prescribes 10 maintenance activities (14). The maintenance activity numbers and their descriptions are listed in Table 14. One activity was added to the 10 NDOT activities and it was coded as activity 101.11. The data contained several instances where a flush, sand, or a chip seal was applied to only a small portion of a mile. Therefore activity 101.11 was established as a general seal activity to include flush, sand, and chip seals which covered less than 2500 square yards.

Maintenance data for all the projects that were used in the development of the performance curves were obtained from the Operations Analysis Division of NDOT. The data supplied included: project number, system and route, from and to mileposts, from and to dates, PSI, maintenance activity number, units and costs for each maintenance activity performed on each mile of pavement. The first item that had to be addressed was to update the historical cost data into 1994 dollars. Because the data were obtained from 1981 to the present and maintenance costs have changed over that time period due to increased material and labor costs, it was necessary to bring all of the costs to a common time frame (1994). The construction cost index method was used to update the earlier costs to today's costs. The construction cost index method produces a current estimated cost based on the cost at the time it was incurred and an index which is based on actual historical price trends (15). The following equation was used:

$$C_c = C_o*(I_c/I_o)$$

where: C_c = Current estimated cost

C_o = Cost at other time "0"

I_c = Current index number

I_o = Index number at other time "0"

The index numbers employed were obtained from *Price Trends for Federal-Aid Highway Construction* as compiled by the Federal Highway Administration from reports by state transportation agencies (15)(1987 is the base year for this publication).

After updating the maintenance costs to the current year, relational plots were developed to determine general trends in annual maintenance costs. There were no distinguishable trends due to the high variability of the data. The data was further broken down by district and rehabilitation or maintenance treatment. Again no distinguishable trends were observed due to the high variability of the data. There are many factors which could contribute to the variability in the data, including: geographical location, several climatic factors, asphalt cement and mixture properties, traffic, and even maintenance philosophy, to name a few. An example of different maintenance philosophies would be the engineer who fills the cracks as they first appear and the engineer who waits for the cracks to open up to the maximum allowable width under the Maintenance Management System (MMS) Manual of Instructions.

The overall objective was to develop a system by which annual maintenance costs could be established for each maintenance and rehabilitation technique with minimal variability. Several approaches were investigated, including the following:

1. Develop annual maintenance models which can predict annual maintenance costs as a function of PSI.

2. Develop a probability of occurrence and associated costs models which can predict the need for a certain type of annual maintenance and the associated cost in the years following a certain treatment.

3. Develop an overall maintenance cost system which predicts the total expenditures on a given treatment after the initial construction regardless of the type of annual maintenance being applied.

4. Develop a fixed period cumulative maintenance cost system which predicts the cumulative expenditures for a given treatment as a function of number of years after construction.

Reference 16 includes an extensive discussion of all four systems. The fourth system was the only one that showed a significant reduction in the variability of the annual maintenance costs. This system is described below.

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Fixed Period Cumulative Maintenance Costs

As a final attempt to reduce the variability in the data, the fixed period cumulative annual maintenance costs were determined. The idea here was to cumulate the annual overall maintenance costs from year to year reducing the effect of cyclic maintenance on the overall cost variability. The data were sorted by district and rehabilitation or maintenance treatment. The total cost of all annual maintenance performed in each year following the application of a rehabilitation or maintenance treatment was determined for each project. These costs were then divided by the project length to obtain a cost per mile in each year. The cost per mile for each project was then divided by 7040 (one milex12 feet lane width =7040 yd^2) to obtain an overall annual maintenance cost per square yard for each project in each year. These costs were then cumulated from year to year for each project. For example, if a project received 0, 5, 0, 6, and 7 cents per square yard of maintenance in the first five years after a rehabilitation treatment, the cumulative maintenance costs would be 0, 5, 5, 11, and 18 cents per square yard in years 1 through 5 respectively. The cumulative cost for each project in each year was then summed and divided by the total number of projects in each year to determine the fixed period cumulative maintenance cost.

Additionally standard error and margin of error are evaluated. Standard error (σ_x) is a measure of the reliability of the mean (x), as an estimate of the mean probability distribution (μ). Standard error decreases in proportion to the square root of the number of observations; for example, it is necessary to quadruple the sample size in order to halve the standard deviation of the sampling distribution of the mean. Standard error may be represented as:

$$\sigma_x = (\sigma / \ n)$$

where:

σ = standard deviation of the probability distribution.

n = number of observations.

The margin of error is the range in which ninety-five percent of the maintenance costs will lay based on the mean. As an example, if a fixed period cumulative maintenance cost is 50 cents per square yard and the margin of error is 10 cents, then it may be stated that with 95 percent confidence, maintenance costs are between (50-10) = 40 and (50+10) = 60 cents, or simply, 50 cents +_ 10 cents. The margin of error is established by multiplying the standard error (σ_x) by the area (α) under a student t-distribution for a specified number of degrees of freedom. The number of degrees of freedom may be considered the same as the number of observations (n) in this case.

Using this approach, it was discovered that variability in maintenance costs goes down with time for a particular treatment until a point at which the variability starts to increase again, after which they may decrease again. Tables 15-19 summarize the average values of cumulative maintenance costs and their associated variability at various fixed periods for the maintenance and rehabilitation techniques. As previously mentioned, the cyclic nature of actual maintenance is the reason for this. The increase in variability usually occurs just beyond the average performance life of the treatment. This is reasonable because the number of projects which last longer than average obviously goes down and their associated maintenance costs typically go up, driving the standard error up. Based on this rational it is recommended that the fixed period cumulative maintenance cost be determined in a year in which variability is low for a particular treatment and that this cost be spread over the number of cumulated years. Variability is determined by inspecting the standard error relative to the mean, or simply what percentage of the mean the standard error is. The lower the percentage, the lower the variability.

For some maintenance and most rehabilitation treatments, there are two variability cycles. Therefore the cumulative maintenance cost at the end of the first cycle would be spread over the first cycle, and the cumulative maintenance costs for the second cycle would be spread over the second cycle. For example, for district 1 overlays the variability or error increases up to year 5, then drops in year 6 before increasing again in years 7 and 8, and finally drops again in year 10. The annual maintenance cost after applying an overlay in district 1 for the first six year would then be determined by dividing the mean cost for cumulative years 1 through 6 by six years ($0.453 per square yard divided by 6 years) = $0.0755 per square yard per year. Then for year 7 through 10 the annual maintenance cost would be [($0.523 - $0.453 per square yard) divided by 4 years)] = $0.018 per square yard per year. This requires that the first cycle maintenance costs be subtracted from the second cycle maintenance costs when performing LCCA, as described above.

The expected life of a treatment coupled with the periods in Tables 15 through 19 where the variability is relatively low will dictate the annual maintenance cost to employ. The following is a list of recommended cumulative years to be used for determining annual maintenance costs:

Treatment	Cumulative Year
Sand Seal District 1	4
Sand Seal District 2,3	3
Chip Seal District 1	5
Chip Seal District 2	3,6
Chip Seal District 3	3
AC Overlay District 1	6,10
AC Overlay District 2	6,9

AC Overlay District 3	5,10
Roadbed Modification District 1	3
Roadbed Modification District 2	6
Roadbed Modification District 3	6,8
Mill and Overlay Statewide	4,8

The variability in annual maintenance cost is significantly reduced when the cumulative approach is employed. It is also very useful when performing economic analysis where salvage value must be calculated, because only the cumulative maintenance cost up to the end of the analysis period need be included. It was recommended that this fixed period cumulative maintenance cost be employed for estimating annual maintenance costs.

IV.3.c. Road User Costs

Road user costs are associated with driving on the road. They consist of increase in travel time, increase in fuel consumption, increase in vehicle operation and maintenance costs, and accidents. It is very difficult to put monetary value on these items, especially accidents. Currently, there are models available for estimating traffic delay and user operating costs using the AASHTO guidelines. A traffic delay model was developed by Scrivner et al, and has been revised by others (17). This model basically aims to predict the length of delay as well as the number of vehicles delayed due to a construction project. Necessary input for the model includes: construction production rates, quantity of work to be done, average daily traffic, daily traffic distribution, traffic detour models, and traffic speed profiles. This information is not stored in the PMS and would have to be gathered for each individual project. Obviously this model would require detailed study of each site prior to actual construction. This would be quite costly and therefore not worthwhile for most projects. Traffic delays, especially in urban areas, do need to be given serious consideration, however. Engineering judgement could play a significant role in this consideration. Employing several maintenance procedures over time, rather than overlaying, for instance, could reduce traffic delays and keep the motoring public happy.

Zaniewski developed an operating cost model for the FHWA (18). The model estimates operating costs based on a decrease in PSI. Zaniewski developed consumption rate tables for use with his model. His data are based on a five percent inflation rate, zero grade, and a fifty-five miles per hour operating speed. If Zaniewski's model were used, these tables would need to be continually updated to reflect current conditions. User input includes: detailed vehicle class distribution, initial PSI, terminal PSI, and PSI after completion of work. This model would also require detailed study of each site and would not be economically feasible for all projects.

Accident data is collected by the Department of Motor Vehicles (DMV) from respectable investigating agencies. Urban data is referenced by intersection and rural data is referenced by milepost. Rural data is sorted by computer, but urban data must be sorted by individual NDOT districts and summarized manually. Accidents that are directly related to or have the potential to be directly related to pavement condition are included in the PMS. Accidents that are potentially related to pavement condition include wet weather and pavement condition only. At the present time this data is only informational in the PMS, however, it can and does influence the prioritization and type of repair. At the present time NDOT is not collecting skid data on a defined basis and is not certain when or on what basis the skid data will be collected in the future.

Considering the extensive data requirements needed for the implementation of user costs and after consultation with NDOT's PMS Committee, it was recommended that user costs not be included in the LCCA.

IV.3.d. Salvage Value

Salvage value is the residual value of the pavement at the end of the performance period or its design life if they coincide. Salvage values may be positive or negative depending on the remaining life of the pavement at the end of the performance period. A situation in which a negative salvage value would be encountered would be when a roadway section has to be completely removed and replaced to be rehabilitated. This is a common scenario with rigid pavements. Salvage value must be expressed in terms of dollars.

There are three possible methods of determining salvage value. The economical analysis approach (PW or EUAC) employed in the analysis will dictate the method to be used. If PW analysis is used, a percentage of the initial construction cost should be applied for the salvage value. Fifty percent of the initial cost was most commonly cited for salvage value in the literature (7,8). If EUAC is employed, then the EUAC may be multiplied by the remaining life at the end of the analysis period to determine a salvage value. AASHTO recommends the use of PW analysis, which is the method most commonly found in the literature (10). The method used in the analysis to determine salvage value consists of multiplying the last construction or resurfacing cost applied to the section by the ratio of the unused expected life to the total expected life.

Salvage Value = C*(UL/TL)

where: C = Last rehabilitation or construction cost

UL = Unused life

TL = Total expected life

IV.4 State Highway Agencies Survey

The objective of this subtask was to gather information on what other states are currently using in the areas of prioritization, LCCA, and network optimization. Such investigation would provide guidance as to what really works in real life situations and will help to eliminate the processes which could not be implemented in the field.

As part of this subtask, letters were sent to all State Highway Agencies (SHA) in an attempt to determine what different agencies are using for Prioritization, Life-Cycle Cost Analysis, and Network Optimization schemes. Seventeen SHA's sent written responses. This was followed by telephone surveys with the SHA's that have not responded. Thirteen phone surveys were successfully collected, therefore a total of 30 agencies were surveyed. The findings concerning each of these items are discussed individually in the following section.

IV.4.a. Prioritization

The majority of the SHA's surveyed are prioritizing projects based on condition data accumulated annually and stored in their PMS databases. Agencies that don't prioritize on this basis either have not implemented a PMS or are using network optimization schemes. Table 20 indicates that a total of 28 SHA's out of 30 are presently employing prioritization process.

IV.4.b. Life-Cycle Cost Analysis

Twenty-three of the 30 (77%) agencies contacted are presently using LCCA in one form or another, however most are using it only on the project level. The majority of the agencies are performing their calculations by hand with a few exceptions who are using PC-based software (either commercial or developed in-house). For example, Colorado is using DARWIN 2.0 which was developed for the FHWA. Table 21 is a summary of the LCCA survey results. The agencies that are not using LCCA have implementation plans in the near future.

The majority of the agencies employing LCCA are using it to compare asphalt concrete with portland cement concrete alternatives for new roadway surfaces. Pavement performance models were not typically used in these analyses. Most states have fixed maintenance and rehabilitation strategies which are employed for the LCCA, based on historical data and engineering judgement. Oregon is using a probabilistic approach which is fairly simple, but probabilities are assigned to different repair strategies used which could be difficult to define/verify. Kansas uses the Markov principle in its LCCA.

IV.4.c. Economic Analysis

All agencies surveyed are using the present worth analysis method with the exception of two, which are using both the present worth and equivalent uniform annual cost methods.

IV.4.d. Analysis Period

Analysis periods ranged from 20 to 60 years. The majority of SHA's used 20 to 40 years which is in-line with AASHTO recommendations. A few states, like New York, use the longest of all possible alternatives, all of which must include at least one rehabilitation. Pennsylvania uses 20 years for rehabilitation and maintenance of existing roadways and 40 years for new construction.

IV.4.e. Discount Rate

Discount rate, which is the difference between market interest rate and inflation, ranged from 3 to 7 percent. Sixty-two percent of the SHA's surveyed employed a rate of 4 percent. South Carolina starts with 4 percent and performs a sensitivity analysis on the LCCA using higher and lower rates to arrive at a final rate. Two agencies do not use discount rates, they use the construction price index to estimate the cost of future construction.

IV.4.f. User Costs

Only seven of the agencies are including user costs in their LCCA. Several states have attempted to include user costs, but found them difficult to quantify or that they commonly skewed the analysis. Some states felt they lacked the necessary database for calculation, but most indicated that user costs, when calculated, were generally high relative to the other costs involved. Washington and Maryland only include costs related to traffic delays. Pennsylvania includes user costs on high volume roads only, and Montana includes them in all initial analysis, but they are often dropped in the final analysis.

IV.4.g. Salvage Value

Salvage value is considered in LCCA by 62% of the SHA's surveyed. Some agencies calculate salvage value as a percentage of the initial construction cost, while others applied EUAC times remaining life or the last rehabilitation cost times the ratio of remaining life to total life. Illinois and Indiana only consider salvage value when the existing roadway surface is recycled, and Arizona uses the condition of the roadway surface as a base for a salvage value. The longer the analysis period, the lower the salvage value will be using the PW analysis. For this reason Iowa doesn't consider salvage value because an analysis period of 50 to 60 years is used.

IV.4.h. Network Optimization

Seven of the SHA's surveyed claimed to be employing network optimization, and several are attempting to develop and implement it. The basis of the systems that are presently being used is fundamentally the same. A threshold roadway condition, for example minimum PSI, is established and the objective of the network optimization is to maintain the entire state roadway system at or above this threshold with a given budget. Some states allow a small percentage of low-volume roads to drop below the threshold in the optimization process.

V. OPTIMIZATION ANALYSIS

The objective of this task was to develop a system to prioritize the various rehabilitation or maintenance techniques and to recommend a technique which will provide the best performance at the lowest cost. This task provides the pavement engineer a system by which to compare the various rehabilitation alternatives (treatments or sequences). For example, the pavement engineer will be able to compare the performance and economic benefits generated by applying an overlay followed by a chip seal and followed by another overlay versus applying two consecutive chip seals followed by an overlay and then followed by two consecutive chip seals. Both of these schemes will lead to the same analysis period but each one will have different cost figures spanned over the entire period.

In order to develop a network optimization system, several factors must be established in addition to the performance models and the LCCA. These factors are discussed below.

V.1 Pavement Segments Data Base

In order for any agency to be able to conduct network optimization, it must have a full inventory of the current pavement network. The current NDOT PMS evaluates pavement performance based on milepost units. Conducting optimization by milepost units would present an overwhelming problem. This approach was found to be unrealistic and unpractical. Therefore, it was recommended that the NDOT pavement network be divided into pavement sections where each segment would be considered a unique project.

Following this recommendation it was decided to subdivide the pavement network based on the following criteria:

$ Pavement type

$ Pavement classification

$ Pavement structure

Following the above criteria, the entire NDOT pavement network was divided into 658

segments with each segment presenting close to uniform conditions. The segments were numbered using a combination of route numbers and numerical values while allowing for future expansion of the data base through the subdivision of existing segments due to changes in the conditions within the segments. For example, two consecutive segments on interstate 80 are numbered as IR080180 and IR080190. The reason the numerical numbering jumped from 180 to 190 is to allow for future insertion of a segment between the two segments.

Once the segment identification and numbering task was completed, a data base was established which provides all the necessary input parameters for the full analysis of each pavement segment. Figure 10 shows a typical section of the segment data base. The information included in this data base must be updated every year to reflect changes in the structural, environmental and performance data of the pavement segments.

V.2 Selecting the Best Action

The serviceability of any pavement section can be upgraded through rehabilitation or maintenance activities. The decision on whether to apply a rehabilitation or a maintenance action should be driven by the current serviceability of the pavement section along with the policy of the agency. For example, if a pavement section has a current PSI level of 2.5, the section should be recommended for rehabilitation instead of maintenance. The engineer assigning the action should be very well aware of the fundamental differences that exist between rehabilitation and maintenance and where each type of action can provide the most benefit.

NDOT uses the PMS system along with the 3R committee to select the appropriate action to be taken for any pavement section. As discussed earlier, the NDOT PMS system combines the actual pavement conditions along with traffic, environment, accident, and previous maintenance activity data to come up with a recommended action. Using the PMS recommendations along with the observations of the 3R committee presents the best approach since it combines the actual performance data with the experience of the 3R committee personnel. The researchers believe that the current NDOT approach is an excellent one and decided to use it in the network optimization process.

V.3 Generating Alternative Designs

Identifying all potential alternatives that will satisfy design or rehabilitation requirements is a critical step in the network optimization process. For a proposed pavement project, there will be various alternatives to choose from including several combinations of rehabilitation and maintenance treatments. To an extent, the alternative choices will be dictated by the condition of the pavement surface (at least the first action).

An initial thorough understanding of the design parameters for the particular pavement being planned must be grasped, followed by identification of all possible alternatives using creative thinking or brainstorming. The objective here is to generate a range of possible solutions to the problem.

It is expected that pavement engineers will be using this system to identify the best alternative to be used for a given highway segment. It should also be recognized that not all engineers share the same common believes when it comes to what type of treatment works best on a given class of road. Therefore, selecting multiple alternatives for the network optimization process must be flexible enough where individual engineers can input their personal experiences. The engineers must also be aware of the current agency=s policy on maintenance and rehabilitation. For example, NDOT does not allow the use of chip seals and sand seals on interstate routes, therefore, selecting an alternative which uses these activities on interstate routes would be meaningless.

The network optimization system developed in this research recommends four default alternatives for each of maintenance and rehabilitation actions. The default alternatives were established based on the experience of the research team and discussions with NDOT personnel. Each of the alternatives however, can be modified by the engineer conducting the analysis. This option was provided to allow the maximum flexibility for the engineer to use their experience.

V.4 Optimization Process

The optimization process consists of selecting the best alternative for a given pavement section. This analysis relies on the various steps and processes that have been identified earlier, including: performance modeling, life-cycle cost analysis, selection of best action, and generating of alternative designs.

The optimization process is conducted on individual segments regardless of how many sections are being selected at one time. The overall process consists of the following seven steps:

1) The engineer is requested to select the best repair to be taken on a given pavement section. This selection includes two options: maintenance or rehabilitation. The engineer should rely on the combined recommendations of the PMS and the 3R committee.

2) Once the repair is selected, the engineer is given the opportunity to look at the various data concerning the section that is being

analyzed. These data include: weather, traffic, structural, and economic parameters. At this stage, the engineer can modify any data element or stay with the default values. It should be recognized that the default values represent the best estimate of these parameters that the researchers identified based on the most current section information.

3) After the engineer reviews and modifies whatever necessary in the input parameters list, he/she is given a chance to review the recommended alternatives. Again, the engineer is given the choice of accepting the recommended alternatives or modify them as he/she sees fit. A total of four alternatives are given for each action (i.e. maintenance or rehabilitation). The engineers does not have to activate all four alternatives. The total number of active alternatives can range between 1 an 4.

4) Once the engineer completes the selection of input parameters and the appropriate alternatives, the performance modeling process starts. This process uses the performance models to estimate the variation of the PSI as a function of the pavement age. The result of this analysis is a graphical relationship between the PSI and pavement age similar to the one shown in Figure 12.

5) The relationship between PSI and pavement age is then used to perform the LCCA. The LCCA uses the economic analysis identified in Chapter 4. The result of this analysis is a summary of the annual cost over the entire analysis period.

6) Using the PSI versus age and the cost summary, the optimization process evaluates the benefit-cost ratio for each alternative.

$$\text{Benefit-Cost Ratio} = \frac{\text{Area under the PSI versus age curve}}{\text{Total cost per square yard } (\$/yd^2)}$$

7) Using the benefit-cost ratio for each alternative, the optimization process selects the most desirable alternative as being the one generating the highest ratio.

V.5 Network Optimization Analysis

As mentioned above, the optimization process is conducted by executing steps 1 through 7 on every pavement section. Using this approach, the engineer can conduct a full network optimization analysis following any one of the following three options:

1. Project-Level Analysis

2. System Analysis

3. Complete Network Analysis

Each one of the above options offers a different method of conducting the network optimization process. The term Afull analysis@ in each of the processes means that performance modeling, LCCA, and benefit-cost ratio analyses will be conducted for each alternative.

V.5.a. Project-Level Analysis

This option allows the engineer to conduct full analysis for one pavement section at a time. It provides the highest flexibility in modifying input parameters, and changing alternatives. The engineer can conduct the analysis while changing any input parameter and selecting any combination of alternatives. The analysis generates a PSI versus age relationship, cost summary table, and a benefit-cost ratio for each alternative as shown in Figures 13 and 14. The engineer can use this data to decide on the best action to be taken for a given pavement section.

The project-level analysis is offered to the engineer to evaluate the impact of various parameters on the expected pavement performance. Using this analysis, the engineer can assess the significance of weather, traffic, materials, and structural parameters on the expected performance of a given maintenance or rehabilitation treatment.

Even though the project level analysis is provided to allow the utmost flexibility while analyzing individual pavement sections, this analysis can also be used to conduct complete network optimization. If the engineer elected to conduct network optimization using the project level analysis, he/she will have to assess each segment individually and manually combine the results to derive network optimization recommendations. The question becomes, why would the engineer elect to use the project level to optimize the network if it involves lots of manual work? The answer to this question is that the project-level analysis provides the utmost flexibility when analyzing individual pavement sections which can not be achieved in the more automated analyses (i.e., system analysis and complete network analysis). For example, in the case of the system-analysis process, the engineer can analyze numerous pavement sections at one time and generate summary recommendations concerning each individual section, however, the selection of some input parameters and the evaluated alternatives will have to be common for all the evaluated sections.

V.5.b. System Analysis

This option allows the engineer to conduct full analysis for a user-selected group of pavement sections. The objective of this analysis is to provide the engineer with an analysis tool to respond to the 3R committee recommendations without having to conduct the full analysis on each individual section. The process used in this system analysis can be summarized as follows:

1. The PMS and 3R committee recommendations are presented to the engineer.

2. The engineer identifies the pavement sections that are recommended for maintenance and the pavement sections that are recommended for rehabilitation.

3. The engineer selects the appropriate input parameters and the alternatives to be used for each group of projects. The majority of input parameters will be set on their default values while some limited parameters can be modified for each group of sections (refer to the software users manual for details on the various input options). The alternatives will then be selected by the engineer. The same set of alternatives will be evaluated for each group of sections (i.e. maintenance or rehabilitation). At this stage, the engineer can use the default set of alternatives or he/she can modify them as needed.

4. The result of this analysis will consist of a graphical relationship of PSI versus age and a cost summary table for each pavement section for the most effective alternative as shown in Figures 15 and 16. Figure 15 shows a typical graphical presentation where the PSI versus age relationship is presented for the most effective alternative. The difference between this figure and Figure 13 is that Figure 13 provides the engineer with the option of printing any one alternative while Figure 15 only prints the most effective alternative based on the benefit-cost ratio.

5. A cumulative cost summary table is also produced (Figure 16). This table presents a ranking of the pavement sections in terms of their benefit-cost ratios and the annual expenditures associated with the group of sections recommended for maintenance and those recommended for rehabilitation.

Using the above analysis along with the cumulative summary table, the engineer can optimize the network by recommending the projects with the highest ranking while at the same time matching the available budget with the projected cumulative cost. The summary also provides an indication as to how much expenditures are needed for maintenance and how much are needed for rehabilitation. Also the PSI versus age relationships for the individual sections provide the engineer with an expanded picture for the entire network.

V.5.c. Complete Network Analysis

This analysis option is a fully automated one with very limited flexibility. The objective of this option is to conduct analysis for the entire state pavement network. All 650^{+} sections are analyzed at once and a cumulative cost summary table is presented for the entire network. The network sections are divided into the following three action categories.

- $ Annual routine maintenance
- $ Maintenance
- $ Rehabilitation

The criterion used to categorize the pavement sections is based on the current PSI level of the pavement section. The engineer is allowed to provide the threshold PSI levels which delineates the three action categories. The following values represent the default PSI threshold levels provided in the current analysis:

	PSI Upper Limit (PSI-UL)	PSI Lower Limit (PSI-LL)
Interstate Routes	4.1	3.5
U.S. Routes	4.0	3.0
State Routes	4.0	2.5

Where:

PSI > PSI-UL	Annual Routine Maintenance
PSI-LL < PSI < PSI-UL	Maintenance
PSI < PSI-LL	Rehabilitation

Once the PSI thresholds are provided, the segments data base is accessed and the pavement sections are classified into their respective action categories. Each category of pavement sections is then subjected to a full life-cycle cost analysis and the best sequence of treatments is selected for each pavement section. Because it is difficult to assess the immediate impact of annual routine maintenance activities on the PSI, the pavement sections that are initially categorized into the annual routine maintenance category are subjected to five years of routine maintenance and then moved into the maintenance category.

The cumulative cost summary table is then produced for the entire network, ranking the sections based on their benefit-cost ratios and providing the cumulative cost for each year. Table 22 shows portions of the cumulative cost summary for the complete network analysis. The first part of the table shows the cost figures for years 0 through 5 for the pavement sections that were categorized into annual routine maintenance. As discussed earlier, these projects are scheduled for routine maintenance for the first five years and then moved into the maintenance category as shown under year 5. The activity shown for each project at year 5 represents the first activity of the most effective alternative for that project selected based on the benefit-cost ratio data. The second part of Table 22 shows the cost figures for years 0 through 2 for the pavement sections that were categorized into maintenance. The activity shown for each project at year 0 represents the first activity of the most effective alternative for that project selected based on the benefit-cost ratio data. Following year 0, these projects are then subjected to annual routine maintenance activities until such time that the second activity in the alternative kicks in for each project.

Using the complete network analysis, the engineer can establish the funding requirements for the entire network. It should be noted, however, that the funding requirements are based on the current state of the network and these requirements will change as the state of the network changes. In other words as the agency maintains and rehabilitates some sections, the state of the network would change from one year to another and therefore, the funds requirements, as established through the complete network analysis, will change accordingly. One major advantage of the complete network analysis is that it provides the engineer with the opportunity to evaluate the impact of changing the pavement performance criterion (i.e., PSI threshold) on the required level of expenditures. For example, the engineer can change the PSI threshold used to separate between the maintenance and rehabilitation actions and evaluate its impact on the required level of funds.

VI. SUMMARY AND RECOMMENDATIONS

A computerized method has been develop to conduct network optimization analysis. The analysis uses pavement performance models generated based on NDOT=s pavement performance data along with life-cycle cost analysis to identify the most effective treatment to be applied for a specific pavement section.

Using regression analyses, performance models were developed for the most common maintenance treatments: sand and chip seals, and rehabilitation treatments: overlay, roadbed modification, and mill and overlay. The models were developed using actual pavement management data collected on field sections for the past 15 years. All the available pavement sections for each of the maintenance and rehabilitation treatments were used in the development of performance models (a total of 319 projects). For each pavement section, the structural, materials, traffic, environmental, and condition data were collected and used in a statistical analysis to develop the performance models. The majority of the models resulted in high R^2 values which indicate a good fit of the field performance data.

The life-cycle cost analysis (LCCA) generates the total costs needed to construct a given alternative. An alternative is defined as a sequence of maintenance and/or rehabilitation treatments necessary to carry a pavement section for the 20-year analysis period above a desired level of performance. The LCCA uses the present worth approach to convert future expenditures into current dollars for comparing alternatives. The LCCA includes both initial construction and annual routine maintenance costs for the alternative selected on each pavement section. User costs are not included in the LCCA process but salvage values are considered.

In summary, the individual treatments are used to create alternatives that can provide the acceptable performance level for a given pavement section over the entire analysis period of 20 years. The performance of pavement sections is modeled in terms of the present serviceability index (PSI). The LCCA is used to generate the present cost for each alternative. The most effective alternative is selected based on the highest benefit-cost ratio which is defined as the ratio of the area under the PSI vs. age curve divided by the total cost of the alternative. Once the most effective alternative is selected for each pavement section, a summary of annual expenditures is provided for the group of pavement sections that have been selected for analysis. The group of projects can be the entire network or a group of pavement sections that have been selected by the engineer.

Based on the research conducted in this project, the following recommendations can be made:

$ The roadbed modification model should be used with extreme caution. The performance models represent the best estimate of performance based on the PMS data that have been collected for the past 15 years. The majority of the models resulted in a good fit of the data, except for the roadbed modification model which showed a R^2 value lower than 50%. This lack of good fit for the roadbed modification activity is attributed to the low number of roadbed modification projects which went through their entire life cycle. In other words, most of the roadbed modification projects required more performance years than were available in NDOT=s PMS.

$ The inclusion of material properties made a significant difference in the ability of the developed models to fit the measured performance data. Therefore, it is recommended that NDOT keeps good records of materials properties to effectively model the performance of maintenance and rehabilitation activities. Also the combination of all districts into one statewide model for each treatment provide good stability of the model over a wide range of parameters.

$ The LCCA process uses the fixed period cumulative annual routine maintenance costs. This method showed the least variability in the routine maintenance costs and should be updated routinely to reflect the actual costs for a given time period.

$ The entire NDOT pavement network was divided into 658 pavement sections. The appropriate information for these sections have been summarized into a data base which is used to conduct the network optimization analysis. It is highly critical that this data base be kept up to date to reflect the current conditions of the entire network. If this data base is not kept up to date, the network optimization analysis will produce erroneous results.

$ NDOT should use this system to conduct all levels of optimization: project analysis, systems analysis, and entire network. This system represents the best optimization analysis that can be conducted using the current PMS data. Future updates of the system should be considered at five-year intervals to incorporate new materials and new design techniques. Updates at shorter intervals are not recommended due to their ineffectiveness in capturing the true contribution of new materials, and new design techniques.

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