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In the interest of providing tools for the cost-effective maintenance of an aging inventory of bridges, a method for comparing feasible repair/replacement sequences for low-slump concrete overlays for bridge decks is developed. The method relies on a technique for computing deterioration curves using inspection data from the National Bridge Inventory. Over twenty years of inspection data for bridge decks in Minnesota, which were overlaid with low-slump concrete overlays placed between 1974 and 1981, was used. The deterioration curves were assumed dependent on several material and geometric variables identified by means of a literature review, and the statistical significance of these parameters on deterioration rates was examined. These variables include span length, average daily traffic, and superstructure material type, and piecewise linear deterioration curves were constructed for various subgroups with similar deterioration characteristics. Present value cost analysis was used to price the available options by identifying the sequence of repairs that has the least cost while maintaining a specified performance measure. The present value analysis considers the costs and timing of repair/replacement sequences, inflation, and the discount rate.

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Determining Economic Strategies for Repair and Replacement of Low Slump Overlays of Bridge Decks

Final Report

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Executive Summary

Agencies responsible for maintaining bridges, such as state transportation departments, are currently faced with the problem of maintaining inventories of highway bridges under tight budgetary constraints. This situation requires agencies to determine the most effective way to use their resources. If a large population of bridges has subgroups with similar performance characteristics, strategies can be developed to determine which sequence of several different repair or replacement operations minimize costs for each of the subgroups.

On major state and interstate highways in Minnesota during the time period of 1974 to 1981, low-slump concrete overlays were used for both rehabilitating existing bridge decks and to provide additional durability to newly constructed bridge decks. The use of low-slump overlays in Minnesota began in 1974 with a handful of bridges, and rapidly gained acceptance as a means of protecting and rehabilitating concrete bridge decks. These bridge decks are beginning to reach the end of their anticipated service lives. This study looks at bridges with decks that were overlaid with low-slump concrete between 1974 and 1981. The combined deck area of the bridges in this study is over 8.5 million square feet. Using an assumed deck replacement cost of $40 a square foot, replacing the decks on all the bridges in the study would require over $300 million. The objective of this research was to generate economic strategies that the Minnesota Department of Transportation (Mn/DOT) can use to minimize the costs associated with this particular bridge population.

The economic model used to perform the analysis was assembled in three steps. The first step was to gather existing information. A literature review examined the performance of concrete overlays and bridge decks and identified material and geometric parameters that could potentially affect the performance and deterioration of low-slump concrete overlays. Bridge inventory and historic inspection data was obtained from the FHWA and Mn/DOT. The data collected from a total of 492 bridges comprised the data set.

During the second step the available data was analyzed. An iterative statistical analysis was performed to determine which variables, (some proposed at the outset of the project and others identified in the literature review) influenced the rate of deterioration significantly. Deterioration was defined as a lowering of the condition code assigned to the bridge deck by highway bridge inspectors. Bridge inspections are typically performed on an annual or biannual basis and uploaded to the National Bridge Inventory maintained by the Federal Highway Administration. Average deterioration rates were calculated for each bridge based on 21 years of inspection data extracted from the National Bridge Inventory (NBI). The statistical analysis determined that the most significant variables affecting the deterioration rates of the bridges under consideration were material type of the superstructure, maximum span length of the superstructure, and the average daily traffic (ADT). Using these results, the data was subdivided into three different groups that displayed similar deterioration characteristics. Subsequently, the NBI deck condition data for the three subgroups were used to assemble deterioration curves that are piecewise linear (for each drop in condition rating), but are overall nonlinear. The deterioration curves formed the basis for the economic analysis.

The third and final step was to perform the economic analysis. Cost data was collected from Mn/DOT for the repair and replacement procedures typically utilized by Mn/DOT. A spreadsheet and Visual Basic program was created in Microsoft EXCEL to perform a present value cost analysis. This type of cost analysis is often used by businesses to determine the best sequence of actions associated with acquiring and maintaining a particular piece of capital. A present value cost analysis was performed for every bridge in the data set to determine its least cost repair/replacement strategy. Using the results of this cost analysis, flow charts were developed that identify the least cost repair/replacement strategy anticipated for any particular bridge. Lastly, a parametric study was conducted to investigate the sensitivity of the analysis to several input values and several key assumptions. The goal of this project was to develop repair/replacement strategies for a particular type of bridge deck, but the methods developed in this project can be applied to other bridge elements, for which NBI data exists and for which the most cost effective repair strategies are not readily apparent.

The economic analysis indicated that based on current prices, repairs provided the most cost-effective use of maintenance funds assuming they could elevate a deteriorated deck to an acceptable condition state. Which repairs to use and when they should be performed depends largely on the condition of the deck, the applicable type of deterioration curve for the deck, and the minimum acceptable condition state for a deck. In general, if R_{min} = 4 (Figure 4.7), then reoverlay is typically recommended as the first action, after the deck has deteriorated to a condition rating of 4, and a secondary action in the form of redecking or reoverlay may be needed. For R_{min} = 5 (Figure 4.8), redecking is necessary if the initial condition rating of a deck is 4, whereas either reoverlay or mill & patch repairs are recommended for decks with a condition rating of 5 or 6. A secondary action may be needed. Lastly, for R_{min} = 6 (Figure 4.9), either reoverlay or mill & patch repairs are recommended, with a possible secondary action.

The parametric study revealed that for some parameters (e.g., discount rate and inflation rate) and assumptions (e.g., limit on initial condition reduction due to years in service), the overall outcome of the present value cost analysis is fairly insensitive. For other parameters and assumptions that were investigated, the outcome of the present value analysis did have significant changes depending on the choice of the input parameter or assumption that was used. For example, by increasing the enhacement in condition rating afforded by a given repair strategy, the order of the most frequently selected repair strategies can be reversed (see section 4.7). The last parameter investigated was the duration of the analysis, the period of which was increased from 20 years to 30 years. The number of bridges selected for repair/replacement was observed to increase by approximately 100%, but the most popular repair strategy options were mostly insensitive to the choice of analysis duration.

Chapter 1: Introduction

1.1 Problem Statement

Agencies responsible for maintaining bridges, such as state transportation departments, are currently faced with the problem of maintaining and replacing vast numbers of highway bridges within very tight budgetary constraints. This situation requires that these agencies determine the most efficient way to use the resources at their disposal. If a population of bridges has a great deal of similarity amongst some or all of their elements, it makes sense to develop a rational, economically sound framework for repair and replacement strategies. If this is not done, each bridge must be evaluated individually, and a great deal of knowledge that might help in determining the most efficient and cost effective repair and replacement strategy is underutilized.

On major state and interstate highways in Minnesota during the time period of 1974 to 1981, low slump concrete overlays were used for both rehabilitating existing bridge decks and for providing extra protection to newly constructed bridge decks. Figure 1.1 shows the number of low slump concrete overlays that were placed in each year from 1974 to 1981 on old and new bridge decks. In this study, a deck is considered to be new if the overlay was placed within 3 years of deck construction, whereas an old deck is one which was overlaid more than 3 years after construction.

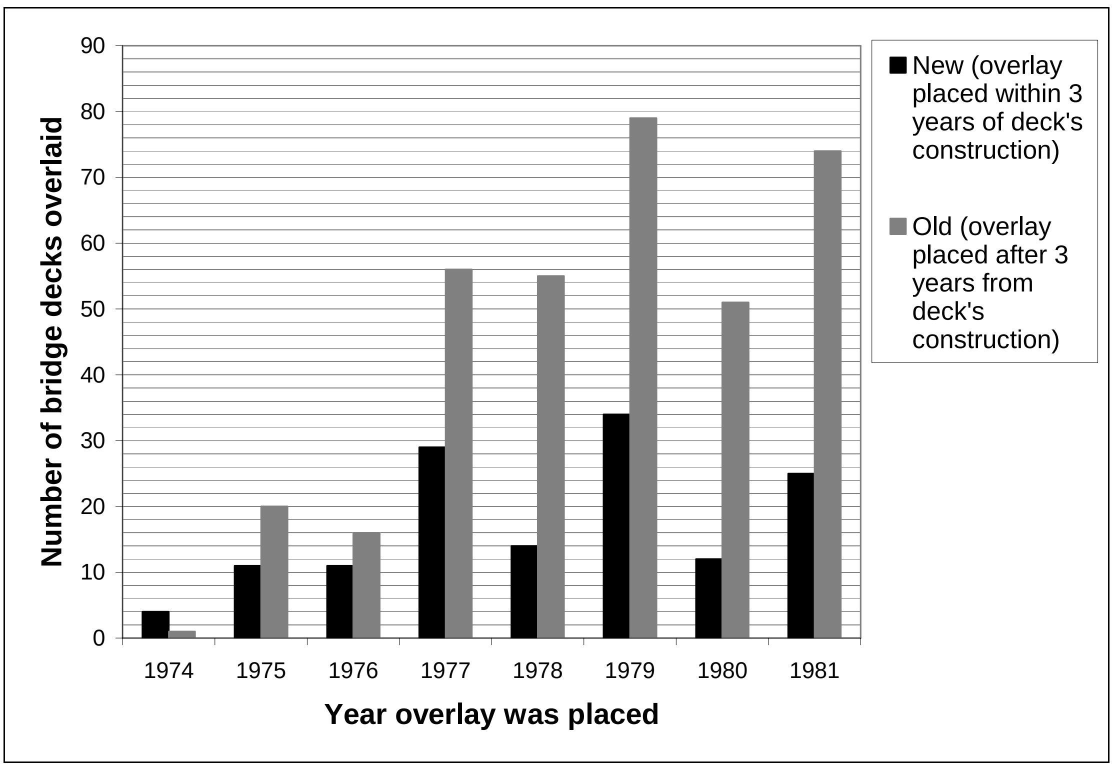

Figure 1.1 Number of New and Old Decks Overlaid from 1974 to 1981

The use of low slump overlays in Minnesota began in 1974 and rapidly gained acceptance as an efficient way of protecting and rehabilitating concrete bridge decks. However, these bridge decks are beginning to reach the end of their service lives. Due to the large number of these decks in use, repairing and replacing them is anticipated to be very costly. The Minnesota Department of Transportation (Mn/DOT) decided that due to the large number of very similar decks needing repairs, performing an economic analysis of repair/replacement options was warranted. The University of Minnesota was contracted to perform the research. The ultimate goal of this research was to generate economic strategies that Mn/DOT can use to minimize the costs associated with the repair and replacement of this particular bridge population.

1.2 Approach

The approach used to generate these economic strategies has three main steps. The first step was to gather existing information and data that could be used to help perform an economic analysis. A literature review was performed that investigated concrete overlay and deck performance. Physical variables that potentially affect the performance and deterioration of low slump concrete overlays and concrete bridge decks were identified. Bridge data was collected from both the Federal Highway Administration and Mn/DOT. Using this data, a list of bridges that met the projects criteria was formed.

The second step in generating economic strategies was to analyze the data that was collected in the first part of the project. A statistical analysis was performed that sought to determine which variables that were previously identified as potentially affecting the deterioration rates of the bridges actually have significant effects on the rates of deterioration. Next, using the results of the statistical analysis, the data was subdivided into groups that have similar deterioration rates. Lastly deterioration curves were assembled for the subgroups. The curves correlate deck condition with time based on the average performance of bridges in a particular subgroup, which is essentially the service life of the decks in the subgroup. These deterioration curves are necessary input for performing an economic analysis.

The third and final step was to perform the economic analysis, for which a present value cost analysis was used. This type of cost analysis is often used by businesses to determine the best sequence of actions for acquiring and maintaining a particular piece of capital. To perform a present value cost analysis, three types of information are needed. The first type of information is data on how much the various actions considered in the analysis cost. For this project, cost data was collected from Mn/DOT regarding current repair and replacement techniques. The second type of information is data on how often the various actions are required. In a business situation this information would be the anticipated frequency and effects of repairs, maintenance, as well as the useful life for the particular piece of capital that the analysis is considering. For this research the deterioration curves that describe bridge condition through time, which were generated in the data analysis portion of the project, fit into this category. Also, information about the anticipated effects of repairs on deck condition, which was provided by Mn/DOT, falls into this second category of information. The last type of information needed concerns time and its effects on money. An analysis period, inflation, and discount rate all fall into this type of information. In this project the values used were typical for financial analyses of this nature, or were based on previous research in economic strategies for bridge management.
Due to the large number of calculations involved in the present value analysis for a sizable population of bridges, manual computation would not be efficient. To handle this problem, a

spreadsheet and Visual Basic program were created in Microsoft EXCEL to perform the present value cost analysis. The spreadsheet performs a present value cost analysis that determines the least cost repair/replacement strategy for every bridge included for study in this project. Using the results of this cost analysis, flow charts were developed that show the least cost repair/replacement strategy most likely for any particular bridge that is part of the population under study. Lastly, a parametric study was conducted that investigated the sensitivity of the analysis to some important input values and several key assumptions.

Chapter 2 of this report summarizes the literature review and data collection activities performed for this project. Chapter 3 describes the methods used and the results of the data analysis portion of this project. Chapter 4 describes the methods used and the results of the economic analysis. Chapter 5 of this report contains a summary of the entire project as well as conclusions and recommendations.

Chapter 2: Literature Review and Data Collection

2.1 Literature Review

The purpose of this research project is to determine economic strategies for repair and replacement of low slump concrete overlays on bridge decks that were overlaid during the time period from 1974 to 1981. The overlays were either part of repairs to bridges constructed before 1974, or were included as part of new bridge construction. In order to devise these economic strategies, three general types of information were needed from existing studies and research. The first type concerns background information about low slump concrete (LSC) overlays. Construction practices and techniques, material properties, and other general information about the overlays installed from 1974 to 1981 fell into this category. The second type of information that was needed concerns the performance and deterioration of the overlays. In order to determine economic strategies, knowledge about what factors affect the service lives and deterioration rates of bridge decks with low slump concrete overlays was needed. Lastly, information about current approaches and techniques for performing an economic analysis that includes life cycle costs was needed.

As previously noted, the use of LSC overlays in Minnesota began in 1974. The popularity of LSC overlays as a rehabilitation technique for existing bridges as well as deck protection for new bridges grew rapidly, with the number of installations increasing quickly during the first few years that LSC overlays were used in Minnesota. The installation procedure for LSC overlays did not change much in terms of mix design or construction/curing techniques during the time period in question. Also, detailed records of the installation of LSC overlays on specific bridges with information such as weather, placement sequence, or the exact method and duration of curing are difficult to obtain for a large data subset. Some of this information is available in construction documents and records for individual bridges, but is not currently available in a consistent digitized form as would be required to perform a statistical analysis.

While much research has been performed concerning construction practices to enhance the service life of LSC overlays, the results of this research is of fairly limited value to the current project in light of the difficulty in obtaining detailed installation records, and because construction practices did not change much during the first few years that LSC overlays were used. Material properties and construction practice, while playing a significant role in the service life of LSC overlays, are not variables that can be effectively considered for this research project (1, 2, 3). For detailed information on the current mix design and placement requirements for low slump concrete overlays refer to Specifications 2461 and 2404 in the 2000 Mn/DOT Standard Specifications for Construction. From their initial use in 1974 to today, the specifications for low slump concrete overlays have remained relatively constant.

A significant amount of research has also been performed that investigated the effects of bridge design, material type, and traffic demands on LSC overlays (3-7). This type of information is likely to be very valuable to this project because information about the physical and geometric bridge characteristics, as well as traffic loads for specific bridges, is readily available. Thus relationships between deterioration and bridge geometry, design, and loading have been the fopcus of a significant portion of the existing literature on the subject. The most important findings concerning design, geometry, and loading are summarized below.

- There is a direct correlation between deck and overlay cracking and the deterioration rate of the deck. Therefore, factors that affect deck and overlay cracking also affect deck deterioration rates (3).
- Prestressed girder bridges that had their current deck placed on them while the girders were new exhibit little cracking and have performed very well. If a bridge with prestressed girders is re-decked at a later time during its lifespan, the benefits of having young concrete with similar creep rates in both the deck and girders is lost since the old girders will not creep enough to significantly reduce residual deck stress (4).
- Steel girder bridge decks are more likely to crack than concrete girder bridge decks. Reasons for the poorer resistance of steel girder bridges to deck cracking include dissimilar coefficients of thermal expansion for steel and concrete and negligible creep in steel girders leading to higher residual deck stresses from drying and shrinkage (3).
- The continuity of a deck and girders in a bridge has a large effect on the extent of cracking in support regions. Simply supported bridges as well as bridges with expansion joints exhibit much less cracking in support regions than continuous systems (4, 5).
- The amount of restraint on the deck is important. Deep girders, close girder spacing, and tight spacing of shear studs all impose significant restraint on the deck. This restraint causes stresses to build up in the deck when temperature gradients are present, and these stresses result in cracking when the tensile strength of the concrete is exceeded (4).
- Thicker bridge decks are more resistant to cracking than thin bridge decks (4).
- Decks in bridges with longer span lengths are more prone to cracking than decks in bridges with shorter spans (5, 6).
- Annual average daily traffic (AADT) has a small, but discernible effect on the amount and severity of cracking. Also, traffic impact exacerbates deterioration caused by cracking that resulted from other factors, thereby accelerating the rate of overlay deterioration (6).
- The removal depth of old damaged concrete when repairing and preparing deck surfaces before overlay placement affects the subsequent deterioration rate of the overlay. Deep removal of damaged concrete as opposed to shallow scarification results in longer lasting overlays (7).

A fairly wide selection of literature and research was reviewed in this first portion of the project. Some of the literature that was reviewed was either not directly applicable to this research, or the results and findings of the research were not used in this project (8 - 20).

2.2 Data Collection

As a first step in developing repair and replacement strategies for decks with LSC overlays, data about the bridge decks was collected. The data that was collected was obtained primarily from two sources. The first data source is the National Bridge Inventory (NBI) database which was obtained from the Federal Highway Administration. The second data source was Mn/DOT. The data collected from Mn/DOT includes three databases, a general bridge record database, selected elements from the PONTIS database, and the bridge maintenance database. The data that was collected contains information about several important aspects of the bridge decks.

The first important type of data is bridge information that allowed it to be included or excluded from consideration. While this task may appear to be trivial, it proved to be challenging. To accomplish this task, data from the general bridge record database was used in combination with the PONTIS data to form a selection criterion. A total of 464 bridges were found to meet the project criteria. After Mn/DOT reviewed this list of bridges, it was found that the bridges that had been reoverlaid after their initial 1974-1981 overlay were not included. The reason for this omission was that the date of overlay recorded in the general record database is the most recent date of overlay (or re-overlay). The original overlay date had been written over by the new date in the database. But, while these bridges had already been repaired, information concerning their deterioration after their initial overlay was still a valuable resource for the project. Members of the Mn/DOT Technical Advisory Panel (TAP) manually identified bridges that have already been reoverlaid and compiled a list of the structure numbers, as well as the date of the original bridge overlays. When the manually identified bridges were added to the previously mentioned list of 464 bridges, the total number of bridges included for study rose to 492.

The second important type of data is information about the general design and construction of the bridge. Such information is available from both the NBI and Mn/DOT general bridge record database. This information was used in the data analysis portion of the project to subdivide the population of bridges under consideration into various subgroups that display similar deterioration rates and characteristics.

The third important type of data is information about how the bridges deteriorate. An excellent source of this information is the PONTIS database, which has been designed specifically for the purpose of recording inspection data for use in determining deterioration rates as well as general bridge management. However, since the bridges under consideration were built on or before the time period of 1974 to 1981 and the PONTIS database was not started until the early 1990's, other sources of deterioration information were needed as well. A record of deterioration is maintained in the NBI database. While this information is not as detailed as that in PONTIS, it is much more complete with respect to the time period of interest, and it proved to be essential for the project. Some information was obtained from the Mn/DOT maintenance records as well. Repair information including dates, types of repairs, costs, and material quantities are found in the Mn/DOT maintenance records.

In order to work with the data, it was necessary that all of it be organized in a compatible format and that it be linked to maximize its usefulness. This was accomplished by importing all of the databases that were collected into the Microsoft database program ACCESS as tables. The tables were then linked to each other using the common field of the structure number which is unique to each bridge. With the data in this format, it was possible to efficiently extract information by searching and querying the data.

Chapter 3: Data Analysis

3.1 Data Sources

The data that was used came from two sources. The first source was part of the PONTIS database used by Mn/DOT which pertained to deck elements. The PONTIS data was used only to determine the presence of low slump concrete overlays on the bridge decks so that they could be included in this study, and to determine whether or not epoxy coated bars were used in the deck. The second data source was the NBI databases from 1983 until 2003. The NBI deck condition field was used from all of 21 of the databases, but information about the variables considered in the statistical analysis was taken solely from the 2003 NBI database.

3.2 Overview of Data Analysis

The bridges being analyzed in this second phase of the project consist only of bridges which were constructed on or before 1981 and received low slump concrete overlays during the time period of 1974 to 1981. Thus, the results of the data analysis activities are only applicable to this particular subset of the bridge population. In this second phase of the project, statistical methods were used to decide whether or not the physical and geometric variables identified in the literature review, as well as the variables proposed in the work plan for this project which were found to be feasible for analysis, actually affect the deterioration rates of the bridge decks under consideration. Once these variables were investigated and their relative importance identified, the bridge population was subdivided in such a manner as to group bridges with similar deterioration rates together, thus increasing the accuracy of the deterioration rates and the service lives that are calculated.

Once the bridges were grouped, service life plots (deterioration curves) showing NBI deck condition rating versus time were constructed for these groups to be used in the economic analysis portion of the project. It should be clarified that different methods and techniques were used for the statistical analysis than for the assembly of service lives, but the same NBI data was used for both of these parts of the data analysis process.

3.3 Data Preparation

The first step in the data analysis process was to obtain some measure or metric of the performance of each deck that could be used in the analysis of variance (ANOVA) method. From all the data that was collected for this project, the most promising for use in calculating deterioration rates is the NBI database. The NBI database contains condition ratings for various bridge elements from bridge inspections from 1983 until present. For this project NBI data was obtained through 2003, which provided a record of the bridge condition over time for twenty one years. The field in the NBI data of most interest for studying bridge deck service lives is the field containing condition ratings for bridge decks. This field contains deck condition ratings on scale from 0 to 9, with 9 being perfect condition and 0 being a failed condition.

Using the Microsoft Office database program ACCESS, the NBI deck condition ratings from 1983 to 2003 were assembled using a query. The results of this query were then exported into Microsoft EXCEL. Next, based on the 21 NBI deck condition ratings for each bridge (i.e., one for each year from 1983 to 2003), an average deck deterioration rate was calculated. While the actual NBI condition rating versus time curve for each bridge is nonlinear, a single parameter for comparing all bridges is needed for the statistical analysis for the ANOVA analyses. Thus, an average (linear) deterioration rate for each bridge was determined to be the best parameter for this purpose, since the comparison of multiple nonlinear curves would be difficult.

There is, however, a potential drawback to the technique discussed above. The drawback arises from the fact that the bridges of this project were overlaid over a period of time from 1974 to 1981 rather than all in one year. Thus, different amounts of time passed, and potentially different levels of deterioration occurred in the bridges before the first record in 1983. When using a linear approximation to a nonlinear curve, using different periods of time along the actual deterioration curves for the bridges can magnify inaccuracies. However, the only way to avoid this inaccuracy is to guess an initial condition for the bridge decks immediately after being overlaid and then use the same time frame for all bridges.

The technique discussed above was initially tried, but problems arose with the manner in which to handle the difference between old decks which were rehabilitated and new decks which had overlays placed during initial construction. It was discovered that making assumptions about the initial deck conditions introduced significant error into the statistical analysis. Thus, simply using the 21 year period for which NBI data exists was determined to be the most accurate way of using the data to calculate average deterioration rates. The actual effect of this decision was investigated during the statistical analysis and proved to be negligible. The results of this investigation will be discussed in more detail later.

During the process of calculating the average deterioration rates, several other problems were encountered for which assumptions had to be made. The first problem encountered is that the NBI condition rating of the deck, particularly in the 8 to 7 range, occasionally fluctuates up and down by one point. A decrease in deck condition rating of 1 point followed the next year by a 1 point increase in deck condition rating is not likely the result of any significant repairs being performed on the bridge, but rather is probably the result of different evaluations and different opinions on the part of the bridge inspectors. This fluctuation is really not surprising given the rather subjective nature of a 0-9 NBI rating scale for which an entire bridge deck must be given a single average rating. To account for this, all single point increases in condition rating were not considered to be the result of repairs or intervention, for the purpose of calculating the average deterioration rate for each bridge.

The second problem encountered was the manner in which to handle the effects of major repairs done to the bridge that resulted in a greater than one unit increase in deck condition. If these increases in deck condition rating arising from repairs are ignored, the actual deterioration rates of the bridges will be greatly distorted and a bridge that actually had a high rate of deterioration may appear to have had a lower rate of deterioration than a bridge that performed very well. To account for this feature, the deterioration rates for periods before and after repairs were calculated separately and then a weighted average of the two rates was calculated and used in the statistical analysis. This is equivalent to adding up the total number of drops in the condition rating and dividing by the total number of years over which the drops occurred.

The third problem encountered concerned the choice of the lowest NBI deck condition to be used, that is, the final rating used in calculating average deterioration rates. Upon inspecting the NBI data it was noticed that there is lack of data for the drop in condition state from 5 to 4. In fact, there are only 13 drops in condition rating of 5 to 4 in the NBI data for the population of bridges in this study. Most bridges in this project simply had not yet deteriorated to a condition state below five. Thus, due to the lack of data for the drop in condition rating from 5 to 4, a rating of five was taken to be the final rating used in the calculation of average deterioration rates. The year in which a bridge received its first rating of 5 was taken to be the final year for that bridge for the purpose of calculating the average deterioration rate (for the particular deterioration segment being analyzed). If the bridge remained at a level of 5 for several years before repairs took place those years at which the deck condition rating was 5 were skipped for the purpose of calculating the average deterioration rate.

The last problem that needed to be dealt with was that for a small number of bridges the NBI deck condition rating was missing in the late 1990's. However, data existed on either side of the gap for these bridges. Because of the data on both sides of the missing years, it was decided to interpolate between the two values to fill in the missing data. The following rules were used in this process. If the condition rating was the same on both sides of the gap, that rating was used for the missing years. If there was a one-year gap in which there was a two point difference in the rating, the rating in between the two recorded values was used. Lastly, if there was a one point difference in the recorded values on either side of the data gap, the lower value of condition rating was used. Filling in the missing data was necessary in order for the program that was written to loop through the data and calculate the average deterioration rates for each bridge to function properly.

Once the above problems had been dealt with, an EXCEL macro was written to perform the actual average deterioration rate calculations. Figure 3.1 is an example of actual NBI data for a bridge, along with a plot of a line that has the same slope as the average deterioration rate that was calculated on the basis of the NBI data. The plot is provided to illustrate the calculations that were just described. It is noted, once again, that this average deterioration rate was used for the ANOVA statistical analyses only. The cost analyses decribed in Chapter 4 were conducted using the nonlinear deterioration curves assembled in section 3.7.

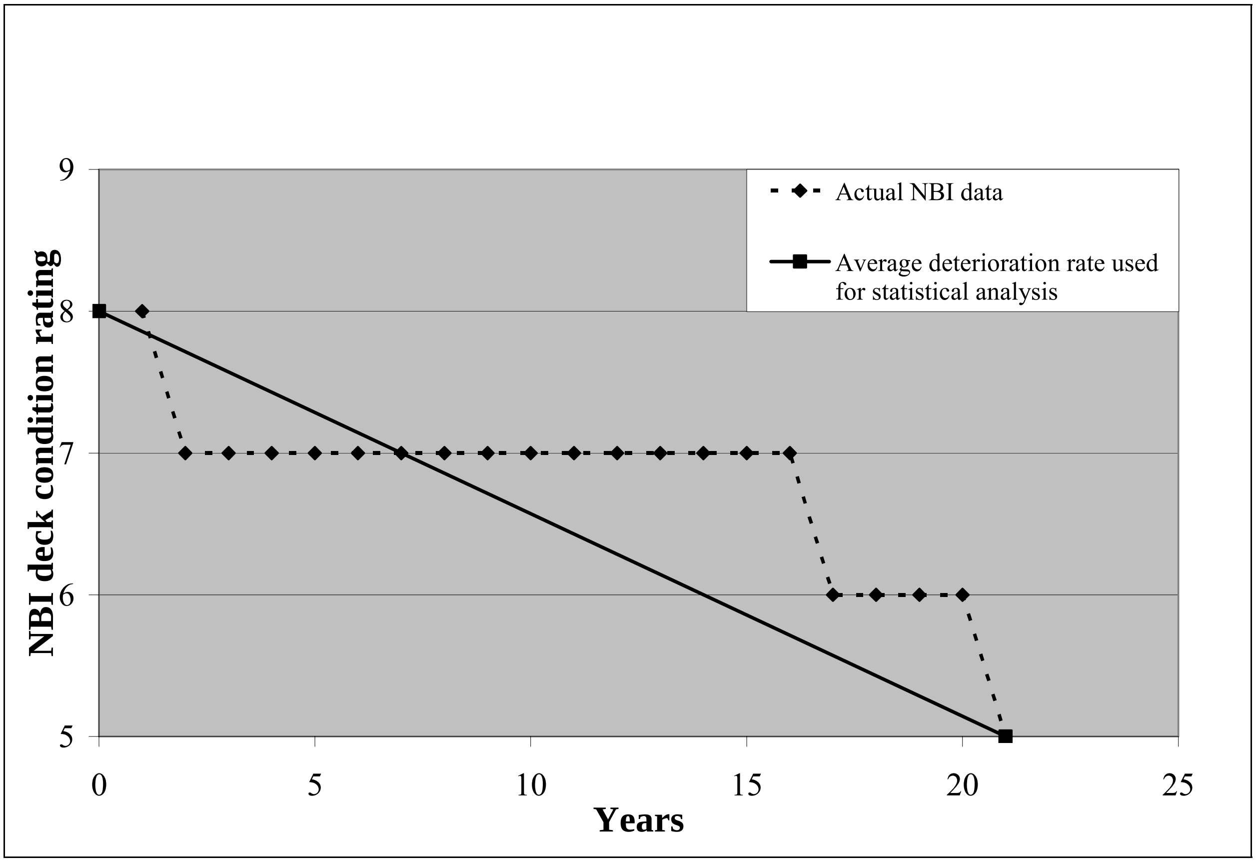

Figure 3.1 Actual NBI Data and Linear Approximation

After the average deterioration rate for each bridge was calculated, the resulting list of structure numbers and corresponding average deterioration rates were imported into ACCESS as a table that was linked to all of the other tables containing data for this project. Using this table and the NBI database, another table was constructed containing structure numbers and average deterioration rates as well as selected fields from the NBI database containing information about the potential variables that were identified in the literature review. Also, one field was included (derived from the PONTIS database) which contained information about the protection of deck reinforcement with epoxy coating. The following fields were included in this table; date that overlay was placed, date that bridge was built, material type of the superstructure, whether the deck was continuous or simply supported, overall structure length, average daily traffic, average daily truck traffic, skew, length of maximum span, out-to-out deck width, Mn/DOT district and rebar protection (i.e., plain or epoxy coated).

The final step in preparing the data for the statistical analysis was to subdivide the ranges of ariables that have continuous values, such as maximum span length, into discrete groups that could be statistically analyzed for their effects on deterioration rates. This was also done in an EXCEL spreadsheet using macros. The following variables were created by grouping continuous variables into discrete groups or categories;

Age: The age of bridge, in years, since its initial construction, grouped into discrete periods of time.

Old or New: Defined by the amount of time passing from the initial bridge construction until the time when the overlay was placed. Bridges for which the overlay was placed within 3 years of its initial construction are defined as new bridges. Bridges for which the overlay was installed more than three years after the bridges initial construction are defined as old bridges.

Overall Structure Length: The overall length of the structure, in feet, grouped into different length ranges.

Average Daily Traffic: The average daily traffic on the bridge, in cars per day, grouped into different ranges.

Average Daily Truck Traffic: Defined in NBI as a percent of the average daily traffic, grouped into different ranges.

Skew: The angle of skew of the bridge, in degrees, grouped into different ranges.

Maximum Span Length: The maximum span length of the bridge, in feet, grouped into different ranges.

Out to Out Deck Width: The out-to-out deck width of the bridge deck, in feet, grouped into different ranges.

The task of grouping continuous variables in discrete ranges was performed using an iterative technique. First, the data was broken down into several different groups often using a convenient break point such as dividing a continuous variable into thirds or fourths based on its maximum and minimum values. The data was then analyzed using this initial grouping of the variable and the results checked for any significant differences between discrete groups. If significant differences were detected, the means of the groups were then compared with each other to determine which groupings of the variable were not significantly different from each other, and which groups had larger differences between their means. Based on this comparison, the continuous variable was then regrouped to combine similar groups and the data was reanalyzed using the new grouping. This process was repeated several times if necessary until a minimum number of groups that contained significantly different means were obtained.

3.4 Statistical Analysis Methods

The general framework of the statistical analysis used in this project is based on some research which is fairly similar to this project that also used NBI data to determine the effect of physical variables on the deterioration rates of bridge decks (21). The statistical technique that was chosen to investigate the variables with is the analysis of variance method (ANOVA). ANOVA is used to determine if there is a statistically significant difference between the means of two or more data groups that arise from one or more variables or treatments which are found in a data set (22). ANOVA is a technique for comparing the variation of data within particular groups to the variation between the groups. The measure used to detect variation between groups is called the mean square for treatments (*MSTr*). The measure used to detect variation in the data within a particular group is called the mean square for error (*MSE*). The test statistic used in ANOVA is the ratio of these two measurements, *MSTr / MSE*. If there are no real differences between the data groups within a variable, *MSTr* will be very small and the ratio will be small as well. However, if there are differences between groups then *MSTr* will be large, and provided that within group variations are fairly low in comparison, the ratio will be large as well (22). The *MSTr / MSE* ratio is subsequently compared to a value which has been calculated using a predetermined confidence level in conjunction with a probability distribution known as an *F distribution*. *F distributions* are used for probabilistic analysis of problems involving a ratio in which the numerator and denominator have separate degrees of freedom. The degrees of freedom are related to the sample size and the number of different treatments or groups being used (22).

ANOVA can be used with only one variable at a time, that is, single-factor ANOVA, or with multiple variables at a time, or multiple-factor ANOVA. Multiple factor ANOVA is more mathematically complicated, but is derived in a very similar way to single factor ANOVA, which is described above (22). Multiple factor ANOVA not only considers the effects of the variables themselves, but also considers the interaction of the two variables to detect if the variables are truly independent of one another. Once ANOVA has been used to show that the means of at least one of the groups is significantly different from the other groups, other techniques called multiple comparison procedures are used for pair wise comparisons amongst the groups to determine which groups are different from one another, and which groups are not. The significance level is chosen and is usually taken to be a 95% confidence level. A 95% confidence level was used for this project as well, for both the ANOVA analyses and multiple comparison analyses. ANOVA proves that at least one group is different based on the chosen confidence level, but does not provide more information than that. Multiple comparison procedures are necessary to glean more detailed information about particular differences between groups.

The multiple comparison procedure used for this project is called Tukey's method. Tukey's method uses the previously calculated *MSE* value in conjunction with a predetermined confidence level and a probability distribution called the *studentized range distribution*. Tukey's method results in a series of simultaneous confidence statements that allows for comparisons to be made easily between groups to determine which groups are in fact significantly different from each other (22). There are several commercial statistics programs that will perform ANOVA and multiple comparisons. The statistics package MINITAB 14 was used to perform ANOVA and Tukey's method for this project.

3.5 Statistical Analysis Results

Once the data preparation was complete, the data was imported in the statistics program MINITAB to perform the ANOVA analysis and pairwise comparisons using Tukey's method. The following variables were analyzed: superstructure material type, superstructure continuity, old vs. new at time of overlay, average daily traffic, average daily truck traffic, overall structure length, age of the bridge from its initial construction, skew, maximum span length, Mn/DOT district, deck width, and rebar protection type (epoxy coated or bare). Some general characteristics of the data set for these variables are provided in Table 3.1.

Table 3.1 Basic Description of Variables Investigated in the Statistical Analysis

Continuous Variable Name	**Minimum value**	**Maximum Value**	**Average Value**
Average Daily Traffic	370	137,000	17,343
Overall Structure Length (ft)	21.9	5,184.6	345
Age (years)	25	89	39
Average Daily Truck Traffic	0	6,400	1,091
Skew (degrees)	0	70	15.4
Length of Max Span (ft)	19.7	456	85.1
Deck Width (ft)	23	149	50.8

Discrete Variable Name	**Number of Decks in Subgroup**		
Superstructure Material	cast in place concrete	steel	prestressed concrete
	35	251	206
Superstructure Continuity	simply supported	continuous	
	271	221	
Old or New Deck (at time of overlay)	old	new	
	352	140	
Bar Type (reinforcing steel)	uncoated steel	epoxy coated steel	
	350	142	

Mn/DOT District	1	2	3	4	5	6	7	8
	71	12	53	26	182	85	38	25

Of these variables, continuity, average daily truck traffic, skew, and rebar protection type were found to have no statistically significant effect on the deterioration rates of the bridge decks in this study. The rest of the variables were found to have significant effects on deck deterioration rates. One of the variables with the highest statistical significance was superstructure material type. The three superstructure material types found in the bridges of this study are cast-in-place reinforced concrete, prestressed concrete, and steel. Of these three material types, it was found that bridges with cast-in-place concrete superstructures exhibited significantly higher deterioration rates than bridges with either steel or prestressed concrete superstructures. Based on the substantial difference in deterioration rates, bridges with cast-in-place concrete superstructures were separated from the other two material types and no further analysis was performed on them due to the small sample size. Table 3.2 summarizes the results of the initial ANOVA analysis. All variables were included, but only variables that had a significance level under 0.05 were deemed statistically significant. The smaller the significance level for a variable, the higher the level of confidence that the means for the groups are different. For example a 0.05 significance level corresponds to a 95% confidence level.

Table 3.2 Summary of ANOVA Results for all Superstructure Types

Variable	Significance Level	Description of multiple comparison using Tukey's method
Old or new	0.031	Newer bridges have lower deterioration rates than older bridges
Age, grouping 4	0	Bridges built before or in 1955 have higher deterioration rates than bridges built after 1955
Material type	0	Bridges with cast-in-place concrete superstructures have higher deterioration rates than bridges with steel or prestressed concrete superstructures.
Overall structure length, grouping 5	0.013	Bridges with overall structure lengths 300 feet and less have lower deterioration rates than bridges with overall structure lengths of over 300 feet
Length of max span grouping 2	0.004	Bridges with a maximum span length of 100 feet or less have lower deterioration rates than bridges with a maximum span length greater than 100 feet
Mn/DOT district	0.001	Because there are 8 districts, a description of the Tukey comparison is complicated. See discussion of the variable for a table containing the means of the average deterioration rate.
Average daily traffic, grouping 2	0.018	Bridges with an ADT of 20,000 or less have lower deterioration rates than bridges with a ADT greater than 20,000
Deck width, grouping 2	0.052	Bridges with a deck width of 60 feet or less have lower deterioration rates than bridges with deck widths greater than 60 feet. **Note: variable does not meet 95% confidence level for this analysis but is very close.**
Continuity	0.261	Variable was not statistically significant
Average daily truck traffic	0.369	Variable was not statistically significant
Skew	0.131	Variable was not statistically significant
Bar Type	0.18	Variable was not statistically significant

After the data was separated based on superstructure material type, the combined data for bridges with steel or prestressed concrete superstructures was reanalyzed. Table 3.3 summarizes the results of this analysis. All variables were included, but only variables that had a significance level under 0.05 were deemed statistically significant.

Table 3.3 Summary of Results for Steel and Prestressed Concrete Superstructures

Variable	Significance Level	Description of multiple comparison using Tukey's method
Old or new	0.1	Variable was not statistically significant
Age, grouping 4	0.002	Bridges built before or in 1955 have higher deterioration rates than bridges built after 1955
Material type	0.058	Bridges with prestressed concrete superstructures have lower deterioration rates than bridges with steel superstructures **Note: variable does not meet 95% confidence level for this analysis but is very close.**
Overall structure length, grouping 5	0.028	Bridges with an overall structure length less than or equal to 200 feet have lower deterioration rates than those with a structure length greater than 300 feet
Average daily traffic, grouping 2	0.006	Bridges with an ADT of 20,000 or less have lower deterioration rates than bridges with a ADT greater than 20,000
Length of maximum span, grouping 2	0.002	Bridges with a maximum span length of 100 feet or less have lower deterioration rates than bridges with a maximum span length greater than 100 feet
Deck width, grouping 2	0.005	Bridges with a deck width of 60 feet or less have lower deterioration rates than bridges with deck widths greater than 60 feet.
Mn/DOT district	0.002	Because there are 8 districts, a description of the Tukey comparison is complicated. See discussion of the variable for a table containing the means of the average deterioration rate.
Continuity	0.215	Variable was not statistically significant
Average daily truck traffic	0.111	Variable was not statistically significant
Skew	0.521	Variable was not statistically significant
Bar Type	0.464	Variable was not statistically significant

Of these variables, length of maximum span and ADT were chosen for further subdivision of the population before assembly of service lives. Further analysis of maximum span length and ADT revealed that only one of the four resulting subgroups was statistically significantly different from the other three groups. However, of the three subgroups which were determined to not be statistically different from each other, one subgroup had a much higher mean deterioration rate than the other two groups. Thus for the final data breakdown, the two very similar groups were combined, and the other two groups were left separate despite the fact that one of the two was not statistically significantly different. The reasons for this decision will be discussed later in further detail.

Once the preliminary assembly of service lives for the various subgroups was performed, it was noticed that bridges with cast-in-place concrete superstructures, and bridges with steel or prestressed concrete superstructures which had maximum span lengths greater than 100 feet and an ADT of over 20,000, had nearly identical service life plots. Because of this commonality, the two data groups were combined into one group before the assembly of service lives. Thus, three final data groupings were created prior to the assembly of service lives by constructing piecewise linear NBI condition state versus time plots. The following flow chart (Figure 3.2) illustrates the final breakdown of the bridge population. In the sequel, all of the variables that were found in the preceding discussison to be statistically significant are discussed in greater detail.

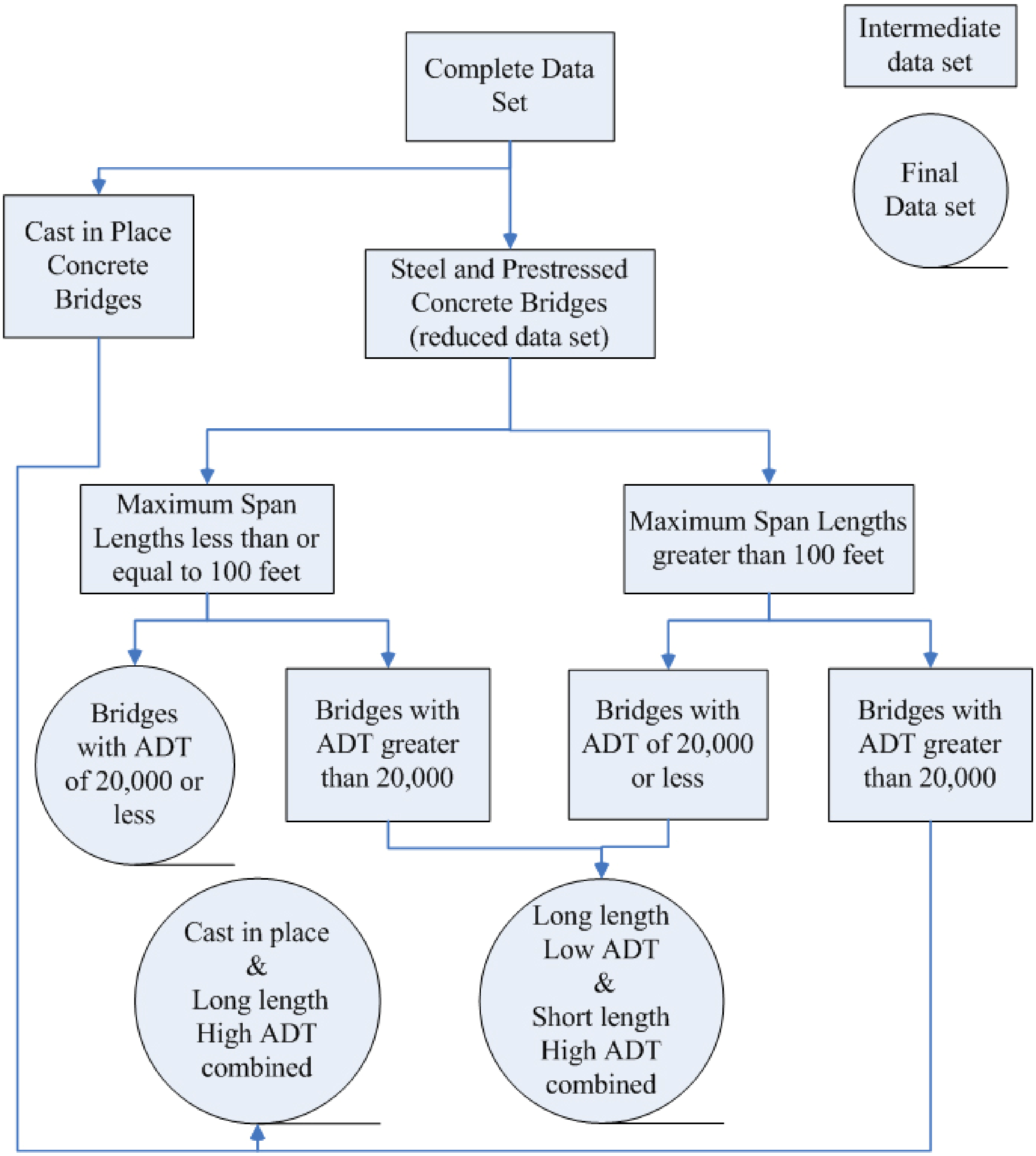

Figure 3.2 Final Data Breakdown

3.6 Detailed Discussion of Statistical Analysis Results

3.6.1 Age: Several different data groupings of age were tried. All of these groupings revealed that very old bridges have higher deterioration rates than newer bridges. The worst time period was identified as being from 1941 to 1950. This was found using the third grouping of the age variable which had 5 groups. Bridges from 1917 to 1940 were the first group, and single decades were used as groupings after that. The second grouping used contained three groups, group 1 was from 1917 to 1955, group 2 was from 1956 to 1969 and group 3 was from 1970 to 1981. This second grouping was intended to see if the increase in clear cover to the reinforcement in bridge decks from 1.5 inches to 2 inches, which occurred around 1970, had any effect on the deterioration rates of the bridge decks. However, for the second grouping as well as all other groupings, the only significant differences in deterioration rates was between very old bridges and more recent bridges. This led to the grouping 4 which simply separates very old bridges from newer bridges. Age was significant both before and after the removal of bridges with cast-in-place concrete superstructures from the data. However, the significance level was slightly stronger before the removal of these bridges. The means and standard deviations of the variable age, grouping 4, for the reduced data set are in Table 3.4.

Table 3.4 Age Grouping 4 (After Initial Data Reduction)

Range of years	Number of bridges	Mean deterioration rate (NBI points per year)	StDev
In or before 1955	22	0.1208	0.1232
After 1955	435	0.06988	0.07257

Two-way ANOVA with material type, age grouping 4, and their interactions as variables was performed. It was determined that there is very strong dependency between the two, with a significance level of 0.005. This is not surprising since bridges with cast-in-place concrete superstructures make up nearly half of the bridges in the before 1955 category of age. Thus, only one of the two could be used for initial separation of data. It was concluded that material type was a more logical choice for the first data reduction than age. Also, after the initial data reduction, age was not used for further data separation due to the small sample size of the first group compared to the second group for this variable.

3.6.2 Material Type: The means and standard deviations for the three different material types are shown in Table 3.5. It was found that bridges with cast-in-place concrete superstructures performed significantly worse than bridges with either prestressed concrete or steel superstructures. There was no significant difference between the performances of bridge decks with steel or prestressed concrete superstructures when the dataset being analyzed contained all superstructure types. However, once the dataset was reduced by the removing bridges with cast-in-place concrete superstructures, there was a nearly significant difference between bridge decks with steel superstructures and bridge decks with prestressed concrete superstructures. It was found that bridge decks with prestressed concrete superstructures performed slightly better than those with steel superstructures. As mentioned previously, no further analysis was performed for the cast-in-place (CIP) concrete group. Bridges with steel or prestressed concrete superstructures (the reduced data set) were then lumped together for further analysis and subdivision. Table 3.4 contains the means and standard deviations for the groups in the variable material type.

Table 3.5 Material Type (Before Initial Data Reduction)

Material Type	Number of bridges	Mean deterioration rate (NBI points per year)	StDev
CIP concrete	35	0.1319	0.1486
Prestressed concrete	206	0.06487	0.06593
Steel	251	0.07845	0.08359

3.6.3 Old or new: The old or new variable was defined as follows. New bridges are those on which the overlay was placed within three years of the initial construction of the bridge. Old bridges are bridges which were overlaid after more than three years had elapsed from the original construction date of the bridge to the date when the overlay was placed. Old or new was only significant for the data before bridges with cast-in-place concrete superstructures were removed. This suggests that the two were dependent on each other, which is very likely since bridges with cast-in-place concrete superstructures would tend to fall in the old category.

3.6.4 Overall structure length: In the literature review portion of this project, it was found that bridges with longer span lengths experienced greater problems with deck cracking than shorter bridges. Two fields were found in the NBI data that are related to span length. Overall structure length was the first of these. It was thought that structures with a greater overall length would be more likely to have longer span lengths. Overall structure length was significant before and after the data set was reduced. It was found for the reduced data set that bridges with an overall structure length less than or equal to 200 feet have lower deterioration rates than those with a structure length greater than 300 feet.

3.6.5 Maximum span length: This variable was thought to be the best indicator of span length. While the field does not contain the lengths of all the spans in a bridge, the length of the longest span is a good indicator of long spans in a bridge in general. Significant differences in the means of the average deterioration rates for bridges with maximum span lengths of under 100 feet and those with maximum span lengths over 100 feet were found. Maximum span length was significant before and after the data set was reduced. Also, maximum span length was found to be a more precise indicator of the influence of span length than overall structure length. For these reasons maximum span length was used as a criterion for further subdivision of the data. Table 3.6 contains the means and standard deviations for the groups within the maximum span length variable.

Table 3.6 Maximum Span Length, Grouping 2 (After Initial Data Reduction)

Length	Number of bridges	Mean deterioration rate (NBI points per year)	StDev
100 feet or less	346	0.0662	0.06665
More than 100 feet	111	0.09145	0.09875

3.6.6 Average daily traffic: Average daily traffic was significant both before and after the initial data reduction. However, the significance of average daily traffic increased substantially after the initial data reduction. It was found that bridges with an ADT of 20,000 or less have lower average deterioration rates than bridges with an ADT greater than 20,000. Two way ANOVA was performed with average daily traffic, length of longest span, and their interaction as variables. The significance for the interaction of these two variables was 0.880, much greater than the threshold value of 0.05. This means that for a very high level of confidence, there is no interaction between these two variables. Because of the statistical significance of average daily traffic and its lack of dependency on the other important variable, maximum span length, average daily traffic was used as a criterion for further subdivision of the data. Table 3.7 contains the means and standard deviations for the groups within the variable ADT.

Table 3.7 ADT Grouping 2 (After Initial Data Reduction)

ADT	Number of bridges	Mean deterioration rate (NBI points per year)	StDev
20,000 or less	344	0.06669	0.066
More than 20,000	113	0.08951	0.10001

3.6.7 Deck width: Deck width was not significant in the first ANOVA analysis performed on the entire data set, but was very close to the 95% confidence cutoff. However, after the initial data reduction, and reanalysis of the data, deck width was determined to be significant. It was suspected that deck width and maximum span length might be dependent on each other. To investigate this possibility, two way ANOVA was performed with deck width, maximum span length, and their interaction as variables. The significance level of this interaction was 0.076, which is higher than 0.05 cutoff that has been used for rest of the analyses, but it reveals some degree of dependence between these two variables. Because of the dependence, as well as the fact that length of longest span has a higher significance level, it was decided to use length of longest span as a criterion for further subdivision and to neglect the effects of deck width. Table 3.8 contains the means and standard deviations for the groups within the variable deck width.

Table 3.8 Deck Width Grouping 2 (After Initial Data Reduction)

Deck Width	Number of bridges	Mean deterioration rate (NBI points per year)	StDev
60 feet or less	363	0.06722	0.06287
More than 60 feet	94	0.0921	0.1127

3.6.8 MDOT district: Mn/DOT district was found to have a significant effect on average deterioration rates before and after removal of bridges with cast-in-place concrete superstructures from the data. District 2 was found to have significantly higher deterioration rates than other districts, and district 8 was found to have significantly lower deterioration rates than other districts. In an attempt to determine whether the effect of Mn/DOT district was being caused by a non-uniform distribution of some of the other variables being investigated (for instance, if bridges in district 2 contained a disproportionate share of bridges with maximum span lengths greater than 100 feet), the data was separated by district and basic descriptive statistics such as sample sizes, mean, and standard deviation for all of the other variables under investigation were calculated for each region. However, no explanation for the differences in the means between districts was found based on an uneven distribution of the other variables under investigation. This means that the differences are likely due to some other effect. Possibilities include differences in bridge inspections, which bridges were selected to be overlaid, differences in construction quality, and differences in the amount and types of maintenance, such as crack repairs, that the bridges received.

At the third technical advisory panel meeting with Mn/DOT for this project, panel members stated that the observation above regarding average deterioration rates in district 2 have been previously noticed and investigated. They attributed the trend in average deterioration rates to harsher than normal evaluations of bridge condition by inspectors in district 2. Since differences in deterioration rates between districts seem to be caused in part by differences in inspections between districts rather than by actual tangible differences in bridge condition and deterioration, the effect of district was disregarded as a criterion for further subdivision of the data.

Table 3.9 contains the means and standard deviations for the groups within the variable Mn/DOT district after removal of bridges with cast-in-place concrete superstructures from the data. It is interesting that the standard deviations for both districts 2 and 8 are fairly low which means that the differences in means are not caused by a few bridges with wildly different deterioration rates, but rather suggests that a more uniform or consistent phenomena as discussed above is responsible for these differences.

Table 3.9 Mn/DOT District (After Initial Data Reduction)

Mn/DOT District	Number of bridges	Mean deterioration rate (NBI points per year)	StDev
1	69	0.05994	0.07288
2	12	0.1236	0.0574
3	49	0.07697	0.04937
4	24	0.0719	0.0642
5	169	0.07826	0.08711
6	77	0.08266	0.08056
7	38	0.05301	0.06112
8	19	0.01754	0.02844

3.6.9 Final Data Grouping of Max Span Length and ADT: As mentioned previously, maximum span length and ADT were chosen for use in further subdividing the data. Two-way ANOVA was performed to check for interactions between the variables, and Tukey's method was used for pair wise comparison after the two-way ANOVA. The results from Tukey's method show that of the four data groups obtained using this breakdown of the data, only one of the groups was significantly different from the other groups. For ease of discussion the four sub-groups resulting from the variables maximum span length and ADT are given reference numbers in the following table. Group 1 performed significantly better than the other groups. While the Tukey multiple comparisons showed no significant differences between group 4 and groups 2 and 3, group 4 has a much higher mean than groups 2 and 3. The reason that Tukey's method revealed no significant differences between group 4 and groups 2 and 3 is that the standard deviation for group 4 is much larger than those for groups 2 and 3, i.e. group 4 possesses a large amount of internal variation. Even though groups 2 and 3 are not statistically significantly different from group 4, combining group 4 with groups 2 and 3 would greatly reduce their average service life which could have substantial consequences in the economic analysis. Thus it was decided for the purpose of assembling service lives for the bridges, to combine groups 2 and 3 together due to their similar performance and to leave groups 1 and 4 separate. Table 3.10 contains the means and standard deviations for the groups within the variables maximum span length and ADT for the reduced data set.

Table 3.10 Max Span Length and ADT (After Initial Data Reduction)

Data group	Number of bridges	Mean deterioration rate (NBI points per year)	StDev
Max span length ≤ 100' and ADT ≤ 20,000 (Group 1)	260	0.06066	0.06074
Max span length ≤ 100' and ADT > 20,000 (Group 2)	86	0.08293	0.08007
Max span length > 100' and ADT ≤ 20,000 (Group 3)	84	0.08533	0.07763
Max span length > 100' and ADT > 20,000 (Group 4)	27	0.1105	0.1467

3.6.10 Effect of Overlay Placement Date: In the previous section of this report that dealt with the procedure used to calculate the average deterioration rates, which were used in the statistical analysis, it was mentioned that a further discussion would be made about the consequences of neglecting the range of years over which the overlays were placed. To investigate this potential problem, a variable called "time lag from overlay date" was created and its effects on the deterioration rates were analyzed. The 8 year period from 1974 thru 1981 was separated into two year intervals, and ANOVA was performed on the data both before and after the initial data reduction. The effect of the time lag was significant both before and after the data was reduced. However, the significance was less after the initial data reduction. When Tukey's multiple comparison procedure was performed on the data, it was determined that the only time period that was different from the rest was the first two years, 1974 and 1975. These two years had substantially higher deterioration rates than the other years. Table 3.11 shows the means of the average deterioration rates for the different year groups.

Table 3.11 Effect of Time Lag (Before Initial Data Reduction)

Years	Number of bridges	Mean deterioration rate (NBI points per year)	StDev
80-81	161	0.07295	0.05862
78-79	183	0.06777	0.06765
76-77	112	0.06834	0.06796
74-75	36	0.1631	0.1954

Because the deterioration rates of the bridges overlaid in the period 1976-1981 are fairly consistent with each other, it is doubtful that the high deterioration rates of the 1974-1975 period are caused by the inaccuracy of using a linear approximation to a nonlinear curve. Rather it appears that when the first overlays were placed, the selection of candidate bridges that were in need of rehabilitation targeted bridges that were not performing well. Table 3.12 shows the distribution of years in which the bridges of the 1974-1975 time period were constructed as well as the deterioration rates for these construction time frame groups.

Table 3.12 Time Period of Initial Construction for Bridges from the 1974 to 1975 Time Period (Before Initial Data reduction)

Time period of initial construction	Number of bridges	Mean deterioration rate (NBI points per year)	StDev
1941-1950	3	0.5556	0.0962
1951-1960	10	0.1426	0.0736
1961-1970	6	0.35	0.25
1971-1981	17	0.03979	0.03524

It is readily apparent that bridges which were fairly new at the time of being overlaid and were being overlaid merely for added deck protection are performing quite well. Only bridges that are old enough to have been rehabilitation candidates have above normal deterioration rates and are responsible for difference in the means of the average deterioration rates for the 1974 to 1975 time period in comparison to the 1976-1981 time period. At the third technical advisory panel meeting with Mn/DOT for this project, panel members mentioned several different factors that could be contributing to above average deterioration rates of the 1974 to 1975 time period. One reason listed was that as previously mentioned, the bridges in worse condition were more likely to be overlaid first. Also, in the first few years that low slump concrete overlays were being installed, a thinner layer of deck was milled off before overlaying than was milled off in later years. This probably resulted in more damaged, chloride infiltrated concrete being left in the deck under the early overlays and could have affected their performance relative to overlays placed in later years. Lastly the newness of the technique at the time (mix designs and installation techniques were still being perfected) and differences in deck thickness requirements for some of the older bridges being re-overlaid were listed as possible reasons for the above average deterioration rates of the 1974 to 1975 time period.

3.7 Assembly of Service Lives

Once all variables that were shown to have significant effects on the deterioration rates of the bridges were identified, the data was then subdivided into smaller populations based on these variables. This subdivision was accomplished by first using queries in ACCESS, and then exporting the resulting data subsets as EXCEL spreadsheets. The EXCEL spreadsheets were subsequently converted to text files for the final portion of the data analysis, the calculation of deterioration rates.

After reviewing the work of several researchers in the area of calculating bridge component deterioration rates, a technique developed by Al-Rahim and Johnston (23) was chosen for use. This technique involves calculating the average change from a particular condition rating in a one year period, and then repeating the process for all years for which data is present. Thus, an average change in condition rating for all bridges in the data set for one particular initial condition rating is obtained. This process is then repeated for all desired initial condition ratings (in this project, ratings of 8 through 5). Next, the time it takes on average for a unit drop in condition rating is calculated by computing the inverse of the average change. Each of the times for a unit drop in condition rating can then be plotted to obtain a piecewise linear deterioration curve for each of the data subsets. To implement this technique, a C++ computer program was written to loop through a text file containing the condition ratings of bridges from 1983 to 2003 for each data subset. The resulting times for a unit drop in condition rating were then plotted in EXCEL to produce the deterioration curves (Figures 3.3 and 3.4).

For the three variables considered, a consistent nomenclature is used throughout this report for the three principal variables. *Superstructure material type* can be either **CIP** for cast-in-place concrete or **S&P** for either steel or prestressed concrete. *Average daily traffic* (ADT) *count* can be either **Low ADT**, which is less than or equal to 20,000 vehicles per day, or **High ADT**, which is more than 20,000 vehicles per day. *Maximum span length* can be either **Short Span**, for bridges that have the longest span shorter than or equal to 100 feet, or **Long Span**, for bridges that have the longest span exceeding 100 feet.

It is emphasized that the technique used to assemble the service life plots is completely independent of the average or linear deterioration rate calculations that were used in the statistical analysis. The statistical analysis served solely to identify trends in the performance of the bridges under consideration in this project so that the data could be separated into groups of bridges with similar performance. However, both the statistical analysis and the technique used to assemble service lives are directly based on the NBI deck condition data and so a high degree of agreement between the two techniques was expected, and was observed.

In order to compare the linear deterioration rates used in the statistical analysis to the nonlinear deterioration curves generated in the service life assembly process, plots showing both the non linear curve calculated using the Al-Rahim and Johnston method and the linear plot obtained using the average deterioration rates from the statistical analysis were created. A comparison plot was created for each of the five groups that were obtained from the data analysis before they were combined to arrive at the final three data groups. The five groups are; cast-in-place concrete and the 4 subgroups created from the various ADT and Maximum Span Length combinations. These five groups illustrated graphically in a flow chart in Figure 3.2.

Using MINITAB, mean values of the average deterioration rates for the bridges in each of five groups were calculated. These mean values of the average deterioration rates for each group were then plotted with a *y*-intercept (NBI deck condition rating) of 8 and continued with a negative slope until the line reached a *y* value of 5. These five plots (Figures 3.5-3.9) show a high level of agreement between the two techniques.

The Abed-Al-Rahim and Johnston method is desirable because it deals with several key problems that were found in the data. The first of these problems was how to handle bridges which received rehabilitation or repair as evidenced by a two or more increase in condition rating. By assuming a normal distribution of repair timing, the authors of this technique decided to assign a 0.5 unit decline in condition rating to bridges that received rehabilitation since the exact timing of these repairs is not known (23).

The second problem was how to handle bridges that had a unit increase in condition rating between two years. As mentioned previously, this increase is most likely due to a different opinion about the condition of a bridge by a different inspector. The authors decided that the best way to handle these bridges was to exclude them from the analysis for the particular initial condition rating that was under consideration (23). Following is a plot (Figure 3.3) containing the NBI condition state versus time for the three final data sets. Also included is a plot (Figure 3.4) containing the NBI condition state versus time for the five primary data sets arising from the data analysis (cast-in-place concrete and the 4 subgroups created from the ADT/Max Span Length combination, (see Figure 3.2) before their combination to form the final three data sets. Figure 3.4 illustrates graphically why the five primary data sets arising from the data analysis were combined to form the final three data sets.

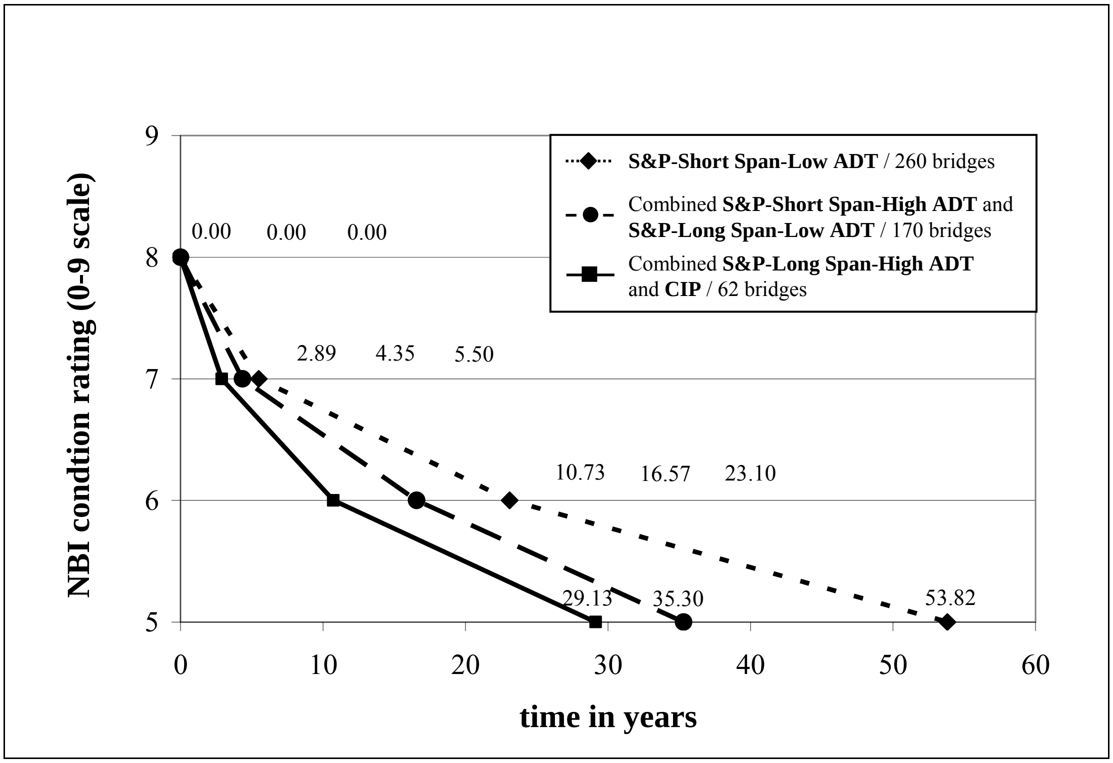

Figure 3.3 NBI Condition Rating vs. Time for Selected Sub Groups

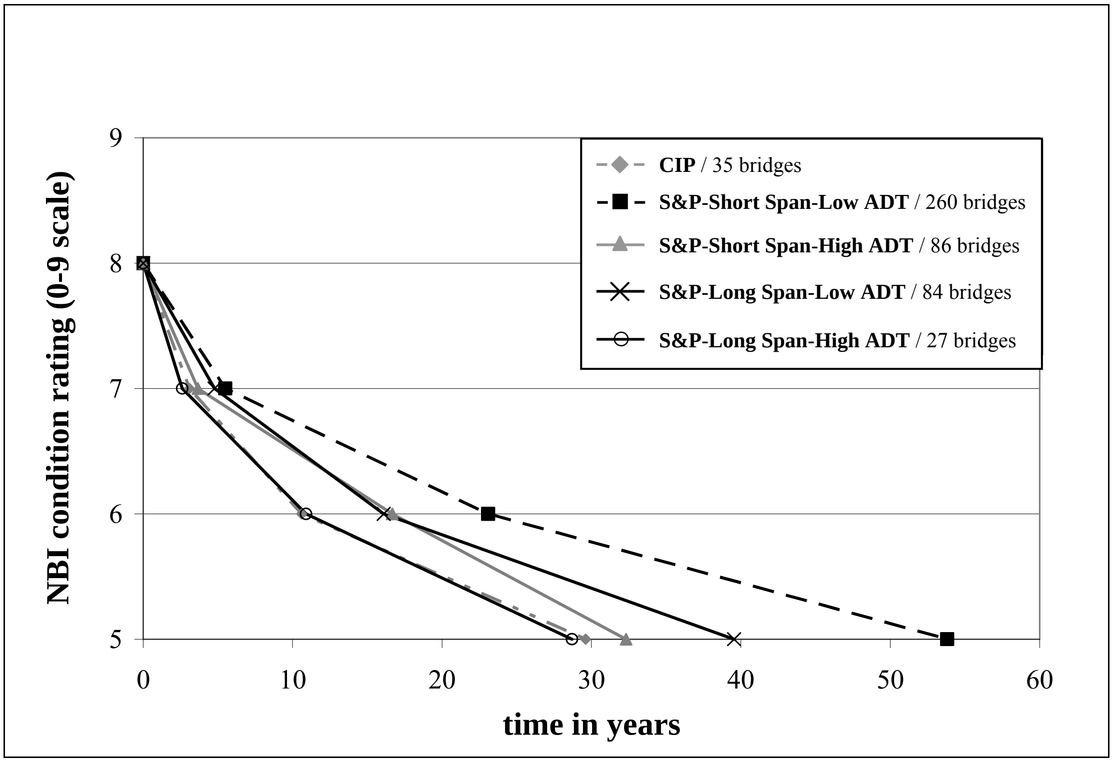

Figure 3.4 NBI Condition Rating vs. Time for Five Primary Data Groups with No Data Group Combination

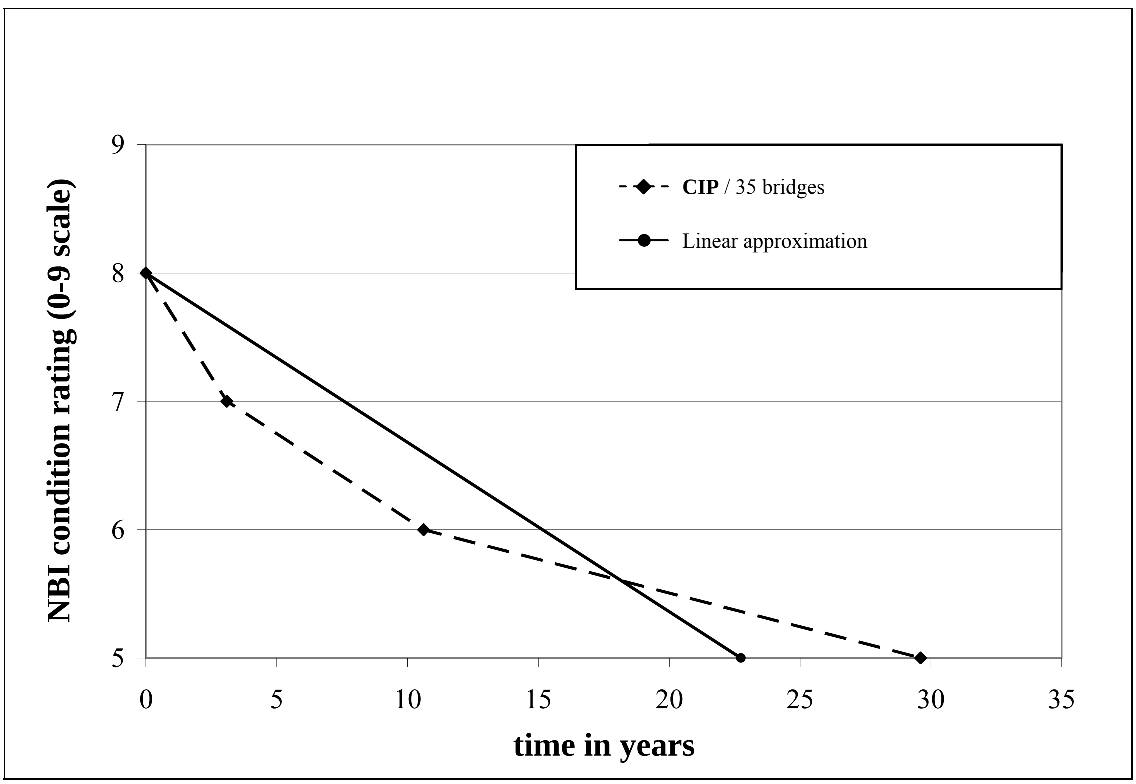

Figure 3.5 NBI Condition Rating vs. Time for Cast in Place Concrete Superstructures with Linear Approximation

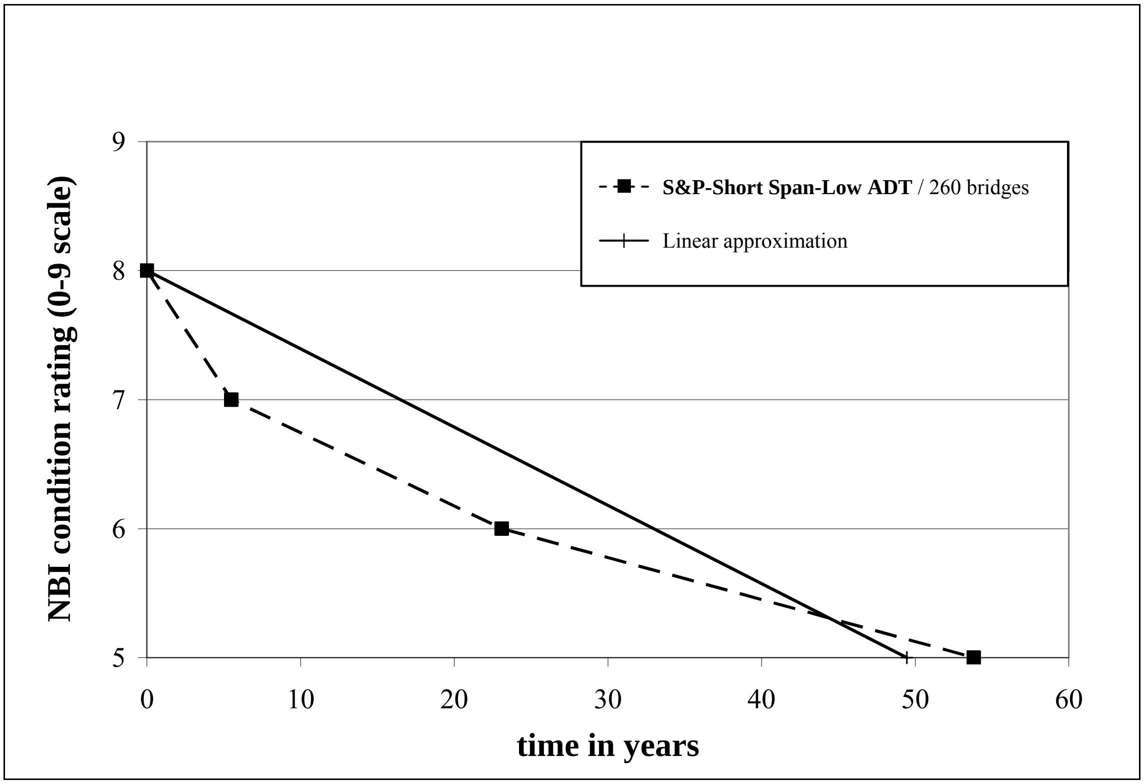

Figure 3.6 NBI Condition Rating vs. Time for Short Low with Linear Approximation

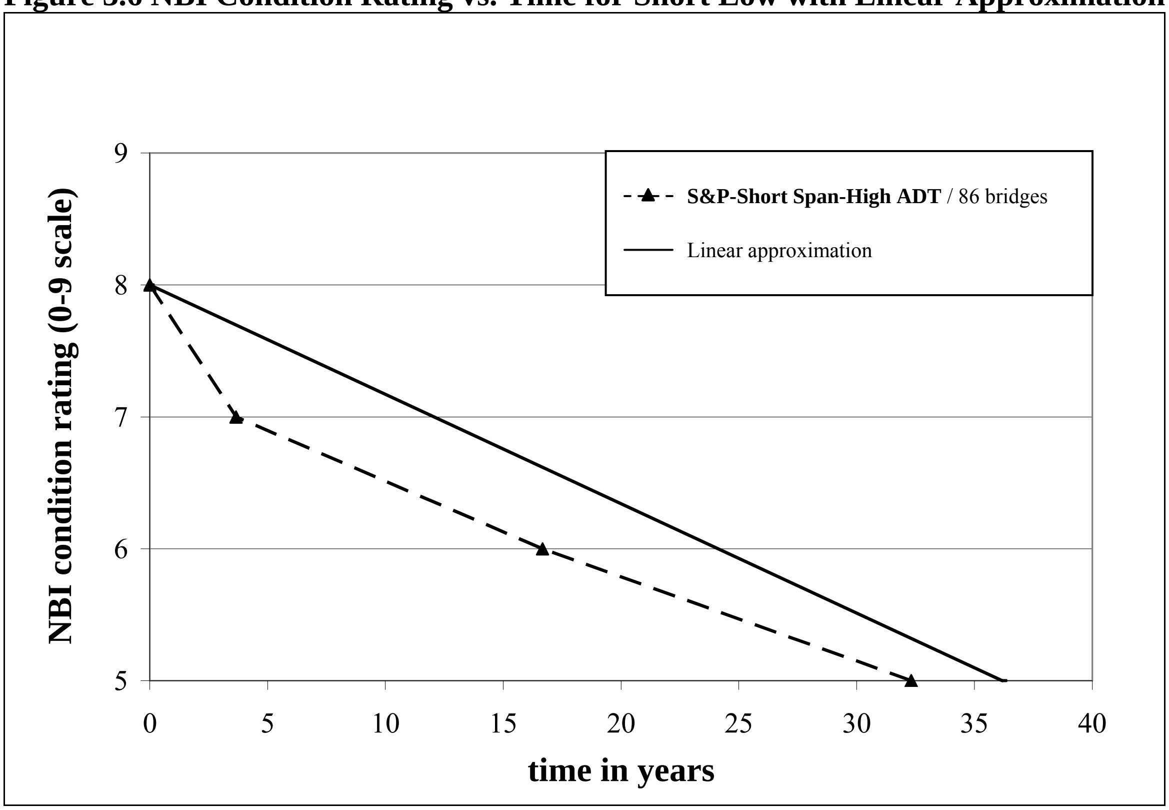

Figure 3.7 NBI Condition Rating vs. Time for Short High with Linear Approximation

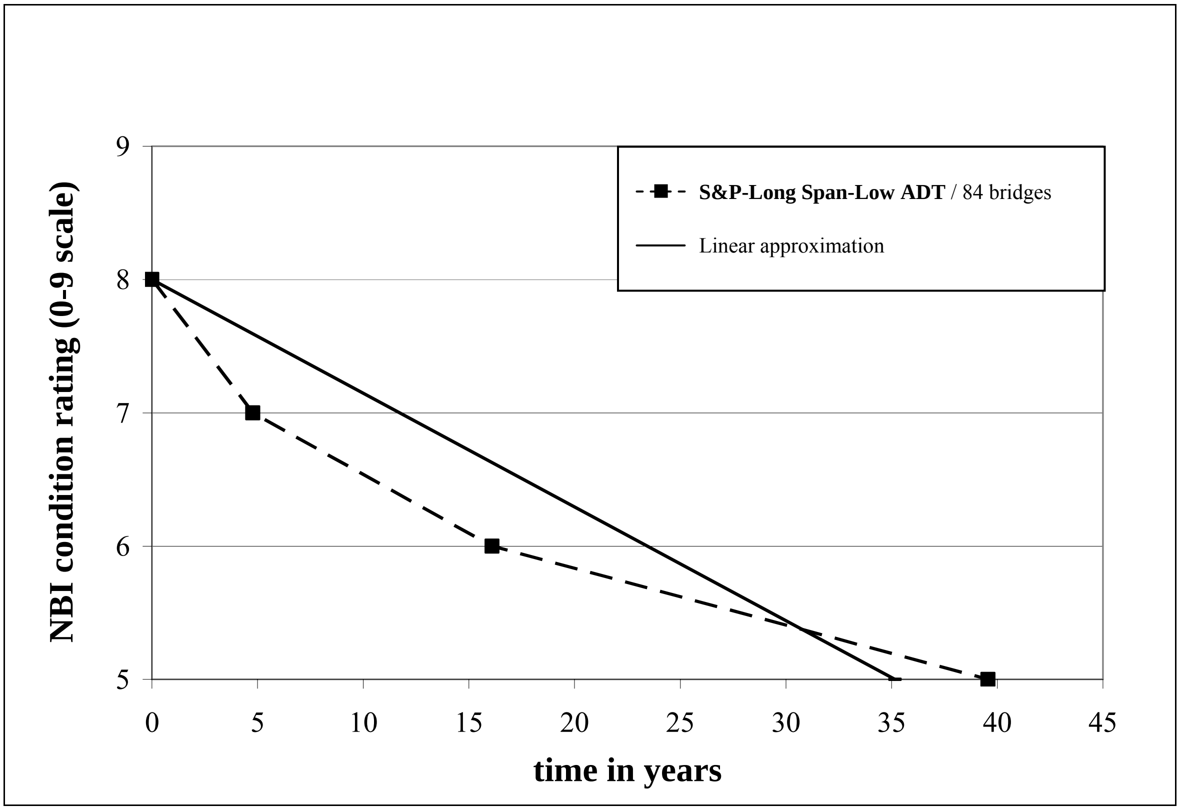

Figure 3.8 NBI Condition Rating vs. Time for Long Low with Linear Approximation

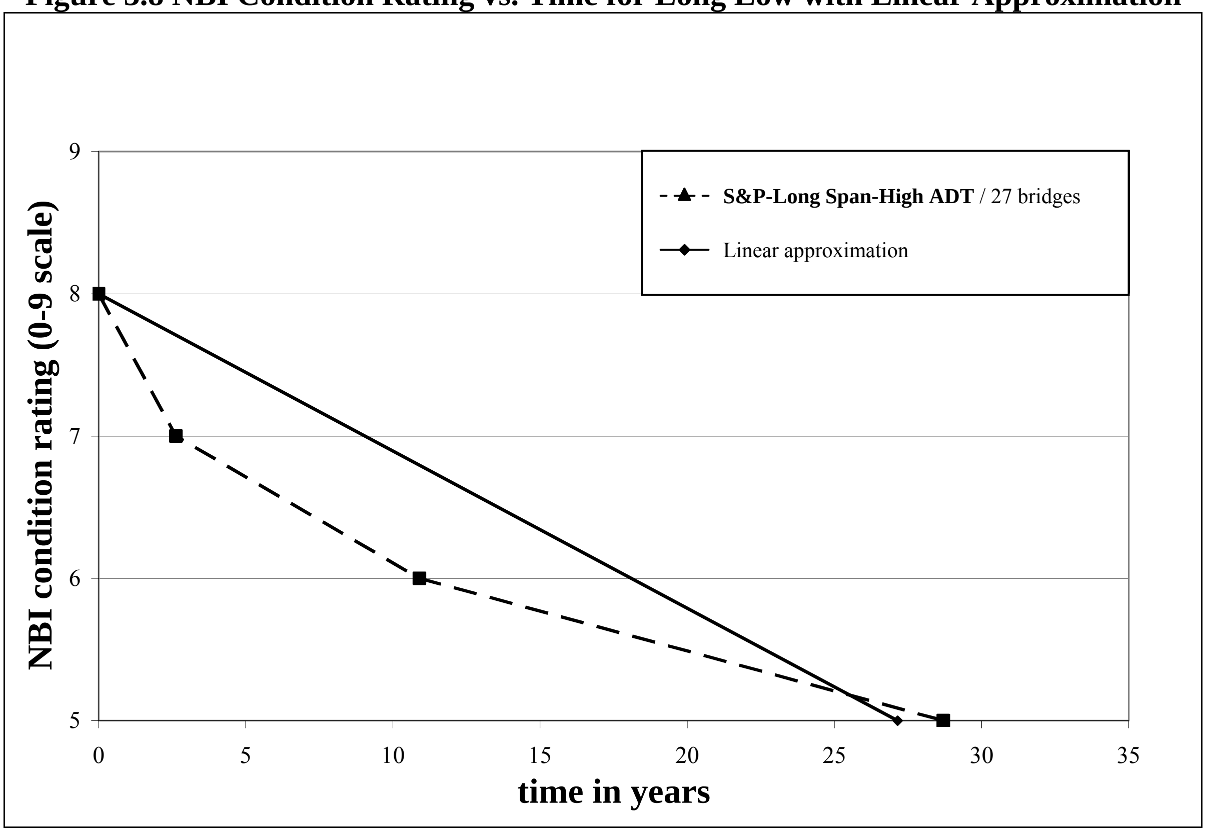

Figure 3.9 NBI Condition Rating vs. Time for Long High with Linear Approximation

Chapter 4: Cost Analysis

4.1 Overview of the Cost Analysis

The goal of the cost analysis portion of the project was to generate strategies that Mn/DOT could use to assist the decision making process for the repair or replacement of the bridge decks being studied in this project. The group of bridges for which repair/replacement strategies were developed consists only of bridges which were constructed on or before 1981 and received low slump concrete overlays during the time period of 1974 to 1981. Thus, the results of the economic analysis are applicable only to this particular subset of the bridge population.

In the data analysis portion of this project, deck deterioration versus time plots were created for various sub-groupings of bridges. These deterioration curves were used in the economic analysis to predict the deterioration of the bridge decks under consideration. Cost data for various repair and replacement procedures were provided by the members of the Mn/DOT Technical Advisory Panel (TAP). Various combinations of repair and replacement sequences were defined based on the current deck repair and replacement practices of Mn/DOT. Finally all of this information was combined and used to perform a present value cost analysis to calculate the present value of the various combinations of future repair and replacement actions. Based on this present value cost analysis, flow charts were created that graphically illustrate the least cost repair/replacement sequence likely for a particular bridge, given a target deck condition that is to be maintained. In addition, a parametric study was conducted to investigate the effects that the various input parameters and initial assumptions have on the least cost sequence of repair/replacement actions.

4.2 Definition of Repair/Replacement Techniques

4.2.1 Reoverlaying: Reoverlaying involves milling the entire existing overlay on the deck and replacing it with a new overlay. A large milling machine is typically used for the removal of the existing overlay to a depth approximately 1 in. above the top layer of reinforcing bars. Any areas of unsound deck that are detected are fixed using Type 1 repairs. A Type 1 repair involves removal of the damaged structural concrete all the way down to the top mat of rebar. Typically pneumatic tools are used for the removal of the structural concrete. The milled deck surface is then sandblasted and cleaned. Immediately before the placement of the new overlay, cement slurry is brushed on the deck to assure good bond between the deck and the new overlay. The new overlay concrete is mixed on site, and is packed and consolidated onto the deck by a paving machine that rides a rail along the deck to assure the correct overlay depth and an even riding surface. The areas where Type 1 repairs were made are filled with new concrete as the overlay is placed. Figure 4.1 and Figure 4.2 show photographs that depict the reoverlaying process.

Figure 4.1 Milled deck, and Type 1 Repairs before Reoverlaying

Figure 4.2 Application of the New Overlay

4.2.2 Mill and Patch Repairs: Mill and patch repairs involve the removal of all overlay and structural concrete down to the top mat of rebars and then patching the removed area with concrete. With mill and patch repairs, only selected areas of the deck are repaired as opposed to removing the entire expanse of old overlay. Small milling machines and pneumatic tools are used for the removal process. If more than 10% of the deck is unsound, mill and patch repairs are typically not performed.

4.2.3 Redecking: Redecking involves complete removal of the existing deck and then replacement with a new deck. When the new deck is built, the roadway is typically widened to meet newer guidelines on lane and shoulder widths. The amount of widening required for the deck varies depending on factors such as the number and configuration of lanes the deck carries. To simplify the economic analysis, a uniform deck width increase of 6 feet was assumed for all redecking considered in the analysis. For decks that are cast integrally with the superstructure such as T-beam and box girder bridges, redecking is not an option since the entire superstructure must be replaced as well.

4.3 Input Data and Assumptions

The present value cost analysis was performed using a macro in Visual Basic for Applications that interfaced with two Excel worksheets. Most of the input data that was used in performing the analysis is stored in these two worksheets. The only critical input data that is stored in the program code instead of the worksheets are the slopes of the piecewise linear deterioration curves. There are only three general deterioration curves used in the analysis, and these curves are not specific to any one bridge. Rather, a particular curve is based on the average behavior of all bridges that fall into the group of data used to construct the curve.

Data pertaining to individual bridges is stored in one of the worksheets. This data contains information about all of the bridges included for study in this project such as length, width, and some parameters necessary to determine which deterioration curve is appropriate for a specific bridge deck. Also included in this sheet is all 21 years of NBI deck condition field data. This data is organized by structure number so that there is one row in the sheet for every bridge. When the cost analysis is performed, the NBI data for a specific bridge is used in combination with one of the three general deterioration curves to determine the best repair/replacement strategy for that bridge.

The second worksheet contains the cost data, assumed values for percent unsound deck for a given condition state, and the specified effect of reoverlaying or mill and patch repairs on a given condition state for the deck. Since the cost and repair effects data are referenced directly from the worksheet and not stored in the program code, it is easy to change them if better information (i.e., more accurate or current) becomes available in the future, as well as to assist in performing the parametric study. Table 4.1 summarizes the cost data that was used for the present value cost analysis.

Table 4.1 Cost Data Used in the Present Value Analysis

Item	Cost	Per/unit
Reoverlay with traffic control costs	$10.00	ft^2
Deck replacement cost with traffic control	$50	ft^2
Widening of roadway when replacing deck (assumed 6 ft wide swath)	$110	ft^2
Mill and Patch - must be less than 10% delamination/unsound deck to be considered	$30	ft^2
Use 4% for rate of inflation		
Use 12% for discount rate (note this value was not provided by Mn/DOT)		

In addition to the data in Table 4.1, several assumptions were made in order to perform the present value cost analysis.

- A time frame of twenty years is used in the analysis. The accuracy of results obtained decreases with longer time frames since the time value of money tends to obscure other temporal trends for time periods significantly longer than 20 years (24).

- An NBI deck condition of 4 was taken to be the lowest permissible rating in the present value cost analysis. NBI deck condition ratings lower than 4 are extremely rare for bridges on the trunk highway system.

- No repair actions were considered for NBI deck conditions of 7 or higher. For bridges that were predicted to deteriorate to levels requiring repairs during the analysis period whose NBI deck condition ratings were 7 or higher initially, repairs were not allowed until the deck had deteriorated to below a rating of 7. However, for bridges that were predicted to need repairs, immediate deck replacement was considered a feasible option.

- For the purpose of the calculations used in the present value analysis, partial NBI deck condition ratings in decimal form were used. While in reality, NBI deck ratings must have integer values; this does not lend itself well to modeling the continuous deterioration processes and their associated costs.

- The number of years that a deck has been at a particular rating is considered in the cost analysis. A deck that has been at a particular NBI deck condition rating for several years would have a greater amount of deterioration than a deck that just reached that particular rating. NBI deck condition ratings represent a range of possible values for things such as percent deck delamination and cracking. Thus, bridges that have been at a rating longer will be expected to have slid farther toward the next lower value. This assumption was implemented by using the 3 deterioration curves assembled in the data analysis portion of the project to predict the current decimal value of deck condition rating. A problem with this approach is that if a bridge is experiencing above average performance, it may remain at single rating for much longer than the average deterioration curves will predict. It was decided that a rating should not be lowered by more than ¾ point. The bridge would have received a lower rating if the cumulative damage incurred over the years at the particular rating had gone beyond the range of values permitted for the current rating, and thus the true rating must lie between the bridges actual rating and the next lower rating. The ¾ point limit on the reduction of the current rating allows the economic analysis to consider bridges that are performing above average. It is obvious that the precise value chosen for this limit is rather arbitrary. It is possible that a better choice for this limit might be a slightly larger or smaller value than ¾. However, the effect of this choice was investigated in the parametric study, and it was found that the analysis is insensitive to the choice for this limit. For an example of how this assumption is implemented see the second present value cost analysis example in Appendix B.

- Only two repair/replacement actions were permitted during the 20 year analysis period.

- It was assumed that the first application of reoverlaying raised the condition state of the deck by 1 NBI deck condition state point and that the second application of reoverlaying raised the condition state of the deck by ½ NBI deck condition state point. For example, if a deck was estimated to have a current decimal NBI deck condition of 4.3, and the deck was re-overlaid, the program would raise the decks NBI deck condition state to 5.3. It was assumed that the first application of mill and patch repairs raised the condition state of the deck by ½ NBI deck condition state point and that the second application of mill and patch repairs raised the condition state of the deck by ¼ NBI deck condition state point. The reason that reoverlaying was assumed to be more effective is due to the fact that a reoverlay repairs a larger portion of the deck than mill and patch repairs. These assumptions are based on the experience Mn/DOT has with the effectiveness of these repair techniques. The effect of these assumptions on the present value cost analysis was investigated in the parametric analysis.

- It was assumed that after the effects of repairs on a bridge raised its deck condition rating, the deterioration of the deck after the repairs follows the same deterioration curve as before the repairs. For instance, if a bridge is repaired and its condition rating goes from 4 to 5, it will take the same the number of years for the bridge to deteriorate back to 4 as it took the bridge to deteriorate from 5 to 4 before the repairs.

- The deterioration curves that were generated in the data analysis portion of the project did not include all deck condition ratings that are necessary to perform the present value analyses. Thus, assumptions about bridge behavior at ratings above and below those which are included in the deterioration curves needed to be made. There are three different deterioration curves, and these curves were numbered type 0-2 for simplicity when coding the present value analysis program (see Figure 4.3). The actual numerical data, including assumed values, that was used to construct the complete curves needed for the present value analysis is tabulated in the spreadsheet program in Appendix A. The highest rating of the deterioration curves assembled in the data analysis portion of the project is 8, but a rating of 9 must be considered in the present value analyses. It was assumed that the slope of the deterioration curve from 9 to 8 is the same as the slope from 8 to 7.

  When the deterioration curves were assembled in the data analysis portion of the project, they were only plotted for NBI ratings of 8 to 5. The principle reason for the cutoff at a rating of 5 is because there are very few bridges with ratings below 5. Only 13 data points are available for the drop in deck condition rating from 5 to 4, which is a very limited amount of data for creating statistically reliable deterioration curves. The program that generated the deterioration curves using the Rahim/Johnston method was coded, however, to include the drop in condition rating from 5 to 4 since some data is available. There are 4 data points available for the type 0 curve, 7 data points available for the type 1 curve, and 2 data points available for the type 2 curve.

After viewing the deterioration curves, the members of the Mn/DOT TAP suggested that the slopes for the 5-4 drop generated by the Rahim/Johnston method should not be used as is for the type 0 and type 2 curves. There was concern that these two slopes were considerably overpredicting the amount of time it actually takes for a deck to drop from a condition state of 5 to 4. It was decided, after discussion, that the slope for the 5 to 4 drop which is considerably steeper than the 5-4 slope for the type 0 and type 2 curves was more intuitive and better aligned with Mn/DOT experience with deck deterioration in the 5-4 condition state region. Due to the lack of better alternatives, it was decided to use the slope from the type 1 curve for these other two curves as well. While this is an imperfect solution, it can be refined in the future when better data is available for deck deterioration in the 5-4 condition state region for the bridges of this project. The effects of this assumption for the deterioration of the bridge decks below a condition state of 5 were investigated in the parametric analysis.

It is noted that the above assumption essentially provides a worse case or lower bound for the type 0 and type 2 deterioration curves. The small amount of data present for the 5-4 drop in type 1 and type 2 curves suggested that the real 5-4 slope may be similar to the 6-5 slope. Figure 4.3 is a plot containing the final deterioration curves used in the present value analysis, including the assumptions just discussed. The slopes determined using the limited data for the type 0 and type 2 curves are shown as well.

A specific nomenclature was defined earlier and used here for *superstructure material type* (**CIP** for cast-in-place concrete, and **S&P** for either steel or prestressed concrete), *average daily traffic count* (**Low ADT** is for 20,000 vehicles per day or less, and **High ADT** is for more than 20,000 vehicles per day), and *maximum span length* (**Short Span** is for bridges with the longest span shorter than or equal to 100 feet, and **Long Span** is for bridges with the longest span exceeding 100 feet). Note that the solid lines in Figure 4.3 represent regions where good data existed, the heavy dashed lines are assumed slopes, and the fine dashed lines are the actual slopes based on limited data. For economic analysis calculations involving the drop from 5 to 4, both the type 2 and type 0 curves use the assumed slopes shown.

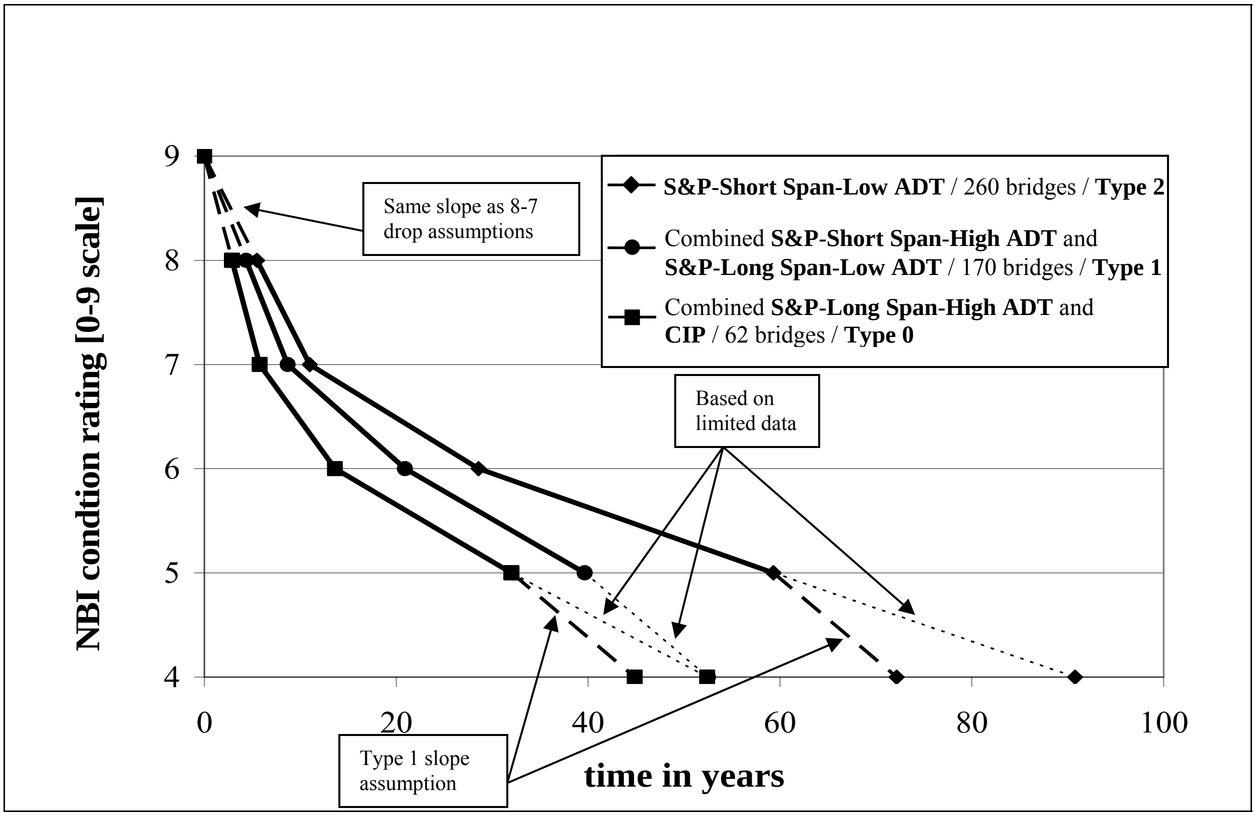

Figure 4.3 Deterioration Curves Used in the Economic Analysis (Note: These three deterioration curves ONLY represent the deterioration behavior of bridges which were included for study in this project and should not be considered representative of concrete bridge deck deterioration in general.)

- When performing the present value analysis, a value is placed on the bridge deck at the end of twenty years, and this value is then subtracted from the total costs incurred in repairing and or replacing the bridge deck. The value at the end of twenty years is based on the cost of replacing the deck. During the time passing since the original construction of the bridges being studied in this project, geometric design standards have changed. Lane and shoulder widths have been increased and new decks need to be built to meet the new standards. Since a replacement deck would have to be built wider, this widening is taken into account in the value of the replacement. While the actual increase in deck width required varies, a representative value of 6 feet was used for all bridges in the present value cost analysis. The final NBI deck condition of the bridge is estimated using the appropriate deterioration curve from the data analysis portion of the project. A bridge with an NBI deck condition of zero is not functional and thus was assigned a value of 0. A bridge with an NBI deck condition of 9 is in perfect condition and is thus assigned a value equal to the cost of redecking the bridge taking into account 20 years of inflation. The value of bridge is then determined by multiplying its percent of new condition (final estimated condition divided by nine) by the cost of redecking the bridge in 20 years. Assigning a value to the bridge at the end of twenty years is a necessary part of the present value analysis. If this was not done, a comparison of multiple repair/replacement strategies that resulted in different final conditions of the bridge deck would not be possible. It should be noted that if the final value of the bridge deck is greater than the cost of repairs incurred throughout the analysis, the final cost value will be negative, since the costs were taken to have a positive sign for simplicity.

- In order to calculate the cost of performing a mill and patch repair to a deck, it is necessary to know the percentage of deck area that is being repaired. In the Bridge Inspection Field Booklet, condition descriptions are given for NBI deck condition ratings. In these descriptions, a range for percent of unsound deck is given. When calculating the cost of performing mill and patch repairs on a deck at the beginning of a cost analysis, the average of the range of percent unsound deck listed in the Bridge Inspection Field Booklet is used. The range used corresponds to the current NBI condition state recorded for the deck, not its predicted decimal NBI deck condition. It was decided that given the imprecise nature of the range of unsound deck percentages, interpolating based on the predicted decimal NBI deck condition rating would not result in greater accuracy. For example the Bridge Inspection Field Booklet says that if a deck has a NBI deck condition state of 5, the percent unsound deck can range from 5-10% (25). Thus if the recorded NBI deck condition state for a bridge is 5, 7.5% unsound deck is used in determining the cost of the mill and patch repairs. However, when the deck is allowed to deteriorate to a specified minimum condition state in the cost analysis, the smallest value in the range of unsound deck percentages is used since the repairs are made to the deck as soon the deck reaches the minimum condition state. For example, if a bridge being analyzed was allowed to deteriorate to 5 before performing repairs, then a value of 5% unsound deck would be used since the specified range for a NBI deck condition of 5 is 5-10% and the deck just reached 5. The values from the Bridge Inspection Field Booklet are used as default values. The user of the cost analysis spreadsheet may enter different values for the percentage of unsound deck corresponding to a given condition state, if the user has more exact data such as that obtained from actual chain dragging or bridge inspection data. Also, after consulting the Mn/DOT TAP members on the issue, it was determined that twice the unsound area of deck should be used in determining the actual cost of mill and patch repairs, since some of the undamaged surrounding deck is removed along with the damaged deck in the repair process. Thus, in the above example where the unsound deck was figured to be 7.5%, 15% of the deck area would be assumed to be subject to repair. All percent unsound deck values used in the analysis are tabulated in Appendix A.

- When the program considers redecking of the bridge, the new deck is given an initial condition state of 9. Based on the definitions of the NBI deck condition states, this seemed to be the most appropriate choice. This choice was coded directly into the present value analysis program.

- To simplify calculations, it was assumed that all repairs took place at the beginning of the year in which they were performed. Also, when the program allows bridges to deteriorate to a specified minimum value before performing repairs, the number of years it took to reach the value is rounded up or down to the nearest whole year.

4.4 Present Value Cost Analysis Implementation

As previously mentioned, the present value cost analysis was performed using an Excel macro. This was necessary given the vast number of calculations necessary in performing the analysis for 492 bridges. The first step in determining the least cost repair/replacement strategy for a particular bridge is to decide on a minimum acceptable NBI deck condition state for the bridge, R_{min}. Once a bridge reaches R_{min}, repairs or replacement must be performed. The choice of R_{min} has significant effects on what repair/replacement strategy will have the lowest cost. It was realized that having one value of R_{min} for all bridges in this study would not be a very good idea, since in reality these bridges will likely have different goals set for their condition and performance depending on factors like the level of usage a bridge receives and the amount of money available for maintaining and repairing it. Thus the present value cost analysis was performed for all reasonable choices of R_{min}.

Three NBI deck condition states were determined to be realistic values for R_{min}, R_{min}=4, 5, or 6. A NBI deck condition state rating of 4 represents bridge decks that have some serious problems and seldom are bridges allowed to deteriorate to levels below 4. Bridge decks that have NBI deck condition states of 7 have very minor deterioration and it is not practical to require bridges to have condition states of 7 or higher. Based on the information about repairs provided by Mn/DOT as well as the above assumptions, the following list of possible repair/replacement strategy options (Table 4.2) was developed for each action threshold, R_{min} = 4, 5, or 6. Note that some combinations of these actions would typically not be used by Mn/DOT, such as reoverlaying decks twice, but were included in an effort to make the repair/replacement option strategies comprehensive and consistent.

Table 4.2 Repair and Replacement Strategy Options

Option number	Description
0	No valid options, replacement of the bridge is needed
1	Redeck now
2	Let deteriorate to R_{min}, then redeck
3	Reoverlay now, nothing else if rating stays above R_{min}
4	Reoverlay now, redeck when a NBI deck condition of R_{min} is reached
5	Reoverlay now, reoverlay again when R_{min} is reached
6	Reoverlay now, mill and patch when R_{min} is reached
7	Let deteriorate to R_{min}, then reoverlay, nothing else for if rating stays above R_{min}
8	Let deteriorate to R_{min} then reoverlay, then redeck when R_{min} is reached
9	Let deteriorate to R_{min}, then reoverlay, let deteriorate to R_{min}, then reoverlay
10	Let deteriorate to R_{min}, then reoverlay, let deteriorate to R_{min}, then mill and patch
11	Mill and patch now, nothing else if rating stays above R_{min}
12	Mill and patch now, then redeck when R_{min} is reached
13	Mill and patch now, mill and patch when R_{min} is reached
14	Mill and patch now, reoverlay when R_{min} is reached
15	Let deteriorate to R_{min}, then mill and patch, nothing else if rating stays above R_{min}
16	Let deteriorate to R_{min}, then mill and patch, then redeck when R_{min} is reached
17	Let deteriorate to R_{min}, then mill and patch, let deteriorate to R_{min}, then mill and patch
18	Let deteriorate to R_{min}, then mill and patch, let deteriorate to R_{min}, then reoverlay

It is easy to see when inspecting the above list that if some options are true, then other options are automatically redundant. For instance if option 15 is valid, logically options 16-18 would not make sense. Also, some of the options might not be valid if the repair sequence is incapable of keeping the bridges rating high enough for the entire analysis period.

The calculations involved in the present value cost analysis are fairly straightforward. Inflation is handled with Equation 4.1 for repairs that are performed in the future or for determining the residual value of a deck at the end of the analysis period:

$$FV = PV(1+r)^{t}$$

Equation 4.1

In Equation 4.1 FV is the future value, PV is the present value, r is the interest rate per period, and t is the number of time periods. The time period t was taken to be months. Thus the inflation rate used was 4% divided by 12 to yield the monthly rate. Once inflation was taken into account, Equation 4.2 was used to bring each future cost or residual value back to the present:

$$PV = FV(1+r)^{-t}$$

Equation 4.2

In Equation 4.2 t was also taken to be months and r was taken to the 12% annual discount rate divided by 12 months. The discount rate is simply the rate of return that could be expected from the money if it was invested in something else. Lastly Equation 4.3 was used to calculate the present cost of a sequence of repair/replacement actions:

$$PC_{total} = \sum PC_{repair/replacment} - R_{20}$$

Equation 4.3

In Equation 4.3 PC_{total} is the total cost in present dollars, $PC_{repair/replacement}$ are the costs of the individual repair or replacement actions in present dollars, and R_{20} is the residual value of the bridge in 20 years in present dollars.

A specific value for R_{min} is required in the input worksheet prior to performing the present value cost analysis. Once this value along with the other values discussed above are entered into the input worksheet, the program implementing the present value analysis iterates through the entire list of bridges that is located in the second worksheet calculating the cost of all relevant repair/replacement strategy options and determines which option is the least cost option. The program places the results in two output worksheets. The first output worksheet contains output data for all of the bridges. If a bridge deck did not need repairs to stay above R_{min}, the program outputs the final predicted decimal NBI deck condition after 20 years. If a bridge deck needed repairs, data is also placed in the second output worksheet. Separating the data in this manner simplified the process of interpreting the cost analysis results for bridges that needed repairs. To clarify how these calculations are performed, a present value cost analysis is performed for two different bridges by hand in Appendix B.

4.5 Results of the Present Value Cost Analysis

The results of the economic analysis are broken down first by the choice of the R_{min} in the analysis, and secondarily by which of the three possible repair/replacement actions was performed first. The three possible repair/replacement actions are redecking, reoverlaying, and mill and patch repairs. Thus, groups are formed by options 1-2, options 3-10, and options 11-18.

4.5.1 R_{min} = 4:

When R_{min}=4, 60 bridges are predicted to require corrective action in the form of the major repair/replacement interventions defined in Table 4.2 to keep NBI deck condition ratings above R_{min}. This means that 432 bridges are estimated to not require major repair/replacement action to keep NBI deck condition ratings above R_{min}. It should be emphasized that these numbers are based on past deterioration trends and that a number of assumptions were made about the deterioration behavior of the bridges in this project in regions for which actual deterioration data was not available, and about the effects of various repair actions on the deck condition states of the bridges. The least cost option for a particular bridge when R_{min}=4 is predominately a function of the condition rating of the deck, and to a much lesser extent a function of the deterioration type assigned to the deck. Figure 4.4 shows the distribution of least cost options for R_{min}=4, with the number of bridges for each option shown in parentheses.

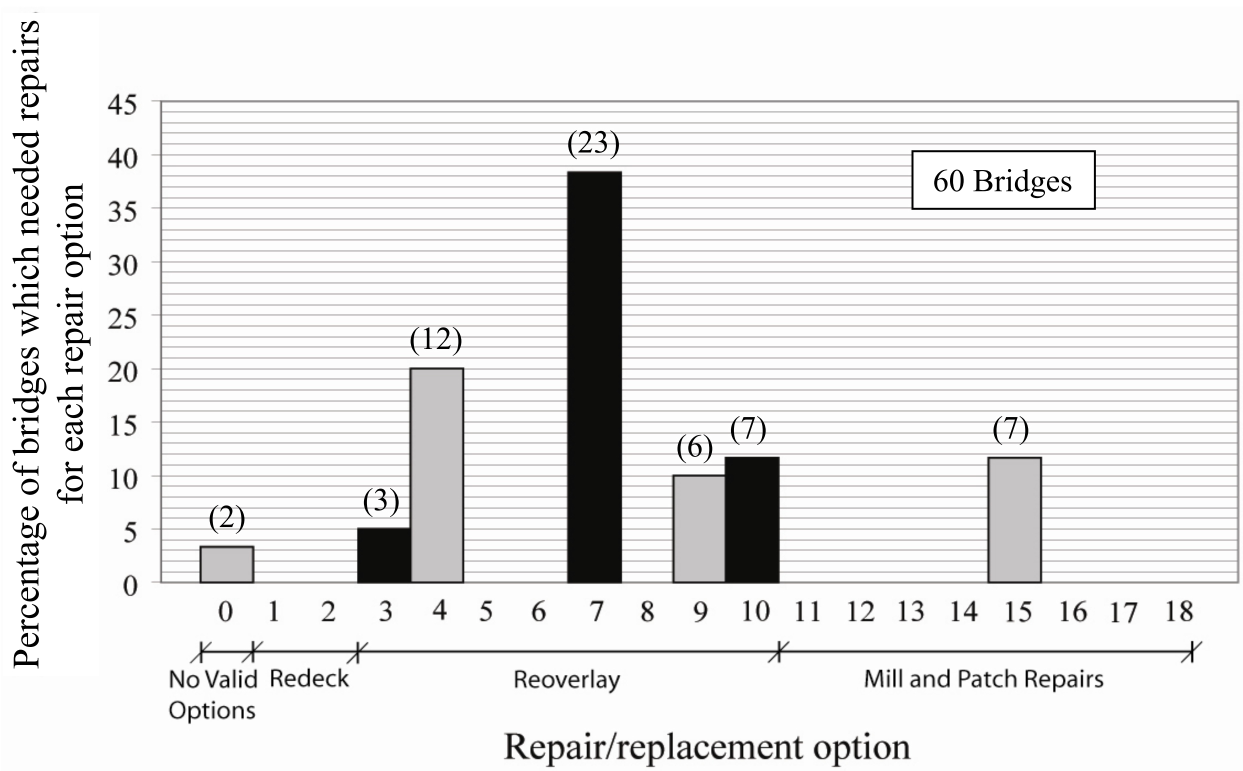

Figure 4.4 Distribution of Least Cost Options in Percentage for R_{min}=4

4.5.1.1 Redeck as first action:

Repair/replacement strategy options that used redecking as the first action were never the least cost option when R_{min}=4. When R_{min}=4, repairs of the decks were always possible. When R_{min} is chosen to be 5 or 6, deck condition of some bridges cannot be raised above R_{min} by repairs, and thus redecking is the only alternative. Note that bridges that have current recorded NBI deck condition of 4 always needed redecking as a secondary action in the R_{min}=4 present value analysis.

4.5.1.2 Reoverlay as first action:

When R_{min}=4, reoverlaying was the least cost repair/replacement strategy for 51 bridges. Of the 8 possible repair/replacement strategy options that use reoverlaying as the first repair action, only 5 of these options were least cost options. When the default set of assumptions that are user controllable in the present value analysis are used, performing mill and patch repairs costs less per square foot than reoverlaying. Reoverlaying costs \$10 per ft^2 and performing mill and patch repairs costs \$30 per ft^2. Thus for performing mill and patch repairs to cost more than reoverlaying, more than one-third of deck surface area must be milled and patched. However, Mn/DOT TAP members indicated that mill and patch repairs are rarely performed when more than 10% of the deck is unsound. Also, it was stated that the actual area of repair is roughly twice the area of unsound deck, and this doubled area concept is used for mill and patch repair calculations in the present value analysis. Thus, milling and patching is not use in the present value analysis if more than 20% of the deck needs repair. This limit is well below the 33.3% break even point. Because of this cost disadvantage, reoverlaying is only the least cost option for two possible reasons. The first reason is the case when performing mill and patch repairs is not possible, i.e. for bridge decks that have over 10% unsound decks. Based on the definition of the different NBI deck condition states given in the Bridge Inspection Field Booklet, bridges with over 10% unsound decks are bridges that have a NBI deck condition rating of 4 or lower. The second reason is the case when mill and patch repairs do not allow the deck to remain above R_{min} for the entire 20 year analysis period. Reoverlaying was assumed to raise the deck condition state twice as much as mill and patch repairs, so it is not difficult to understand why it is the dominant least cost repair technique for R_{min}=4. Eleven decks have been at a NBI deck condition of 4 for more than one year, and thus have reoverlaying as the least cost repair technique for the first reason; these decks have over 10% unsound deck. The remaining 40 bridges have reoverlaying repair strategies as the least cost option for the second reason; mill and patch repairs do not allow the bridge deck to stay above R_{min} for the entire 20 year analysis period.

For three bridges, repair/replacement strategy option 3 was the least cost option. Option 3 consists of reoverlaying immediately and doing nothing else provided the deck rating stays above R_{min} for the rest of the 20 year analysis period. All three of these bridges have Type 2 deterioration curves, which have the slowest deterioration rates of all three deterioration curves. All three bridges have current NBI deck condition ratings of 5. All three bridges had been at a rating of 5 for 11 years. If a bridge is at a rating of 5 for more than 9 years, its reduced decimal NBI deck condition rating at the beginning of the analysis is 4.25 due to the limit on how much the rating can be reduced. It might seem more likely that due to the time value of money postponing repairs until the deck deteriorates to R_{min}, like option 7, would be a better course of action. However, due the higher rates of deterioration that were assumed to exist for the drop from 5-4 this is not the case. If the deck is reoverlaid immediately, only one repair action is needed. If the deck is allowed to deteriorate to R_{min} first and, therefore, be subjected to the higher rates of deterioration, two repair actions are needed which greatly increases the overall costs of repairs for the analysis period.

For 12 bridges, repair/replacement strategy option 4 was the least cost option. Option 4 consists of reoverlaying now and redecking when R_{min} is reached. The deck condition rating for these bridges could not remain above R_{min} with only 1 or even two repair actions, thus redecking had to be performed. Due to the time value of money postponing redecking as long as possible makes the most economic sense, thus reoverlaying first and then redecking when the bridge deck condition reaches R_{min} can be considerably cheaper than redecking immediately. These bridges include all three types of deterioration curves. The critical factor is that they also all have current NBI deck condition ratings of 4. All bridges included for study in this project that have current NBI deck conditions of 4 require redecking as a secondary action. If the deck has been at a rating of 4 for long time, the cost savings of reoverlaying first and then redecking later is much smaller than for decks that have just reached a rating of 4. For these decks, redecking as the first action is more logical. However, if the deck has just reached 4, the cost savings associated with postponing the redecking by reoverlaying first can be substantial.

For 23 bridges, repair/replacement strategy option 7 was the least cost option. Option 7 consists of letting the deck deteriorate to R_{min} then reoverlaying, and taking no other action provided the deck condition rating stays above R_{min} for the remainder of the 20 year analysis period. These bridge decks all have current NBI deck conditions of 5 and also include all types of deterioration curves. Decks with Type 0 deterioration have been at a rating of 5 for a period of 1 to 5 years, which corresponds to initial conditions ranging from 4.92 to 4.61. Decks with Type 1 deterioration have been at a rating of 5 for a period of 0 to 3 years, which corresponds to initial conditions ranging from 5 to 4.77. Decks with Type 2 deterioration have been at a rating of 5 for a period of 1 to 2 years, which corresponds to initial ratings ranging from 4.92 to 4.84.

For 6 bridges, option 9 was the least cost option. Option 9 consists of letting the deck deteriorate to R_{min} then reoverlaying, and then reoverlaying a second time when the deck again deteriorates to R_{min}. These bridges have Type 0 and 1 deterioration curves, all have current NBI deck condition ratings of 5, and all have been at a condition state of 5 for a period of 11 to 18 years. As previously mentioned, if a deck is at a rating of 5 for more than 9 years, the reduced partial NBI condition rating used at the start of the analysis would be 4.25 due the limit imposed in this study on the amount the rating can be reduced. These bridges are very similar to the group of bridges for which option 3 was the least cost option. The difference is that all of the bridges for which option 3 was the least cost option have Type 2 deterioration curves. In the case of bridges for which option 3 was the least cost option, reoverlaying immediately allows the lower deterioration rate of the Type 2 curves, as the rating drops from 6 to 5, to be fully exploited thereby eliminating the need for secondary repair actions. Since the bridges for which option 9 was the least cost option do not have this lower deterioration rate to exploit, in the period during which the rating drops from 6 to 5, they must have 2 repair actions to keep their ratings above R_{min} for the analysis duration.

For 7 bridges, option 10 was the least cost option. Option 10 consists of allowing the deck to deteriorate to R_{min} and reoverlaying, and then performing mill and patch repairs when the deck again deteriorates to R_{min}. These decks had Type 1 and Type 2 deterioration curves and all have current NBI deck condition ratings of 5. These decks have been at a rating of 5 for a period of 6 to 9 years. Since they are in slightly better condition than the bridges for which option 9 was the least cost option, the less expensive but less effective second repair action of mill and patch repairs is enough to keep their ratings above R_{min}. Decks with Type 1 deterioration have been at a rating of 5 for a period of 8 to 9 years which corresponds to initial conditions ranging from 4.38 to 4.30. Decks with Type 2 deterioration have been at a rating of 5 for a period of 6 to 8 years which corresponds to an initial condition range of 4.53 to 4.38.

4.5.1.3 Mill and Patch as first action:

When R_{min}=4, performing mill and patch repairs was the least cost repair/replacement strategy for 7 bridges. Of the 8 possible repair/replacement strategy options that use mill and patch repairs as the first repair action, only 1 of these options was the least cost option. Option 15 was the least cost option for all 7 bridges. Option 15 consists of letting the deck deteriorate to R_{min} then milling and patching, and taking no action provided the decks condition stays above R_{min} for the remainder of the analysis duration. These bridges have Type 0 or Type 1 deterioration curves, and all have current NBI deck conditions of 6. Due to the higher deterioration rates of the Type 0 and Type 1 curves these bridges needed some repairs to last for the 20-year analysis duration, but the most inexpensive and minimal option was adequate. Decks with Type 0 deterioration have been at rating of 6 for a period of 16 to 18 years, which corresponds to an initial rating of 5.25. Decks with Type 1 deterioration have been at a rating of 6 for a period of 13 to 20 years which corresponds to an initial condition range of 5.31 to 5.25.

4.5.1.4 No Valid Options:

For two bridges, none of the available options allowed the decks to keep their condition rating above R_{min} for the entire 20 year analysis duration. These bridges have either T-beam or box girder type superstructures that are integral with the deck and thus redecking is not an option. Both decks have current NBI deck condition ratings of 4. All other bridges that have current NBI deck conditions of 4 have option 4 as the least cost option. However, option 4 requires redecking as a secondary action.

4.5.2 R_{min} = 5:

When R_{min}=5, 161 bridges require corrective action in the form of the major repair/replacement techniques defined in Table 4.2 to keep their NBI deck condition ratings above R_{min}. This means that 331 bridges will not require any major repair/replacement action to keep their NBI deck condition ratings above R_{min}. Figure 4.5 shows the distribution of least cost options for R_{min}=5, with the number of bridges for each option shown in parentheses.

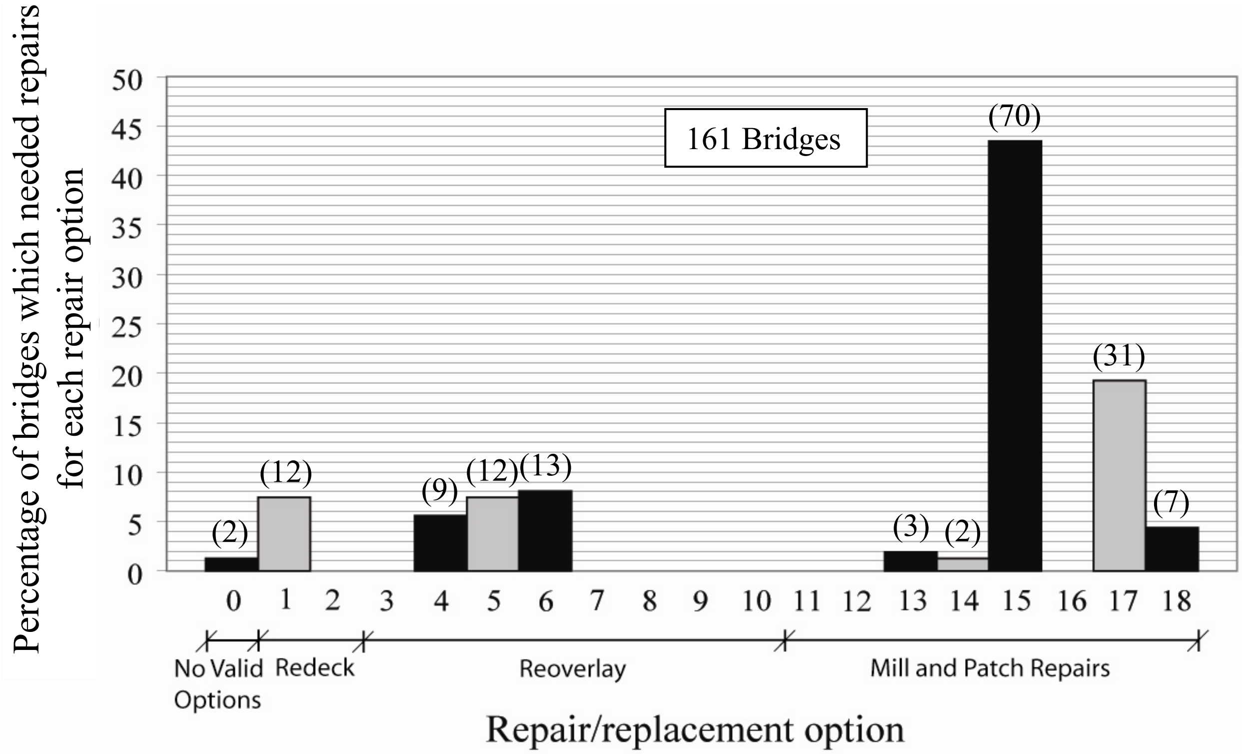

Figure 4.5 Distribution of Least Cost Options in Percentage for R_{min}=5

4.5.2.1 Redeck as first action:

For twelve bridges, redecking was the least cost repair/replacement strategy. Of the two possible options for redecking, option 1, which is to redeck immediately, and option 2, which is to wait until the bridge deteriorates to R_{min} and then redeck, option 1 was always the least cost repair strategy option. All twelve of these bridges have current NBI deck condition ratings of 4 which is a full point below R_{min}. Because of this, redecking was the only repair/replacement strategy that was valid.

4.5.2.2 Reoverlay as first action:

With R_{min}=5, reoverlaying was the least cost action for 34 bridges. Of the eight possible repair/replacement strategies, only 3 options were least cost options. All bridges that had reoverlaying as the first action have current NBI deck conditions of 5.

For 9 bridges, option 4 was the least cost option. Option 4 consists of reoverlaying now, and then redecking when R_{min} is reached. These bridges have Type 1 and Type 0 deterioration curves. Decks with Type 0 deterioration have been at a rating of 5 for a period of 17 to 18 years which corresponds to an initial rating of 4.25. Decks with Type 1 deterioration have been at a rating of 5 for 8 for 11 years which corresponds to an initial condition range of 4.38 to 4.25.

Option 5 was the least cost option for 12 bridges. Option 5 consists of reoverlaying now, and reoverlaying again when R_{min} is reached. The bridges include all three types of deterioration curves and all have a current NBI deck condition state of 5. Decks with Type 0 deterioration curves have been at a rating of 5 for a period of 4 to 5 years which corresponds to initial conditions of 4.69 to 4.61. Decks with Type 1 deterioration have been at a rating of 5 for 3 years which corresponds to a initial rating of 4.77. Decks with Type 2 deterioration have been at a rating of 5 for a period of 8 to 11 years which corresponds to initial conditions of 4.38 to 4.25.

Option 6 was the least cost option for 13 bridges. Option 6 consists of reoverlaying now and then milling and patching when deck deteriorates to R_{min}. These bridges include all types of deterioration curves and all have current NBI deck condition ratings of 5. These bridges tended to have been at a rating of 5 for fewer years than the bridges for which option 5 was the least cost option. Since option 6 uses a lower cost, but less effective secondary repair technique compared to option 5, it is logical that the bridges for which option 6 was the least cost option have slightly higher initial conditions. Decks with Type 0 deterioration have been at a rating of 5 for 1 to 2 years which corresponds to initial conditions of 4.92 to 4.84. Decks with Type 1 deterioration have been at a rating of 5 for 0 to 2 years which corresponds to initial conditions of 5 to 4.84. Decks with Type 2 deterioration have been at a rating of 5 for 6 years which corresponds to an initial rating of 4.53.

4.5.2.3 Mill and Patch as first action:

When R_{min}=5, mill and patch repairs are the least cost repair/replacement strategy for 113 bridges. Of the 8 possible repair/replacement strategy options involving mill and patch repairs as the first action, only 5 options were least cost options.

For 3 bridges option 13 was the least cost option. Option 13 consists of performing mill and patch repairs now, and then performing mill and patch repairs again when the bridge deteriorates to R_{min}. All of these bridges have Type 2 deterioration curves and have been at a rating of 5 for only 1 year which corresponds to an initial condition of 4.92. Because the Type 2 curve has the slowest deterioration rates of all the curves considered (for the drop in conditiong rating from 6 to 5), and when combined with the high initial ratings for these bridges, two applications of mill and patch repairs was sufficient to keep their ratings above R_{min} for the entire analysis period.

For 2 bridges option 14 was the least cost option. Option 14 consists of performing mill and patch repairs now, and then reoverlaying when the bridge deteriorates to R_{min}. Both bridges have Type 2 deterioration curves and have been at a rating of 5 for two years which corresponds to an initial condition of 4.84. Because of the extra years worth of deterioration compared to the bridges for which option 13 was the least cost option, mill and patch repairs as the secondary action did not allow the bridge to last for the entire analysis period, thus reoverlaying was needed as the secondary action.

For 70 bridges, option 15 was the least cost option. Option 15 consists of letting a bridge deteriorate to R_{min}, performing mill and patch repairs, and then taking no action provided the bridge deck condition rating stays above R_{min} for the remaining portion of the analysis period. These bridges have current NBI deck condition ratings of 6 and include all three types of deterioration curves. Due to their fairly high initial rating, one repair action is sufficient to keep their rating above R_{min} for the duration of the analysis period. Decks with Type 0 deterioration have been at a rating of 6 for a period of 0 to 6 years which corresponds to a range of initial ratings from 6 to 5.67. Decks with Type 1 deterioration have been at a rating of 6 for a period of 0 to 7 years which corresponds to initial condition ratings ranging from 6 to 5.63. Decks with

Type 2 deterioration have been at a rating of 6 for a period of 12 to 20 years which corresponds to an initial rating range from 5.61 to 5.35.

Option 17 was the least cost option for 31 bridges. Option 17 consists of letting the bridge deck deteriorate to R_{min}, performing mill and patch repairs as the first repair action, letting the bridge deteriorate back to R_{min}, and performing mill and patch repairs as the secondary repair action. These bridges have current NBI deck condition ratings of 6 and have Type 1 and 0 deterioration curves. Decks with Type 0 deterioration have been at a rating of 6 for a period of 7 to 11 years which corresponds to initial ratings ranging from 5.62 to 5.40. Decks with Type 1 deterioration have been at a rating of 6 for a period of 8 to 12 years which corresponds to an initial rating range of 5.57 to 5.36.

Option 18 was the least cost option for 7 bridges. Option 18 consists of letting the bridge deck deteriorate to R_{min}, performing mill and patch repairs, letting the bridge deteriorate to R_{min}, and then reoverlaying. These bridges have current NBI deck condition ratings of 6 and either Type 1 or Type 0 deterioration curves. These bridges have been a rating of 6 for a period of 13 to 20 years, which is long enough for all but one of them to have reached the ¾ point rating reduction limit and thus have initial ratings at the beginning of the analysis of 5.25. Since these bridge decks have slightly lower initial ratings than the bridge decks for which option 17 was the least cost option, reoverlaying has to be the secondary repair action instead of milling and patching. Decks with Type 0 deterioration have been at a rating of 6 for a period of 16 to 18 years which corresponds to an initial rating of 5.25. Decks with Type 1 deterioration have been at a rating of 6 for a period of 13 to 20 years which corresponds to initial ratings ranging from 5.31 to 5.25.

4.5.2.4 <u>No Valid Options:</u>

For 2 bridges, none of the repair/replacement strategies considered were sufficient to keep the bridge deck condition ratings above R_{min}. Both of these bridges have current NBI deck condition ratings of 4 and thus redecking would normally be the only valid option. However, these bridges have either T-beam or Box Girder type superstructures. Since the deck is integral with the superstructure, redecking is not an option.

4.5.3 R_{min} = 6:

When R_{min}=6, all bridges included in this project are predicted to require corrective action in the form of the major repair/replacement techniques defined in Table 4.2 to keep their NBI deck condition ratings above R_{min}. Figure 4.6 shows the distribution of least cost options for R_{min}=6, with the number of bridges for each option shown in parentheses.

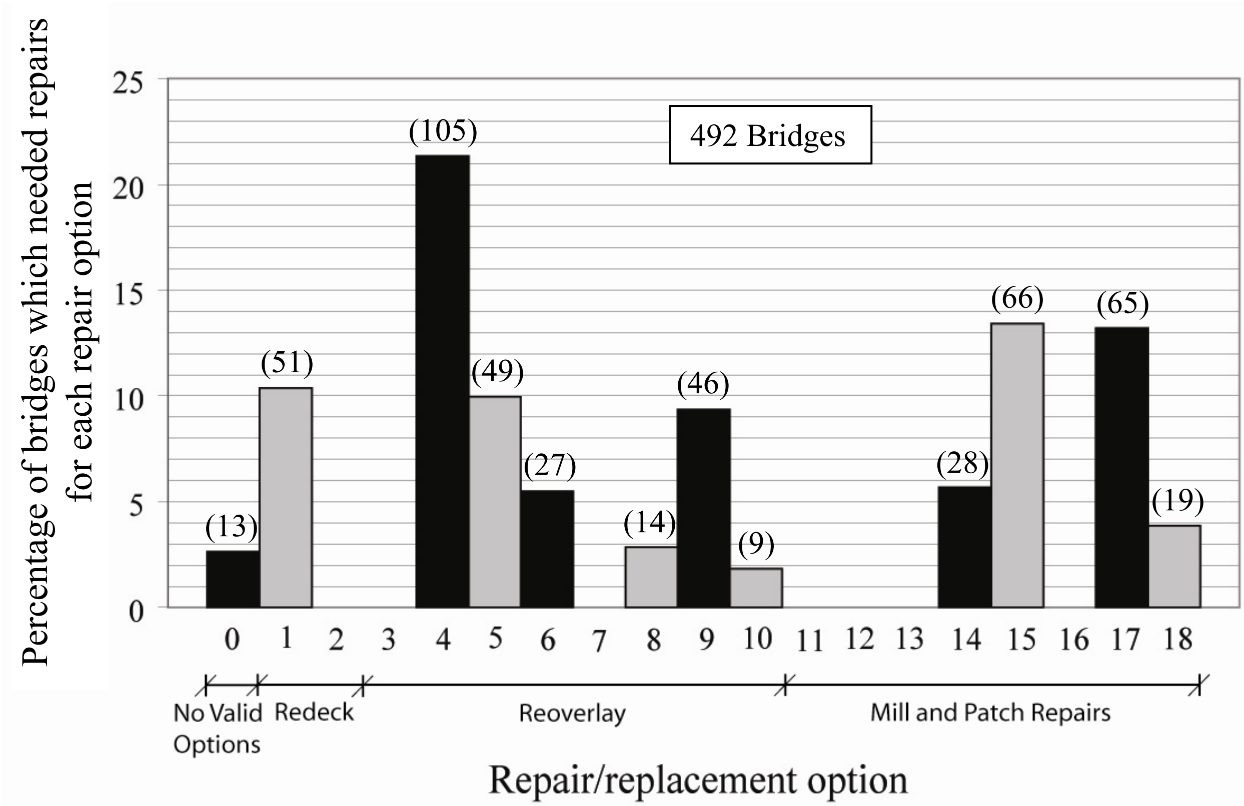

Figure 4.6 Distribution of Least Cost Options in Percentage for R_{min}=6

4.5.3.1 Redeck as first action:

When R_{min}=6, redecking is the least cost repair/replacement strategy for 51 bridges. Of these bridges, 48 have current NBI deck condition ratings of 4 or 5 and option 1 was not only the least cost option, but also the only option that was valid in the analysis. Three bridges have current NBI deck conditions of 6, but reoverlaying first, and then redecking when the deck had deteriorated back to R_{min} (option 4) was the only other option that was valid and lasted long enough, but this cost more than simply redecking now. All three of these bridges have Type 0 deterioration, and have had a rating of 6 for a period of 16 to 18 years which corresponds to an initial condition of 5.25. Since these 3 bridges have the most rapid deterioration (Type 0) and have been at a rating of 6 long enough to reach the lowest possible initial condition of 5.25, it is not surprising that redecking was the least cost strategy for these three bridges.

4.5.3.2 Reoverlay as first action:

When R_{min}=6, reoverlaying was the least cost repair/replacement strategy for 250 bridges. Of the 8 possible strategy options involving reoverlaying, 6 were least cost options. These bridges all have current NBI deck condition ratings of 6 or 7.

Option 4 was the least cost option for 105 bridges. Option 4 consists of reoverlaying now, and then redecking when the bridge deteriorates down to R_{min}. These bridge decks include all three types of deterioration curves, and all have current NBI deck conditions of 6. The decks that have Type 0 deterioration have been at a rating of 6 for a period of 0 to 17 years which corresponds to initial conditions ranging from 6 to 5.25. Decks with Type 1 deterioration have been at a rating of 6 for a period of 0 to 20 years, which corresponds to an initial condition rating range of 6 to 5.25. Decks with Type 2 deterioration have been at a rating of 6 from 11 to 20 years, which corresponds to initial conditions ranging from 5.64 to 5.35.

Option 5 was the least cost option for 49 bridges. Option 5 consists of reoverlaying now, and then reoverlaying again when the deck deteriorates down to R_{min}. These bridges have Type 2 deterioration curves, and all have current NBI deck conditions of 6. These decks have been at a condition rating of 6 for a period of 4 to 10 years which corresponds to an initial condition range of 5.87 to 5.67.

Option 6 was the least cost option for 27 bridges. Option 6 consists of reoverlaying now, and then performing mill and patch repairs when the deck deteriorates back to R_{min}. These bridges have Type 2 deterioration curves, and all have current NBI deck condition ratings of 6. The decks have been at a rating of 6 for a period of 0 to 3 years which corresponds to initial conditions ranging from 6 to 5.90.

Option 8 was the least cost option for 14 bridges. Option 8 consists of letting the deck deteriorate to R_{min}, reoverlaying, and then redecking when the deck deteriorates back to R_{min}. These bridges have Type 0 deterioration curves and all have current NBI deck conditions of 7. The decks have been at a rating of 7 for a period of 0 to 20 years which corresponds to an initial condition range of 7 to 6.25.

Option 9 was the least cost option for 46 bridges. Option 9 consists of letting the deck deteriorate to R_{min}, reoverlaying, and then reoverlaying again when deck deteriorates back to R_{min}. All but one of these bridges have Type 1 deterioration curves and have current NBI deck conditions of 7. The bridges with Type 1 deterioration have been at a rating of 7 for a period of 9 to 20 years which corresponds to initial ratings ranging from 6.26 to 6.25. One bridge has Type 0 deterioration and current NBI deck condition rating of 8. This bridge has been at a rating of 8 for 10 years which corresponds to an initial condition of 7.25

Option 10 was the least cost option for 9 bridges. Option 10 consists of letting the deck deteriorate to R_{min}, reoverlaying, and then performing mill and patch repairs when the deck deteriorates back down to R_{min}. All of these bridges have type 1 deterioration curves and the current NBI deck condition rating is 7. The decks have been at a rating of 7 for a period of 5 to 7 years which corresponds to initial ratings ranfing from 6.59 to 6.43.

4.5.3.3 Mill and Patch as first action:

When R_{min}=6, performing mill and patch repairs was the least cost repair/replacement strategy for 178 bridges. Of the 8 possible strategy options involving reoverlaying, 4 were least cost options. These bridges have current NBI deck condition ratings of 7 or 8 and have only Type 1 or Type 2 deterioration.

Option 14 was the least cost option for 28 bridges. Option 14 consists of milling and patching now, and then reoverlaying when the deck deteriorates back down to R_{min}. These bridges have Type 2 deterioration and current NBI deck condition ratings of 7. The decks have been at a rating of 7 for a period of 14 to 20 years which corresponds to an initial condition of 6.25.

Option 15 was the least cost option for 66 bridges. Option 15 consists of letting the deck deteriorate to R_{min}, milling and patching, and doing nothing else provided the deck condition rating stays above R_{min} for the duration of the analysis period. These decks have either Type 1 or Type 2 deterioration and have current NBI condition states of either 7 or 8. Due to their fairly high initial rating, one repair action is sufficient to keep their rating above R_{min} for the duration of the analysis period. Decks with Type 1 deterioration have current NBI deck condition of 8 which is the initial condition state (i.e., for periof of 0 years). Decks with Type 2 deterioration have current NBI deck conditions of both 7 and 8. The decks with Type 2 deterioration and current condition ratings of 7 have been at a rating of 7 for periods of 0 to 6 years which corresponds to initial conditions ranging from 7 to 6.66. The decks with Type 2 deterioration and current condition ratings of 8 have been at a rating of 8 for periods of 6 to 20 years which corresponds to an initial condition of 7.25.

For 65 bridges, option 17 is the least cost option. Option 17 consists of letting the deck deteriorate to R_{min}, performing mill and patch repairs, and then performing mill and patch repairs again when the deck deteriorates back to R_{min}. These bridge decks have current NBI deck condition ratings of 7 and 8 and have Type 1 or Type 2 deterioration curves. Decks with Type 1 deterioration and current condition ratings of 7 have been at a rating of 7 for periods of 0 to 1 years which corresponds to initial conditions ranging from 7 to 6.92. Decks with Type 1 deterioration and current condition ratings of 8 been at a rating of 8 for periods of 3 to 14 years which corresponds to a range of initial conditions from 7.31 to 7.25. Decks with Type 2 deterioration all have current condition ratings of 7 and have been at a rating of 7 for periods of 7 to 11 years which corresponds to initial condition ratings ranging from 6.60 to 6.37.

Option 18 was the least cost option for 19 bridges. Option 18 consists of letting the deck deteriorate to R_{min}, performing mill and patch repairs, and then reoverlaying when the deck deteriorates back down to R_{min}. These bridge decks have Type 1 or Type 2 deterioration curves, and have current NBI deck condition ratings of 7. Decks with Type 1 deterioration have been at a rating of 7 for periods of 2 to 4 years which corresponds to initial conditions ranging from 6.84 to 6.67. Decks with Type 2 deterioration have been at a rating of 7 for periods of 12 to 13 years which corresponds to an initial condition range of 6.32 to 6.26.

4.5.3.4 No Valid Options:

For 13 bridges, no repair/replacement strategies considered in this analysis (Table 4.2) were sufficient to keep the bridge deck condition ratings above R_{min}. All of these bridges have either T-beam or Box Girder type superstructures. Since the deck is integral with the superstructure, redecking is not an option. Some of these bridges have current NBI deck conditions of 4 and 5 for which redecking is the only repair/replacement strategy that would be possible, and others have a current NBI deck condition rating of 6 but no combination of two repairs can keep the bridge decks above R_{min} for the duration of the analysis period.

4.6 Summary of Cost Analysis and Recommended Repair Strategies

In order to develop general repair/replacement strategies for the decks of the bridges included for study in this project, a present value cost analysis for a 20 year period was performed. This analysis used the default set of assumptions for user-controlled input quantities in the present value analysis program. Default assumptions for input quantities specific to the bridges were based on input from Mn/DOT TAP members. These items include repair cost data and the effects of repairs on the condition states of the decks. Some of the other default input quantities used were based on values used in similar research in bridge management as well as intuition and common sense. Based on the findings of this present value analysis, a set of generalized strategies and recommendations for the repair/replacement of the bridge decks studied in this project was developed. These strategies are described in the sequel. And illustrated as a flowchart in Fig. 4.7.

4.6.1 Strategies for R_{min}=4:

When R_{min} is chosen to be 4, approximately 12% of the bridges being considered in this project will need repairs to keep their NBI deck condition states above R_{min}. The bridges that need repairs have NBI deck condition ratings of 6 or lower. Very few bridges with current NBI deck condition states of 6 will need repairs though, and all of these bridges have Type 1 or Type 0 deterioration curves. None of the bridges of this project required immediate redecking to keep their NBI deck condition ratings above 4. Thus repair strategies involve either performing mill and patch repairs or reoverlaying and often secondary repair or replacement actions are necessary as well.

In general, reoverlaying is usually the first action for most decks. When they should be reoverlaid and whether or not a secondary action will be needed is mostly a function of the initial rating of the deck. If the current NBI deck condition rating is 4, redecking will be necessary as a secondary action. If the current NBI deck condition rating is 5, and the deck has been at that rating for approximately 6 years or less, then letting the deck deteriorate to 4 and then reoverlaying is the least cost strategy. No secondary repairs are needed for these decks. If the deck has been a rating of 5 for approximately 8-9 years, then waiting until the deck deteriorates to 4 and reoverlaying is the least cost strategy. Milling and patching will probably be sufficient as the secondary action. If the deck has been at a rating of 5 for over 9 years, the same applies except reoverlaying as the secondary action will probably be necessary. The exception to this situation is the case in which the deck has been at a rating of 5 for over 9 years and has a Type 2 deterioration curve. For such case reoverlaying immediately is the least cost strategy, and no secondary repairs will likely be needed.

Some decks that have current NBI deck conditions of 6 and that also have Type 1 or Type 0 deterioration curves will require 1 repair action to keep their ratings above 4 for the entire 20 year analysis period. These decks have all been at a condition of 6 long enough for their initial conditions to be either at, or very close to, 5.25. The least cost strategy for these decks is to wait until they deteriorate to a state of 4, and then perform mill and patch repairs. The flowchart in Figure 4.7 describes the recommended strategies for R_{min}=4. Bridges with current NBI deck conditions of 6, Type 1 and Type 0 deterioration curves, and higher initial ratings were not predicted to need repairs to keep their deck conditions above R_{min} for the 20-year analysis duration. All decks with current NBI deck conditions of 6 and Type 2 deterioration were predicted to not need repairs as well.

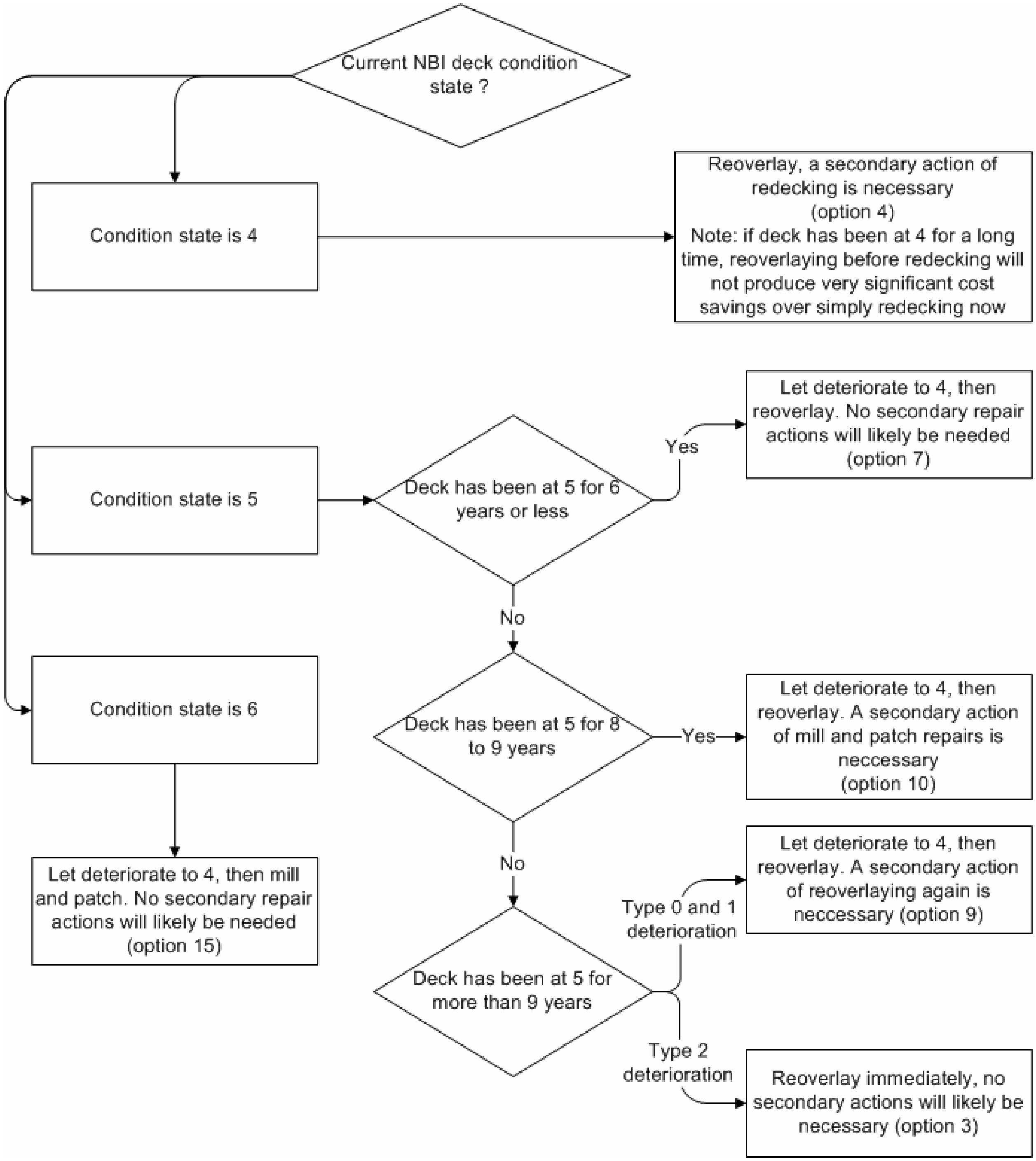

Figure 4.7 Flow Chart Summarizing Strategies for R_{min}=4

4.6.2 Strategies for R_{min}=5:

When R_{min} is chosen to be 5, the present value analysis predicts that approximately 33% of the bridges under consideration in this project will need repair or replacement of their decks to keep their NBI deck condition states above R_{min}. The bridges that need repairs have NBI deck condition ratings of 6 or lower. For bridges that currently have NBI deck condition ratings of 4, redecking now is the only action allowed by the analysis since that is the only way to raise the deck condition above R_{min} under the set of assumptions being used. Redecking immediately was needed for approximately 7% of bridge decks needing repair or replacement. However, if a bridge is designed such that the deck is integral with the superstructure and thus cannot be redecked, then there are no valid repair options and the entire bridge would have to be replaced in order to keep the deck condition above R_{min}.

Reoverlaying was the least cost repair strategy for approximately 21% of the bridge decks needing repairs. All decks that had reoverlaying as a least cost strategy have current NBI deck condition states of 5. The need for a secondary repair action is governed by how long the deck has been at a rating of 5. Since the present value analysis program estimates the current partial NBI rating (the initial rating used in the analysis) based on how many years a deck has been at its present rating, more years at the present rating translate into a lower initial condition state in the analysis. Bridge decks that have been at a rating of 5 for only a few years only needed milling and patching as a secondary action. If they had been at a rating of five for a longer period of time, reoverlaying was needed as the secondary action. For some bridges with Type 1 and Type 0 deterioration curves, redecking was needed as the secondary action.

Performing mill and patch repairs was the least cost repair strategy for approximately 81% of the bridge decks needing repair or replacement. Bridge decks that have Type 2 deterioration, a current NBI deck condition of 5, and have been at that rating for only 1 year can keep their ratings above R_{min} for the entire analysis period if milling and patching is used as a secondary repair action. If the decks have been at a rating of 5 for 2 years then the secondary repair action has to be reoverlaying. For all bridges that have current NBI deck conditions of 6, letting the decks deteriorate R_{min}, and then performing mill and patch repairs is the least cost strategy. If a bridge deck has a Type 2 deterioration curve, then a single application of mill and patch repairs once the deck deteriorates to R_{min} is enough to keep the deck condition above 5 for the entire 20 year analysis period. If a deck has a Type 1 or 0 deterioration curve, then a second repair/replacement action may be needed to keep the bridge deck condition rating above 5 for the 20 year analysis period. Depending on the initial condition of the deck, another application of mill and patch repairs may be sufficient as the second action. If not, then reoverlaying has to be the second action. A flowchart is given in Figure 4.8 describing the recommended strategies for R_{min}=5.

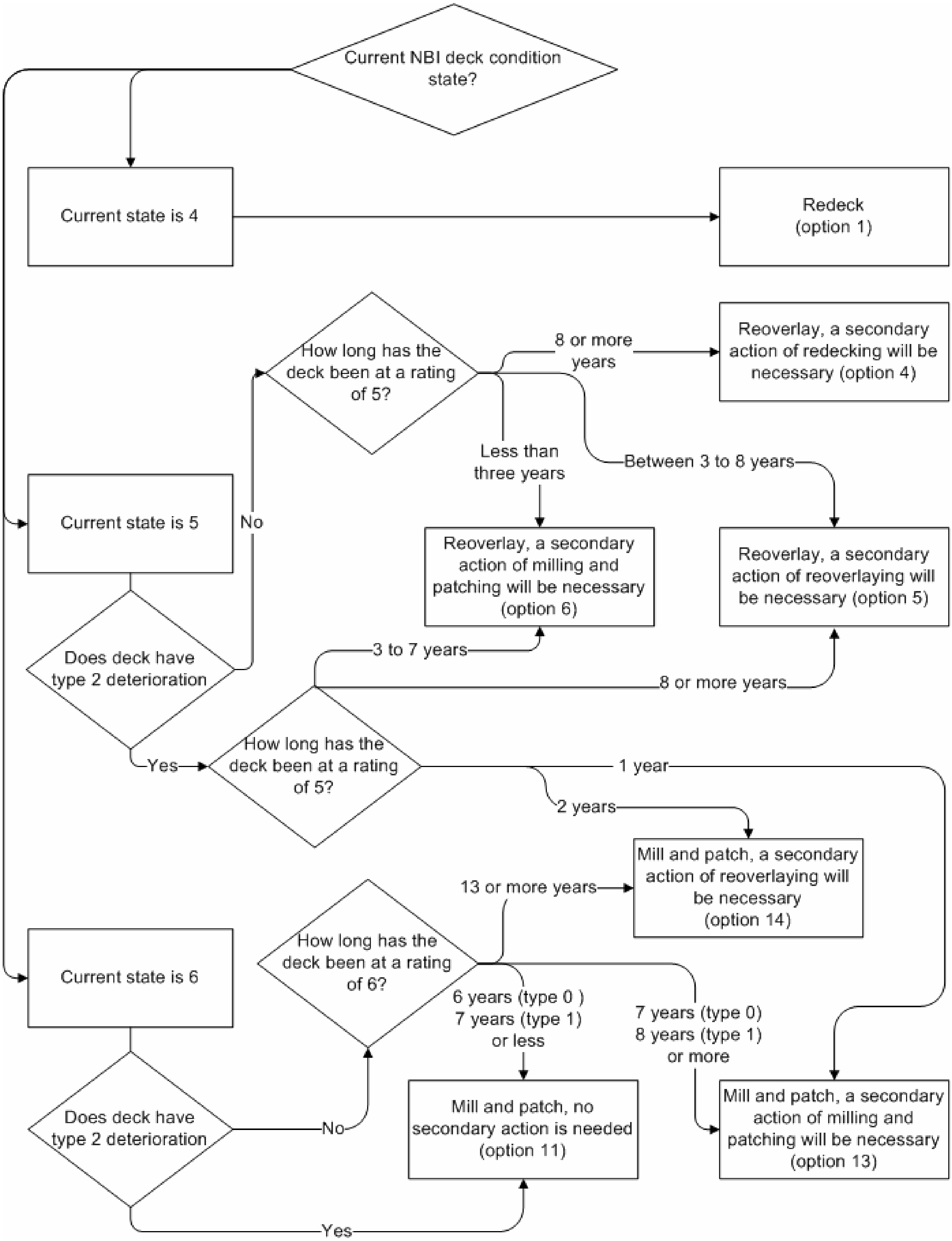

Figure 4.8 Flow Chart Summarizing Strategies for R_{min}=5

4.6.3 Strategies for R_{min}=6:

When R_{min} is chosen to be 6, the present value analysis predicts that all of the bridges under consideration in this project will need repair or replacement of their decks to keep their NBI deck condition states above R_{min}. For bridges that currently have NBI deck conditions of 4 or 5, redecking immediately is the only valid action since that is the only way to raise the deck condition above R_{min} under the set of assumptions being used in the analysis. Redecking immediately was needed for approximately 10% of bridge decks. However, if a bridge is designed such that the deck is integral with the superstructure and thus cannot be redecked, then there are no valid repair options and the entire bridge would have to be replaced in order to keep the deck condition above R_{min}.

For decks with initial conditions of 6 and Type 0 and Type 1 deterioration, reoverlaying now and then redecking later was the least cost strategy. In general, due to the time value of money, postponing redecking as long as possible is the most economic option. However, the longer a deck has been at a rating of six, and consequently the lower the initial rating used in the analysis, the smaller the cost savings from reoverlaying and then redecking compared with the corst of simply redecking now. For some bridges the cost savings are very large, and for others the savings are more minimal.

Decks with Type 2 deterioration and initial conditions of 6 have both reoverlaying and redecking, and reoverlaying followed by a secondary repair action, as least cost strategies. The lower the initial condition of the deck used in the analysis, the effectiveness of the secondary action has to be to allow a deck to keep its rating above 6 for the entire analysis period. The ranking of secondary actions by effectiveness from least to most effective is mill and patch repairs, reoverlaying, and lastly redecking.

For bridges with current NBI deck conditions of 7 and 8, generalizations about the analysis results are more difficult to make. Since 11 of the possible 18 repair/replacement options were least cost options, which strategy is the least cost strategy is fairly complicated. The least cost strategy for a particular bridge is basically dependent on two factors. The first factor is the type of deterioration curve for the bridge deck. The second factor is how many years the deck has been at its current NBI deck condition rating, which corresponds directly to the initial condition used for the deck in the analysis. The combined effect of these two factors is readily apparent in the results of the analysis for R_{min}=6 with very logical transitions between least cost strategies. Both the first and second repair/replacement actions used by a least cost strategy are controlled by these two factors. Figure 4.9 is a flow chart describing the recommended strategies for R_{min}=6. Note that analysis for the first of the two repair/replacement actions, the results of the analysis which are graphically depicted in Figure 4.9, is much simpler than analysis for both of the repair/replacement actions.

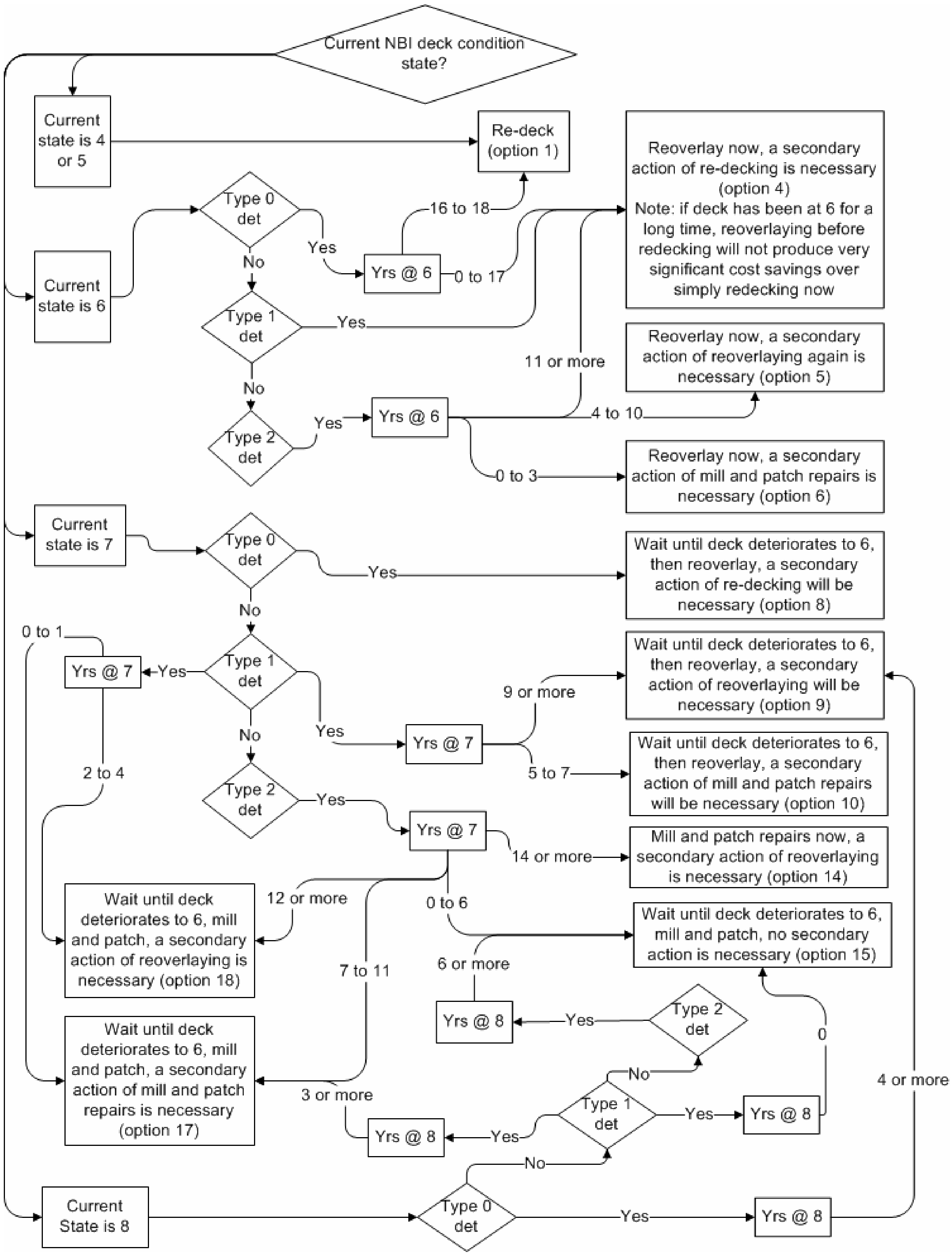

Figure 4.9 Flow Chart Summarizing Strategies for R_{min}=6

4.7 Parametric analysis

Due to the large number of assumptions that were made in order to be able to perform the present value cost analysis, a parametric analysis was conducted. This analysis investigated the effects of several key assumptions on the outcome of the present value analysis. The effects on costs, in general, were not investigated; rather determination of the least cost repair/replacement strategy was investigated. To simplify the process and clarify the results, options were grouped by their first repair/replacement action. Thus, only three outcomes were investigated instead of 18.

4.7.1 Assumptions about increases in deck condition due to repairs:

The default values for the increase in NBI deck condition rating for reoverlays are a 1-point increase for the first repair, and ½-point increase for the second repair. The default values for the increase in NBI deck condition rating for mill & patch repairs are a ½-point increase for the first repair, and a ¼-point increase for the second repair. Little to no data is available to determine the actual effect of these repairs on the NBI deck condition rating of the bridges. The default values were chosen based on engineering judgment that considered the definitions of the different NBI deck condition states as well as the experience of the Mn/DOT TAP members. Due to the subjective nature of these choices for default values, the effect of the choice on the outcome of the present value analysis was investigated. To perform this investigation, the default value for one of the two repair techniques was held constant, and the default value for the other repair technique was changed in 5% increments and a present value analysis was performed. The results were summarized, and the process was repeated. This was done for the minimum allowable NBI deck condition rating (R_{min}) equal to 4, 5 and 6.

The members of the Mn/DOT TAP stated that the value used for realistic increases in deck condition due to repairs would not exceed 1 point. Thus, when the value of the increase in deck condition due to mill and patch repairs was varied, it was varied from 200% to 5% to cover a range of deck condition increase values from between 1 and 0. When the increase in deck condition due to reoverlaying was varied, it was only varied from 100% to 5%, which also covered a range of deck condition increase values from between 1 and 0. To summarize the results of each present value analyses, the number of times a repair strategy option (RSO) was selected as the least cost option for a bridge, was tallied for all bridges that needed repairs to have their condition ratings stay above R_{min}. This tally was then divided by the total number of bridges needing repairs to obtain the percentage of bridges for which the RSO was the least cost option. This was performed for all 18 RSOs, and the RSOs were then combined by the type of their first corrective action. All options which considered redecking as the first option were grouped together, as were all options which considered reoverlaying, mill & patch repairs, and bridges for which no RSO worked respectively. The percentages of bridges falling into each of these categories were then plotted vs. the percentage of the default value used for the repair technique being changed.

4.7.1.1 Variation of the increase in deck condition due to mill & patch repairs:

4.7.1.1.1 R_{min}=4:

According to Figure 4.10, when mill & patch repairs have 2 times their default effects on a decks' condition state (thus reoverlaying and mill and patch repairs would have the same effect), reoverlaying is the least cost option 15% of the time and mill & patch repairs are the least cost option 82% of the time. This is a major difference between R_{min}=4 and R_{min}=5 (Figure 4.11) or R_{min}=6 (Figure 4.12). When mill & patch repairs have 2 times their default effects on the deck condition state and R_{min}=5 or 6, reoverlaying is never the least cost option. The reason for this difference is that the program that performs the present value analysis does not consider mill & patch repairs an option if the actual recorded NBI deck condition state has been at a 4 or below for more than one year. Mn/DOT TAP members stated that mill & patch repairs are not typically performed on bridges that have over 10% delaminated or unsound deck. A NBI deck condition rating of 4 has a range of unsound deck area from 10-25%. Thus mill & patch repairs are only a valid option for the bridge if the condition state is above 4, or has just reached 4. Because of this, the only available options for some bridges are reoverlaying or redecking. Of these two options, reoverlaying is almost always the lower cost option of the two.

As the increase in deck condition resulting from mill & patch repairs is reduced, the number of bridges for which mill & patch repairs is the least cost option also goes down, and the number of bridges for which reoverlaying is the least cost option goes up. When the increase in deck condition resulting from mill & patch repairs is between 120-115% of the default value, reoverlaying becomes the least cost option a higher percentage of time than mill & patch repairs. The analysis also shows a high level of sensitivity to the relative magnitudes of the increases in deck condition due to repairs in this region. Both cost of mill and patch repairs and the percentage of deck area needing repairs for a given condition state were not varied. Thus, the increase in the number of bridges for which reoverlaying is the least cost option as the effect of mill & patch repairs on deck condition is reduced is due to bridges not being able to stay above R_{min} for the 20 year analysis period when mill & patch repairs are used.

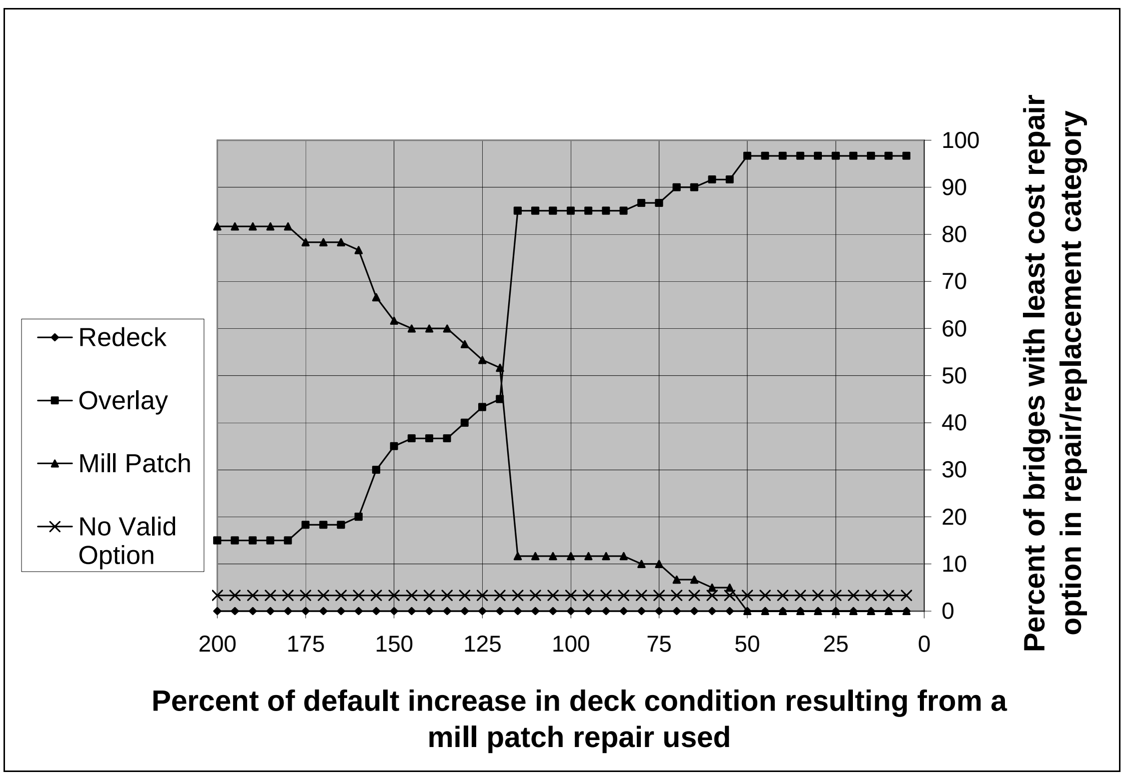

Figure 4.10 Mill and Patch Repair Deck Condition Increase Parametric Study for R_{min}=4

4.7.1.1.2 R_{min}=5:

As the effect mill & patch repairs on bridge deck condition is reduced, the number of bridges for which reoverlaying is the least cost option increases (Figure 4.11). This increase is fairly slow at first, but when the effect of mill and patch repairs is between 60-55% of the default values, the increase in the number of bridges for which reoverlaying is the least cost option is very rapid and reoverlaying is the least cost option a higher percentage of the time than mill & patch repairs.

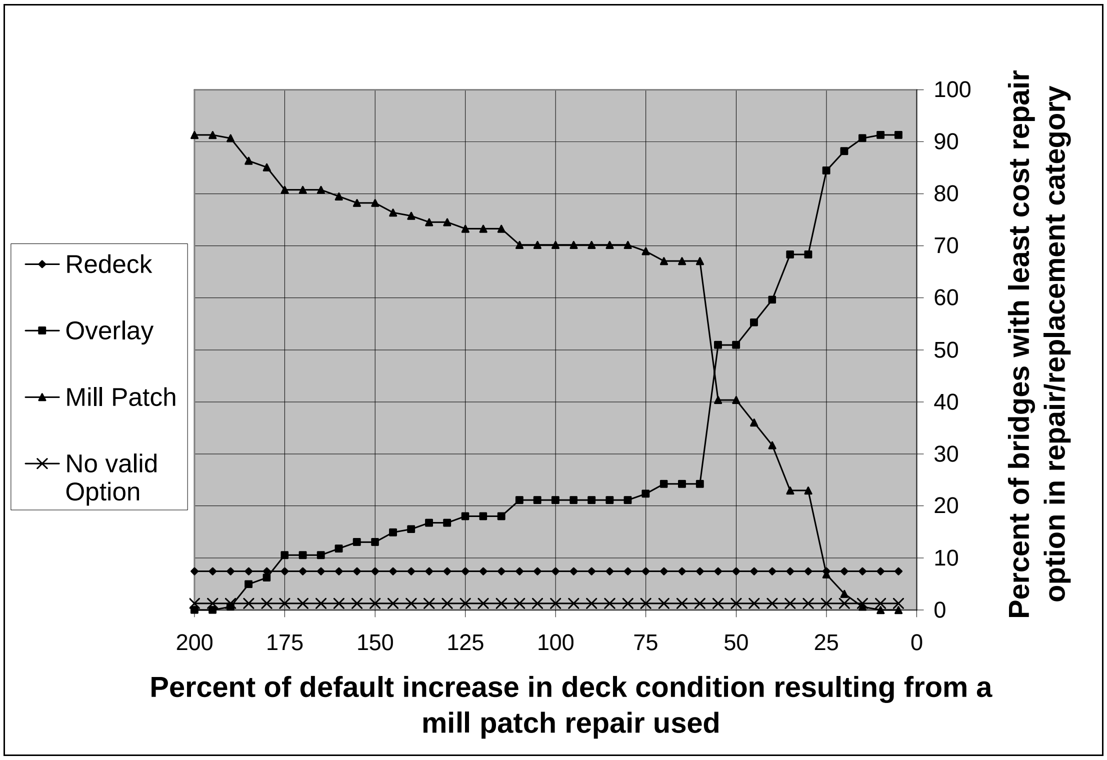

Figure 4.11 Mill and Patch Repair Deck Condition Increase Parametric Study for R_{min}=5

4.7.1.1.3 R_{min}=6:

The trends for R_{min}=6 are fairly similar to R_{min}=5 and R_{min}=4 as noted in Figure 4.12. If the effect of mill & patch repairs on deck condition is changed to less than 140% of the default values, reoverlaying becomes the least cost option a higher percentage of time than mill & patch repairs.

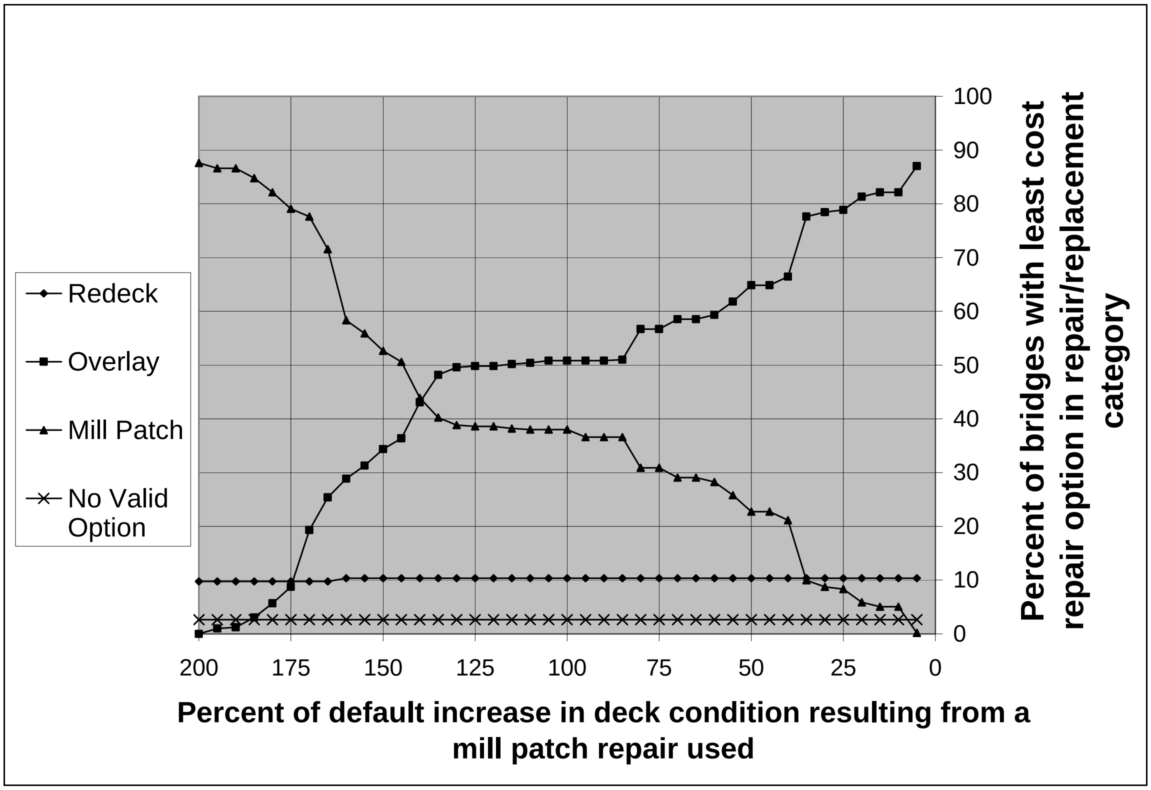

Figure 4.12 Mill and Patch Repair Deck Condition Increase Parametric Study for R_{min}=6

4.7.1.2 <u>Variation of the increase in deck condition due to reoverlaying</u>:

4.7.1.2.1 R_{min}=4:

When default values are used for both reoverlaying and mill and patch repairs, reoverlaying is the least cost option 85% of the time (Figure 4.13). As the effect of reoverlaying on deck condition is reduced, the number of bridges for which reoverlaying is the least cost RSO decreases while the number of bridges for which mill and patch repairs are the least cost RSO, and the number of bridges for which redecking is the least cost RSO increases. The number of bridge decks for which there are no valid options increases, but very slowly. For bridges with low initial NBI deck conditions, mill and patch repair is not an option, which only leaves reoverlaying or redecking. However, for some bridges the deck is integral with the superstructure and thus redecking is not an option. Therefore as the effects of reoverlaying on the deck condition are diminished, the number of bridges for which no RSO works is expected to rise. When the effect of reoverlaying is less the 65% of its default value, milling and patching is the least cost RSO for a greater number of bridges than reoverlaying. Once the effect of reoverlaying is reduced to 50% of its default value, and therefore has the same effects on deck condition as mill and patch repairs, the curves change very little.

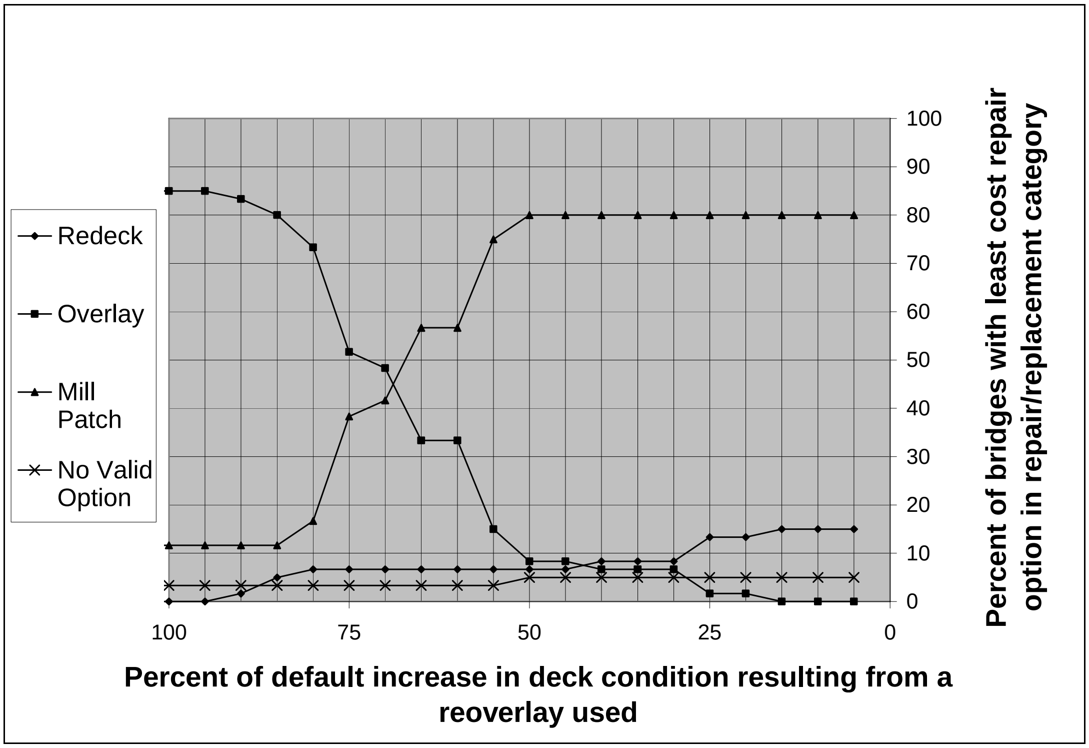

Figure 4.13 Reoverlaying Deck Condition Increase Parametric Study R_{min}=4

4.7.1.2.2 R_{min}=5 and R_{min}=6:

The results of varying the effect of reoverlaying for R_{min} =5 and R_{min}=6 are very similar (Figures 4.14 and 4.15) and will be discussed together. When default values are used for both reoverlaying and mill and patch repairs, reoverlaying is the least cost RSO 21% of the time for R_{min}=5 and 51% of the time for R_{min}=6. As the effect of reoverlaying is reduced, little happens until the effect is reduced to about 85% of its default value. As the effect of reoverlaying is reduced from 85% to 50% of its default value the number of bridges for which reoverlaying is the least cost RSO falls to zero and the number of bridge decks for which mill and patch repairs are the least cost RSO rises. The number of bridge decks for which redecking is the least cost RSO also rises. As the effect of reoverlaying is reduced from 50% to 5% no changes in what the least cost RSO's are occur.

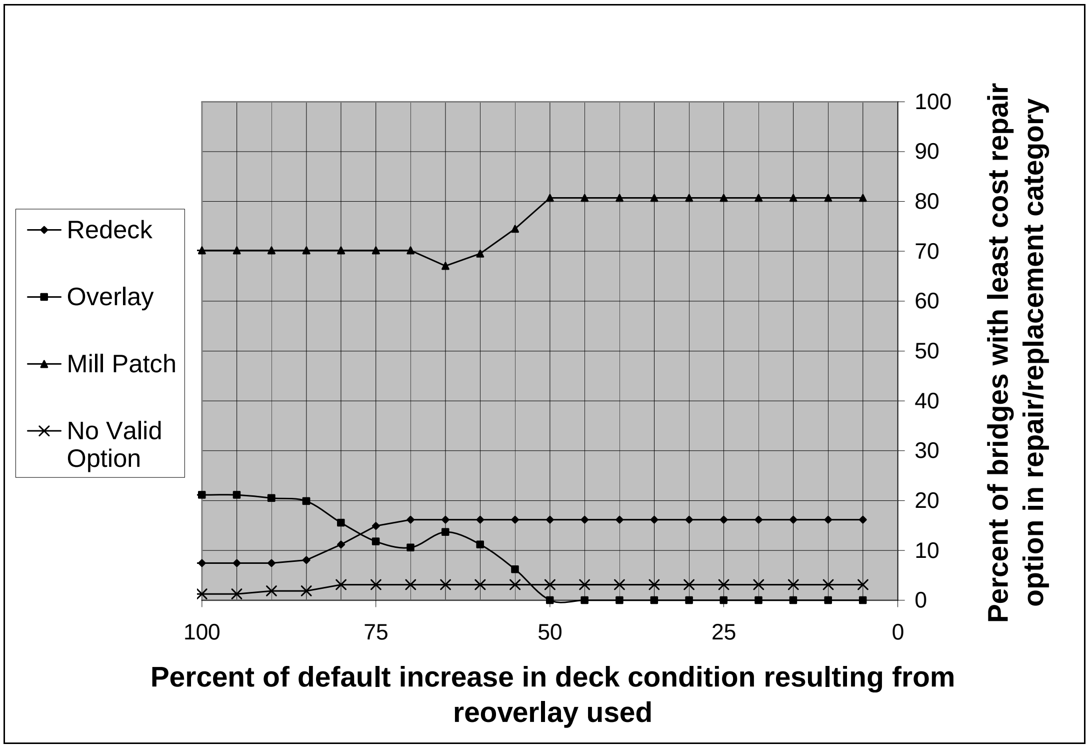

Figure 4.14 Reoverlaying Deck Condition Increase Parametric Study R_{min}=5

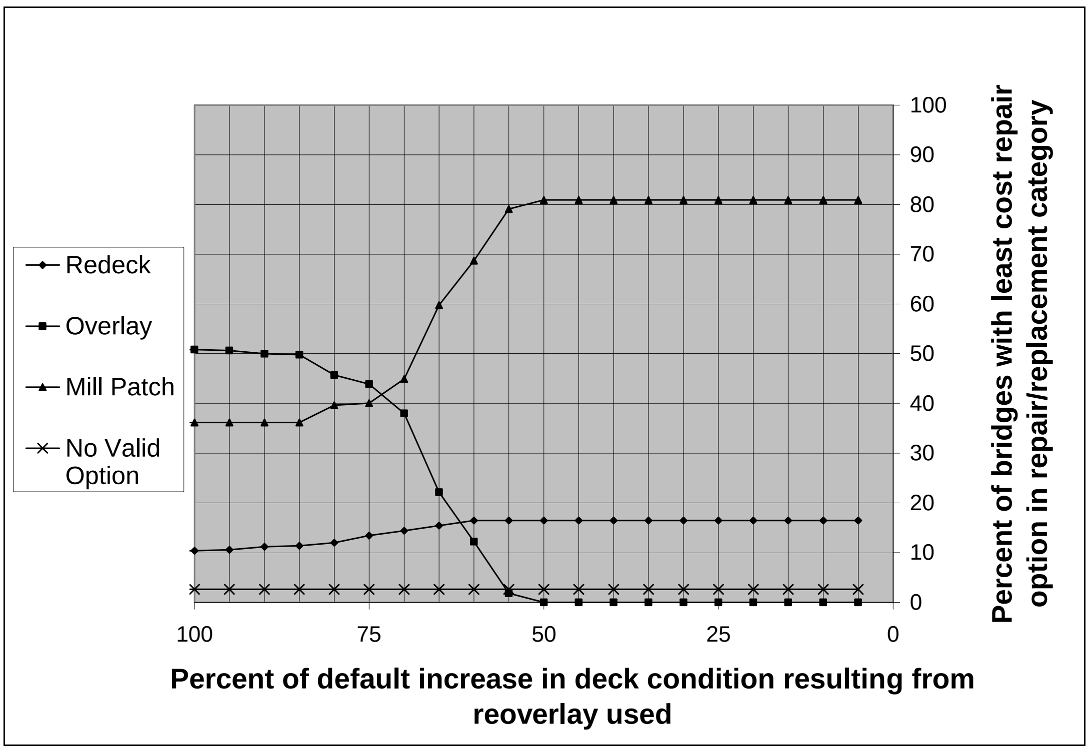

Figure 4.15 Reoverlaying Deck Condition Increase Parametric Study R_{min}=6

4.7.2 Discount Rate:

The discount rate was varied from 5% to 25% in 1% increments and a present value analysis performed for each different discount rate. It was determined that varying the discount rate had significant effects on which RSO was more likely to be the least cost option when R_{min}=4 (see Figure 4.16), but fairly minimal effects for R_{min}=5 and R_{min}=6 (see Figures 4.17 and 4.18).

When R_{min}=4 the distribution of least cost RSOs does not change much for discount rates between 5% and 8%. However, for discount rates in the reange of 8% to 16% there is a large amount of change in the distribution of least cost RSOs. At first the number of bridge decks for which reoverlaying is the least cost RSO increases, and the number of decks for which mill and patch repairs are the least cost RSO decreases. At a discount rate of roughly 13% this trend reverses and the distribution returns to values similar to those in the 5% to 8% range. Once the discount rate reaches 20% the number of bridge decks for which milling and patching is the least cost RSO narrowly exceeds the number of bridge decks for which reoverlaying is the least cost RSO.

It is interesting that for all values of R_{min} that when the discount rate is close to the rate of inflation the number of decks for which redecking is the least cost RSO increases. This phenomenon occurs because without the time value of money, if a deck needs to be replaced in order to keep the condition rating above R_{min} it makes much less difference in the overall costs during the analysis period if the deck is replaced now or at some point in the future.

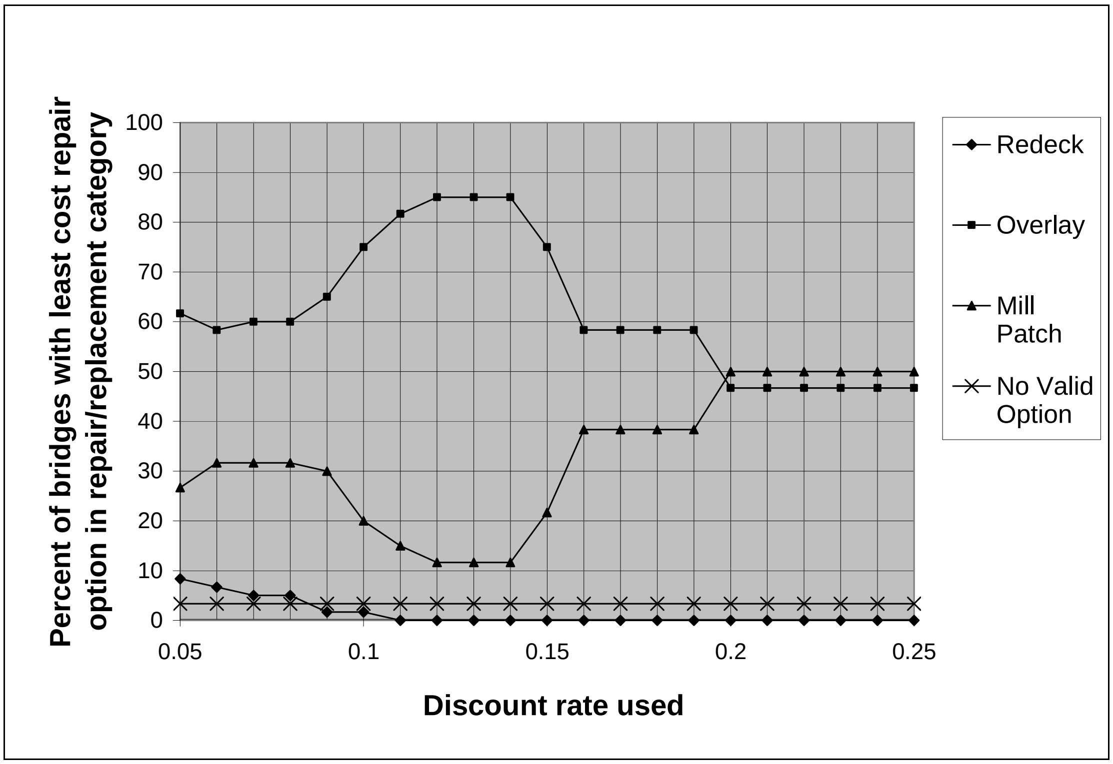

Figure 4.16 Discount rate parametric study R_{min}=4

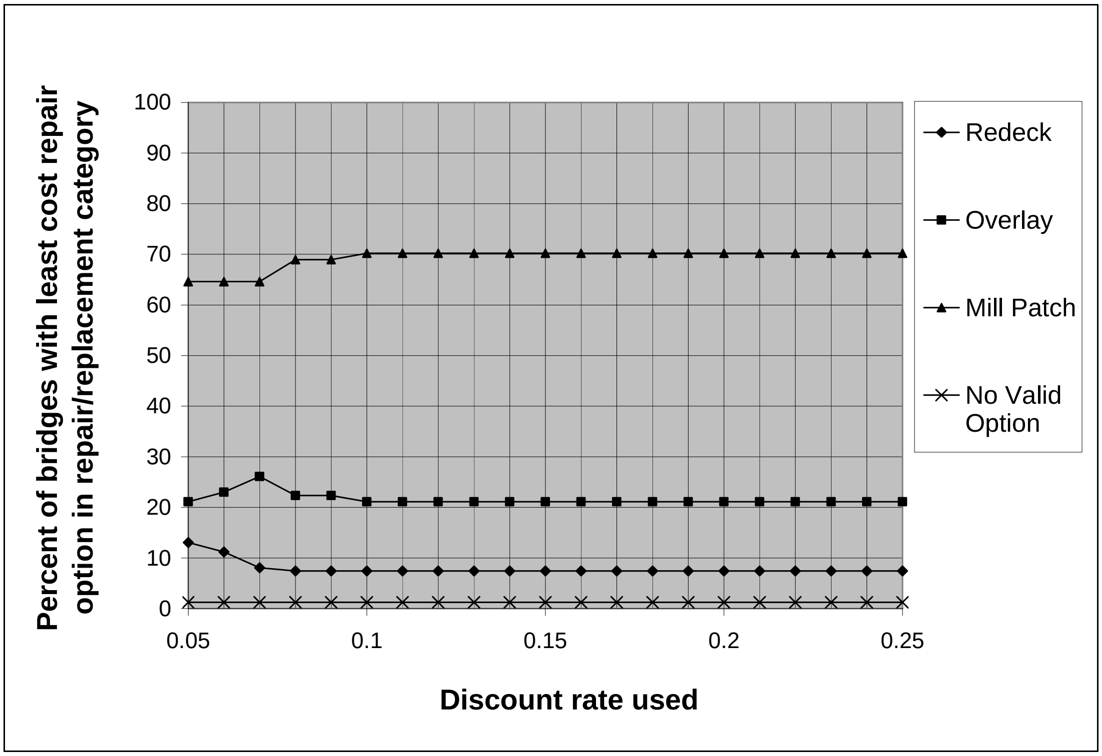

Figure 4.17 Discount rate parametric study R_{min}=5

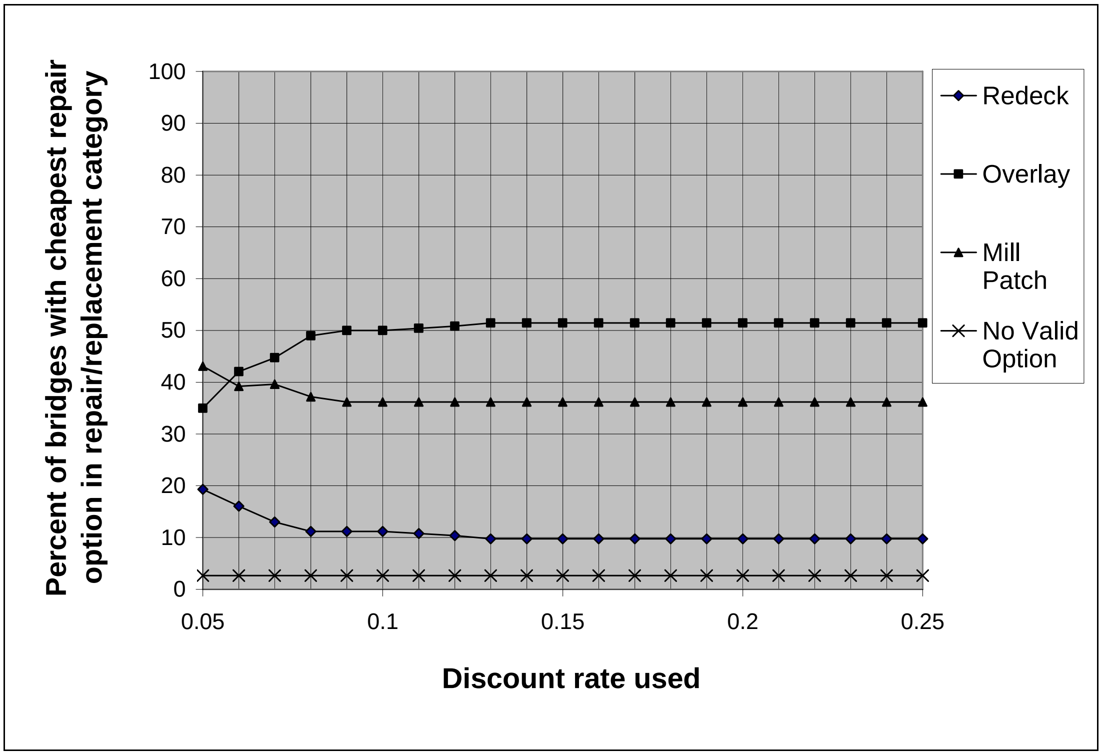

Figure 4.18 Discount rate parametric study R_{min}=6

4.7.3 Rate of Inflation:

The rate of inflation was varied from 2% to 8% in 1% increments and a present value analysis performed for each different discount rate. It was determined that varying the rate of inflation had virtually no effect on which RSOs were the least cost options when R_{min}=5 and R_{min}=6 (Figures 4.20 and 4.21), but did have some impact when R_{min}=4 (see Figure 4.19). There are no changes in the distribution of least cost RSOs until the rate of inflation is greater than 4% at which point the number of bridge decks for which reoverlaying is the least cost RSO decreases while the number of bridge decks for which mill and patch repairs are the least cost RSO increases. In addition, the number of bridges for which redecking is the least cost RSO increases slowly. This effect is intuitive since the discount rate is less effectively as the rate of inflation increases, thus the time value of money is diminished.

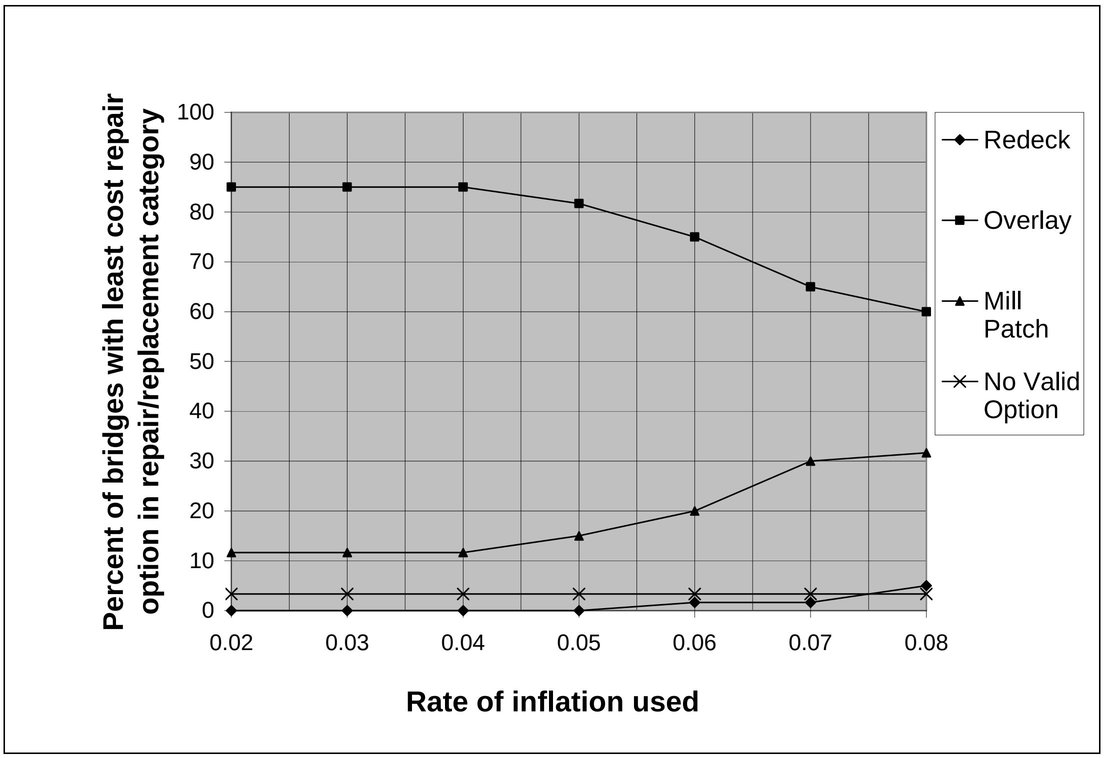

Figure 4.19 Inflation rate parametric study R_{min}=4

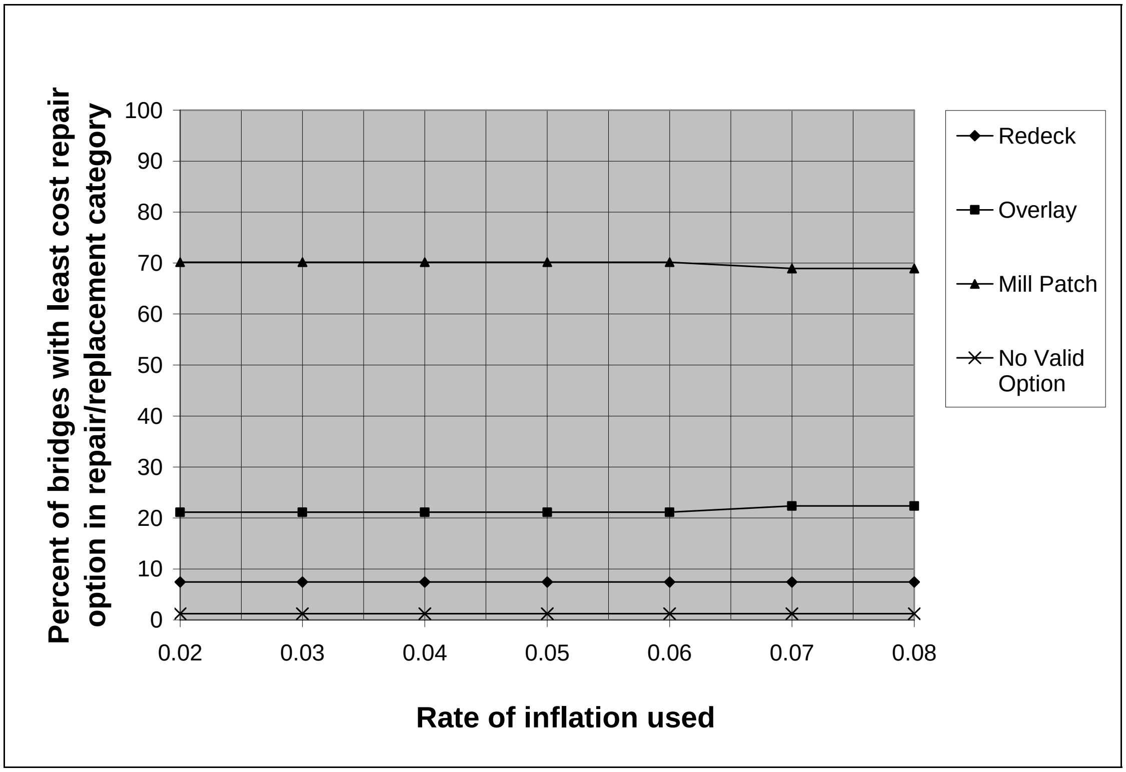

Figure 4.20 Inflation rate parametric study R_{min}=5

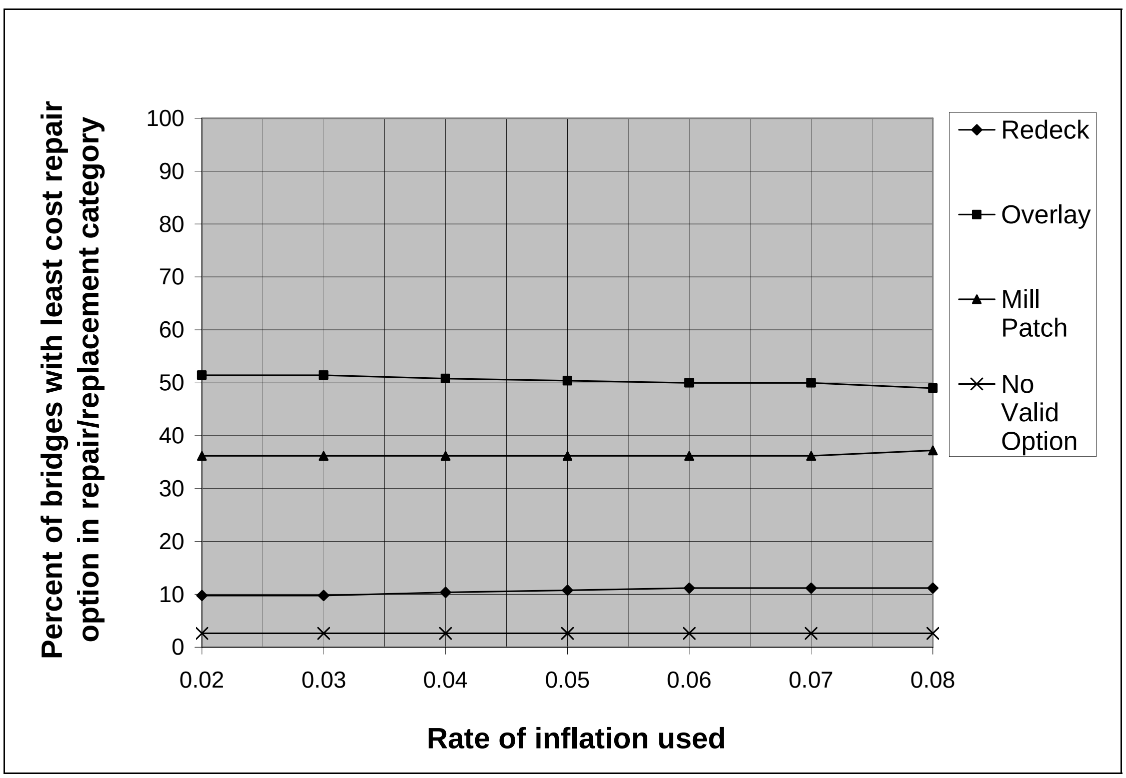

Figure 4.21 Inflation rate parametric study R_{min}=6

4.7.4 Assumptions for deterioration curves above 8 and below 5:

Deterioration curves generated in the data analysis portion of the project were used in the economic analysis portion of the project to predict the deterioration of bridge decks. However, the curves only contained information about the deterioration of bridges from NBI deck condition ratings of 8 to 4 and the drop from 5 to 4 was determined based on limited data (not many bridges included in this project have dropped from 5 to 4). Because of this scarcity of data, assumptions needed to be made regarding what slopes to use to predict bridge deck deterioration for NBI deck condition states above 8 and below 5. Three sets of assumptions about these slopes were used. For all three sets of assumptions it was assumed that the slope of the deterioration curve from a NBI deck condition rating of 9 to a rating of 8 was the same as the slope of the deterioration curve from 8 to 7 (Figure 4.3).

4.7.4.1 Deterioration assumption 1:

For the drop from 5 to 4 the slopes generated from the data analysis portion of the project were used. While these slopes were based on very small number of data points, the slopes of the deterioration curves from 5 to 4 were fairly similar to the slopes of the deterioration curves from 6 to 5, which were based on a good sized portion of the data, thus the 5 to 4 slopes seemed reasonable. The slope for the drop from 5 to 4 was also used in predicting deterioration below NBI deck conditions of 4.

4.7.4.2 Deterioration assumption 2:

All deterioration below a NBI deck condition rating of 5 was determined using the same slope as the drop from 6 to 5.

4.7.4.3 Deterioration assumption 3:

This assumption is the one that was actually used in the present value analysis in general. All deterioration below a NBI deck condition rating of 5, for all three deterioration curves, was determined using the slope based on the actual data for the Type 1 deterioration curve. As mentioned previously, this is basically an upper bound on the deterioration rates designed to provide a worst case scenario. This assumption is based on the intuition and experience of the Mn/DOT technical advisory panel members.

4.7.4.4 Effect of Deterioration Assumption:

The present value analysis was performed for all three sets of assumptions concerning the deterioration curves. For each set of assumptions, the present value analysis was performed for R_{min} = 4, 5, and 6. Thus, a total of nine analyses were performed. For each analysis the options were grouped and tallied according to the first repair/replacement action performed to form three groups, and then converted to percentages. Figures 4.22 thru 4.24 show the percentage of bridges falling into the three groups for the three sets of assumptions about the deterioration curves. One plot was made for each different value of R_{min}.

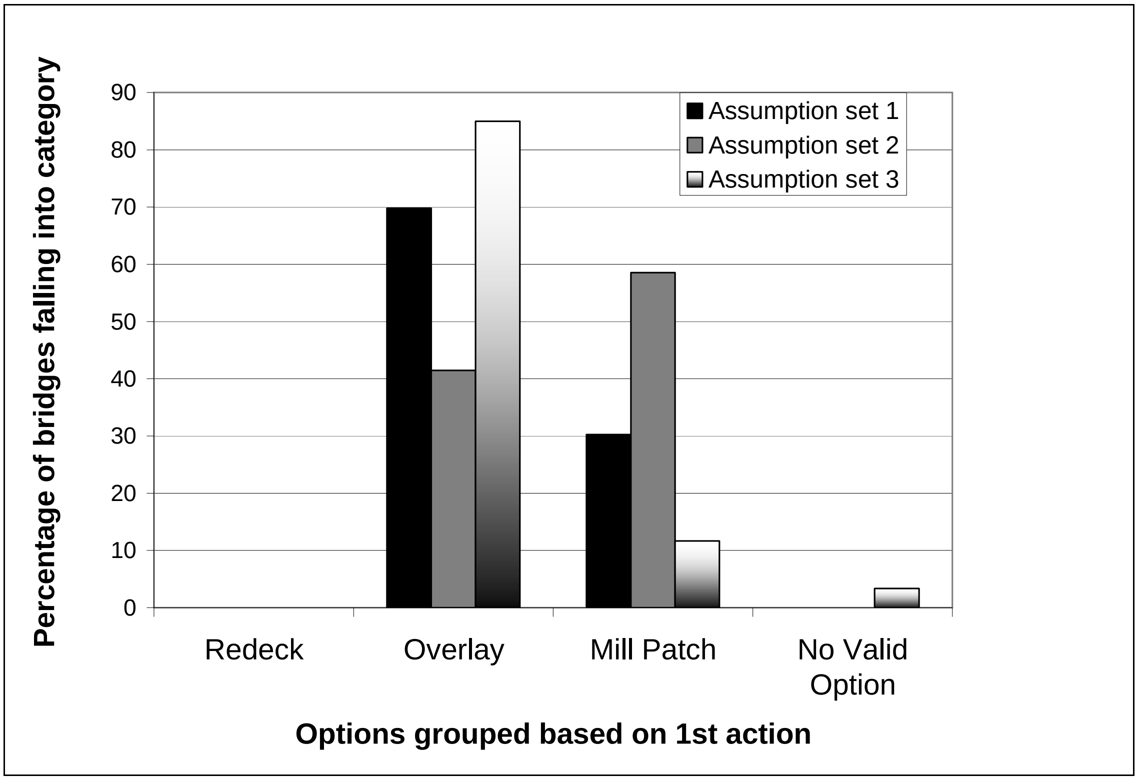

Figure 4.22 Deterioration Curve Assumption Investigation, R_{min}=4

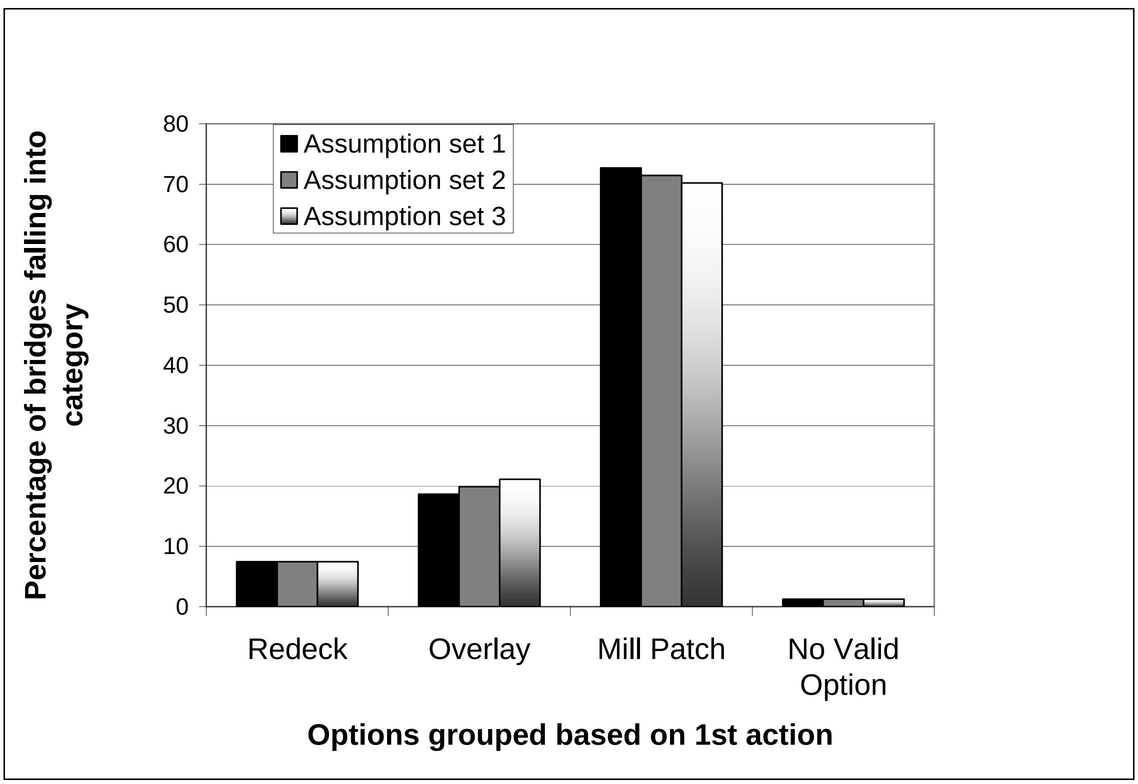

Figure 4.23 Deterioration Curve Assumption Investigation, R_{min}=5

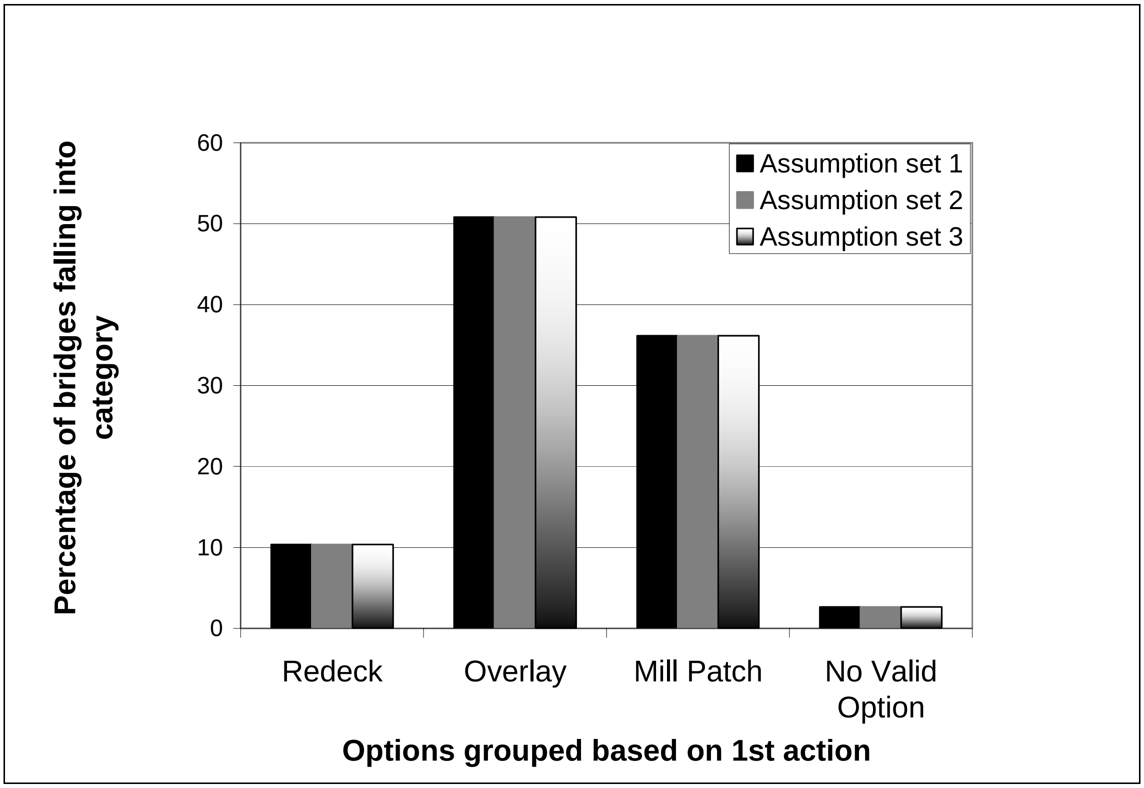

Figure 4.24 Deterioration Curve Assumption Investigation, R_{min}=6

The effect of the deterioration curve assumption for the drop in condition rating of 5 to 4 is large for R_{min}=4, slight (i.e., negligible) for R_{min}=5, and nonexistent for R_{min}=6. This is what was expected since the deterioration curves in the drop from 5 to 4 region are used heavily in the R_{min}=4 analysis, are used slightly in the R_{min}=5 analysis, and are not used at all in the R_{min}=6 analysis. For R_{min}=4 the third assumption set, which was actually used in the present value analyses clearly results in a larger portion of bridges having reoverlaying as their least cost RSO. Assumption set 2 is the other extreme with mill and patch repairs being favored as the least cost RSO. Assumption set 1 has an intermediate distribution of RSOs between assumption set 1 and 3. The trend is that the greater the deterioration rates in a given assumption set, the more reoverlaying is favored as the least cost RSO. The ranking of the assumptions from highest deterioration rates to lowest is set 3, set 1, and set 2. These results are consistent with reoverlaying having doubled the increase in deck condition rating offered by mill and patch repairs. Mill and patch repairs cost less, but with higher deterioration rate predictions, they are less likely to be able to keep the decks condition ratings above R_{min} for the entire analysis period.

4.7.5 Initial Value limit:

As previously discussed in this report, a limit of ¾ points was adopted on the amount that a bridge deck rating could be dropped when calculating the decimal value of the current NBI deck condition rating in the cost analysis. This limitation was intended to estimate more accurately the decimal value of the condition of bridges that are deteriorating at rates lower than average. For R_{min} = 4, 5, and 6, this limit was varied from 0.5 to 0.95 and a present value analysis performed for each increment. It was determined that the present value cost analysis is nearly insensitive to this assumption. There are small amounts of variation in the distribution of least cost RSOs, but none are very significant. Figures 4.25 thru 4.27 show the results of this investigation graphically. These plots were constructed in the same manner as the plots which investigated the assumptions about increases in deck condition due to repairs (Figures 4.10 thru 4.15).

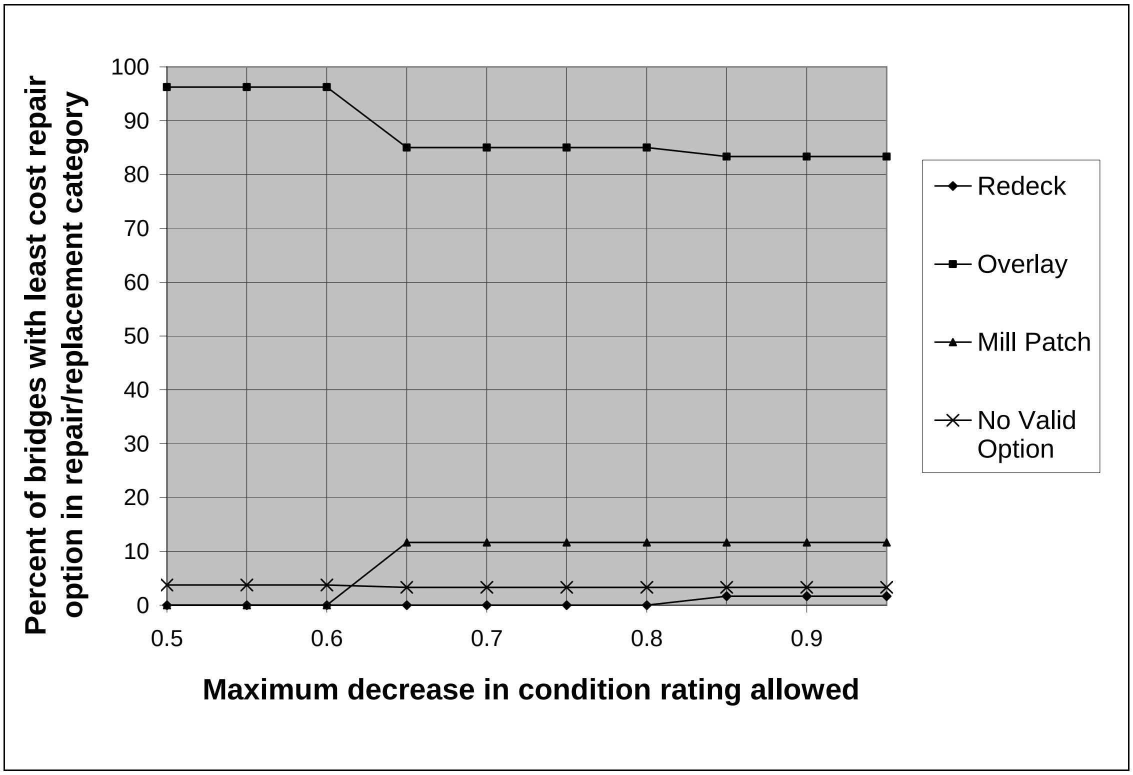

Figure 4.25 Initial Value Limit Parametric Study R_{min}=4

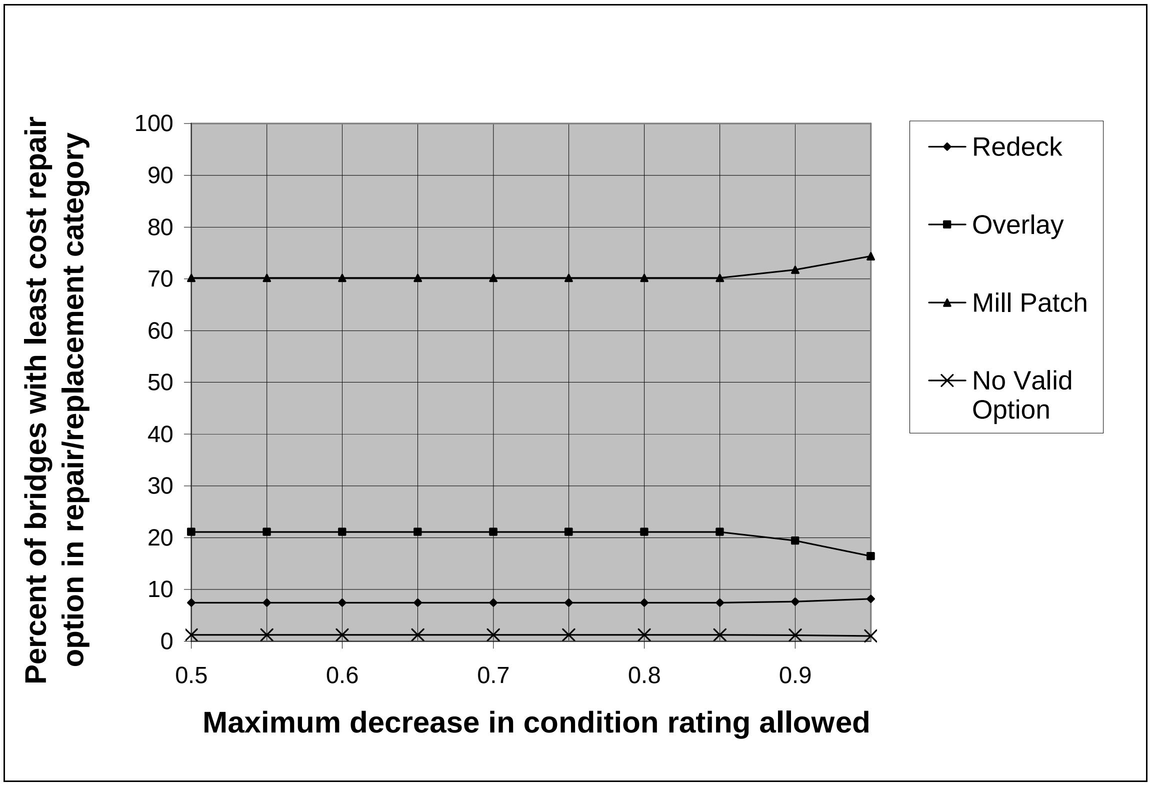

Figure 4.26 Initial Value Limit Parametric Study R_{min}=5

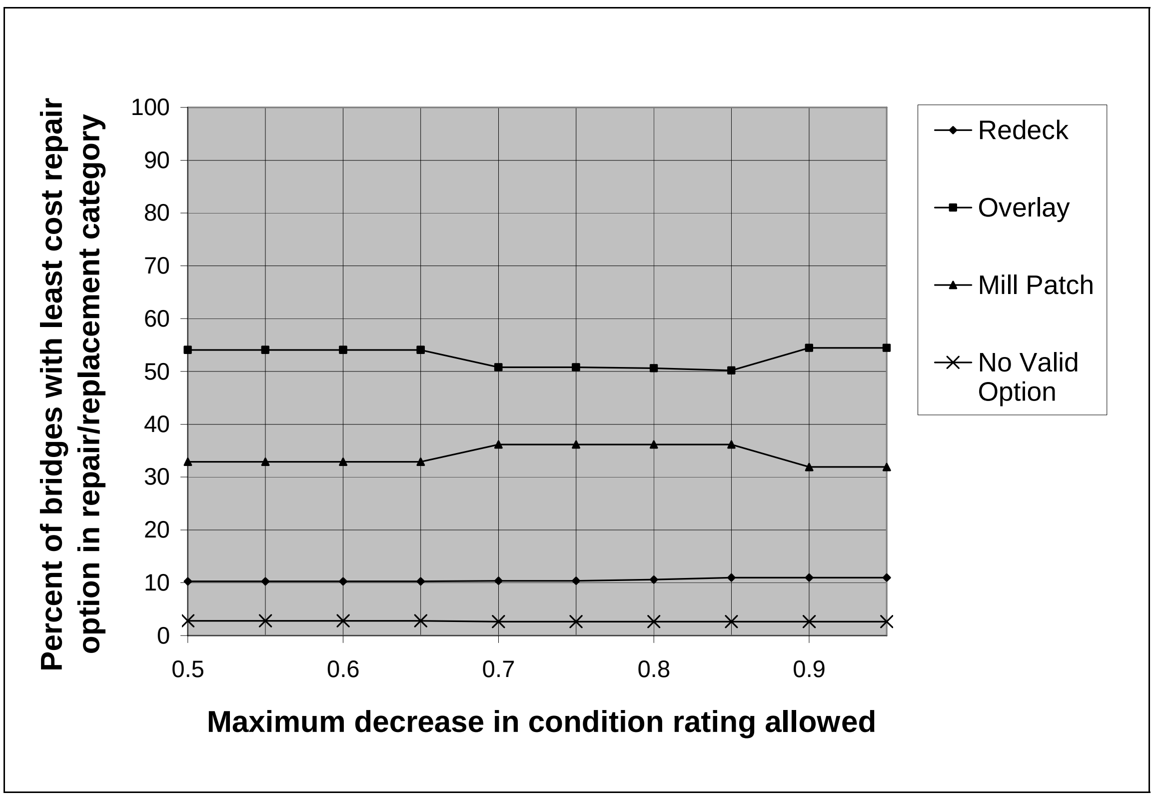

Figure 4.27 Initial Value Limit Parametric Study R_{min}=6

4.7.6 Analysis period:

During the last Mn/DOT TAP meeting for this project, a request was made for extension of the parameter study to include study of the duration of the analysis. In particular, several of the TAP members were interested in the effect on the economic analysis of increasing the analysis duration from a period of 20 years to one of 30 years. In response to this request the spreadsheet and macro for the present value analysis were modified to make the analysis time period a user-specified option. The economic analyses were conducted again for a 30-year analysis period using R_{min} = 4, 5, and 6. Graphs were prepared for these three analyses and are shown in Figures 4.28-4.30 using a similar format to those for the 20-year economic analyses (Figures 4.4-4.6). In addition, side-by-side comparison of the 20-year and 30-year distributions of least cost options is provided in Figure 4.31 for the case of a minimum deck condition rating (R_{min}) of 4. Similar graphs are shown in Figures 4.32 And 4.33, respectively, for R_{min} equal to 5 and 6.

Changing the duration of the analysis period from 20 years to 30 years, as expected, produces some differences in the distribution of least cost repair strategy options. However, these differences do not represent a significant departure from the trends in the distribution of least cost options established using the 20-year analysis period. By far the most obvious change in the results of the economic analysis, as the duration increased from 20 to 30 years, was that the total number of bridges requiring action increased for all three values of R_{min} that were analyzed. The analyses for R_{min} of 4 and 5 identified approximately twice as many bridges requiring repair or replacement when the analysis duration increased from 20 to 30 years. This effect was not evident for a minimum condition rating (R_{min}) of 6 because for both durations the entire population of 492 bridges required repair or replacement. In what concerns the distribution of least cost repair strategy options, there was some shifting of the percentages. But, the repair strategy options that were popular for a 20-year period were also selected frequently in the economic analysis for 30-year period.

For the case of R_{min} = 4 (Fig. 4.31), the most frequently selected RSOs for the 20-year duration were options 7, 4, 15 and 9, in that order. These three options represent 82% of the population of bridges requiring repair/replacement intervention for the 20-year analysis duration. Upon increasing the analysis period to 30 years, the most frequently selected RSOs were options 7, 15, and 4, in that order, with option 9 being the fifth most frequent. These four options encompassed 80% of the bridges requiring repair/replacement actions in the 30-year economic analysis. There were minor differences in the distribution of the remaining 20% of the bridges with the 20-year analysis favoring overlay options 3 and 10, whereas the 30-year analysis favored overlay options 5, 6 and 8. However, the largest difference was, by far, the increase in bridges requiring repair/replacement action from the 60 selected using the 20-year analysis duration to the 130 selected using the 30-year duration.

The distribution of least cost options for R_{min} = 5 using a 30-year duration included options 15, 17, 18 as the most frequent selections, with option 4 being the fifth most frequent (Figure 4.32). Options 15 and 17 were also found to be most frequent for the 20-year analysis period, with options 4 and 18 being the fifth and sixth most frequent. In both cases, these four options accounted for at least 72% of the bridges selected for study. The distribution of least cost RSOs differed somewhat for the remaining 28% of the bridges, with the 20-year analysis favoring reoverlay options 5 and 6 while the 30-year analysis emphasized reoverlay options 9 and 10. As noted above, however, the largest difference in economic analysis results was the total number of bridges selected for repair/replacement action which increased by nearly 100% when the analysis duration was increased from 20 years (161 bridges) to 30 years (306 bridges).

When R_{min} = 6 (Fig. 4.33), the most frequently selected repair/replacement option for both the 20-year and 30-year durations was option 4. Other options that were frequently selected for the both analyses included numbers 1, 9, and 17 (4th, 6th and 3rd for the 20-year analysis; 5th, 3rd and 6th for the 30-year analysis). These four options represent at least 54% of the population of bridges requiring repair/replacement intervention for the both analyses. There were minor differences in the distribution of the remaining bridges with the 20-year analysis favoring overlay options 5 and 6, and mill & patch options 14 and 15, and the 30-year analysis favoring overlay options 8 and 10.

The overall conclusion that can be drawn from this facet of the parameter study is that increasing the analysis duration from 20 to 30 years affects primarily the number of bridges that are selected for repair/replacement. The most frequently selected repair strategy options remained the same for all three values considered for R_{min}. The deviations in the distribution of the low-frequency repair strategy options are not considered important here. First, the effect of the time value of money for analysis periods in excess of 20 years tends to minimize these deviations. Second, the strategies that were developed for repair and replacement in section 4.6 of this report (Figures 4.7 – 4.9) are affected by the most frequently selected options. Thus, final recommendations on strategies developed from the economic analyses are based on a 20-year duration.

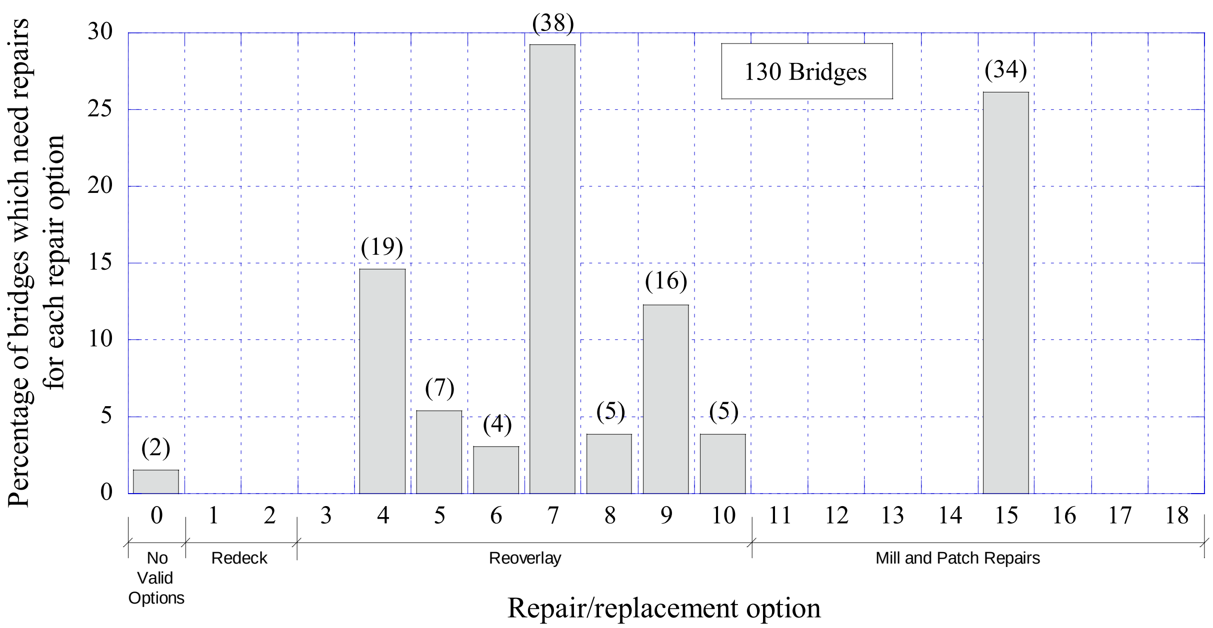

Figure 4.28 Least Cost Options for 30 Year Analysis and R_{min}=4

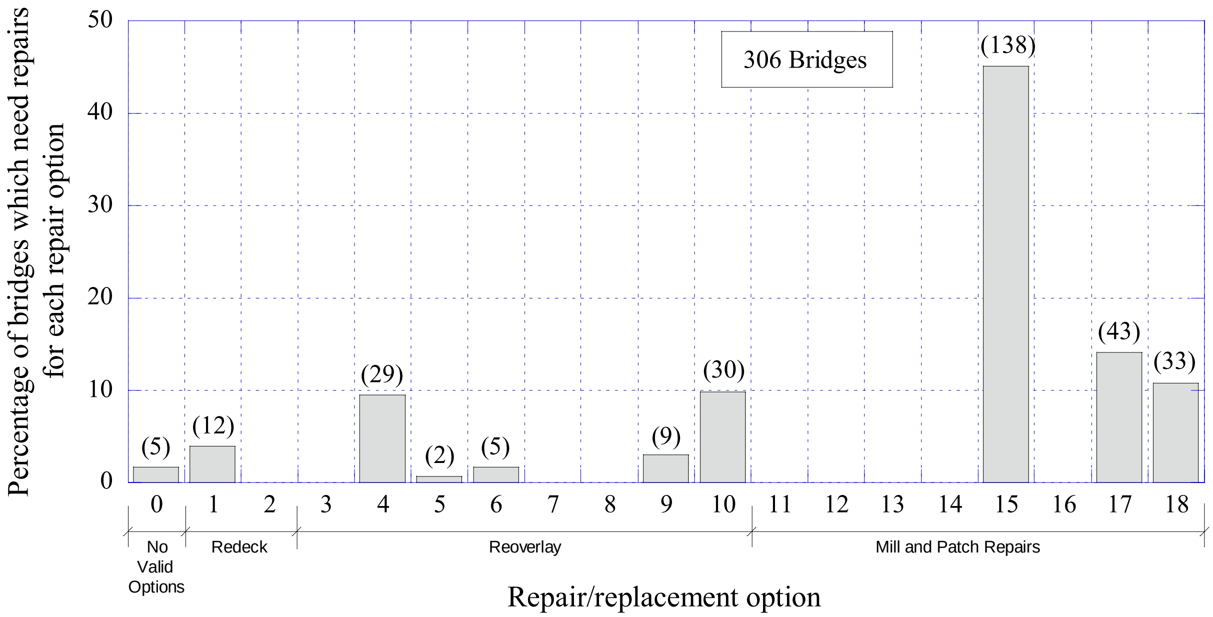

Figure 4.29 Least Cost Options for 30 Year Analysis and R_{min}=5

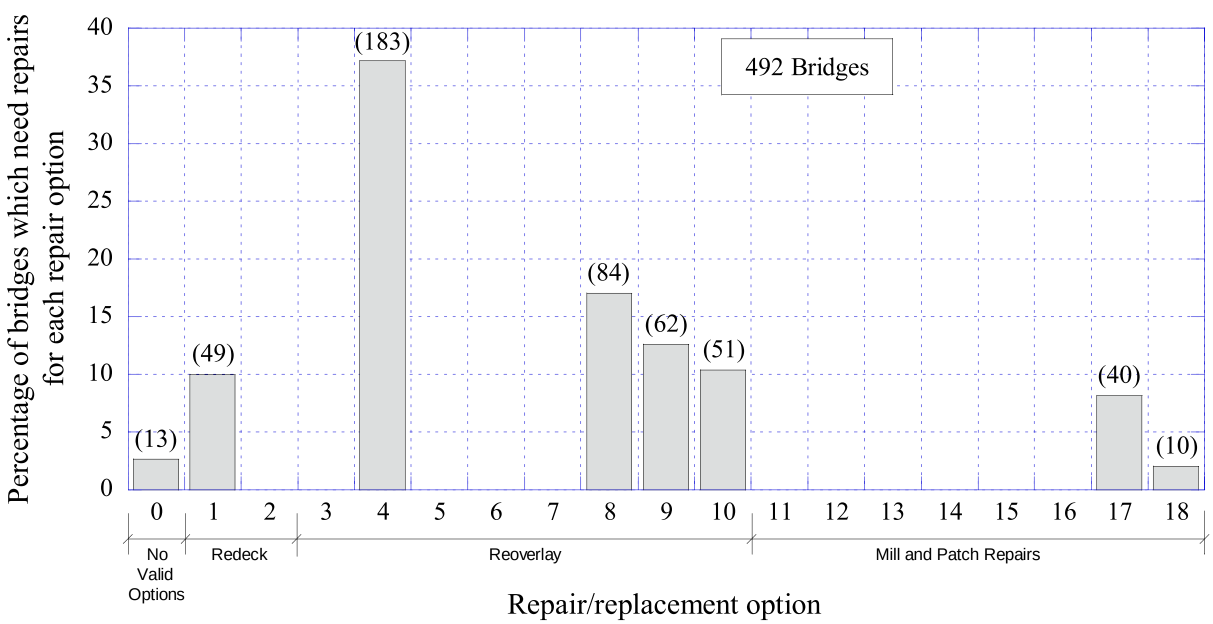

Figure 4.30 Least Cost Options for 30 Year Analysis and R_{min}=6

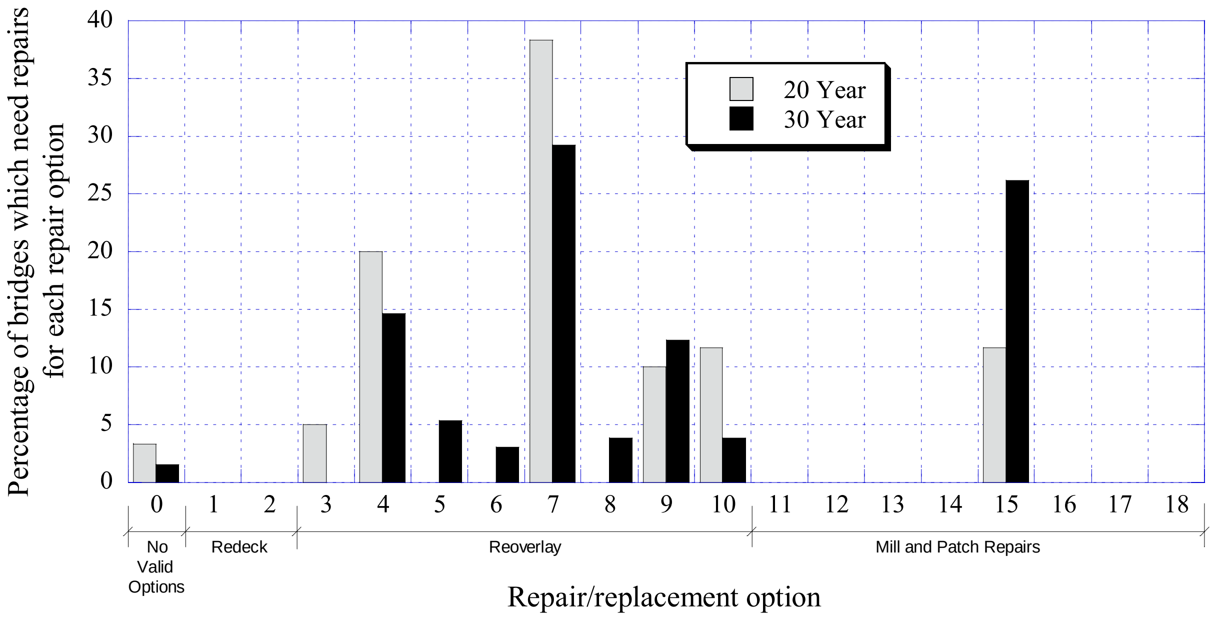

Figure 4.31 Comparison of Least Cost Options for 20 & 30 Year Analyses and R_{min}=4

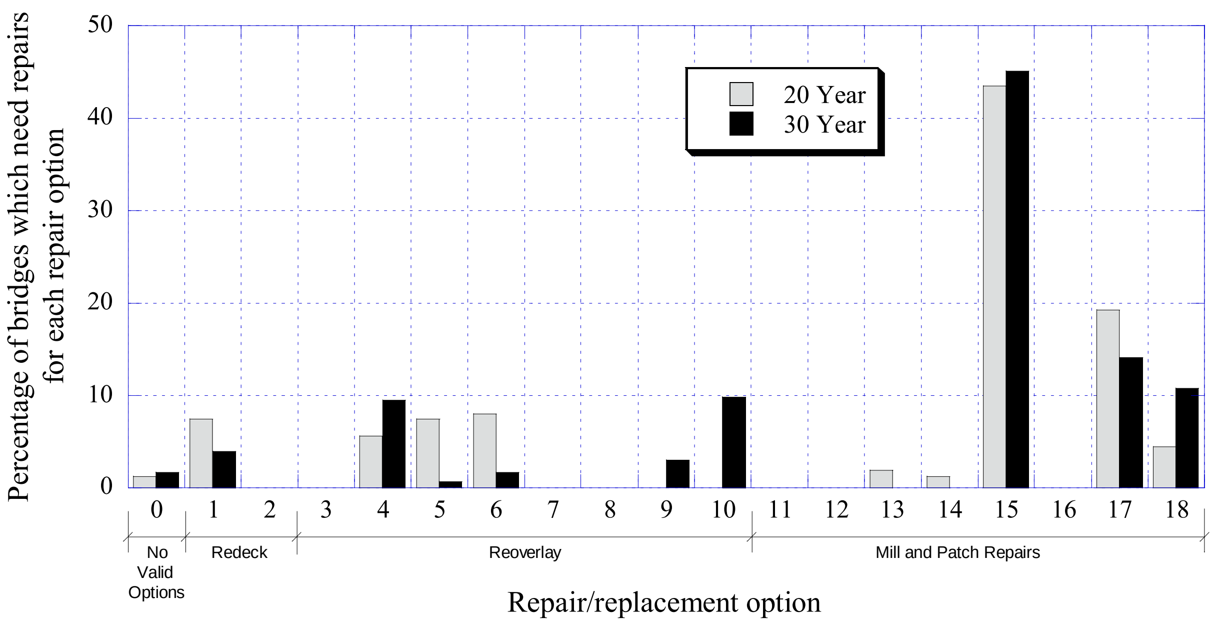

Figure 4.32 Comparison of Least Cost Options for 20 & 30 Year Analyses and R_{min}=5

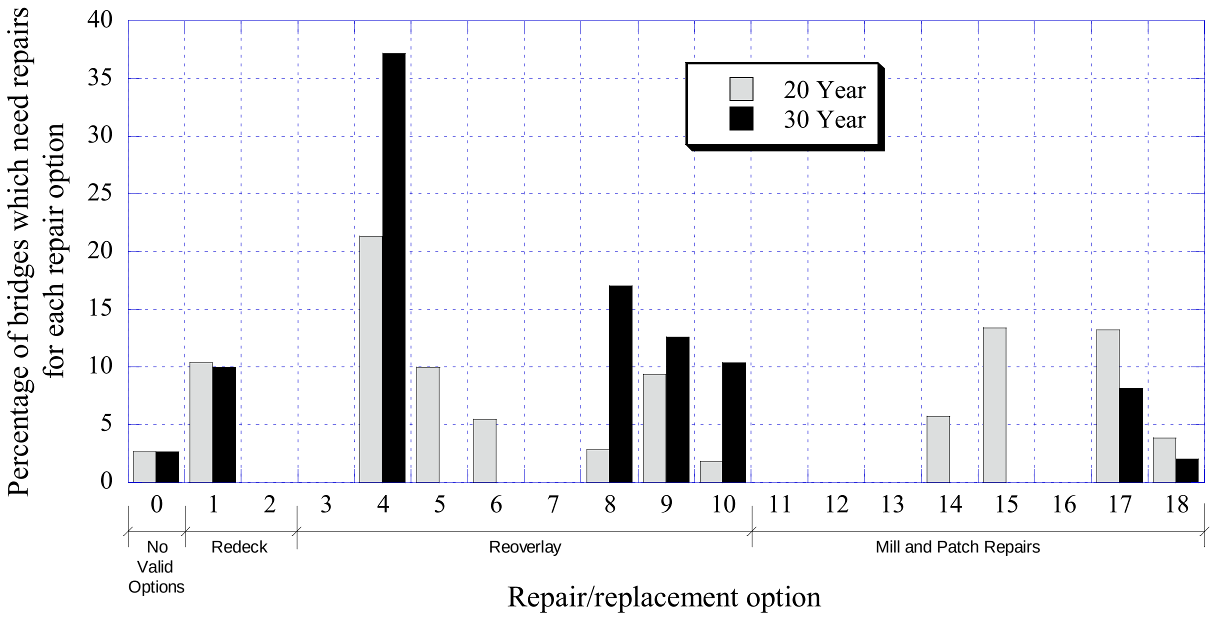

Figure 4.33 Comparison of Least Cost Options for 20 & 30 Year Analyses and R_{min}=6

Chapter 5: Summary and Conclusions

5.1 Summary

The goal of this research was to develop economic strategies to help minimize the costs of repairing and replacing concrete bridge decks with low slump concrete overlays. The decks studied in this research were overlaid from 1974 to 1981, and thus the results of this research are only directly applicable to this set of bridges.

The first step in achieving this goal was to perform a literature review of current research into the causes of concrete deck and overlay deterioration and performance, and to collect data for the bridges included for study in this project. The literature review identified several physical and geometric variables that have the potential to affect the deterioration and performance of concrete bridge decks and overlays. Data was collected from both the Federal Highway Administration (FHWA) and Mn/DOT. The collected data provided information about the physical and geometrical characteristics of the bridges as well as information about their deterioration over time. Using this data, a list of bridges that met the projects criteria was developed.

The data that was collected in the first step of the project was then used in a statistical analysis to determine whether or not the variables that were identified in the literature review have significant effects on the deterioration of the bridges under consideration. The statistical techniques of ANOVA and Tukey's method were used in this analysis. The statistical analysis revealed that several variables indeed have effects on the deterioration rates of the bridge decks. Superstructure material type, maximum span length, and average daily traffic were determined to be the most significant variables and were used to subdivide the data into three separate groups of bridges. Piecewise linear curves correlating NBI deck condition and time were constructed for these three subgroups, and these curves were used in the last portion of the project, the economic analysis.

Cost data was collected from Mn/DOT for the repair and replacement techniques being considered. A spreadsheet and Visual Basic program were created to implement a present value cost analysis using the cost data, the deteriation curves and the population of bridges selected for study. The present value cost analysis was performed for three different scenarios, with each scenario maintaining the bridge deck condition ratings above a particular rating. Analyses were conducted for minimum deck condition ratings equal to 4, 5, and 6. Based on the results of these three analyses, three flow charts were constructed that graphically show the least cost repair/replacement strategy likely is for a particular bridge deck given a desired minimum condition rating.

Lastly, a parametric study was conducted to investigate the sensitivity of the present value cost analyses to several important input parameters and key assumptions. It was found that for some parameters and assumptions, the overall outcome of the present value cost analysis is mostly insensitive. For other parameters and assumptions that were investigated, the outcome of the present value analysis did have significant changes depending on the choice of the input parameter or assumption that was used.

5.2 Observations and Conclusions

In the literature review activity for this project, several important parameters and variables were identified as potentially affecting the deterioration rates of concrete bridge decks with low slump concrete overlays. Some of these parameters relate mostly to the initial design and construction of the decks and overlays, and, in particular, to the causes of deck cracking. For the bridge decks being considered in this research, most of these parameters were either constant, or there was a lack of easily obtainable electronic data describing them. Thus, they were not included for study in the data analysis portion of the project. However, there are many differences in the decks being studied in this research with regards to geometrical and physical variables such as span length and ADT, and credible data exists documenting these variables. Therefore, these latter variables were the focus of the data analysis in the project.

The data analysis portion of the project provided several interesting results. It was surprising that some of the variables which were investigated, such as the use of epoxy coated reinforcement and the level of average daily truck traffic (ADTT), had no significant effects on the deterioration rates for the bridge decks. Another interesting finding was the effect that Mn/DOT district has on the deterioration rates of the bridge decks. This underscores the impact of the human side of the bridge inspection process, as well as the need for uniform application of inspection criteria. Lastly, the significant differences in deterioration rates between the among the three subgroups of bridge decks are worth noting. These differences in performance played a large role in the economic analysis in determining the least cost repair/replacement strategy for a given bridge deck.

The most general observation from this research is that it is possible to keep the condition of a bridge deck satisfactorily high by means of repairs, it is much more economically favorable than redecking. Which repairs to use and the timing of their application depends mostly on the condition of the deck and the type of deterioration curve that describes the deck. It was also observed that increasing the duration of analysis from 20 to 30 years had little impact on the most commonly selected least cost repair strategy options.

At the time this research was conducted, little data was available to verify the assumptions concerning the effects of repairs on the condition of the bridge decks. In the years to come, the population of bridges that have been repaired will be much larger. Consequently, more precise estimates of the influence of the repairs considered in this research on deck condition will be possible. Additionally, as data becomes available in the future concerning the behavior of the bridge decks analyzed in this project, it would be wise to check the accuracy of the assumptions made concerning deck deterioration at lower NBI deck condition states, as well as assumptions about deck deterioration after repairs are performed. The methods developed in this project could easily be applied to this new data and the present value analysis, or the deterioration curves it uses, could be modified with little effort.

Despite the need for more data to check the validity of some aspects of this research, the tools that were developed in this study, and the results that were obtained, are a significant advancement in the management of concrete bridge decks with low slump concrete overlays. The combination of large amounts of inspection data that reveal how these bridges have been performing in the past with statistics, financial principles, and a wealth of engineering experience is sure to bring significant improvements to the bridge management decision-making process.

5.3 Recommendations

Further refinement of the methods and tools developed in this study is recommended as more accurate information concerning the performance and deterioration of low-slump concrete overlays for bridge decks becomes available. Additional effort should be expended towards the reconciliation of the deterioration curves developed in this study for low-slump concrete overlays with physical models of the deterioration processes in concrete bridge decks. Finally, the methods developed in this project could very well be applied to other bridge elements and systems for which NBI data exists, including, but not limited to, other superstructure elements such as prestressed concrete girders or structural steel girders. The methods developed here can be used to develop deterioration curves useful for a wide variety of purposes, including the development of cost effective management techniques (i.e., maintenance, repair and replacement strategies) as well as service life estimation and life-cycle modeling of bridge systems.

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Appendix A

Deterioration Curve and Percent Unsound Deck Data

Table A.1 Deterioration Curve Data – As Used in the Present Value Cost Analysis

Type 0: Combined cast in place and long high					
Drop in rating	9 to 8	8 to 7	7 to 6	6 to 5	5 to 4
Average number of years for drop in rating	2.89091	2.89091	7.83824	18.4	12.8571
Sum of years (this is the x axis value)	2.89091	5.78182	13.62006	32.02006	44.87716
Slope for drop (1/avg number of years)	0.34591	0.34591	0.12757	0.054347	0.077778
Type 1: Combined steel and prestressed long low and steel and prestressed short high					
Drop in rating	9 to 8	8 to 7	7 to 6	6 to 5	5 to 4
Average number of years for drop in rating	4.34831	4.34831	12.2238	18.7273	12.8571
Sum of years (this is the x axis value)	4.34831	8.69662	20.92042	39.64772	52.50482
Slope for drop (1/avg number of years)	0.22997	0.22997	0.081807	0.053397	0.077778
Type 2: Steel and prestressed short low traffic					
Drop in rating	9 to 8	8 to 7	7 to 6	6 to 5	5 to 4
Average number of years for drop in rating	5.49688	5.49688	17.5984	30.7241	12.8571
Sum of years (this is the x axis value)	5.49688	10.99376	28.59216	59.31626	72.17336
Slope for drop (1/avg number of years)	0.18192	0.18192	0.056823	0.032547	0.077778

Table A.2 Percent Unsound Deck Used In the Cost Analysis

Condition	Percent unsound deck used in the analysis
Current recorded condition is 5	0.15
Current recorded condition is 6	0.07
Current recorded condition is 7	0.02
Deck just reached 4	0.2
Deck just reached 5	0.1
Deck just reached 6	0.04

Table A.3 Deterioration Curve Data – As Generated by the Rahim/Johnston Method

Type 0: Combined cast in place and long high				
Drop in rating	8 to 7	7 to 6	6 to 5	5 to 4
Average number of years for drop in rating	2.89091	7.83824	18.4	20.4
Sum of years (this is the x axis value)	2.89091	10.72915	29.12915	49.52915
Slope for drop (1/avg number of years)	0.34591	0.12757	0.054347	0.049019
Type 1: Combined steel and prestressed long low and steel and prestressed short high				
Drop in rating	8 to 7	7 to 6	6 to 5	5 to 4
Average number of years for drop in rating	4.34831	12.2238	18.7273	12.8571
Sum of years (this is the x axis value)	4.34831	16.57211	35.29941	48.15651
Slope for drop (1/avg number of years)	0.22997	0.081807	0.053397	0.077778
Type 2: Steel and prestressed short low traffic				
Drop in rating	8 to 7	7 to 6	6 to 5	5 to 4
Average number of years for drop in rating	5.49688	17.5984	30.7241	31.4286
Sum of years (this is the x axis value)	5.49688	23.09528	53.81938	85.24798
Slope for drop (1/avg number of years)	0.18192	0.056823	0.032547	0.031818

Appendix B

Present Value Cost Analysis Examples

B.1 Present Value Cost Analysis Example #1

Note: For the slopes of the deterioration curves used in this example as well as data for percent unsound deck corresponding to a given NBI deck condition, see appendix A. For the rate of inflation, 4% was used, and for the discount rate, 12% was used. Rmin was taken to be a NBI deck condition of 4.The effect on deck condition of reoverlaying was taken to be 1 point for the 1st application, and 1/2 point for the second application. The effect on deck condition of mill and patch repairs was taken to be 1/2 point for the first application a 1/4 point for the second application

Structure # 74819 is the bridge used in this example. This bridge has oneway traffic and is one lane wide.

<u>Basic Data:</u>

Steel superstructure, an ADT of less than 20,000, a maximum span length of over 100 feet.
--> So bridge has type 1 deterioration

$\text{overall\_length} = 202.09728\text{ft}$ $\text{width} = 20.01312336\text{ft}$ $\text{deck\_area} = \text{overall\_length} \times \text{width}$

$\text{OutToOut\_width} = 25.59055\text{ft}$ $\text{redeck\_area} = \text{overall\_length} \times \text{OutToOut\_width}$

Note: length and width are input with high precision so that this example will give the same results as the spreadsheet

$\text{deck\_area} = 4044.6\ \text{ft}^2$ $\text{redeck\_area} = 5171.78\ \text{ft}^2$

If deck is replaced, it must be wider than the old deck to meet current standards a average value of 6 feet is used in the analysis for all decks

$\text{widen\_area} = 6 \times \text{ft} \times \text{overall\_length}$ $\text{widen\_area} = 1212.58\ \text{ft}^2$

In 2000 the bridge deck first received a rating of 5, and in 2003 the deck still has a rating of 5. Thus there have been three years of deterioration past 5.

Define deterioration curve slopes used in this example

$\text{slope\_9\_8} = 0.22997$ $\text{slope\_8\_7} = 0.22997$ $\text{slope\_7\_6} = 0.081807$

$\text{slope\_6\_5} = 0.053397$ $\text{slope\_5\_4} = 0.0777778$

<u>Initial Calculations:</u>

Determine the present decimal NBI deck condition

$\text{current\_condition} = 5 - 3 \times \text{slope\_5\_4}$ $\text{current\_condition} = 4.77$

Calculate the cost of replacing the deck in today's dollars at $50/ft^2 redeck cost and $110/ft^2 for widening costs

$$\text{Present\_deckcost} = \left(\frac{50}{ft^2} \times \text{redeck\_area} + \frac{110}{ft^2} \times \text{widen\_area}\right) \quad \text{Present\_deckcost} = 391973.23$$

Calculate the cost of replacing the deck in 20 years

$$\text{deck\_20year} = \text{Present\_deckcost} \times \left(1 + \frac{0.04}{12}\right)^{12\times 20} \quad \text{deck\_20year} = 871192.68$$

Calculate the cost of reoverlaying in today's dollars at $10/ft^2

$$\text{present\_overlay} = \text{deck\_area} \times \frac{10}{ft^2} \quad \text{present\_overlay} = 40445.98$$

Calculate the cost of mill and patch repairs in today's dollars at $30/ft^2. Recorded deck condition is 5 so percent unsound deck must be between 5%-10%. Use the average of 7.5%. Also, typically roughly twice the actual unsound area is replaced during the repairs, thus the cost of mill and patch repairs should be calculated using 15% of the deck's area.

$$\text{present\_mill} = 0.15 \times \text{deck\_area} \times \frac{30}{ft^2} \quad \text{present\_mill} = 18200.69$$

<u>Option 1 - Redeck now</u>

After redecking, rating goes to 9. The final condition of the deck needs to be determined. It takes 8.7 years to reach a NBI deck condition of 7, which leaves 11.3 years.

$$R_{final\_1} = 7 - (20 - 8.69662) \times \text{slope\_7\_6} \quad R_{final\_1} = 6.08$$

Calculate the final value of the deck at the end of the 20 year analysis period.

$$\text{Value}_{final\_1} = \frac{R_{final\_1}}{9} \times \text{deck\_20year} \quad \text{Value}_{final\_1} = 588084.53$$

Calculate the cost of option #1.

$$\text{Cost}_{opt1} = \text{Present\_deckcost} - \text{Value}_{final\_1} \times \left(1 + \frac{0.12}{12}\right)^{-12\times 20}$$

$$\text{Cost}_{opt1} = 337983.64$$

Option 2 - Let deck deteriorate to Rmin=4, then redeck

Determine how many years it takes deck to reach 4.

$$Remainder = current\_condition - 4 \quad Remainder = 0.77$$

$$YearsTo4\_actual = \frac{Remainder}{slope\_5\_4} \quad YearsTo4\_actual = 9.86$$

This number needs to be rounded to the nearest year. $YearsTo4 = round(YearsTo4\_actual, 0)$

$$YearsTo4 = 10$$

Calculate the cost of redecking in 10 years.

$$deck\_10 = Present\_deckcost \times \left(1 + \frac{0.04}{12}\right)^{12 \times YearsTo4} \qquad deck\_10 = 584366.51$$

Calculate the final value of the deck after 20 analysis period (there is only 10 years left after redecking).

It takes 8.7 years for the deck to reach 7 $R_{final2} = 7 - (10 - 8.69662) \times slope\_7\_6$

$$R_{final2} = 6.89$$

$$Final_{val2} = \frac{R_{final2}}{9} \times deck\_20year \qquad Final_{val2} = 667273.04$$

Calculate the cost of option #2.

$$Cost_{opt2} = deck\_10 \times \left(1 + \frac{0.12}{12}\right)^{-10 \times 12} - Final_{val2} \times \left(1 + \frac{0.12}{12}\right)^{-12 \times 20}$$

$$Cost_{opt2} = 115800.44$$

Option 3 - Reoverlay now, and perform no additional repairs provided the deck condition stays above Rmin=4

After reoverlaying immediately, deck condition rating rises 1 point.

$$\text{repaired\_condition} = \text{current\_condition} + 1 \qquad \text{repaired\_condition} = 5.77$$

Calculate the final value of the deck at the end of the analysis period.

$$\text{remainder\_2} = \text{repaired\_condition} - 5 \qquad \text{remainder\_2} = 0.77$$

$$\text{years\_to5} = \frac{\text{remainder\_2}}{\text{slope\_6\_5}} \qquad \text{years\_to5} = 14.36$$

$$R_{final3} = 5 - (20 - \text{years\_to5}) \times \text{slope\_5\_4} \qquad R_{final3} = 4.56$$

$$Final_{val3} = \frac{R_{final3}}{9} \times \text{deck\_20year} \qquad Final_{val3} = 441517.23$$

Calculate the cost of option #3.

$$Cost_{opt3} = \text{present\_overlay} - Final_{val3} \times \left(1 + \frac{0.12}{12}\right)^{-20\times12}$$

$$Cost_{opt3} = -87.88$$

Since option 3 is valid (one repair action is enough to keep the deck's condition above Rmin=4 for the entire analysis period), options 4-6, which involve reoverlaying immediately plus a secondary repair/replacement action, are redundant.

Option 7 - Let the deck deteriorate to Rmin=4, then reoverlay and perform no secondary repair/replacement actions provided the deck's condition stays above Rmin=4 for the entire 20 year analysis period

It was previously calculated that it will take 10 years for the deck's condition to reach 4. Then a reoverlay will be performed and the deck's condition will rise 1 point to 5.

Calculate the final value of the deck at the end of the analysis period.

$$R_{final7} = 5 - 10 \times \text{slope\_5\_4} \qquad R_{final7} = 4.22 \qquad Final_{val7} = \frac{R_{final7}}{9} \times \text{deck\_20year}$$

$$Final_{val7} = 408707.66$$

Calculate the cost of a reoverlay in 10 years.

$$overlay\_10 = present\_overlay \times \left(1 + \frac{0.04}{12}\right)^{12\times10} \qquad overlay\_10 = 60298.19$$

Calculate the cost of option 7

$$Cost_{opt7} = overlay\_10 \times \left(1 + \frac{0.12}{12}\right)^{-12\times10} - Final_{val7} \times \left(1 + \frac{0.12}{12}\right)^{-12\times20}$$

$$Cost_{opt7} = -19251.71$$

Since option #7 is valid, options 8-10 are redundant.

<u>Option 11 - Mill and patch now, and perform no secondary repair/replacement actions provided the deck's condition stays above Rmin=4 for the entire analysis period</u>

After mill and patch repair immediately, deck condition rating rises 1/2 point.

$$repaired\_condition\_mill = current\_condition + 0.5 \qquad repaired\_condition\_mill = 5.27$$

Calculate the final value of the deck at the end of the analysis period.

$$remainder\_3 = repaired\_condition\_mill - 5 \qquad remainder\_3 = 0.27$$

$$years\_to5 = \frac{remainder\_3}{slope\_6\_5} \qquad years\_to5 = 4.99$$

$$R_{final11} = 5 - (20 - years\_to5) \times slope\_5\_4 \qquad R_{final11} = 3.83$$

Since the final rating is less than 4, option 11 doesn't last long enough (DLLE in spreadsheet)

<u>Option 12 - Mill and patch now, then redeck when Rmin is reached</u>

Calculate the number of years required for the deck to deteriorate back down to 5.

$$Remainder\_4 = repaired\_condition\_mill - 5 \qquad Remainder\_4 = 0.27$$

$$YearsTo5\_opt12 = \frac{Remainder\_4}{slope\_6\_5} \qquad YearsTo5\_opt12 = 4.99$$

It then takes 12.9 years to deteriorate from 5 to 4

$$YearsTo4\_opt12 = YearsTo5\_opt12 + 12.9571 \qquad YearsTo4\_opt12 = 17.95$$

This number needs to be rounded to the nearest year.

$$YrsTo4\_opt12\_rd = round(YearsTo4\_opt12, 0) \qquad YrsTo4\_opt12\_rd = 18$$

Calculate the cost of redecking in 18 years.

$$deck\_18 = Present\_deckcost \times \left(1 + \frac{0.04}{12}\right)^{12\times18} \qquad deck\_18 = 804319.21$$

Calculate the final value of the deck after 20 analysis period (there is only 2 years left after redecking).

$$R_{final12} = 9 - 2 \times slope\_9\_8 \qquad R_{final12} = 8.54$$

$$Final_{val12} = \frac{R_{final12}}{9} \times deck\_20year \qquad Final_{val12} = 826670.87$$

Calculate the cost of option #12.

$$Cost_{opt12} = present\_mill + deck\_18 \times \left(1 + \frac{0.12}{12}\right)^{-18\times12} - Final_{val12} \times \left(1 + \frac{0.12}{12}\right)^{-12\times20}$$

$$Cost_{opt12} = 36066.21$$

Option 13 - Mill and patch now, then mill and patch again when Rmin is reached

Determine the final value of the deck after the 20 year analysis period. In year 18 the decks condition will go up 1/4 point due to milling and patching again.

$R_{final13} = 4.25 - 2 \times 0.077778$ $R_{final13} = 4.09$

$Final_{val13} = \frac{R_{final13}}{9} \times deck\_20year$ $Final_{val13} = 396338.85$

Calculate the cost of mill and patch repairs in 18 years. The deck will have just reached an NBI deck condition of 4, so based on repairing double the amount of unsound deck for the lower end of the range of unsound deck deck for a rating of 4, 20% of the decks area will need repairs.

$mill\_18 = 0.20 \times deck\_area \times \frac{30}{ft^2} \times \left(1 + \frac{0.04}{12}\right)^{18\times12}$ $mill\_18 = 49796.48$

Calculate the cost of option #13

$$Cost_{opt13} = present\_mill + mill\_18 \times \left(1 + \frac{0.12}{12}\right)^{-18\times12} - Final_{val13} \times \left(1 + \frac{0.12}{12}\right)^{-12\times20}$$

$Cost_{opt13} = -12380.8$

Option 14 - Mill and patch now, then reoverlay when Rmin is reached

Determine the final value of the deck after the 20 year analysis period. In year 18 the decks condition will go up 1/2 point due to reoverlaying.

$R_{final14} = 4.5 - 2 \times 0.077778$ $R_{final14} = 4.34$

$Final_{val14} = \frac{R_{final14}}{9} \times deck\_20year$ $Final_{val14} = 420538.65$

Calculate the cost of reoverlaying in 18 years.

$$overlay\_18 = present\_overlay \times \left(1 + \frac{0.04}{12}\right)^{18 \times 12} \qquad overlay\_18 = 82994.13$$

Calculate the cost of option #14

$$Cost_{opt14} = present\_mill + overlay\_18 \times \left(1 + \frac{0.12}{12}\right)^{-18 \times 12} - Final_{val14} \times \left(1 + \frac{0.12}{12}\right)^{-12 \times 20}$$

$$Cost_{opt14} = -10732.67$$

Option 15 - Let the deck deteriorate to Rmin=4, then perform mill and patch repairs, and perform no secondary repair/replacement actions provided the deck's condition stays above Rmin=4 for entire analysis period.

Calculate the decks final value - the decks condition goes up 1/2 point in year 10 do to mill and patch repairs

$$R_{final15} = 4.5 - 10 \times 0.077778 \qquad R_{final15} = 3.72$$

Since the final rating is less than 4, option 15 doesn't last long enough (DLLE in spreadsheet)

Option 16 - Let the deck deteriorate to Rmin=4, then perform mill and patch repairs, then redeck when the deck deteriorates back to Rmin

Calculate the cost of mill and patch repairs in 10 years.

In 10 years the decks condition will have just reached 4. The lower end of the percent unsound deck for a NBI deck condition of 4 is 10%. When doubled to account for the actual size of the repaired area, 20% of the deck will be repaired.

$$mill\_10year = 0.2 \times deck\_area \times \frac{30}{ft^2} \times \left(1 + \frac{0.04}{12}\right)^{12 \times 10} \qquad mill\_10year = 36178.91$$

Calculate how many years it takes the deck to deteriorate back to 4.

$$years\_to4\_opt16 = \frac{0.5}{0.077778} \qquad years\_to4\_opt16 = 6.43$$

This rounds down to 6, so in year 16 the bridge is redecked. Calculate the cost of redecking in year 16

$$deck\_16 = Present\_deckcost \times \left(1 + \frac{0.04}{12}\right)^{16\times 12} \qquad deck\_16 = 742578.99$$

Determine the final value of the deck at the end of the analysis period.

$$R_{final16} = 9 - 4 \times 0.22997 \qquad R_{final16} = 8.08$$

$$Final_{val16} = \frac{R_{final16}}{9} \times deck\_20year \qquad Final_{val16} = 782149.05$$

Calculate the cost of option #16.

$$Cost_{opt16} = mill\_10year \times \left(1 + \frac{0.12}{12}\right)^{-12\times 10} + deck\_16 \times \left(1 + \frac{0.12}{12}\right)^{-16\times 12} \ldots$$
$$+ \left(-1 \times Final_{val16}\right) \times \left(1 + \frac{0.12}{12}\right)^{-12\times 20}$$

$$Cost_{opt16} = 49066.6$$

<u>Option 17 - Let the deck deteriorate to Rmin=4, then perform mill and patch repairs, then perform mill and patch repairs when the deck deteriorates back to Rmin</u>

Determine the final value of the deck in 20 years. In year 16 the decks condition goes up 1/4 point to performing mill and patch repairs again.

$$R_{final17} = 4.25 - 0.077778 \times 4 \qquad R_{final17} = 3.94$$

Since the final rating is less than 4, option 17 doesn't last long enough (DLLE in spreadsheet)

Option 18 - Let the deck deteriorate to Rmin=4, then perform mill and patch repairs, then reoverlay when the deck deteriorates back to Rmin

Calculate the final value of the deck at the end of the analysis period. In year 16 the deck's condition goes up 1/2 point due to the reoverlay.

$R_{final18} = 4.5 - 4 \times 0.077778$ $\qquad R_{final18} = 4.19$

$Final_{val18} = \frac{R_{final18}}{9} \times deck\_20year$ $\qquad Final_{val18} = 405480.95$

Calculate the cost of reoverlaying in 16 years.

$$overlay\_16 = present\_overlay \times \left(1 + \frac{0.04}{12}\right)^{12\times16} \qquad overlay\_16 = 76623.43$$

Calculate the cost of option #18.

$$Cost_{opt18} = mill\_10year \times \left(1 + \frac{0.12}{12}\right)^{-12\times10} + overlay\_16 \times \left(1 + \frac{0.12}{12}\right)^{-16\times12} \ldots$$
$$+ \left(-1 \times Final_{val18}\right) \times \left(1 + \frac{0.12}{12}\right)^{-12\times20}$$

$Cost_{opt18} = -14922.33$

Determining the least cost option for this bridge

A quick comparison of the above calculated costs for all relevant repair/replacement strategy options reveals that option 7 is the least cost option for this bridge based on the input assumptions and data specified at the beginning of the example.

B.2 Present Value Cost Analysis Example #2

Note: For the slopes of the deterioration curves used in this example as well as data for percent unsound deck corresponding to a given NBI deck condition, see appendix A. For the rate of inflation, 4% was used, and for the discount rate, 12% was used. Rmin was taken to be a NBI deck condition of 4.The effect on deck condition of reoverlaying was taken to be 1 point for the 1st application, and 1/2 point for the second application. The effect on deck condition of mill and patch repairs was taken to be 1/2 point for the first application, and 1/4 point for the second application.

Structure #69880 is the bridge used in this example. There are 4 lanes on this bridge.

Basic Data:

Steel superstructure, an ADT of greater than 20,000, a maximum span length under 100 feet.
--> So bridge has type 1 deterioration

$overall\_length = 1163.0436ft$ $width = 71.8503937ft$ $OutToOut\_width = 80.708659ft$

$redeck\_area = overall\_length \times OutToOut\_width$ $deck\_area = overall\_length \times width$

Note: length and width are input with high precision so that this example will give the same results as the spreadsheet.

$deck\_area = 83565.14\ ft^2$

$redeck\_area = 93867.69\ ft^2$

If deck is replaced, it must be six feet wider than the old deck to meet current standards

$widen\_area = 6ft \times overall\_length$ $widen\_area = 6978.26\ ft^2$

In 1989 the bridge deck first received a rating of 5, and in 2003 the deck still has a rating of 5. Thus there have been 14 years of deterioration past 5.

Define deterioration curve slopes used in this example

$slope\_9\_8 = 0.22997$ $slope\_8\_7 = 0.22997$ $slope\_7\_6 = 0.081807$

$slope\_6\_5 = 0.053397$ $slope\_5\_4 = 0.0777778$

Initial Calculations:

Determine the present decimal NBI deck condition.

$current\_condition\_predicted = 5 - 14 \times slope\_5\_4$

$current\_condition\_predicted = 3.91$

If the decks condition was actually 3.91, the decks recorded condition would be a 4. Since the recorded condition is a 5, the deck must be performing above average. Therefore the reduction in condition state will be limited to 4.25 to account for this above average performance.

$current\_condition = 4.25$

Calculate the cost of replacing the deck in today's dollars at $50/ft^2 redeck cost and $110/ft^2 for widening costs

$$\text{Present\_deckcost} = \left(\frac{50}{ft^2} \times \text{redeck\_area} + \frac{110}{ft^2} \times \text{widen\_area}\right) \qquad \text{Present\_deckcost} = 5460993.24$$

Calculate the cost of replacing the deck in 20 years

$$\text{deck\_20year} = \text{Present\_deckcost} \times \left(1 + \frac{0.04}{12}\right)^{12\times 20} \qquad \text{deck\_20year} = 12137505.76$$

Calculate the cost of reoverlaying in today's dollars at $10/ft^2

$$\text{present\_overlay} = \text{deck\_area} \times \frac{10}{ft^2} \qquad \text{present\_overlay} = 835651.41$$

Calculate the cost of mill and patch repairs in today's dollars at $30/ft^2. Recorded deck condition is 5 so percent unsound deck must be between 5%-10%. Use the average of 7.5%. Also, typically roughly twice the actual unsound area is replaced during the repairs, thus the cost of mill and patch repairs should be calculated using 15% of the deck's area.

$$\text{present\_mill} = 0.15 \times \text{deck\_area} \times \frac{30}{ft^2} \qquad \text{present\_mill} = 376043.13$$

<u>Option 1 - Redeck now</u>

After redecking, rating goes to 9. The final condition of the deck needs to be determined. It takes 8.7 years to reach a NBI deck condition of 7, which leaves 11.3 years.

$$R_{final\_1} = 7 - (20 - 8.69662) \times \text{slope\_7\_6} \qquad R_{final\_1} = 6.08$$

Calculate the final value of the deck at the end of the 20 year analysis period.

$$\text{Value}_{final\_1} = \frac{R_{final\_1}}{9} \times \text{deck\_20year} \qquad \text{Value}_{final\_1} = 8193226.89$$

Calculate the cost of option #1.

$$\text{Cost}_{opt1} = \text{Present\_deckcost} - \text{Value}_{final\_1} \times \left(1 + \frac{0.12}{12}\right)^{-12\times 20}$$

$$\text{Cost}_{opt1} = 4708807.19$$

<u>Option 2 - Let deck deteriorate to Rmin=4, then redeck</u>

Determine how many years it takes deck to reach 4.

$Remainder = current\_condition - 4$ $Remainder = 0.25$

$$YearsTo4\_actual = \frac{Remainder}{slope\_5\_4} \qquad YearsTo4\_actual = 3.21$$

This number needs to be rounded to the nearest year. $YearsTo4 = round(YearsTo4\_actual, 0)$

$YearsTo4 = 3$

Calculate the cost of redecking in 3 years.

$$deck\_3 = Present\_deckcost \times \left(1 + \frac{0.04}{12}\right)^{12 \times YearsTo4} \qquad deck\_3 = 6156024.09$$

Calculate the final value of the deck after 20 analysis period (there is only 17 years left after redecking).

It takes 8.7 years for the deck to reach 7 $R_{final2} = 7 - (17 - 8.69662) \times slope\_7\_6$

$R_{final2} = 6.32$

$$Final_{val2} = \frac{R_{final2}}{9} \times deck\_20year \qquad Final_{val2} = 8524204.54$$

Calculate the cost of option #2.

$$Cost_{opt2} = deck\_3 \times \left(1 + \frac{0.12}{12}\right)^{-3 \times 12} - Final_{val2} \times \left(1 + \frac{0.12}{12}\right)^{-12 \times 20}$$

$Cost_{opt2} = 3520027.1$

<u>Option 3 - Reoverlay now, and perform no additional repairs provided the deck condition stays above Rmin=4</u>

After reoverlaying immediately, deck condition rating rises 1 point.

$repaired\_condition = current\_condition + 1$ $repaired\_condition = 5.25$

Calculate the final value of the deck at the end of the analysis period.

$remainder\_2 = repaired\_condition - 5$ $\qquad remainder\_2 = 0.25$

$years\_to5 = \frac{remainder\_2}{slope\_6\_5}$ $\qquad years\_to5 = 4.68$

$R_{final3} = 5 - (20 - years\_to5) \times slope\_5\_4$ $\qquad R_{final3} = 3.81$

This rating is less than 4 so this option fails to keep the deck's rating above Rmin and thus doesn't last long enough (DLLE in the spreadsheet).

<u>Option 4 - Reoverlay now, redeck when the deck deteriorates back to Rmin=4</u>

Rating initially goes to 5.25, and as previously calculated in option 3 it takes 4.68 years for the bridge to deteriorate to 5.

$years\_to4 = \frac{1}{slope\_5\_4}$ $\qquad years\_to4 = 12.86$

$years\_to4 + years\_to5 = 17.54$ This will be rounded to 18 years.

Calculate the cost of redecking in 18 years.

$deck\_18year = Present\_deckcost \times \left(1 + \frac{0.04}{12}\right)^{18 \times 12}$ $\qquad deck\_18year = 11205820.67$

Calculate the final value of the deck at the end of the analysis period.

$Final_{cond4} = 9 - 2 \times slope\_9\_8$ $\qquad Final_{cond4} = 8.54$

$Final_{val4} = \frac{Final_{cond4}}{9} \times deck\_20year$ $\qquad Final_{val4} = 11517225.27$

Calculate the cost of option 4.

$$Cost_{opt4} = present\_overlay + deck\_18year \times \left(1 + \frac{0.12}{12}\right)^{-12 \times 18} - Final_{val4} \times \left(1 + \frac{0.12}{12}\right)^{-12 \times 20}$$

$Cost_{opt4} = 1084554.79$

<u>Option 5, Reoverlay now, reoverlay again when the deck deteriorates back to Rmin=4</u>

From the calculations performed for option 4, it takes 18 years for the deck to deteriorate to 4. Then after the second reoverlay is performed, the decks condition goes to 4.5

Calculate the final value of the deck.

$Final_{cond5} = 4.5 - 2 \times slope\_5\_4$ $\qquad Final_{cond5} = 4.34$

$Final_{val5} = \dfrac{Final_{cond5}}{9} \times deck\_20yea$ $Final_{val5} = 5858968.77$

Calculate the cost of reoverlay in 18 years.

$$overlay\_18year = present\_overlay \times \left(1 + \frac{0.04}{12}\right)^{12\times18} \qquad overlay\_18year = 1714735.65$$

Calculate the cost of option 5.

$$Cost_{opt5} = present\_overlay + overlay\_18year \times \left(1 + \frac{0.12}{12}\right)^{-12\times18} - Final_{val5} \times \left(1 + \frac{0.12}{12}\right)^{-12\times20}$$

$Cost_{opt5} = 497648.98$

Option 6 - Reoverlay now, perform mill and patch repairs when the deck deteriorates back to Rmin=4

Calculate the final value of the deck at the end of the analysis period. In year 18 the deck condition rating increases by 1/4 point due to the mill and patch repairs.

$R_{final6} = 4.25 - 2 \times 0.077778$ $\qquad R_{final6} = 4.09$

$Final_{val6} = \dfrac{R_{final6}}{9} \times deck\_20year$ $\qquad Final_{val6} = 5521815.29$

Calculate the cost of mill and patch repair in 18 years. The deck just reached a condition of 4, so 20% of the decks area will need mill and patch repairs.

$$mill\_18year = 0.2 \times deck\_area \times \frac{30}{ft^2}\left(1 + \frac{0.04}{12}\right)^{12\times18} \qquad mill\_18year = 1028841.39$$

$$Cost_{opt6} = present\_overlay + mill\_18year \times \left(1 + \frac{0.12}{12}\right)^{-12\times18} - Final_{val6} \times \left(1 + \frac{0.12}{12}\right)^{-12\times20}$$

Calculate the cost of option #6.

$Cost_{opt6} = 448647.6$

Option 7 - Let the deck deteriorate to Rmin=4, then reoverlay and perform no secondary repair/replacement actions provided the deck's condition stays above Rmin=4 for the entire 20 year analysis period

It was previously calculated that it will take 3 years for the deck's condition to reach 4. Then a reoverlay will be performed and the deck's condition will rise 1 point to 5.

Calculate the final value of the deck at the end of the analysis period.

$R_{final7} = 5 - 17 \times slope\_5\_4$ $\qquad R_{final7} = 3.68$

This rating is less than 4 so this option fails to keep the deck's rating above Rmin and thus doesn't last long enough (DLLE in the spreadsheet).

Option 8 - Let the deck deteriorate to Rmin=4, then reoverlay. Redeck when the deck deteriorates back to Rmin=4

It was calculated for option 7 that it will take 3 years for the deck to deteriorate to 3. Calculate the cost of a reoverlay in 3 years.

$$overlay\_3year = present\_overlay \times \left(1 + \frac{0.04}{12}\right)^{12 \times 3} \qquad overlay\_3year = 942006.33$$

After reoverlaying, the decks rating goes up one point to 5. Calculate how much time it will take to deteriorate back to 4.

$$time\_to4 = \frac{1}{slope\_5\_4} \qquad time\_to4 = 12.86$$

Round this to 13 years.

So at 16 years, the decks rating will go to 9 after redecking occurs. Calculate the deck's final value at the end of the analysis.

$R_{final8} = 9 - 4 \times slope\_9\_8$ $\qquad R_{final8} = 8.08$

$$Final_{val8} = \frac{R_{final8}}{9} \times deck\_20year \qquad Final_{val8} = 10896944.78$$

Calculate the cost of redecking in 16 years.

$$redeck\_16 = Present\_deckcost \times \left(1 + \frac{0.04}{12}\right)^{12 \times 16} \qquad redeck\_16 = 10345652.5$$

Calculate the cost of option #8.

$$Cost_{opt8} = overlay\_3year \times \left(1 + \frac{0.12}{12}\right)^{-3\times12} + redeck\_16 \times \left(1 + \frac{0.12}{12}\right)^{-12\times16} \ldots$$
$$+ -Final_{val8} \times \left(1 + \frac{0.12}{12}\right)^{-12\times20}$$

$Cost_{opt8} = 1189266.87$

Option 9 - Let the deck deteriorate to Rmin=4 then reoverlay, Reoverlay again when the deck deteriorates back to Rmin=4.

This option is very similar to option 8 except that a reoverlay is used as the second action. Calculate the cost of reoverlaying in 16 years.

$$reoverlay\_16 = present\_overlay \times \left(1 + \frac{0.04}{12}\right)^{12\times16} \qquad reoverlay\_16 = 1583111.11$$

Calculate the decks final value. At year 16 the decks condition will rise from 4 to 4.5 after the reoverlay.

$R_{final9} = 4.5 - 4 \times slope\_5\_4 \qquad R_{final9} = 4.19$

$$Final_{val9} = \frac{R_{final9}}{9} \times deck\_20year \qquad Final_{val9} = 5649184.66$$

Calculate the cost of option #9.

$$Cost_{opt9} = overlay\_3year \times \left(1 + \frac{0.12}{12}\right)^{-12\times3} + reoverlay\_16 \times \left(1 + \frac{0.12}{12}\right)^{-12\times16} \ldots$$
$$+ -Final_{val9} \times \left(1 + \frac{0.12}{12}\right)^{-12\times20}$$

$Cost_{opt9} = 374082.67$

Option 10 - Let the deck deteriorate to Rmin=4 then reoverlay, perform mill and patch repairs when the deck deteriorates back to Rmin=4.

Calculate the value of the deck at the end of the analysis period. The decks condition rating goes up by 1/4 point in year 16 due to mill and patch repairs.

$R_{final10} = 4.25 - 4 \times 0.077778 \qquad R_{final10} = 3.94$

Since this final rating is less than 4, option 10 doesn't last long enough (DLLE in the spreadsheet)

Option 11 - Mill and patch now, and perform no secondary repair/replacement actions provided the deck's condition stays above Rmin=4 for the entire analysis period

Since the effect of mill and patch repairs on the deck is 1/2 that of reoverlaying (a 1/2 point increase) it is obvious that this option will not last long enough since option three did not last long enough.

Option 12 - Perform mill and patch repairs now. Redeck once the deck deteriorates back to Rmin=4.

Calculate the final value of the deck at the end of the analysis period. The decks condition rises by 1/2 point due to the mill and patch repairs.

First determine the number of years to deteriorate back to 4.

$$YearsTo4\_opt12 = \frac{0.75}{slope\_5\_4} \qquad YearsTo4\_opt12 = 9.64$$

This is then rounded to 10 years. After redecking in year 10, it takes 8.7 years to deteriorate to 7.

$$R_{final12} = 7 - (10 - 8.69662) \times slope\_7\_6 \qquad R_{final12} = 6.89$$

$$Final_{val12} = \frac{R_{final12}}{9} \times deck\_20year \qquad Final_{val12} = 9296485.71$$

Calculate the cost of redecking in year 10.

$$deck\_10year = Present\_deckcost \times \left(1 + \frac{0.04}{12}\right)^{12\times10} \qquad deck\_10year = 8141427.2$$

Calculate the cost of option #12.

$$Cost_{opt12} = present\_mill + deck\_10year \times \left(1 + \frac{0.12}{12}\right)^{-12\times10} - Final_{val12} \times \left(1 + \frac{0.12}{12}\right)^{-12\times20}$$

$$Cost_{opt12} = 1989381.43$$

Option 13 - Perform mill and patch repairs now. Perform mill and patch repairs again once the deck deteriorates back to Rmin=4.

Calculate the final value of the deck at the end of the analysis period. The decks condition rating goes up 1/4 point in year 10 due to the mill and patch repairs.

$$R_{final13} = 4.25 - 10 \times slope\_5\_4 \qquad R_{final13} = 3.47$$

Since this final rating is less than 4, option 13 doesn't last long enough (DLLE in the spreadsheet)

Option 14 - Perform mill and patch repairs now. Reoverlay once the deck deteriorates back to Rmin=4.

Calculate the final value of the deck at the end of the analysis period. The decks condition rating goes up 1/2 point in year 10 due to the reoverlaying.

$R_{final14} = 4.5 - 10 \times slope\_5\_4$ $\qquad R_{final14} = 3.72$

Since this final rating is less than 4, option 14 doesn't last long enough (DLLE in the spreadsheet)

Option 15 - Let the deck deteriorate to Rmin=4, then perform mill and patch repairs, and perform no secondary repair/replacement actions provided the deck's condition stays above Rmin=4 for entire analysis period.

Since the effect of mill and patch repairs on the deck is 1/2 that of reoverlaying (a 1/2 point increase) it is obvious that this option will not last long enough since option 7 did not last long enough.

Option 16 - Let the deck deteriorate to Rmin=4, then perform mill and patch repairs. Redeck once the deck again deteriorates to Rmin=4.

This option is very similar to option 8. Calculate the cost of mill and patch repairs in 3 years.

$$mill\_3year = 0.2 \times deck\_area \times \frac{30}{ft^2} \times \left(1 + \frac{0.04}{12}\right)^{3\times12} \qquad mill\_3year = 565203.8$$

Determine how many years the deck takes to deteriorate back to 4. The decks condition rating goes up 1/2 point in year 3 due to the mill and patch repairs.

$$YearsTo4\_opt16 = \frac{0.5}{slope\_5\_4} \qquad YearsTo4\_opt16 = 6.43$$

Round this to 6 years.

Calculate the final value of the deck at the end of the analysis period. The decks condition goes to 9 in year 9 due to the redecking.

It takes 8.7 years to deteriorate to 7

$R_{final16} = 7 - (11 - 8.69662) \times slope\_7\_6$ $\qquad R_{final16} = 6.81$

$$Final_{val16} = \frac{R_{final16}}{9} \times deck\_20year \qquad Final_{val16} = 9186159.83$$

Calculate the cost of redecking in 9 years.

$$deck\_9year = Present\_deckcost \times \left(1 + \frac{0.04}{12}\right)^{12\times9} \qquad deck\_9year = 7822717.62$$

Calculate the cost of option 16.

$$Cost_{opt16} = mill\_3year \times \left(1 + \frac{0.12}{12}\right)^{-3\times12} + deck\_9year \times \left(1 + \frac{0.12}{12}\right)^{-9\times12} \ldots$$
$$+ -Final_{val16} \times \left(1 + \frac{0.12}{12}\right)^{-12\times20}$$

$Cost_{opt16} = 2222540.64$

<u>Option 17 - Let the deck deteriorate to Rmin=4, then perform mill and patch repairs. Perform mill and patch repairs again once the deck deteriorates back to Rmin=4.</u>

Calculate the final value of the deck at the end of the analysis period. The decks condition goes up by 1/4 point in year 9 due to mill and patch repairs.

$Final_{val17} = 4.25 - 11 \times slope\_5\_4 \quad Final_{val17} = 3.39$

Since this final rating is less than 4, option 17 doesn't last long enough.

<u>Option 18 - Let the deck deteriorate to Rmin=4, then perform mill and patch repairs. Reoverlay once the deck deteriorates back to Rmin=4.</u>

Calculate the value of the deck at the end of the analysis period. The decks condition goes up by 1/2 point in year 9 due to reoverlaying.

$Final_{val18} = 4.5 - 11 \times slope\_5\_4 \qquad Final_{val18} = 3.64$

Since this final rating is less than 4, option 18 doesn't last long enough.

<u>Determining the least cost option for this bridge</u>

A quick comparison of the above calculated costs for all relevant repair/replacement strategy options reveals that option 9 is the least cost option for this bridge based on the input assumptions and data specified at the beginning of the example.

Appendix C

Statistical Analysis Output from Minitab

C.1 Definition of Variables Used In the Statistical Analysis:

Note: Numbers in a variable definition refers to the grouping of the variable, for instance ADT 2 is the second grouping of ADT that was tried.

Material Type:

1	concrete
2	prestressed concrete / post tension concrete
3	steel

Continuity:

1	simple
2	continuous

Old vs. New:

1	if year deck protection added – year built ≤ 3
2	else (bridges with overlays placed significantly later)

ADT 2

1	$\leq$ 20000 cars per day
2	> 20000 cars per day

Overall Structure Length 5:

1	$\leq$ 200 feet
2	$200 < L \leq 300$ feet
3	> 300 feet

Age 4:

1	$\leq$ 1955
2	>1955

Truck Traffic (% of ADT): (truck traffic 1 to 4)

1	0 – 5%
2	6 – 10%
3	11 – 15%
4	>15%

Skew 1

1	skew $\leq 10°$
2	skew $> 10°$

Length of max span 2

1	length $\leq$ 100 feet
2	length > 100 feet

District

Same as actual districts, 1-8

Deck Width 2

1	width ≤ 60 feet
2	width > 60 feet

Material Grouping

1	cast in place concrete
2	steel or prestressed concrete

Lag from Overlay Date 2

1	1981 or 1980
2	1979 or 1978
3	1977 or 1976
4	1975 or 1974

Bar Type

1	bare bars
2	epoxy coated bars

C.2 Descriptive Statistics for Complete data set:

Descriptive Statistics: individual deterioration rate

Variable	old or new	N	N*	Mean	SE Mean	StDev	Minimum
individual deter	1	140	0	0.06350	0.00483	0.05713	0.000000000
	2	352	0	0.08177	0.00496	0.09303	0.000000000

Variable	old or new	Q1	Median	Q3	Maximum
individual deter	1	0.000000000	0.04762	0.09524	0.23077
	2	0.04762	0.04762	0.09524	0.80000

Descriptive Statistics: individual deterioration rate

Variable	age 4	N	N*	Mean	SE Mean	StDev	Minimum
individual deter	1	43	0	0.1264	0.0223	0.1461	0.000000000
	2	449	0	0.07180	0.00353	0.07488	0.000000000

Variable	age 4	Q1	Median	Q3	Maximum
individual deter	1	0.0476	0.0526	0.1429	0.6667
	2	0.04762	0.04762	0.09524	0.80000

Descriptive Statistics: individual deterioration rate

Variable	material type	N	N*	Mean	SE Mean	StDev	Minimum
individual deter	1	35	0	0.1319	0.0251	0.1486	0.000000000
	2	206	0	0.06487	0.00459	0.06593	0.000000000
	3	251	0	0.07845	0.00528	0.08359	0.000000000

Variable	material type	Q1	Median	Q3	Maximum
individual deter	1	0.0476	0.0476	0.1765	0.6667
	2	0.000000000	0.04762	0.09524	0.50000
	3	0.04762	0.04762	0.09524	0.80000

Descriptive Statistics: individual deterioration rate

Variable	Overall structure length 5	N	N*	Mean	SE Mean	StDev	Minimum
individual deter	1	240	0	0.07235	0.00517	0.08013	0.000000000
	2	123	0	0.06567	0.00561	0.06224	0.000000000
	3	129	0	0.09483	0.00939	0.10664	0.000000000

Variable	Overall structure length 5	Q1	Median	Q3	Maximum
individual deter	1	0.04762	0.04762	0.09524	0.66667
	2	0.04762	0.04762	0.09524	0.33333
	3	0.04762	0.04762	0.11806	0.80000

Descriptive Statistics: individual deterioration rate

Variable	length_of_max 2	N	N*	Mean	SE Mean	StDev
individual deter	1	370	0	0.07027	0.00407	0.07827
	2	122	0	0.09567	0.00904	0.09980

Variable	length_of_max 2	Minimum	Q1	Median	Q3
individual deter	1	0.000000000	0.03571	0.04762	0.09524
	2	0.000000000	0.04762	0.05882	0.10526

Variable	length_of_max 2	Maximum
individual deter	1	0.66667
	2	0.80000

Descriptive Statistics: individual deterioration rate

Variable	district	N	N*	Mean	SE Mean	StDev	Minimum
individual deter	1	71	0	0.06174	0.00875	0.07374	0.000000000
	2	12	0	0.1236	0.0166	0.0574	0.0476
	3	53	0	0.07835	0.00726	0.05289	0.000000000
	4	26	0	0.0737	0.0124	0.0634	0.000000000
	5	182	0	0.08299	0.00672	0.09062	0.000000000
	6	85	0	0.0952	0.0121	0.1113	0.000000000
	7	38	0	0.05301	0.00992	0.06112	0.000000000
	8	25	0	0.02095	0.00555	0.02777	0.000000000

Variable	district	Q1	Median	Q3	Maximum
individual deter	1	0.000000000	0.04762	0.04762	0.33333
	2	0.0952	0.0952	0.1538	0.2308
	3	0.04762	0.05263	0.09524	0.23810
	4	0.0476	0.0476	0.0952	0.2500
	5	0.04762	0.04762	0.09524	0.80000
	6	0.0476	0.0476	0.1000	0.6667
	7	0.000000000	0.04762	0.09524	0.20000
	8	0.000000000	0.000000000	0.04762	0.09524

Descriptive Statistics: individual deterioration rate

Variable	ADT 2	N	N*	Mean	SE Mean	StDev	Minimum
individual deter	1	373	0	0.07146	0.00402	0.07757	0.000000000
	2	119	0	0.09258	0.00942	0.10276	0.000000000

Variable	ADT 2	Q1	Median	Q3	Maximum
individual deter	1	0.04762	0.04762	0.09524	0.66667
	2	0.04762	0.04762	0.11111	0.80000

Descriptive Statistics: individual deterioration rate

Variable	Bar type	N	N*	Mean	SE Mean	StDev	Minimum
individual deter	1	350	0	0.07983	0.00484	0.09052	0.000000000
	2	142	0	0.06853	0.00571	0.06800	0.000000000

Variable	Bar type	Q1	Median	Q3	Maximum
individual deter	1	0.04762	0.04762	0.09524	0.80000
	2	0.04762	0.04762	0.09524	0.50000

Descriptive Statistics: individual deterioration rate

Variable	lag from overlay date 2	N	N*	Mean	SE Mean	StDev	Minimum
individual deter	1	162	0	0.07280	0.00459	0.05848	0.000000000
	2	182	0	0.06788	0.00503	0.06782	0.000000000
	3	112	0	0.06834	0.00642	0.06796	0.000000000
	4	36	0	0.1631	0.0326	0.1954	0.000000000

Variable	lag from overlay date 2	Q1	Median	Q3	Maximum
individual deter	1	0.04762	0.04762	0.09524	0.30000
	2	0.000000000	0.04762	0.09524	0.33333
	3	0.000000000	0.04762	0.09524	0.30000
	4	0.0476	0.0976	0.1482	0.8000

Descriptive Statistics: individual deterioration rate

Variable	deck_width 2	N	N*	Mean	SE Mean	StDev	Minimum
individual deter	1	395	0	0.07289	0.00385	0.07657	0.000000000
	2	97	0	0.0916	0.0113	0.1112	0.000000000

Variable	deck_width 2	Q1	Median	Q3	Maximum
individual deter	1	0.04762	0.04762	0.09524	0.66667
	2	0.0476	0.0476	0.1082	0.8000

Descriptive Statistics: individual deterioration rate

Variable	skew 1	N	N*	Mean	SE Mean	StDev	Minimum
individual deter	1	257	0	0.08208	0.00548	0.08783	0.000000000
	2	235	0	0.07054	0.00528	0.08095	0.000000000

Variable	skew 1	Q1	Median	Q3	Maximum
individual deter	1	0.04762	0.04762	0.09524	0.66667
	2	0.04762	0.04762	0.09524	0.80000

Descriptive Statistics: individual deterioration rate

Variable	continuity	N	N*	Mean	SE Mean	StDev	Minimum
individual deter	1	271	0	0.07269	0.00504	0.08291	0.000000000
	2	221	0	0.08133	0.00584	0.08685	0.000000000

Variable	continuity	Q1	Median	Q3	Maximum
individual deter	1	0.04762	0.04762	0.09524	0.66667
	2	0.04762	0.04762	0.09524	0.80000

Descriptive Statistics: individual deterioration rate

average
daily
truck

Variable	traffic 1 t	N	N*	Mean	SE Mean	StDev	Minimum
individual deter	1	175	0	0.08558	0.00749	0.09905	0.000000000
	2	167	0	0.07029	0.00572	0.07393	0.000000000
	3	84	0	0.07275	0.00942	0.08634	0.000000000
	4	66	0	0.07345	0.00792	0.06431	0.000000000

Variable	average daily truck traffic 1 t	Q1	Median	Q3	Maximum
individual deter	1	0.04762	0.04762	0.09524	0.80000
	2	0.04762	0.04762	0.09524	0.50000
	3	0.04762	0.04762	0.09524	0.66667
	4	0.04762	0.04762	0.09524	0.25000

C.3 ANOVA analysis and Tukey's Method for Complete data set:

General Linear Model: individual deterioration rate versus continuity

```
Factor      Type   Levels  Values
continuity  fixed       2  1, 2


Analysis of Variance for individual deterioration rate, using Adjusted SS for
     Tests

Source       DF    Seq SS    Adj SS    Adj MS     F      P
continuity    1  0.009100  0.009100  0.009100  1.27  0.261
Error       490  3.515592  3.515592  0.007175
Total       491  3.524692


S = 0.0847035   R-Sq = 0.26%   R-Sq(adj) = 0.05%


Unusual Observations for individual deterioration rate

        individual
     deterioration
Obs           rate       Fit    SE Fit  Residual  St Resid
 56       0.333333  0.081334  0.005698  0.251999      2.98 R
 59       0.300000  0.081334  0.005698  0.218666      2.59 R
106       0.300000  0.072688  0.005145  0.227312      2.69 R
131       0.300000  0.072688  0.005145  0.227312      2.69 R
143       0.285714  0.081334  0.005698  0.204380      2.42 R
149       0.666667  0.072688  0.005145  0.593979      7.03 R
150       0.500000  0.072688  0.005145  0.427312      5.05 R
155       0.800000  0.081334  0.005698  0.718666      8.50 R
156       0.333333  0.081334  0.005698  0.251999      2.98 R
179       0.272727  0.072688  0.005145  0.200039      2.37 R
185       0.300000  0.072688  0.005145  0.227312      2.69 R
213       0.285714  0.081334  0.005698  0.204380      2.42 R
218       0.333333  0.081334  0.005698  0.251999      2.98 R
300       0.333333  0.081334  0.005698  0.251999      2.98 R
315       0.400000  0.072688  0.005145  0.327312      3.87 R
335       0.315789  0.081334  0.005698  0.234455      2.77 R
453       0.500000  0.072688  0.005145  0.427312      5.05 R
457       0.250000  0.072688  0.005145  0.177312      2.10 R

R denotes an observation with a large standardized residual.


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of continuity
continuity = 1  subtracted from:

continuity      Lower    Center    Upper
2           -0.006438  0.008646  0.02373

continuity  ------+---------+---------+---------+
2           (--------------*--------------)
            ------+---------+---------+---------+
                0.000     0.010     0.020     0.030
```

Tukey Simultaneous Tests
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of continuity
continuity = 1 subtracted from:

continuity	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	0.008646	0.007677	1.126	0.2601

General Linear Model: individual deter versus average daily truck traffic 1 to 4

Factor	Type	Levels	Values
average daily truck traffic 1 t	fixed	4	1, 2, 3, 4

Analysis of Variance for individual deterioration rate, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
average daily truck traffic 1 t	3	0.022645	0.022645	0.007548	1.05	0.369
Error	488	3.502047	3.502047	0.007176		
Total	491	3.524692				

S = 0.0847132   R-Sq = 0.64%   R-Sq(adj) = 0.03%

Unusual Observations for individual deterioration rate

Obs	individual deterioration rate	Fit	SE Fit	Residual	St Resid
7	0.250000	0.073451	0.010427	0.176549	2.10 R
56	0.333333	0.085576	0.006404	0.247757	2.93 R
59	0.300000	0.085576	0.006404	0.214424	2.54 R
106	0.300000	0.085576	0.006404	0.214424	2.54 R
131	0.300000	0.070293	0.006555	0.229707	2.72 R
143	0.285714	0.085576	0.006404	0.200138	2.37 R
149	0.666667	0.072748	0.009243	0.593919	7.05 R
150	0.500000	0.070293	0.006555	0.429707	5.09 R
155	0.800000	0.085576	0.006404	0.714424	8.46 R
156	0.333333	0.085576	0.006404	0.247757	2.93 R
179	0.272727	0.072748	0.009243	0.199979	2.37 R
185	0.300000	0.085576	0.006404	0.214424	2.54 R
213	0.285714	0.070293	0.006555	0.215422	2.55 R
218	0.333333	0.070293	0.006555	0.263041	3.11 R
255	0.250000	0.070293	0.006555	0.179707	2.13 R
300	0.333333	0.070293	0.006555	0.263041	3.11 R
315	0.400000	0.085576	0.006404	0.314424	3.72 R
335	0.315789	0.085576	0.006404	0.230213	2.73 R
453	0.500000	0.085576	0.006404	0.414424	4.91 R
457	0.250000	0.070293	0.006555	0.179707	2.13 R

R denotes an observation with a large standardized residual.

Tukey 95.0% Simultaneous Confidence Intervals
Response Variable individual deterioration rate

```
All Pairwise Comparisons among Levels of average daily truck traffic 1 t
average daily truck traffic 1 t = 1  subtracted from:

average
daily
truck
traffic
1 t          Lower    Center     Upper  -------+---------+---------+---------
2        -0.03881  -0.01528  0.008239   (---------*--------)
3        -0.04169  -0.01283  0.016034  (-----------*----------)
4        -0.04353  -0.01213  0.019284  (-----------*------------)
                                        -------+---------+---------+---------
                                            -0.025     0.000     0.025


average daily truck traffic 1 t = 2  subtracted from:

average
daily
truck
traffic
1 t          Lower    Center    Upper  -------+---------+---------+---------
3        -0.02663  0.002455  0.03154        (-----------*-----------)
4        -0.02846  0.003158  0.03477        (-----------*------------)
                                       -------+---------+---------+---------
                                           -0.025     0.000     0.025


average daily truck traffic 1 t = 3  subtracted from:

average
daily
truck
traffic
1 t          Lower    Center    Upper  -------+---------+---------+---------
4        -0.03506  0.000703  0.03647     (-------------*--------------)
                                       -------+---------+---------+---------
                                           -0.025     0.000     0.025


Tukey Simultaneous Tests
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of average daily truck traffic 1 t
average daily truck traffic 1 t = 1  subtracted from:

average
daily
truck
traffic  Difference       SE of           Adjusted
1 t        of Means  Difference  T-Value   P-Value
2          -0.01528    0.009164   -1.668    0.3408
3          -0.01283    0.011245   -1.141    0.6642
4          -0.01213    0.012237   -0.991    0.7546


average daily truck traffic 1 t = 2  subtracted from:

average
daily
truck
traffic  Difference       SE of           Adjusted
1 t        of Means  Difference  T-Value   P-Value
3          0.002455     0.01133   0.2167    0.9964
```

4	0.003158	0.01232	0.2564	0.9941

average daily truck traffic 1 t = 3 subtracted from:

average daily truck traffic 1 t	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
4	0.000703	0.01393	0.05045	1.000

General Linear Model: individual deterioration rate versus skew 1

Factor	Type	Levels	Values
skew 1	fixed	2	1, 2

Analysis of Variance for individual deterioration rate, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
skew 1	1	0.016350	0.016350	0.016350	2.28	0.131
Error	490	3.508342	3.508342	0.007160		
Total	491	3.524692				

S = 0.0846161   R-Sq = 0.46%   R-Sq(adj) = 0.26%

Unusual Observations for individual deterioration rate

Obs	individual deterioration rate	Fit	SE Fit	Residual	St Resid	
56	0.333333	0.082084	0.005278	0.251249	2.98	R
59	0.300000	0.070543	0.005520	0.229457	2.72	R
106	0.300000	0.082084	0.005278	0.217916	2.58	R
131	0.300000	0.070543	0.005520	0.229457	2.72	R
143	0.285714	0.082084	0.005278	0.203630	2.41	R
149	0.666667	0.082084	0.005278	0.584582	6.92	R
150	0.500000	0.082084	0.005278	0.417916	4.95	R
155	0.800000	0.070543	0.005520	0.729457	8.64	R
156	0.333333	0.082084	0.005278	0.251249	2.98	R
179	0.272727	0.070543	0.005520	0.202184	2.39	R
185	0.300000	0.070543	0.005520	0.229457	2.72	R
213	0.285714	0.082084	0.005278	0.203630	2.41	R
218	0.333333	0.082084	0.005278	0.251249	2.98	R
300	0.333333	0.082084	0.005278	0.251249	2.98	R
315	0.400000	0.070543	0.005520	0.329457	3.90	R
335	0.315789	0.082084	0.005278	0.233705	2.77	R
453	0.500000	0.082084	0.005278	0.417916	4.95	R
457	0.250000	0.070543	0.005520	0.179457	2.13	R

R denotes an observation with a large standardized residual.

Tukey 95.0% Simultaneous Confidence Intervals
Response Variable individual deterioration rate

```
All Pairwise Comparisons among Levels of skew 1
skew 1 = 1  subtracted from:

skew
1         Lower    Center     Upper  -------+---------+---------+---------
2      -0.02655  -0.01154  0.003465  (--------------*--------------)
                                     -------+---------+---------+---------
                                        -0.020    -0.010     0.000
```

```
Tukey Simultaneous Tests
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of skew 1
skew 1 = 1  subtracted from:
```

skew 1	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	-0.01154	0.007637	-1.511	0.1308

General Linear Model: individual deterioration rate versus old or new

Factor	Type	Levels	Values
old or new	fixed	2	1, 2

Analysis of Variance for individual deterioration rate, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
old or new	1	0.033432	0.033432	0.033432	4.69	0.031
Error	490	3.491260	3.491260	0.007125		
Total	491	3.524692				

S = 0.0844098   R-Sq = 0.95%   R-Sq(adj) = 0.75%

Unusual Observations for individual deterioration rate

Obs	individual deterioration rate	Fit	SE Fit	Residual	St Resid
2	0.500000	0.081770	0.004499	0.418230	4.96 R
12	0.666667	0.081770	0.004499	0.584896	6.94 R
18	0.272727	0.081770	0.004499	0.190957	2.27 R
28	0.315789	0.081770	0.004499	0.234019	2.78 R
32	0.333333	0.081770	0.004499	0.251563	2.98 R
33	0.333333	0.081770	0.004499	0.251563	2.98 R
45	0.300000	0.081770	0.004499	0.218230	2.59 R
56	0.300000	0.081770	0.004499	0.218230	2.59 R
72	0.400000	0.081770	0.004499	0.318230	3.78 R
105	0.333333	0.081770	0.004499	0.251563	2.98 R
117	0.800000	0.081770	0.004499	0.718230	8.52 R
163	0.285714	0.081770	0.004499	0.203944	2.42 R
189	0.300000	0.081770	0.004499	0.218230	2.59 R
225	0.333333	0.081770	0.004499	0.251563	2.98 R
279	0.285714	0.081770	0.004499	0.203944	2.42 R
388	0.500000	0.081770	0.004499	0.418230	4.96 R
406	0.300000	0.081770	0.004499	0.218230	2.59 R

```
R denotes an observation with a large standardized residual.


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of old or new
old or new = 1  subtracted from:

old
or
new     Lower   Center    Upper  --------+---------+---------+--------
2    0.001698  0.01827  0.03484  (---------------*----------------)
                                 --------+---------+---------+--------
                                       0.010     0.020     0.030


Tukey Simultaneous Tests
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of old or new
old or new = 1  subtracted from:

old
or   Difference       SE of           Adjusted
new    of Means  Difference  T-Value   P-Value
2       0.01827    0.008434    2.166    0.0303
```

General Linear Model: individual deterioration rate versus age 4

```
Factor  Type   Levels  Values
age 4   fixed       2  1, 2


Analysis of Variance for individual deterioration rate, using Adjusted SS for
     Tests

Source   DF   Seq SS   Adj SS   Adj MS      F      P
age 4     1  0.11695  0.11695  0.11695  16.82  0.000
Error   490  3.40774  3.40774  0.00695
Total   491  3.52469


S = 0.0833941   R-Sq = 3.32%   R-Sq(adj) = 3.12%


Unusual Observations for individual deterioration rate

        individual
     deterioration
Obs           rate       Fit    SE Fit   Residual  St Resid
  1       0.047619  0.126393  0.012717  -0.078774     -0.96  X
  2       0.500000  0.126393  0.012717   0.373607      4.53 RX
  3       0.047619  0.126393  0.012717  -0.078774     -0.96  X
  4       0.047619  0.126393  0.012717  -0.078774     -0.96  X
  5       0.000000  0.126393  0.012717  -0.126393     -1.53  X
  6       0.047619  0.126393  0.012717  -0.078774     -0.96  X
  8       0.133333  0.126393  0.012717   0.006941      0.08  X
  9       0.047619  0.126393  0.012717  -0.078774     -0.96  X
 10       0.047619  0.126393  0.012717  -0.078774     -0.96  X
 11       0.238095  0.126393  0.012717   0.111703      1.36  X
 12       0.666667  0.126393  0.012717   0.540274      6.56 RX
 13       0.095238  0.126393  0.012717  -0.031155     -0.38  X
 14       0.000000  0.126393  0.012717  -0.126393     -1.53  X
```

15	0.100000	0.126393	0.012717	-0.026393	-0.32	X
16	0.047619	0.126393	0.012717	-0.078774	-0.96	X
17	0.047619	0.126393	0.012717	-0.078774	-0.96	X
18	0.272727	0.126393	0.012717	0.146335	1.78	X
19	0.047619	0.126393	0.012717	-0.078774	-0.96	X
20	0.142857	0.126393	0.012717	0.016465	0.20	X
21	0.000000	0.126393	0.012717	-0.126393	-1.53	X
23	0.200000	0.126393	0.012717	0.073607	0.89	X
28	0.315789	0.071800	0.003936	0.243989	2.93	R
32	0.333333	0.071800	0.003936	0.261533	3.14	R
33	0.333333	0.071800	0.003936	0.261533	3.14	R
39	0.100000	0.126393	0.012717	-0.026393	-0.32	X
41	0.000000	0.126393	0.012717	-0.126393	-1.53	X
45	0.300000	0.126393	0.012717	0.173607	2.11	RX
47	0.100000	0.126393	0.012717	-0.026393	-0.32	X
48	0.047619	0.126393	0.012717	-0.078774	-0.96	X
49	0.000000	0.126393	0.012717	-0.126393	-1.53	X
53	0.150000	0.126393	0.012717	0.023607	0.29	X
54	0.142857	0.126393	0.012717	0.016465	0.20	X
56	0.300000	0.126393	0.012717	0.173607	2.11	RX
58	0.000000	0.126393	0.012717	-0.126393	-1.53	X
62	0.142857	0.126393	0.012717	0.016465	0.20	X
64	0.250000	0.126393	0.012717	0.123607	1.50	X
70	0.047619	0.126393	0.012717	-0.078774	-0.96	X
71	0.052632	0.126393	0.012717	-0.073761	-0.89	X
72	0.400000	0.071800	0.003936	0.328200	3.94	R
74	0.095238	0.126393	0.012717	-0.031155	-0.38	X
75	0.000000	0.126393	0.012717	-0.126393	-1.53	X
78	0.142857	0.126393	0.012717	0.016465	0.20	X
79	0.047619	0.126393	0.012717	-0.078774	-0.96	X
94	0.047619	0.126393	0.012717	-0.078774	-0.96	X
103	0.142857	0.126393	0.012717	0.016465	0.20	X
105	0.333333	0.071800	0.003936	0.261533	3.14	R
117	0.800000	0.071800	0.003936	0.728200	8.74	R
158	0.250000	0.071800	0.003936	0.178200	2.14	R
163	0.285714	0.071800	0.003936	0.213914	2.57	R
189	0.300000	0.071800	0.003936	0.228200	2.74	R
222	0.250000	0.071800	0.003936	0.178200	2.14	R
225	0.333333	0.071800	0.003936	0.261533	3.14	R
242	0.250000	0.071800	0.003936	0.178200	2.14	R
279	0.285714	0.071800	0.003936	0.213914	2.57	R
375	0.047619	0.126393	0.012717	-0.078774	-0.96	X
388	0.500000	0.126393	0.012717	0.373607	4.53	RX
406	0.300000	0.071800	0.003936	0.228200	2.74	R

R denotes an observation with a large standardized residual.
X denotes an observation whose X value gives it large influence.

Tukey 95.0% Simultaneous Confidence Intervals
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of age 4
age 4 = 1 subtracted from:

```
age 4     Lower    Center     Upper   --+---------+---------+---------+----
2      -0.08075  -0.05459  -0.02844   (---------*----------)
                                      --+---------+---------+---------+----
                                    -0.075    -0.050    -0.025    -0.000
```

Tukey Simultaneous Tests
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of age 4

age 4 = 1 subtracted from:

age 4	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	-0.05459	0.01331	-4.101	0.0000

General Linear Model: individual deterioration rate versus material type

Factor	Type	Levels	Values
material type	fixed	3	1, 2, 3

Analysis of Variance for individual deterioration rate, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
material type	2	0.136423	0.136423	0.068212	9.84	0.000
Error	489	3.388269	3.388269	0.006929		
Total	491	3.524692				

S = 0.0832405 R-Sq = 3.87% R-Sq(adj) = 3.48%

Unusual Observations for individual deterioration rate

Obs	individual deterioration rate	Fit	SE Fit	Residual	St Resid	
1	0.047619	0.131946	0.014070	-0.084327	-1.03	X
2	0.500000	0.131946	0.014070	0.368054	4.49	RX
3	0.047619	0.131946	0.014070	-0.084327	-1.03	X
4	0.047619	0.131946	0.014070	-0.084327	-1.03	X
5	0.000000	0.131946	0.014070	-0.131946	-1.61	X
6	0.047619	0.131946	0.014070	-0.084327	-1.03	X
7	0.047619	0.131946	0.014070	-0.084327	-1.03	X
8	0.133333	0.131946	0.014070	0.001387	0.02	X
9	0.047619	0.131946	0.014070	-0.084327	-1.03	X
10	0.047619	0.131946	0.014070	-0.084327	-1.03	X
11	0.238095	0.131946	0.014070	0.106149	1.29	X
12	0.666667	0.131946	0.014070	0.534720	6.52	RX
13	0.095238	0.131946	0.014070	-0.036708	-0.45	X
14	0.000000	0.131946	0.014070	-0.131946	-1.61	X
15	0.100000	0.131946	0.014070	-0.031946	-0.39	X
16	0.047619	0.131946	0.014070	-0.084327	-1.03	X
17	0.047619	0.131946	0.014070	-0.084327	-1.03	X
18	0.272727	0.131946	0.014070	0.140781	1.72	X
19	0.047619	0.131946	0.014070	-0.084327	-1.03	X
20	0.142857	0.131946	0.014070	0.010911	0.13	X
21	0.000000	0.131946	0.014070	-0.131946	-1.61	X
22	0.000000	0.131946	0.014070	-0.131946	-1.61	X
23	0.200000	0.131946	0.014070	0.068054	0.83	X
24	0.176471	0.131946	0.014070	0.044524	0.54	X
25	0.095238	0.131946	0.014070	-0.036708	-0.45	X
26	0.047619	0.131946	0.014070	-0.084327	-1.03	X
27	0.047619	0.131946	0.014070	-0.084327	-1.03	X
28	0.315789	0.131946	0.014070	0.183843	2.24	RX
29	0.095238	0.131946	0.014070	-0.036708	-0.45	X
30	0.047619	0.131946	0.014070	-0.084327	-1.03	X
31	0.047619	0.131946	0.014070	-0.084327	-1.03	X
32	0.333333	0.131946	0.014070	0.201387	2.45	RX
33	0.333333	0.131946	0.014070	0.201387	2.45	RX

34	0.095238	0.131946	0.014070	-0.036708	-0.45	X
35	0.157895	0.131946	0.014070	0.025948	0.32	X
45	0.300000	0.078455	0.005254	0.221545	2.67	R
56	0.300000	0.078455	0.005254	0.221545	2.67	R
64	0.250000	0.078455	0.005254	0.171545	2.06	R
72	0.400000	0.078455	0.005254	0.321545	3.87	R
105	0.333333	0.078455	0.005254	0.254879	3.07	R
117	0.800000	0.078455	0.005254	0.721545	8.69	R
158	0.250000	0.078455	0.005254	0.171545	2.06	R
163	0.285714	0.078455	0.005254	0.207260	2.49	R
189	0.300000	0.078455	0.005254	0.221545	2.67	R
222	0.250000	0.078455	0.005254	0.171545	2.06	R
225	0.333333	0.078455	0.005254	0.254879	3.07	R
242	0.250000	0.078455	0.005254	0.171545	2.06	R
279	0.285714	0.078455	0.005254	0.207260	2.49	R
388	0.500000	0.064869	0.005800	0.435131	5.24	R
406	0.300000	0.064869	0.005800	0.235131	2.83	R

R denotes an observation with a large standardized residual.
X denotes an observation whose X value gives it large influence.

Tukey 95.0% Simultaneous Confidence Intervals
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of material type
material type = 1 subtracted from:

```
material
type        Lower    Center     Upper  ------+---------+---------+---------+
2         -0.1027  -0.06708  -0.03146  (--------*--------)
3         -0.0886  -0.05349  -0.01834      (--------*-------)
                                       ------+---------+---------+---------+
                                          -0.080    -0.040     0.000     0.040
```

material type = 2 subtracted from:

```
material
type          Lower   Center    Upper  ------+---------+---------+---------+
3         -0.004731  0.01359  0.03190                          (---*----)
                                       ------+---------+---------+---------+
                                          -0.080    -0.040     0.000     0.040
```

Tukey Simultaneous Tests
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of material type
material type = 1 subtracted from:

material type	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	-0.06708	0.01522	-4.408	0.0000
3	-0.05349	0.01502	-3.562	0.0011

material type = 2 subtracted from:

material type	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
3	0.01359	0.007826	1.736	0.1918

General Linear Model: individual deter versus Overall structure length 5

Factor	Type	Levels	Values
Overall structure length 5	fixed	3	1, 2, 3

Analysis of Variance for individual deterioration rate, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Overall structure length 5	2	0.061924	0.061924	0.030962	4.37	0.013
Error	489	3.462769	3.462769	0.007081		
Total	491	3.524692				

S = 0.0841506   R-Sq = 1.76%   R-Sq(adj) = 1.36%

Unusual Observations for individual deterioration rate

Obs	individual deterioration rate	Fit	SE Fit	Residual	St Resid	
2	0.500000	0.072346	0.005432	0.427654	5.09	R
12	0.666667	0.072346	0.005432	0.594321	7.08	R
18	0.272727	0.072346	0.005432	0.200382	2.39	R
28	0.315789	0.094832	0.007409	0.220958	2.64	R
32	0.333333	0.094832	0.007409	0.238502	2.85	R
33	0.333333	0.094832	0.007409	0.238502	2.85	R
45	0.300000	0.072346	0.005432	0.227654	2.71	R
56	0.300000	0.072346	0.005432	0.227654	2.71	R
64	0.250000	0.072346	0.005432	0.177654	2.12	R
72	0.400000	0.072346	0.005432	0.327654	3.90	R
105	0.333333	0.065667	0.007588	0.267666	3.19	R
117	0.800000	0.094832	0.007409	0.705168	8.41	R
163	0.285714	0.065667	0.007588	0.220047	2.63	R
189	0.300000	0.072346	0.005432	0.227654	2.71	R
225	0.333333	0.094832	0.007409	0.238502	2.85	R
242	0.250000	0.065667	0.007588	0.184333	2.20	R
279	0.285714	0.094832	0.007409	0.190883	2.28	R
388	0.500000	0.094832	0.007409	0.405168	4.83	R
406	0.300000	0.072346	0.005432	0.227654	2.71	R

R denotes an observation with a large standardized residual.

Tukey 95.0% Simultaneous Confidence Intervals
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of Overall structure length 5
Overall structure length 5 = 1 subtracted from:

Overall structure length 5	Lower	Center	Upper
2	-0.02852	-0.006678	0.01516
3	0.00098	0.022486	0.04399

```
Overall
structure
length 5     -+---------+---------+---------+-----
2            (-------*--------)
3                       (--------*--------)
             -+---------+---------+---------+-----
```

```
           -0.025     0.000     0.025     0.050


Overall structure length 5 = 2  subtracted from:

Overall
structure
length 5      Lower   Center    Upper    -+---------+---------+---------+-----
3          0.004343  0.02916  0.05399                (---------*---------)
                                         -+---------+---------+---------+-----
                                       -0.025     0.000     0.025     0.050


Tukey Simultaneous Tests
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of Overall structure length 5
Overall structure length 5 = 1  subtracted from:

Overall
structure  Difference       SE of           Adjusted
length 5     of Means  Difference  T-Value   P-Value
2           -0.006678    0.009332  -0.7157    0.7542
3            0.022486    0.009187   2.4476    0.0382


Overall structure length 5 = 2  subtracted from:

Overall
structure  Difference       SE of           Adjusted
length 5     of Means  Difference  T-Value   P-Value
3             0.02916     0.01060    2.750    0.0164
```

General Linear Model: individual deter versus length_of_max 2

```
Factor           Type   Levels  Values
length_of_max 2  fixed       2  1, 2


Analysis of Variance for individual deterioration rate, using Adjusted SS for
     Tests

Source            DF    Seq SS    Adj SS    Adj MS     F      P
length_of_max 2    1  0.059183  0.059183  0.059183  8.37  0.004
Error            490  3.465509  3.465509  0.007072
Total            491  3.524692


S = 0.0840980   R-Sq = 1.68%   R-Sq(adj) = 1.48%


Unusual Observations for individual deterioration rate

        individual
     deterioration
Obs           rate       Fit    SE Fit  Residual  St Resid
  2       0.500000  0.070274  0.004372  0.429726      5.12 R
 12       0.666667  0.070274  0.004372  0.596393      7.10 R
 18       0.272727  0.070274  0.004372  0.202453      2.41 R
 28       0.315789  0.095672  0.007614  0.220118      2.63 R
 32       0.333333  0.070274  0.004372  0.263059      3.13 R
 33       0.333333  0.095672  0.007614  0.237661      2.84 R
 45       0.300000  0.070274  0.004372  0.229726      2.74 R
```

56	0.300000	0.070274	0.004372	0.229726	2.74 R
64	0.250000	0.070274	0.004372	0.179726	2.14 R
72	0.400000	0.070274	0.004372	0.329726	3.93 R
105	0.333333	0.070274	0.004372	0.263059	3.13 R
117	0.800000	0.095672	0.007614	0.704328	8.41 R
158	0.250000	0.070274	0.004372	0.179726	2.14 R
163	0.285714	0.095672	0.007614	0.190042	2.27 R
189	0.300000	0.070274	0.004372	0.229726	2.74 R
222	0.250000	0.070274	0.004372	0.179726	2.14 R
225	0.333333	0.070274	0.004372	0.263059	3.13 R
279	0.285714	0.070274	0.004372	0.215440	2.57 R
388	0.500000	0.095672	0.007614	0.404328	4.83 R
406	0.300000	0.070274	0.004372	0.229726	2.74 R

R denotes an observation with a large standardized residual.

Tukey 95.0% Simultaneous Confidence Intervals
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of length_of_max 2
length_of_max 2 = 1 subtracted from:

length_of_max 2	Lower	Center	Upper
2	0.008147	0.02540	0.04265

```
length_of_max 2  --+---------+---------+---------+----
2                (----------------*-----------------)
                 --+---------+---------+---------+----
                 0.010     0.020     0.030     0.040
```

Tukey Simultaneous Tests
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of length_of_max 2
length_of_max 2 = 1 subtracted from:

length_of_max 2	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	0.02540	0.008780	2.893	0.0038

General Linear Model: individual deterioration rate versus district

Factor	Type	Levels	Values
district	fixed	8	1, 2, 3, 4, 5, 6, 7, 8

Analysis of Variance for individual deterioration rate, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
district	7	0.178096	0.178096	0.025442	3.68	0.001
Error	484	3.346596	3.346596	0.006914		
Total	491	3.524692				

S = 0.0831532   R-Sq = 5.05%   R-Sq(adj) = 3.68%

Unusual Observations for individual deterioration rate

individual
deterioration

Obs	rate	Fit	SE Fit	Residual	St Resid	
2	0.500000	0.095231	0.009019	0.404769	4.90	R
12	0.666667	0.095231	0.009019	0.571436	6.91	R
18	0.272727	0.095231	0.009019	0.177497	2.15	R
28	0.315789	0.082990	0.006164	0.232799	2.81	R
32	0.333333	0.082990	0.006164	0.250343	3.02	R
33	0.333333	0.082990	0.006164	0.250343	3.02	R
45	0.300000	0.095231	0.009019	0.204769	2.48	R
56	0.300000	0.095231	0.009019	0.204769	2.48	R
64	0.250000	0.082990	0.006164	0.167010	2.01	R
72	0.400000	0.082990	0.006164	0.317010	3.82	R
105	0.333333	0.082990	0.006164	0.250343	3.02	R
115	0.095238	0.123626	0.024004	-0.028388	-0.36	X
117	0.800000	0.082990	0.006164	0.717010	8.65	R
139	0.095238	0.123626	0.024004	-0.028388	-0.36	X
140	0.095238	0.123626	0.024004	-0.028388	-0.36	X
158	0.250000	0.073718	0.016308	0.176282	2.16	R
163	0.285714	0.082990	0.006164	0.202724	2.44	R
189	0.300000	0.082990	0.006164	0.217010	2.62	R
222	0.250000	0.061741	0.009868	0.188259	2.28	R
225	0.333333	0.061741	0.009868	0.271593	3.29	R
279	0.285714	0.061741	0.009868	0.223974	2.71	R
292	0.095238	0.123626	0.024004	-0.028388	-0.36	X
296	0.095238	0.123626	0.024004	-0.028388	-0.36	X
297	0.153846	0.123626	0.024004	0.030220	0.38	X
300	0.095238	0.123626	0.024004	-0.028388	-0.36	X
302	0.230769	0.123626	0.024004	0.107143	1.35	X
303	0.230769	0.123626	0.024004	0.107143	1.35	X
314	0.047619	0.123626	0.024004	-0.076007	-0.95	X
319	0.153846	0.123626	0.024004	0.030220	0.38	X
388	0.500000	0.095231	0.009019	0.404769	4.90	R
406	0.300000	0.061741	0.009868	0.238259	2.89	R
430	0.095238	0.123626	0.024004	-0.028388	-0.36	X

R denotes an observation with a large standardized residual.
X denotes an observation whose X value gives it large influence.

Tukey 95.0% Simultaneous Confidence Intervals
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of district
district = 1 subtracted from:

```
district     Lower    Center    Upper  ---------+---------+---------+-------
2         -0.01684   0.06189  0.14062                   (-------*-------)
3         -0.02918   0.01661  0.06240                  (----*---)
4         -0.04584   0.01198  0.06980                (-----*-----)
5         -0.01405   0.02125  0.05654                    (--*---)
6         -0.00706   0.03349  0.07405                    (---*---)
7         -0.05943  -0.00873  0.04197               (----*----)
8         -0.09945  -0.04079  0.01787           (-----*-----)
                                       ---------+---------+---------+-------
                                             -0.10      0.00      0.10
```

district = 2 subtracted from:

```
district    Lower   Center     Upper  ---------+---------+---------+-------
3         -0.1259  -0.0453   0.03536      (-------*--------)
4         -0.1379  -0.0499   0.03812     (--------*--------)
5         -0.1158  -0.0406   0.03454       (-------*------)
6         -0.1062  -0.0284   0.04939        (-------*-------)
7         -0.1541  -0.0706   0.01291    (-------*-------)
```

```
8         -0.1913  -0.1027  -0.01409  (--------*--------)
                                      ---------+---------+---------+-------
                                          -0.10      0.00      0.10


district = 3  subtracted from:

district    Lower    Center     Upper  ---------+---------+---------+-------
4         -0.0650  -0.00463  0.055763             (------*-----)
5         -0.0347   0.00464  0.044010                 (--*---)
6         -0.0273   0.01688  0.061027                 (----*---)
7         -0.0790  -0.02534  0.028274            (----*-----)
8         -0.1186  -0.05740  0.003802        (-----*-----)
                                       ---------+---------+---------+-------
                                           -0.10      0.00      0.10


district = 4  subtracted from:

district    Lower    Center    Upper  ---------+---------+---------+-------
5         -0.0436   0.00927  0.06216                (----*----)
6         -0.0350   0.02151  0.07804                (-----*-----)
7         -0.0849  -0.02071  0.04349            (-----*-----)
8         -0.1234  -0.05277  0.01789        (------*------)
                                      ---------+---------+---------+-------
                                          -0.10      0.00      0.10


district = 5  subtracted from:

district    Lower    Center      Upper  ---------+---------+---------+-------
6         -0.0209   0.01224   0.045379                  (--*---)
7         -0.0750  -0.02998   0.015006             (---*----)
8         -0.1158  -0.06204  -0.008235        (-----*----)
                                        ---------+---------+---------+-------
                                            -0.10      0.00      0.10


district = 6  subtracted from:

district    Lower    Center     Upper  ---------+---------+---------+-------
7         -0.0914  -0.04222   0.00700           (----*----)
8         -0.1317  -0.07428  -0.01689       (-----*----)
                                       ---------+---------+---------+-------
                                           -0.10      0.00      0.10


district = 7  subtracted from:

district     Lower    Center    Upper  ---------+---------+---------+-------
8         -0.09701  -0.03206  0.03290          (------*-----)
                                       ---------+---------+---------+-------
                                           -0.10      0.00      0.10


Tukey Simultaneous Tests
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of district
district = 1  subtracted from:

          Difference       SE of           Adjusted
district    of Means  Difference  T-Value   P-Value
2            0.06189     0.02595    2.384    0.2489
```

3	0.01661	0.01509	1.100	0.9569
4	0.01198	0.01906	0.628	0.9985
5	0.02125	0.01164	1.826	0.6020
6	0.03349	0.01337	2.505	0.1931
7	-0.00873	0.01671	-0.523	0.9996
8	-0.04079	0.01934	-2.109	0.4088

district = 2 subtracted from:

district	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
3	-0.0453	0.02658	-1.703	0.6853
4	-0.0499	0.02902	-1.720	0.6743
5	-0.0406	0.02478	-1.640	0.7261
6	-0.0284	0.02564	-1.107	0.9555
7	-0.0706	0.02753	-2.565	0.1689
8	-0.1027	0.02920	-3.516	0.0104

district = 3 subtracted from:

district	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
4	-0.00463	0.01991	-0.233	1.0000
5	0.00464	0.01298	0.357	1.0000
6	0.01688	0.01455	1.160	0.9431
7	-0.02534	0.01768	-1.434	0.8417
8	-0.05740	0.02018	-2.845	0.0842

district = 4 subtracted from:

district	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
5	0.00927	0.01743	0.532	0.9995
6	0.02151	0.01864	1.154	0.9445
7	-0.02071	0.02116	-0.979	0.9775
8	-0.05277	0.02329	-2.265	0.3129

district = 5 subtracted from:

district	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
6	0.01224	0.01092	1.121	0.9526
7	-0.02998	0.01483	-2.022	0.4670
8	-0.06204	0.01774	-3.498	0.0111

district = 6 subtracted from:

district	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
7	-0.04222	0.01623	-2.602	0.1550
8	-0.07428	0.01892	-3.926	0.0022

district = 7 subtracted from:

district	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
8	-0.03206	0.02141	-1.497	0.8094

General Linear Model: individual deterioration rate versus ADT 2

```
Factor  Type   Levels  Values
ADT 2   fixed       2  1, 2


Analysis of Variance for individual deterioration rate, using Adjusted SS for
     Tests

Source   DF    Seq SS    Adj SS    Adj MS     F      P
ADT 2     1  0.040218  0.040218  0.040218  5.66  0.018
Error   490  3.484474  3.484474  0.007111
Total   491  3.524692


S = 0.0843278   R-Sq = 1.14%   R-Sq(adj) = 0.94%


Unusual Observations for individual deterioration rate

        individual
     deterioration
Obs           rate       Fit    SE Fit  Residual  St Resid
  2       0.500000  0.071465  0.004366  0.428535      5.09 R
 12       0.666667  0.071465  0.004366  0.595202      7.07 R
 18       0.272727  0.071465  0.004366  0.201262      2.39 R
 28       0.315789  0.092579  0.007730  0.223211      2.66 R
 32       0.333333  0.071465  0.004366  0.261868      3.11 R
 33       0.333333  0.092579  0.007730  0.240755      2.87 R
 45       0.300000  0.071465  0.004366  0.228535      2.71 R
 56       0.300000  0.071465  0.004366  0.228535      2.71 R
 64       0.250000  0.071465  0.004366  0.178535      2.12 R
 72       0.400000  0.092579  0.007730  0.307421      3.66 R
105       0.333333  0.092579  0.007730  0.240755      2.87 R
117       0.800000  0.092579  0.007730  0.707421      8.42 R
158       0.250000  0.071465  0.004366  0.178535      2.12 R
163       0.285714  0.071465  0.004366  0.214249      2.54 R
189       0.300000  0.071465  0.004366  0.228535      2.71 R
225       0.333333  0.092579  0.007730  0.240755      2.87 R
242       0.250000  0.071465  0.004366  0.178535      2.12 R
279       0.285714  0.092579  0.007730  0.193136      2.30 R
388       0.500000  0.071465  0.004366  0.428535      5.09 R
406       0.300000  0.071465  0.004366  0.228535      2.71 R

R denotes an observation with a large standardized residual.


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of ADT 2
ADT 2 = 1  subtracted from:

ADT 2     Lower   Center    Upper  ------+---------+---------+---------+
2      0.003670  0.02111  0.03856  (----------------*-----------------)
                                   ------+---------+---------+---------+
                                       0.010     0.020     0.030     0.040


Tukey Simultaneous Tests
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of ADT 2
ADT 2 = 1  subtracted from:
```

ADT 2	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	0.02111	0.008878	2.378	0.0174

General Linear Model: individual deterioration rate versus deck_width 2

Factor	Type	Levels	Values
deck_width 2	fixed	2	1, 2

Analysis of Variance for individual deterioration rate, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
deck_width 2	1	0.027182	0.027182	0.027182	3.81	0.052
Error	490	3.497510	3.497510	0.007138		
Total	491	3.524692				

S = 0.0844854   R-Sq = 0.77%   R-Sq(adj) = 0.57%

Unusual Observations for individual deterioration rate

Obs	individual deterioration rate	Fit	SE Fit	Residual	St Resid	
2	0.500000	0.072888	0.004251	0.427112	5.06	R
12	0.666667	0.072888	0.004251	0.593778	7.04	R
18	0.272727	0.072888	0.004251	0.199839	2.37	R
28	0.315789	0.072888	0.004251	0.242901	2.88	R
32	0.333333	0.072888	0.004251	0.260445	3.09	R
33	0.333333	0.072888	0.004251	0.260445	3.09	R
45	0.300000	0.072888	0.004251	0.227112	2.69	R
56	0.300000	0.072888	0.004251	0.227112	2.69	R
72	0.400000	0.091571	0.008578	0.308429	3.67	R
105	0.333333	0.091571	0.008578	0.241762	2.88	R
117	0.800000	0.091571	0.008578	0.708429	8.43	R
158	0.250000	0.072888	0.004251	0.177112	2.10	R
163	0.285714	0.072888	0.004251	0.212826	2.52	R
189	0.300000	0.072888	0.004251	0.227112	2.69	R
222	0.250000	0.072888	0.004251	0.177112	2.10	R
225	0.333333	0.072888	0.004251	0.260445	3.09	R
242	0.250000	0.072888	0.004251	0.177112	2.10	R
279	0.285714	0.091571	0.008578	0.194143	2.31	R
388	0.500000	0.091571	0.008578	0.408429	4.86	R
406	0.300000	0.072888	0.004251	0.227112	2.69	R

R denotes an observation with a large standardized residual.

Tukey 95.0% Simultaneous Confidence Intervals
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of deck_width 2
deck_width 2 = 1 subtracted from:

deck_width 2	Lower	Center	Upper
2	-0.000128	0.01868	0.03749

```
deck_width 2    +---------+---------+---------+------
2               (---------------*--------------)
                +---------+---------+---------+------
```

0.000   0.012   0.024   0.036

Tukey Simultaneous Tests
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of deck_width 2
deck_width 2 = 1 subtracted from:

deck_width 2	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	0.01868	0.009574	1.951	0.0510

General Linear Model: individual deterioration rate versus Bar type

Factor	Type	Levels	Values
Bar type	fixed	2	1, 2

Analysis of Variance for individual deterioration rate, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Bar type	1	0.012896	0.012896	0.012896	1.80	0.180
Error	490	3.511796	3.511796	0.007167		
Total	491	3.524692				

S = 0.0846577   R-Sq = 0.37%   R-Sq(adj) = 0.16%

Unusual Observations for individual deterioration rate

Obs	individual deterioration rate	Fit	SE Fit	Residual	St Resid	
7	0.250000	0.079833	0.004525	0.170167	2.01	R
56	0.333333	0.079833	0.004525	0.253501	3.00	R
59	0.300000	0.079833	0.004525	0.220167	2.60	R
106	0.300000	0.079833	0.004525	0.220167	2.60	R
131	0.300000	0.079833	0.004525	0.220167	2.60	R
143	0.285714	0.079833	0.004525	0.205881	2.44	R
149	0.666667	0.079833	0.004525	0.586834	6.94	R
150	0.500000	0.079833	0.004525	0.420167	4.97	R
155	0.800000	0.079833	0.004525	0.720167	8.52	R
156	0.333333	0.079833	0.004525	0.253501	3.00	R
179	0.272727	0.079833	0.004525	0.192894	2.28	R
185	0.300000	0.079833	0.004525	0.220167	2.60	R
213	0.285714	0.079833	0.004525	0.205881	2.44	R
218	0.333333	0.079833	0.004525	0.253501	3.00	R
221	0.250000	0.079833	0.004525	0.170167	2.01	R
255	0.250000	0.079833	0.004525	0.170167	2.01	R
300	0.333333	0.079833	0.004525	0.253501	3.00	R
315	0.400000	0.079833	0.004525	0.320167	3.79	R
335	0.315789	0.079833	0.004525	0.235957	2.79	R
453	0.500000	0.068534	0.007104	0.431466	5.11	R
457	0.250000	0.068534	0.007104	0.181466	2.15	R

R denotes an observation with a large standardized residual.

Tukey 95.0% Simultaneous Confidence Intervals
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of Bar type

```
Bar type = 1  subtracted from:

Bar
type     Lower    Center     Upper  --------+---------+---------+--------
2     -0.02785  -0.01130  0.005251  (----------------*---------------)
                                    --------+---------+---------+--------
                                         -0.020    -0.010     0.000


Tukey Simultaneous Tests
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of Bar type
Bar type = 1  subtracted from:

Bar   Difference       SE of           Adjusted
type    of Means  Difference  T-Value   P-Value
2       -0.01130    0.008423   -1.341    0.1798
```

General Linear Model: individual deter versus lag from overlay

```
Factor                   Type   Levels  Values
lag from overlay date 2  fixed       4  1, 2, 3, 4


Analysis of Variance for individual deterioration rate, using Adjusted SS for
     Tests

Source                    DF    Seq SS    Adj SS    Adj MS      F      P
lag from overlay date 2    3  0.293376  0.293376  0.097792  14.77  0.000
Error                    488  3.231317  3.231317  0.006622
Total                    491  3.524692


S = 0.0813729   R-Sq = 8.32%   R-Sq(adj) = 7.76%


Unusual Observations for individual deterioration rate

        individual
     deterioration
Obs           rate       Fit    SE Fit   Residual  St Resid
  2       0.500000  0.163095  0.013562   0.336905      4.20 RX
 11       0.238095  0.072954  0.006413   0.165141      2.04  R
 12       0.666667  0.163095  0.013562   0.503571      6.28 RX
 18       0.272727  0.068337  0.007689   0.204390      2.52  R
 28       0.315789  0.067773  0.006015   0.248016      3.06  R
 32       0.333333  0.163095  0.013562   0.170238      2.12 RX
 33       0.333333  0.163095  0.013562   0.170238      2.12 RX
 37       0.095238  0.163095  0.013562  -0.067857     -0.85  X
 45       0.300000  0.072954  0.006413   0.227046      2.80  R
 56       0.300000  0.072954  0.006413   0.227046      2.80  R
 64       0.250000  0.068337  0.007689   0.181663      2.24  R
 71       0.052632  0.163095  0.013562  -0.110464     -1.38  X
 72       0.400000  0.163095  0.013562   0.236905      2.95 RX
 81       0.100000  0.163095  0.013562  -0.063095     -0.79  X
 82       0.052632  0.163095  0.013562  -0.110464     -1.38  X
 96       0.111111  0.163095  0.013562  -0.051984     -0.65  X
104       0.095238  0.163095  0.013562  -0.067857     -0.85  X
105       0.333333  0.163095  0.013562   0.170238      2.12 RX
109       0.000000  0.163095  0.013562  -0.163095     -2.03 RX
110       0.095238  0.163095  0.013562  -0.067857     -0.85  X
117       0.800000  0.163095  0.013562   0.636905      7.94 RX
```

```
158       0.250000  0.067773  0.006015   0.182227      2.25  R
163       0.285714  0.067773  0.006015   0.217941      2.69  R
166       0.000000  0.163095  0.013562  -0.163095     -2.03 RX
167       0.047619  0.163095  0.013562  -0.115476     -1.44  X
179       0.000000  0.163095  0.013562  -0.163095     -2.03 RX
189       0.300000  0.067773  0.006015   0.232227      2.86  R
222       0.250000  0.067773  0.006015   0.182227      2.25  R
225       0.333333  0.067773  0.006015   0.265560      3.27  R
242       0.250000  0.068337  0.007689   0.181663      2.24  R
275       0.125000  0.163095  0.013562  -0.038095     -0.47  X
279       0.285714  0.068337  0.007689   0.217377      2.68  R
299       0.150000  0.163095  0.013562  -0.013095     -0.16  X
320       0.047619  0.163095  0.013562  -0.115476     -1.44  X
323       0.142857  0.163095  0.013562  -0.020238     -0.25  X
354       0.142857  0.163095  0.013562  -0.020238     -0.25  X
357       0.117647  0.163095  0.013562  -0.045448     -0.57  X
358       0.105263  0.163095  0.013562  -0.057832     -0.72  X
374       0.047619  0.163095  0.013562  -0.115476     -1.44  X
388       0.500000  0.163095  0.013562   0.336905      4.20 RX
406       0.300000  0.068337  0.007689   0.231663      2.86  R
420       0.047619  0.163095  0.013562  -0.115476     -1.44  X
421       0.047619  0.163095  0.013562  -0.115476     -1.44  X
425       0.142857  0.163095  0.013562  -0.020238     -0.25  X
426       0.142857  0.163095  0.013562  -0.020238     -0.25  X
434       0.000000  0.163095  0.013562  -0.163095     -2.03 RX
447       0.000000  0.163095  0.013562  -0.163095     -2.03 RX
462       0.047619  0.163095  0.013562  -0.115476     -1.44  X
472       0.047619  0.163095  0.013562  -0.115476     -1.44  X
473       0.000000  0.163095  0.013562  -0.163095     -2.03 RX

R denotes an observation with a large standardized residual.
X denotes an observation whose X value gives it large influence.


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of lag from overlay date 2
lag from overlay date 2 = 1  subtracted from:

lag
from
overlay
date 2      Lower     Center    Upper  ------+---------+---------+---------+
2        -0.02775  -0.005181  0.01739  (----*---)
3        -0.03032  -0.004617  0.02108  (----*----)
4         0.05163   0.090141  0.12865                 (-------*-------)
                                       ------+---------+---------+---------+
                                           0.000     0.050     0.100     0.150


lag from overlay date 2 = 2  subtracted from:

lag
from
overlay
date 2      Lower    Center    Upper  ------+---------+---------+---------+
3        -0.02449  0.000564  0.02562   (----*----)
4         0.05724  0.095322  0.13340                  (-------*-------)
                                      ------+---------+---------+---------+
                                          0.000     0.050     0.100     0.150


lag from overlay date 2 = 3  subtracted from:
```

```
lag
from
overlay
date 2     Lower   Center   Upper  ------+---------+---------+---------+
4        0.05474  0.09476  0.1348                  (-------*-------)
                                  ------+---------+---------+---------+
                                      0.000     0.050     0.100     0.150
```

Tukey Simultaneous Tests
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of lag from overlay date 2
lag from overlay date 2 = 1 subtracted from:

lag from overlay date 2	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	-0.005181	0.008793	-0.5892	0.9354
3	-0.004617	0.010012	-0.4611	0.9675
4	0.090141	0.015002	6.0086	0.0000

lag from overlay date 2 = 2 subtracted from:

lag from overlay date 2	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
3	0.000564	0.009762	0.05775	0.9999
4	0.095322	0.014836	6.42492	0.0000

lag from overlay date 2 = 3 subtracted from:

lag from overlay date 2	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
4	0.09476	0.01559	6.078	0.0000

General Linear Model: individual deter versus age 4, material type

Factor	Type	Levels	Values
age 4	fixed	2	1, 2
material type	fixed	3	1, 2, 3

Analysis of Variance for individual deterioration rate, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
age 4	1	0.116953	0.085737	0.085737	12.69	0.000
material type	2	0.051832	0.069738	0.034869	5.16	0.006
age 4*material type	2	0.071695	0.071695	0.035847	5.30	0.005
Error	486	3.284213	3.284213	0.006758		
Total	491	3.524692				

S = 0.0822049   R-Sq = 6.82%   R-Sq(adj) = 5.86%

Unusual Observations for individual deterioration rate

Obs	individual deterioration rate	Fit	SE Fit	Residual	St Resid	
1	0.047619	0.132261	0.017939	-0.084642	-1.06	X
2	0.500000	0.132261	0.017939	0.367739	4.58	RX
3	0.047619	0.132261	0.017939	-0.084642	-1.06	X
4	0.047619	0.132261	0.017939	-0.084642	-1.06	X
5	0.000000	0.132261	0.017939	-0.132261	-1.65	X
6	0.047619	0.132261	0.017939	-0.084642	-1.06	X
7	0.047619	0.131474	0.021970	-0.083855	-1.06	X
8	0.133333	0.132261	0.017939	0.001072	0.01	X
9	0.047619	0.132261	0.017939	-0.084642	-1.06	X
10	0.047619	0.132261	0.017939	-0.084642	-1.06	X
11	0.238095	0.132261	0.017939	0.105834	1.32	X
12	0.666667	0.132261	0.017939	0.534405	6.66	RX
13	0.095238	0.132261	0.017939	-0.037023	-0.46	X
14	0.000000	0.132261	0.017939	-0.132261	-1.65	X
15	0.100000	0.132261	0.017939	-0.032261	-0.40	X
16	0.047619	0.132261	0.017939	-0.084642	-1.06	X
17	0.047619	0.132261	0.017939	-0.084642	-1.06	X
18	0.272727	0.132261	0.017939	0.140466	1.75	X
19	0.047619	0.132261	0.017939	-0.084642	-1.06	X
20	0.142857	0.132261	0.017939	0.010596	0.13	X
21	0.000000	0.132261	0.017939	-0.132261	-1.65	X
22	0.000000	0.131474	0.021970	-0.131474	-1.66	X
23	0.200000	0.132261	0.017939	0.067739	0.84	X
24	0.176471	0.131474	0.021970	0.044997	0.57	X
25	0.095238	0.131474	0.021970	-0.036236	-0.46	X
26	0.047619	0.131474	0.021970	-0.083855	-1.06	X
27	0.047619	0.131474	0.021970	-0.083855	-1.06	X
28	0.315789	0.131474	0.021970	0.184316	2.33	RX
29	0.095238	0.131474	0.021970	-0.036236	-0.46	X
30	0.047619	0.131474	0.021970	-0.083855	-1.06	X
31	0.047619	0.131474	0.021970	-0.083855	-1.06	X
32	0.333333	0.131474	0.021970	0.201860	2.55	RX
33	0.333333	0.131474	0.021970	0.201860	2.55	RX
34	0.095238	0.131474	0.021970	-0.036236	-0.46	X
35	0.157895	0.131474	0.021970	0.026421	0.33	X
39	0.100000	0.105489	0.018382	-0.005489	-0.07	X
41	0.000000	0.105489	0.018382	-0.105489	-1.32	X
45	0.300000	0.105489	0.018382	0.194511	2.43	RX
47	0.100000	0.105489	0.018382	-0.005489	-0.07	X
48	0.047619	0.105489	0.018382	-0.057870	-0.72	X
49	0.000000	0.105489	0.018382	-0.105489	-1.32	X
53	0.150000	0.105489	0.018382	0.044511	0.56	X
54	0.142857	0.105489	0.018382	0.037368	0.47	X
56	0.300000	0.105489	0.018382	0.194511	2.43	RX
58	0.000000	0.105489	0.018382	-0.105489	-1.32	X
62	0.142857	0.105489	0.018382	0.037368	0.47	X
64	0.250000	0.105489	0.018382	0.144511	1.80	X
70	0.047619	0.105489	0.018382	-0.057870	-0.72	X
71	0.052632	0.105489	0.018382	-0.052857	-0.66	X
72	0.400000	0.076114	0.005409	0.323886	3.95	R
74	0.095238	0.105489	0.018382	-0.010251	-0.13	X
75	0.000000	0.105489	0.018382	-0.105489	-1.32	X
78	0.142857	0.105489	0.018382	0.037368	0.47	X
79	0.047619	0.105489	0.018382	-0.057870	-0.72	X
94	0.047619	0.105489	0.018382	-0.057870	-0.72	X
103	0.142857	0.105489	0.018382	0.037368	0.47	X

105	0.333333	0.076114	0.005409	0.257219	3.14	R
117	0.800000	0.076114	0.005409	0.723886	8.82	R
158	0.250000	0.076114	0.005409	0.173886	2.12	R
163	0.285714	0.076114	0.005409	0.209600	2.56	R
189	0.300000	0.076114	0.005409	0.223886	2.73	R
222	0.250000	0.076114	0.005409	0.173886	2.12	R
225	0.333333	0.076114	0.005409	0.257219	3.14	R
242	0.250000	0.076114	0.005409	0.173886	2.12	R
279	0.285714	0.076114	0.005409	0.209600	2.56	R
302	0.230769	0.062821	0.005755	0.167948	2.05	R
303	0.230769	0.062821	0.005755	0.167948	2.05	R
375	0.047619	0.273810	0.058128	-0.226190	-3.89	RX
388	0.500000	0.273810	0.058128	0.226190	3.89	RX
406	0.300000	0.062821	0.005755	0.237179	2.89	R

R denotes an observation with a large standardized residual.
X denotes an observation whose X value gives it large influence.

```
Tukey 95.0% Simultaneous Confidence Intervals
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of age 4
age 4 = 1  subtracted from:

age 4    Lower    Center     Upper  ------+---------+---------+---------+
2      -0.1247  -0.08038  -0.03604  (------------*------------)
                                    ------+---------+---------+---------+
                                       -0.105    -0.070    -0.035     0.000
```

```
Tukey Simultaneous Tests
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of age 4
age 4 = 1  subtracted from:

       Difference       SE of           Adjusted
age 4    of Means  Difference  T-Value   P-Value
2        -0.08038     0.02257   -3.562    0.0004
```

```
Tukey 95.0% Simultaneous Confidence Intervals
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of material type
material type = 1  subtracted from:

material
type         Lower    Center      Upper  ---------+---------+---------+-------
2         -0.03954   0.03645   0.112437              (---------*--------)
3         -0.08112  -0.04107  -0.001009          (----*----)
                                         ---------+---------+---------+-------
                                              -0.080     0.000     0.080


material type = 2  subtracted from:

material
type        Lower    Center      Upper  ---------+---------+---------+-------
3         -0.1495  -0.07751  -0.005573  (--------*--------)
                                        ---------+---------+---------+-------
                                             -0.080     0.000     0.080
```

Tukey Simultaneous Tests

Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of material type
material type = 1 subtracted from:

material type	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	0.03645	0.03247	1.123	0.5001
3	-0.04107	0.01711	-2.400	0.0434

material type = 2 subtracted from:

material type	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
3	-0.07751	0.03074	-2.522	0.0313

Tukey 95.0% Simultaneous Confidence Intervals
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of age 4*material type
age 4 = 1
material type = 1 subtracted from:

age 4	material type	Lower	Center	Upper
1	2	-0.0318	0.14155	0.31490
1	3	-0.1000	-0.02677	0.04642
2	1	-0.0816	-0.00079	0.08004
2	2	-0.1231	-0.06944	-0.01576
2	3	-0.1095	-0.05615	-0.00276

```
       material
age 4  type      ---------+---------+---------+-------
1      2                          (--------*--------)
1      3                       (---*--)
2      1                        (---*---)
2      2                      (--*-)
2      3                       (-*--)
                 ---------+---------+---------+-------
                       -0.20      0.00      0.20
```

age 4 = 1
material type = 2 subtracted from:

age 4	material type	Lower	Center	Upper
1	3	-0.3420	-0.1683	0.00541
2	1	-0.3194	-0.1423	0.03474
2	2	-0.3774	-0.2110	-0.04454
2	3	-0.3641	-0.1977	-0.03134

```
       material
age 4  type      ---------+---------+---------+-------
1      3           (--------*-------)
2      1            (--------*--------)
2      2         (-------*--------)
2      3          (-------*-------)
                 ---------+---------+---------+-------
                       -0.20      0.00      0.20
```

age 4 = 1

```
material type = 3  subtracted from:

       material
age 4  type          Lower    Center    Upper
2      1         -0.05564   0.02598  0.10761
2      2         -0.09756  -0.04267  0.01222
2      3         -0.08398  -0.02937  0.02523

       material
age 4  type      ---------+---------+---------+-------
2      1                         (---*---)
2      2                       (--*--)
2      3                        (--*-)
                 ---------+---------+---------+-------
                       -0.20      0.00      0.20


age 4 = 2
material type = 1  subtracted from:

       material
age 4  type        Lower    Center      Upper
2      2         -0.1334  -0.06865  -0.003933
2      3         -0.1198  -0.05536   0.009117

       material
age 4  type      ---------+---------+---------+-------
2      2                     (---*--)
2      3                      (--*--)
                 ---------+---------+---------+-------
                       -0.20      0.00      0.20


age 4 = 2
material type = 2  subtracted from:

       material
age 4  type            Lower   Center    Upper
2      3         -0.009213  0.01329  0.03580

       material
age 4  type      ---------+---------+---------+-------
2      3                            (*)
                 ---------+---------+---------+-------
                       -0.20      0.00      0.20


Tukey Simultaneous Tests
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of age 4*material type
age 4 = 1
material type = 1  subtracted from:

       material  Difference       SE of           Adjusted
age 4  type        of Means  Difference  T-Value   P-Value
1      2            0.14155     0.06083    2.327    0.1832
1      3           -0.02677     0.02568   -1.042    0.9036
2      1           -0.00079     0.02836   -0.028    1.0000
2      2           -0.06944     0.01884   -3.686    0.0031
2      3           -0.05615     0.01874   -2.997    0.0326


age 4 = 1
```

material type = 2 subtracted from:

age 4	material type	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
1	3	-0.1683	0.06096	-2.761	0.0639
2	1	-0.1423	0.06214	-2.291	0.1978
2	2	-0.2110	0.05841	-3.612	0.0041
2	3	-0.1977	0.05838	-3.386	0.0092

age 4 = 1
material type = 3 subtracted from:

age 4	material type	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	1	0.02598	0.02865	0.907	0.9448
2	2	-0.04267	0.01926	-2.215	0.2306
2	3	-0.02937	0.01916	-1.533	0.6428

age 4 = 2
material type = 1 subtracted from:

age 4	material type	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	2	-0.06865	0.02271	-3.023	0.0301
2	3	-0.05536	0.02263	-2.447	0.1404

age 4 = 2
material type = 2 subtracted from:

age 4	material type	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	3	0.01329	0.007898	1.683	0.5430

C.4 Descriptive Statistics for Reduced data set (steel and prestressed concrete superstructures only):

Descriptive Statistics: individual deterioration rate

Variable	age 4	N	N*	Mean	SE Mean	StDev	Minimum
individual deter	1	22	0	0.1208	0.0263	0.1232	0.000000000
	2	435	0	0.06988	0.00348	0.07257	0.000000000

Variable	age 4	Q1	Median	Q3	Maximum
individual deter	1	0.0476	0.0976	0.1446	0.5000
	2	0.04762	0.04762	0.09524	0.80000

Descriptive Statistics: individual deterioration rate

Variable	Overall structure length 5	N	N*	Mean	SE Mean	StDev	Minimum
individual deter	1	222	0	0.06742	0.00428	0.06377	0.000000000
	2	120	0	0.06572	0.00574	0.06292	0.000000000
	3	115	0	0.08871	0.00976	0.10461	0.000000000

Variable	Overall structure length 5	Q1	Median	Q3	Maximum
individual deter	1	0.04762	0.04762	0.09524	0.40000
	2	0.01190	0.04762	0.09524	0.33333
	3	0.04762	0.04762	0.10000	0.80000

Descriptive Statistics: individual deterioration rate

Variable	ADT 2	N	N*	Mean	SE Mean	StDev	Minimum
individual deter	1	344	0	0.06669	0.00356	0.06600	0.000000000
	2	113	0	0.08951	0.00941	0.10001	0.000000000

Variable	ADT 2	Q1	Median	Q3	Maximum
individual deter	1	0.04762	0.04762	0.09524	0.50000
	2	0.04762	0.04762	0.10526	0.80000

Descriptive Statistics: individual deterioration rate

Variable	length_of_max 2	N	N*	Mean	SE Mean	StDev
individual deter	1	346	0	0.06620	0.00358	0.06665
	2	111	0	0.09145	0.00937	0.09875

Variable	length_of_max 2	Minimum	Q1	Median	Q3
individual deter	1	0.000000000	0.000000000	0.04762	0.09524
	2	0.000000000	0.04762	0.05263	0.09524

Variable	length_of_max 2	Maximum
individual deter	1	0.40000
	2	0.80000

Descriptive Statistics: individual deterioration rate

Variable	deck_width 2	N	N*	Mean	SE Mean	StDev	Minimum
individual deter	1	363	0	0.06722	0.00330	0.06287	0.000000000
	2	94	0	0.0921	0.0116	0.1127	0.000000000

Variable	deck_width 2	Q1	Median	Q3	Maximum
individual deter	1	0.04762	0.04762	0.09524	0.33333
	2	0.0476	0.0476	0.1067	0.8000

Descriptive Statistics: individual deterioration rate

Variable	district	N	N*	Mean	SE Mean	StDev	Minimum
individual deter	1	69	0	0.05994	0.00877	0.07288	0.000000000
	2	12	0	0.1236	0.0166	0.0574	0.0476
	3	49	0	0.07697	0.00705	0.04937	0.000000000
	4	24	0	0.0719	0.0131	0.0642	0.000000000
	5	169	0	0.07826	0.00670	0.08711	0.000000000
	6	77	0	0.08266	0.00918	0.08056	0.000000000
	7	38	0	0.05301	0.00992	0.06112	0.000000000
	8	19	0	0.01754	0.00652	0.02844	0.000000000

Variable	district	Q1	Median	Q3	Maximum
individual deter	1	0.000000000	0.04762	0.04762	0.33333
	2	0.0952	0.0952	0.1538	0.2308
	3	0.04762	0.09524	0.09524	0.19048
	4	0.0476	0.0476	0.0952	0.2500
	5	0.04762	0.04762	0.09524	0.80000
	6	0.04762	0.04762	0.09524	0.50000
	7	0.000000000	0.04762	0.09524	0.20000
	8	0.000000000	0.000000000	0.04762	0.09524

Descriptive Statistics: individual deterioration rate

Variable	material type	N	N*	Mean	SE Mean	StDev	Minimum
individual deter	2	206	0	0.06487	0.00459	0.06593	0.000000000
	3	251	0	0.07845	0.00528	0.08359	0.000000000

Variable	material type	Q1	Median	Q3	Maximum
individual deter	2	0.000000000	0.04762	0.09524	0.50000
	3	0.04762	0.04762	0.09524	0.80000

Descriptive Statistics: individual deterioration rate

Variable	continuity	N	N*	Mean	SE Mean	StDev	Minimum
individual deter	1	250	0	0.06829	0.00442	0.06989	0.000000000
	2	207	0	0.07721	0.00580	0.08341	0.000000000

Variable	continuity	Q1	Median	Q3	Maximum
individual deter	1	0.03571	0.04762	0.09524	0.50000
	2	0.04762	0.04762	0.09524	0.80000

Descriptive Statistics: individual deterioration rate

Variable	old or new	N	N*	Mean	SE Mean	StDev	Minimum
individual deter	1	140	0	0.06350	0.00483	0.05713	0.000000000

	2	317	0	0.07623	0.00468	0.08324	0.000000000

Variable	old or new	Q1	Median	Q3	Maximum
individual deter	1	0.000000000	0.04762	0.09524	0.23077
	2	0.04762	0.04762	0.09524	0.80000

Descriptive Statistics: individual deterioration rate

Variable	average daily truck traffic 1 t	N	N*	Mean	SE Mean	StDev	Minimum
individual deter	1	159	0	0.08348	0.00789	0.09948	0.000000000
	2	156	0	0.06536	0.00504	0.06291	0.000000000
	3	76	0	0.06234	0.00559	0.04869	0.000000000
	4	66	0	0.07345	0.00792	0.06431	0.000000000

Variable	average daily truck traffic 1 t	Q1	Median	Q3	Maximum
individual deter	1	0.04762	0.04762	0.09524	0.80000
	2	0.04762	0.04762	0.09524	0.33333
	3	0.04762	0.04762	0.09524	0.20000
	4	0.04762	0.04762	0.09524	0.25000

Descriptive Statistics: individual deterioration rate

Variable	skew 1	N	N*	Mean	SE Mean	StDev	Minimum
individual deter	1	229	0	0.07462	0.00474	0.07169	0.000000000
	2	228	0	0.07003	0.00536	0.08087	0.000000000

Variable	skew 1	Q1	Median	Q3	Maximum
individual deter	1	0.04762	0.04762	0.09524	0.50000
	2	0.01190	0.04762	0.09524	0.80000

Descriptive Statistics: individual deterioration rate

Variable	Bar type	N	N*	Mean	SE Mean	StDev	Minimum
individual deter	1	318	0	0.07406	0.00446	0.07960	0.000000000
	2	139	0	0.06837	0.00581	0.06847	0.000000000

Variable	Bar type	Q1	Median	Q3	Maximum
individual deter	1	0.04762	0.04762	0.09524	0.80000
	2	0.04762	0.04762	0.09524	0.50000

C.5 ANOVA Analysis and Tukey's Method for the Reduced data set (steel and prestressed concrete superstructure types only):

General Linear Model: individual deterioration rate versus age 4

Factor	Type	Levels	Values
age 4	fixed	2	1, 2

Analysis of Variance for individual deterioration rate, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
age 4	1	0.054277	0.054277	0.054277	9.48	0.002
Error	455	2.604473	2.604473	0.005724		
Total	456	2.658750				

S = 0.0756579   R-Sq = 2.04%   R-Sq(adj) = 1.83%

Unusual Observations for individual deterioration rate

Obs	individual deterioration rate	Fit	SE Fit	Residual	St Resid	
4	0.100000	0.120791	0.016130	-0.020791	-0.28	X
6	0.000000	0.120791	0.016130	-0.120791	-1.63	X
10	0.300000	0.120791	0.016130	0.179209	2.42	RX
12	0.100000	0.120791	0.016130	-0.020791	-0.28	X
13	0.047619	0.120791	0.016130	-0.073172	-0.99	X
14	0.000000	0.120791	0.016130	-0.120791	-1.63	X
18	0.150000	0.120791	0.016130	0.029209	0.40	X
19	0.142857	0.120791	0.016130	0.022067	0.30	X
21	0.300000	0.120791	0.016130	0.179209	2.42	RX
23	0.000000	0.120791	0.016130	-0.120791	-1.63	X
27	0.142857	0.120791	0.016130	0.022067	0.30	X
29	0.250000	0.120791	0.016130	0.129209	1.75	X
35	0.047619	0.120791	0.016130	-0.073172	-0.99	X
36	0.052632	0.120791	0.016130	-0.068159	-0.92	X
37	0.400000	0.069880	0.003628	0.330120	4.37	R
39	0.095238	0.120791	0.016130	-0.025553	-0.35	X
40	0.000000	0.120791	0.016130	-0.120791	-1.63	X
43	0.142857	0.120791	0.016130	0.022067	0.30	X
44	0.047619	0.120791	0.016130	-0.073172	-0.99	X
59	0.047619	0.120791	0.016130	-0.073172	-0.99	X
68	0.142857	0.120791	0.016130	0.022067	0.30	X
70	0.333333	0.069880	0.003628	0.263453	3.49	R
82	0.800000	0.069880	0.003628	0.730120	9.66	R
123	0.250000	0.069880	0.003628	0.180120	2.38	R
128	0.285714	0.069880	0.003628	0.215834	2.86	R
154	0.300000	0.069880	0.003628	0.230120	3.05	R
187	0.250000	0.069880	0.003628	0.180120	2.38	R
190	0.333333	0.069880	0.003628	0.263453	3.49	R
207	0.250000	0.069880	0.003628	0.180120	2.38	R
244	0.285714	0.069880	0.003628	0.215834	2.86	R
267	0.230769	0.069880	0.003628	0.160889	2.13	R
268	0.230769	0.069880	0.003628	0.160889	2.13	R

```
330       0.222222  0.069880  0.003628   0.152342      2.02  R
336       0.222222  0.069880  0.003628   0.152342      2.02  R
340       0.047619  0.120791  0.016130  -0.073172     -0.99  X
353       0.500000  0.120791  0.016130   0.379209      5.13 RX
371       0.300000  0.069880  0.003628   0.230120      3.05  R

R denotes an observation with a large standardized residual.
X denotes an observation whose X value gives it large influence.


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of age 4
age 4 = 1  subtracted from:

age 4     Lower    Center     Upper  ---+---------+---------+---------+---
2      -0.08340  -0.05091  -0.01842  (------------*------------)
                                     ---+---------+---------+---------+---
                                     -0.075    -0.050    -0.025    -0.000


Tukey Simultaneous Tests
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of age 4
age 4 = 1  subtracted from:

       Difference       SE of            Adjusted
age 4    of Means  Difference  T-Value    P-Value
2        -0.05091     0.01653   -3.079     0.0021
```

General Linear Model: individual deter versus Overall structure length 5

```
Factor                      Type   Levels  Values
Overall structure length 5  fixed       3  1, 2, 3


Analysis of Variance for individual deterioration rate, using Adjusted SS for
     Tests

Source                       DF    Seq SS    Adj SS    Adj MS     F      P
Overall structure length 5    2  0.041473  0.041473  0.020736  3.60  0.028
Error                       454  2.617277  2.617277  0.005765
Total                       456  2.658750


S = 0.0759271   R-Sq = 1.56%   R-Sq(adj) = 1.13%


Unusual Observations for individual deterioration rate

        individual
     deterioration
Obs           rate       Fit    SE Fit  Residual  St Resid
 10       0.300000  0.067416  0.005096  0.232584      3.07 R
 21       0.300000  0.067416  0.005096  0.232584      3.07 R
 29       0.250000  0.067416  0.005096  0.182584      2.41 R
 37       0.400000  0.067416  0.005096  0.332584      4.39 R
 70       0.333333  0.065722  0.006931  0.267612      3.54 R
 82       0.800000  0.088715  0.007080  0.711285      9.41 R
123       0.250000  0.088715  0.007080  0.161285      2.13 R
128       0.285714  0.065722  0.006931  0.219993      2.91 R
154       0.300000  0.067416  0.005096  0.232584      3.07 R
```

```
187       0.250000  0.088715  0.007080  0.161285      2.13 R
190       0.333333  0.088715  0.007080  0.244619      3.24 R
207       0.250000  0.065722  0.006931  0.184278      2.44 R
244       0.285714  0.088715  0.007080  0.197000      2.61 R
353       0.500000  0.088715  0.007080  0.411285      5.44 R
371       0.300000  0.067416  0.005096  0.232584      3.07 R

R denotes an observation with a large standardized residual.


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of Overall structure length 5
Overall structure length 5 = 1  subtracted from:

Overall
structure
length 5      Lower     Center    Upper
2          -0.02183  -0.001695  0.01844
3           0.00088   0.021298  0.04172

Overall
structure
length 5     -+---------+---------+---------+-----
2            (---------*---------)
3                       (----------*---------)
             -+---------+---------+---------+-----
           -0.020     0.000     0.020     0.040


Overall structure length 5 = 2  subtracted from:

Overall
structure
length 5       Lower   Center    Upper    -+---------+---------+---------+-----
3          -0.000197  0.02299  0.04618              (----------*-----------)
                                          -+---------+---------+---------+-----
                                        -0.020     0.000     0.020     0.040


Tukey Simultaneous Tests
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of Overall structure length 5
Overall structure length 5 = 1  subtracted from:

Overall
structure  Difference       SE of           Adjusted
length 5     of Means  Difference  T-Value   P-Value
2           -0.001695    0.008603  -0.1970    0.9788
3            0.021298    0.008723   2.4415    0.0388


Overall structure length 5 = 2  subtracted from:

Overall
structure  Difference       SE of           Adjusted
length 5     of Means  Difference  T-Value   P-Value
3             0.02299    0.009908    2.321    0.0530
```

General Linear Model: individual deterioration rate versus ADT 2

```
Factor   Type   Levels  Values
```

```
ADT 2   fixed       2  1, 2


Analysis of Variance for individual deterioration rate, using Adjusted SS for
     Tests

Source   DF    Seq SS    Adj SS    Adj MS     F      P
ADT 2     1  0.044303  0.044303  0.044303  7.71  0.006
Error   455  2.614447  2.614447  0.005746
Total   456  2.658750


S = 0.0758026   R-Sq = 1.67%   R-Sq(adj) = 1.45%


Unusual Observations for individual deterioration rate

        individual
     deterioration
Obs           rate       Fit    SE Fit  Residual  St Resid
 10       0.300000  0.066688  0.004087  0.233312      3.08 R
 21       0.300000  0.066688  0.004087  0.233312      3.08 R
 29       0.250000  0.066688  0.004087  0.183312      2.42 R
 37       0.400000  0.089510  0.007131  0.310490      4.11 R
 70       0.333333  0.089510  0.007131  0.243824      3.23 R
 82       0.800000  0.089510  0.007131  0.710490      9.41 R
123       0.250000  0.066688  0.004087  0.183312      2.42 R
128       0.285714  0.066688  0.004087  0.219027      2.89 R
154       0.300000  0.066688  0.004087  0.233312      3.08 R
187       0.250000  0.089510  0.007131  0.160490      2.13 R
190       0.333333  0.089510  0.007131  0.243824      3.23 R
207       0.250000  0.066688  0.004087  0.183312      2.42 R
244       0.285714  0.089510  0.007131  0.196205      2.60 R
267       0.230769  0.066688  0.004087  0.164082      2.17 R
268       0.230769  0.066688  0.004087  0.164082      2.17 R
330       0.222222  0.066688  0.004087  0.155535      2.05 R
336       0.222222  0.066688  0.004087  0.155535      2.05 R
353       0.500000  0.066688  0.004087  0.433312      5.72 R
371       0.300000  0.066688  0.004087  0.233312      3.08 R

R denotes an observation with a large standardized residual.


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of ADT 2
ADT 2 = 1  subtracted from:

ADT 2     Lower   Center    Upper  ---+---------+---------+---------+---
2      0.006670  0.02282  0.03897  (---------------*---------------)
                                   ---+---------+---------+---------+---
                                    0.010     0.020     0.030     0.040


Tukey Simultaneous Tests
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of ADT 2
ADT 2 = 1  subtracted from:

       Difference       SE of           Adjusted
ADT 2    of Means  Difference  T-Value   P-Value
2         0.02282    0.008219    2.777    0.0055
```

General Linear Model: individual deter versus length_of_max 2

```
Factor           Type   Levels  Values
length_of_max 2  fixed       2  1, 2


Analysis of Variance for individual deterioration rate, using Adjusted SS for
     Tests

Source            DF    Seq SS    Adj SS    Adj MS     F      P
length_of_max 2    1  0.053578  0.053578  0.053578  9.36  0.002
Error            455  2.605171  2.605171  0.005726
Total            456  2.658750


S = 0.0756680   R-Sq = 2.02%   R-Sq(adj) = 1.80%


Unusual Observations for individual deterioration rate

        individual
     deterioration
Obs           rate       Fit    SE Fit  Residual  St Resid
 10       0.300000  0.066198  0.004068  0.233802      3.09 R
 21       0.300000  0.066198  0.004068  0.233802      3.09 R
 29       0.250000  0.066198  0.004068  0.183802      2.43 R
 37       0.400000  0.066198  0.004068  0.333802      4.42 R
 70       0.333333  0.066198  0.004068  0.267135      3.54 R
 82       0.800000  0.091448  0.007182  0.708552      9.41 R
123       0.250000  0.066198  0.004068  0.183802      2.43 R
128       0.285714  0.091448  0.007182  0.194267      2.58 R
154       0.300000  0.066198  0.004068  0.233802      3.09 R
187       0.250000  0.066198  0.004068  0.183802      2.43 R
190       0.333333  0.066198  0.004068  0.267135      3.54 R
207       0.250000  0.091448  0.007182  0.158552      2.10 R
244       0.285714  0.066198  0.004068  0.219516      2.91 R
353       0.500000  0.091448  0.007182  0.408552      5.42 R
371       0.300000  0.066198  0.004068  0.233802      3.09 R

R denotes an observation with a large standardized residual.


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of length_of_max 2
length_of_max 2 = 1  subtracted from:

length_of_max 2     Lower   Center    Upper
2                0.009029  0.02525  0.04147

length_of_max 2   -+---------+---------+---------+-----
2                 (---------------*---------------)
                  -+---------+---------+---------+-----
                 0.010     0.020     0.030     0.040


Tukey Simultaneous Tests
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of length_of_max 2
length_of_max 2 = 1  subtracted from:

                 Difference       SE of           Adjusted
```

```
length_of_max 2    of Means  Difference  T-Value   P-Value
2                   0.02525    0.008254    3.059    0.0022
```

General Linear Model: individual deterioration rate versus deck_width 2

```
Factor        Type   Levels  Values
deck_width 2  fixed       2  1, 2


Analysis of Variance for individual deterioration rate, using Adjusted SS for
     Tests

Source         DF    Seq SS    Adj SS    Adj MS     F      P
deck_width 2    1  0.046072  0.046072  0.046072  8.02  0.005
Error         455  2.612677  2.612677  0.005742
Total         456  2.658750


S = 0.0757770   R-Sq = 1.73%   R-Sq(adj) = 1.52%


Unusual Observations for individual deterioration rate

        individual
     deterioration
Obs           rate       Fit    SE Fit  Residual  St Resid
 10       0.300000  0.067221  0.003977  0.232779      3.08 R
 21       0.300000  0.067221  0.003977  0.232779      3.08 R
 29       0.250000  0.092062  0.007816  0.157938      2.10 R
 37       0.400000  0.092062  0.007816  0.307938      4.09 R
 70       0.333333  0.092062  0.007816  0.241271      3.20 R
 82       0.800000  0.092062  0.007816  0.707938      9.39 R
123       0.250000  0.067221  0.003977  0.182779      2.42 R
128       0.285714  0.067221  0.003977  0.218493      2.89 R
154       0.300000  0.067221  0.003977  0.232779      3.08 R
187       0.250000  0.067221  0.003977  0.182779      2.42 R
190       0.333333  0.067221  0.003977  0.266112      3.52 R
207       0.250000  0.067221  0.003977  0.182779      2.42 R
244       0.285714  0.092062  0.007816  0.193652      2.57 R
267       0.230769  0.067221  0.003977  0.163548      2.16 R
268       0.230769  0.067221  0.003977  0.163548      2.16 R
330       0.222222  0.067221  0.003977  0.155001      2.05 R
336       0.222222  0.067221  0.003977  0.155001      2.05 R
353       0.500000  0.092062  0.007816  0.407938      5.41 R
371       0.300000  0.067221  0.003977  0.232779      3.08 R

R denotes an observation with a large standardized residual.


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of deck_width 2
deck_width 2 = 1  subtracted from:

deck_width 2     Lower   Center    Upper  --+---------+---------+---------+----
2             0.007607  0.02484  0.04207  (----------------*----------------)
                                          --+---------+---------+---------+----
                                          0.010     0.020     0.030     0.040


Tukey Simultaneous Tests
Response Variable individual deterioration rate
```

All Pairwise Comparisons among Levels of deck_width 2
deck_width 2 = 1 subtracted from:

deck_width 2	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	0.02484	0.008770	2.833	0.0046

General Linear Model: individual deterioration rate versus district

Factor	Type	Levels	Values
district	fixed	8	1, 2, 3, 4, 5, 6, 7, 8

Analysis of Variance for individual deterioration rate, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
district	7	0.128595	0.128595	0.018371	3.26	0.002
Error	449	2.530155	2.530155	0.005635		
Total	456	2.658750				

S = 0.0750672   R-Sq = 4.84%   R-Sq(adj) = 3.35%

Unusual Observations for individual deterioration rate

Obs	individual deterioration rate	Fit	SE Fit	Residual	St Resid	
6	0.000000	0.017544	0.017222	-0.017544	-0.24	X
10	0.300000	0.082659	0.008555	0.217341	2.91	R
13	0.047619	0.017544	0.017222	0.030075	0.41	X
21	0.300000	0.082659	0.008555	0.217341	2.91	R
29	0.250000	0.078257	0.005774	0.171743	2.29	R
37	0.400000	0.078257	0.005774	0.321743	4.30	R
44	0.047619	0.017544	0.017222	0.030075	0.41	X
50	0.000000	0.017544	0.017222	-0.017544	-0.24	X
51	0.000000	0.017544	0.017222	-0.017544	-0.24	X
52	0.000000	0.017544	0.017222	-0.017544	-0.24	X
70	0.333333	0.078257	0.005774	0.255076	3.41	R
80	0.095238	0.123626	0.021670	-0.028388	-0.39	X
82	0.800000	0.078257	0.005774	0.721743	9.64	R
104	0.095238	0.123626	0.021670	-0.028388	-0.39	X
105	0.095238	0.123626	0.021670	-0.028388	-0.39	X
123	0.250000	0.071925	0.015323	0.178075	2.42	R
128	0.285714	0.078257	0.005774	0.207457	2.77	R
154	0.300000	0.078257	0.005774	0.221743	2.96	R
187	0.250000	0.059942	0.009037	0.190058	2.55	R
190	0.333333	0.059942	0.009037	0.273392	3.67	R
201	0.000000	0.017544	0.017222	-0.017544	-0.24	X
207	0.250000	0.082659	0.008555	0.167341	2.24	R
244	0.285714	0.059942	0.009037	0.225773	3.03	R
252	0.047619	0.017544	0.017222	0.030075	0.41	X
253	0.000000	0.017544	0.017222	-0.017544	-0.24	X
257	0.095238	0.123626	0.021670	-0.028388	-0.39	X
259	0.095238	0.017544	0.017222	0.077694	1.06	X
261	0.095238	0.123626	0.021670	-0.028388	-0.39	X
262	0.153846	0.123626	0.021670	0.030220	0.42	X
265	0.095238	0.123626	0.021670	-0.028388	-0.39	X
267	0.230769	0.123626	0.021670	0.107143	1.49	X
268	0.230769	0.123626	0.021670	0.107143	1.49	X

```
279       0.047619  0.123626  0.021670  -0.076007     -1.06 X
284       0.153846  0.123626  0.021670   0.030220      0.42 X
317       0.047619  0.017544  0.017222   0.030075      0.41 X
331       0.000000  0.017544  0.017222  -0.017544     -0.24 X
353       0.500000  0.082659  0.008555   0.417341      5.60 R
371       0.300000  0.059942  0.009037   0.240058      3.22 R
393       0.047619  0.017544  0.017222   0.030075      0.41 X
395       0.095238  0.123626  0.021670  -0.028388     -0.39 X
413       0.000000  0.017544  0.017222  -0.017544     -0.24 X
444       0.000000  0.017544  0.017222  -0.017544     -0.24 X
445       0.000000  0.017544  0.017222  -0.017544     -0.24 X
447       0.000000  0.017544  0.017222  -0.017544     -0.24 X
448       0.000000  0.017544  0.017222  -0.017544     -0.24 X
449       0.000000  0.017544  0.017222  -0.017544     -0.24 X

R denotes an observation with a large standardized residual.
X denotes an observation whose X value gives it large influence.


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of district
district = 1  subtracted from:

district    Lower    Center    Upper  ---------+---------+---------+-------
2         -0.0075   0.06368  0.13491                   (------*------)
3         -0.0255   0.01703  0.05957                 (----*---)
4         -0.0420   0.01198  0.06595                (----*-----)
5         -0.0142   0.01832  0.05085                   (--*--)
6         -0.0150   0.02272  0.06047                  (---*---)
7         -0.0529  -0.00693  0.03907               (---*----)
8         -0.1014  -0.04240  0.01660          (-----*-----)
                                      ---------+---------+---------+-------
                                           -0.10      0.00      0.10


district = 2  subtracted from:

district    Lower   Center     Upper  ---------+---------+---------+-------
3         -0.1200  -0.0467   0.02669        (------*-------)
4         -0.1322  -0.0517   0.02881       (-------*-------)
5         -0.1134  -0.0454   0.02266         (-----*------)
6         -0.1116  -0.0410   0.02971         (------*------)
7         -0.1460  -0.0706   0.00479     (-------*------)
8         -0.1900  -0.1061  -0.02212  (-------*--------)
                                      ---------+---------+---------+-------
                                           -0.10      0.00      0.10


district = 3  subtracted from:

district    Lower    Center     Upper  ---------+---------+---------+-------
4         -0.0618  -0.00505  0.051686             (----*-----)
5         -0.0357   0.00128  0.038231               (---*---)
6         -0.0359   0.00569  0.047300               (----*---)
7         -0.0732  -0.02397  0.025257            (----*----)
8         -0.1210  -0.05943  0.002113       (-----*-----)
                                       ---------+---------+---------+-------
                                            -0.10      0.00      0.10


district = 4  subtracted from:
```

```
district    Lower    Center    Upper  ---------+---------+---------+-------
5         -0.0433   0.00633  0.05601               (----*----)
6         -0.0425   0.01073  0.06397               (----*----)
7         -0.0783  -0.01892  0.04046           (-----*-----)
8         -0.1243  -0.05438  0.01555       (------*------)
                                      ---------+---------+---------+-------
                                            -0.10      0.00      0.10
```

district = 5 subtracted from:

```
district    Lower    Center      Upper  ---------+---------+---------+-------
6         -0.0269   0.00440   0.035711                (--*---)
7         -0.0661  -0.02525   0.015633            (---*----)
8         -0.1158  -0.06071  -0.005613       (-----*----)
                                        ---------+---------+---------+-------
                                              -0.10      0.00      0.10
```

district = 6 subtracted from:

```
district    Lower    Center      Upper  ---------+---------+---------+-------
7         -0.0748  -0.02965   0.015493            (---*----)
8         -0.1234  -0.06512  -0.006783       (----*-----)
                                        ---------+---------+---------+-------
                                              -0.10      0.00      0.10
```

district = 7 subtracted from:

```
district     Lower    Center    Upper  ---------+---------+---------+-------
8         -0.09945  -0.03546  0.02852        (-----*------)
                                       ---------+---------+---------+-------
                                             -0.10      0.00      0.10
```

Tukey Simultaneous Tests
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of district
district = 1 subtracted from:

district	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	0.06368	0.02348	2.712	0.1187
3	0.01703	0.01402	1.214	0.9280
4	0.01198	0.01779	0.674	0.9977
5	0.01832	0.01072	1.708	0.6822
6	0.02272	0.01244	1.826	0.6025
7	-0.00693	0.01516	-0.457	0.9998
8	-0.04240	0.01945	-2.180	0.3639

district = 2 subtracted from:

district	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
3	-0.0467	0.02418	-1.930	0.5303
4	-0.0517	0.02654	-1.948	0.5175
5	-0.0454	0.02243	-2.023	0.4661
6	-0.0410	0.02330	-1.758	0.6484
7	-0.0706	0.02486	-2.841	0.0852
8	-0.1061	0.02768	-3.832	0.0032

district = 3 subtracted from:

district	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
4	-0.00505	0.01870	-0.270	1.0000
5	0.00128	0.01218	0.105	1.0000
6	0.00569	0.01372	0.414	0.9999
7	-0.02397	0.01623	-1.477	0.8200
8	-0.05943	0.02029	-2.929	0.0669

district = 4 subtracted from:

district	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
5	0.00633	0.01637	0.387	0.9999
6	0.01073	0.01755	0.612	0.9987
7	-0.01892	0.01957	-0.967	0.9791
8	-0.05438	0.02305	-2.359	0.2618

district = 5 subtracted from:

district	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
6	0.00440	0.01032	0.426	0.9999
7	-0.02525	0.01348	-1.874	0.5693
8	-0.06071	0.01816	-3.343	0.0188

district = 6 subtracted from:

district	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
7	-0.02965	0.01488	-1.992	0.4870
8	-0.06512	0.01923	-3.386	0.0163

district = 7 subtracted from:

district	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
8	-0.03546	0.02109	-1.681	0.6995

General Linear Model: individual deterioration rate versus material type

Factor	Type	Levels	Values
material type	fixed	2	2, 3

Analysis of Variance for individual deterioration rate, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
material type	1	0.020882	0.020882	0.020882	3.60	0.058
Error	455	2.637868	2.637868	0.005798		
Total	456	2.658750				

S = 0.0761414   R-Sq = 0.79%   R-Sq(adj) = 0.57%

Unusual Observations for individual deterioration rate

Obs	individual deterioration rate	Fit	SE Fit	Residual	St Resid	
10	0.300000	0.078455	0.004806	0.221545	2.92	R
21	0.300000	0.078455	0.004806	0.221545	2.92	R
29	0.250000	0.078455	0.004806	0.171545	2.26	R
37	0.400000	0.078455	0.004806	0.321545	4.23	R
70	0.333333	0.078455	0.004806	0.254879	3.35	R
82	0.800000	0.078455	0.004806	0.721545	9.50	R
123	0.250000	0.078455	0.004806	0.171545	2.26	R
128	0.285714	0.078455	0.004806	0.207260	2.73	R
154	0.300000	0.078455	0.004806	0.221545	2.92	R
187	0.250000	0.078455	0.004806	0.171545	2.26	R
190	0.333333	0.078455	0.004806	0.254879	3.35	R
207	0.250000	0.078455	0.004806	0.171545	2.26	R
244	0.285714	0.078455	0.004806	0.207260	2.73	R
267	0.230769	0.064869	0.005305	0.165900	2.18	R
268	0.230769	0.064869	0.005305	0.165900	2.18	R
330	0.222222	0.064869	0.005305	0.157353	2.07	R
336	0.222222	0.064869	0.005305	0.157353	2.07	R
353	0.500000	0.064869	0.005305	0.435131	5.73	R
371	0.300000	0.064869	0.005305	0.235131	3.10	R

R denotes an observation with a large standardized residual.

Tukey 95.0% Simultaneous Confidence Intervals
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of material type
material type = 2 subtracted from:

```
material
type          Lower   Center    Upper   -+---------+---------+---------+-----
3         -0.000482  0.01359  0.02765   (-----------------*-----------------)
                                        -+---------+---------+---------+-----
                                       0.0000    0.0080    0.0160    0.0240
```

Tukey Simultaneous Tests
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of material type
material type = 2 subtracted from:

material type	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
3	0.01359	0.007158	1.898	0.0577

General Linear Model: individual d versus length_of_ma, deck_width 2

Factor	Type	Levels	Values
length_of_max 2	fixed	2	1, 2
deck_width 2	fixed	2	1, 2

Analysis of Variance for individual deterioration rate, using Adjusted SS for

Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
length_of_max 2	1	0.053578	0.058676	0.058676	10.41	0.001
deck_width 2	1	0.033799	0.048095	0.048095	8.53	0.004
length_of_max 2*deck_width 2	1	0.017834	0.017834	0.017834	3.16	0.076
Error	453	2.553538	2.553538	0.005637		
Total	456	2.658750				

S = 0.0750796   R-Sq = 3.96%   R-Sq(adj) = 3.32%

Unusual Observations for individual deterioration rate

Obs	individual deterioration rate	Fit	SE Fit	Residual	St Resid	
10	0.300000	0.064338	0.004440	0.235662	3.14	R
11	0.095238	0.122059	0.012876	-0.026821	-0.36	X
16	0.105263	0.122059	0.012876	-0.016796	-0.23	X
21	0.300000	0.064338	0.004440	0.235662	3.14	R
25	0.000000	0.122059	0.012876	-0.122059	-1.65	X
29	0.250000	0.075064	0.009693	0.174936	2.35	R
31	0.047619	0.122059	0.012876	-0.074440	-1.01	X
37	0.400000	0.075064	0.009693	0.324936	4.36	R
45	0.095238	0.122059	0.012876	-0.026821	-0.36	X
48	0.047619	0.122059	0.012876	-0.074440	-1.01	X
58	0.095238	0.122059	0.012876	-0.026821	-0.36	X
61	0.111111	0.122059	0.012876	-0.010948	-0.15	X
65	0.095238	0.122059	0.012876	-0.026821	-0.36	X
70	0.333333	0.075064	0.009693	0.258270	3.47	R
82	0.800000	0.122059	0.012876	0.677941	9.17	RX
86	0.142857	0.122059	0.012876	0.020798	0.28	X
87	0.142857	0.122059	0.012876	0.020798	0.28	X
113	0.095238	0.122059	0.012876	-0.026821	-0.36	X
123	0.250000	0.064338	0.004440	0.185662	2.48	R
128	0.285714	0.077931	0.008556	0.207783	2.79	R
131	0.000000	0.122059	0.012876	-0.122059	-1.65	X
150	0.095238	0.122059	0.012876	-0.026821	-0.36	X
154	0.300000	0.064338	0.004440	0.235662	3.14	R
158	0.047619	0.122059	0.012876	-0.074440	-1.01	X
162	0.047619	0.122059	0.012876	-0.074440	-1.01	X
173	0.142857	0.122059	0.012876	0.020798	0.28	X
179	0.058824	0.122059	0.012876	-0.063235	-0.85	X
187	0.250000	0.064338	0.004440	0.185662	2.48	R
190	0.333333	0.064338	0.004440	0.268995	3.59	R
197	0.095238	0.122059	0.012876	-0.026821	-0.36	X
207	0.250000	0.077931	0.008556	0.172069	2.31	R
216	0.105263	0.122059	0.012876	-0.016796	-0.23	X
227	0.047619	0.122059	0.012876	-0.074440	-1.01	X
240	0.125000	0.122059	0.012876	0.002941	0.04	X
244	0.285714	0.075064	0.009693	0.210651	2.83	R
250	0.058824	0.122059	0.012876	-0.063235	-0.85	X
257	0.095238	0.122059	0.012876	-0.026821	-0.36	X
267	0.230769	0.077931	0.008556	0.152838	2.05	R
268	0.230769	0.077931	0.008556	0.152838	2.05	R
289	0.095238	0.122059	0.012876	-0.026821	-0.36	X
299	0.190476	0.122059	0.012876	0.068417	0.92	X
300	0.190476	0.122059	0.012876	0.068417	0.92	X
328	0.047619	0.122059	0.012876	-0.074440	-1.01	X
329	0.095238	0.122059	0.012876	-0.026821	-0.36	X
353	0.500000	0.122059	0.012876	0.377941	5.11	RX

```
371       0.300000  0.064338  0.004440   0.235662      3.14  R
394       0.047619  0.122059  0.012876  -0.074440     -1.01  X
406       0.047619  0.122059  0.012876  -0.074440     -1.01  X
415       0.142857  0.122059  0.012876   0.020798      0.28  X

R denotes an observation with a large standardized residual.
X denotes an observation whose X value gives it large influence.


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of length_of_max 2
length_of_max 2 = 1  subtracted from:

length_of_max 2    Lower   Center    Upper
2                0.01184  0.03029  0.04875

length_of_max 2  --------+---------+---------+--------
2                (-----------------*-----------------)
                 --------+---------+---------+--------
                       0.020     0.030     0.040


Tukey Simultaneous Tests
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of length_of_max 2
length_of_max 2 = 1  subtracted from:

                 Difference       SE of           Adjusted
length_of_max 2    of Means  Difference  T-Value   P-Value
2                   0.03029    0.009390    3.226    0.0013


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of deck_width 2
deck_width 2 = 1  subtracted from:

deck_width 2     Lower   Center    Upper
2             0.008974  0.02743  0.04588

deck_width 2   -+---------+---------+---------+-----
2              (-----------------*-----------------)
               -+---------+---------+---------+-----
              0.010     0.020     0.030     0.040


Tukey Simultaneous Tests
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of deck_width 2
deck_width 2 = 1  subtracted from:

              Difference       SE of           Adjusted
deck_width 2    of Means  Difference  T-Value   P-Value
2                0.02743    0.009390    2.921    0.0035


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of length_of_max 2*deck_width 2
length_of_max 2 = 1
deck_width 2 = 1  subtracted from:
```

length_of_max 2	deck_width 2	Lower	Center	Upper
1	2	-0.01664	0.01073	0.03809
2	1	-0.01115	0.01359	0.03834
2	2	0.02276	0.05772	0.09268

```
length_of_max 2  deck_width 2  ---------+---------+---------+-------
1                2                 (-------*-------)
2                1                   (------*------)
2                2                             (--------*---------)
                               ---------+---------+---------+-------
                                      0.000     0.035     0.070
```

length_of_max 2 = 1
deck_width 2 = 2 subtracted from:

length_of_max 2	deck_width 2	Lower	Center	Upper
2	1	-0.03032	0.002867	0.03605
2	2	0.00563	0.046995	0.08836

```
length_of_max 2  deck_width 2  ---------+---------+---------+-------
2                1             (---------*--------)
2                2                        (----------*-----------)
                               ---------+---------+---------+-------
                                      0.000     0.035     0.070
```

length_of_max 2 = 2
deck_width 2 = 1 subtracted from:

length_of_max 2	deck_width 2	Lower	Center	Upper
2	2	0.004446	0.04413	0.08381

```
length_of_max 2  deck_width 2  ---------+---------+---------+-------
2                2                       (-----------*----------)
                               ---------+---------+---------+-------
                                      0.000     0.035     0.070
```

Tukey Simultaneous Tests
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of length_of_max 2*deck_width 2
length_of_max 2 = 1
deck_width 2 = 1 subtracted from:

length_of_max 2	deck_width 2	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
1	2	0.01073	0.010661	1.006	0.7459
2	1	0.01359	0.009639	1.410	0.4929
2	2	0.05772	0.013620	4.238	0.0001

length_of_max 2 = 1
deck_width 2 = 2 subtracted from:

length_of_max 2	deck_width 2	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	1	0.002867	0.01293	0.2218	0.9962
2	2	0.046995	0.01612	2.9160	0.0186

length_of_max 2 = 2
deck_width 2 = 1 subtracted from:

length_of_max 2	deck_width 2	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	2	0.04413	0.01546	2.854	0.0224

General Linear Model: individual deter versus length_of_max 2, ADT 2

Factor	Type	Levels	Values
length_of_max 2	fixed	2	1, 2
ADT 2	fixed	2	1, 2

Analysis of Variance for individual deterioration rate, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
length_of_max 2	1	0.053578	0.042325	0.042325	7.49	0.006
ADT 2	1	0.044820	0.034889	0.034889	6.17	0.013
length_of_max 2*ADT 2	1	0.000129	0.000129	0.000129	0.02	0.880
Error	453	2.560223	2.560223	0.005652		
Total	456	2.658750				

S = 0.0751778   R-Sq = 3.71%   R-Sq(adj) = 3.07%

Unusual Observations for individual deterioration rate

Obs	individual deterioration rate	Fit	SE Fit	Residual	St Resid	
10	0.300000	0.060664	0.004662	0.239336	3.19	R
16	0.105263	0.110475	0.014468	-0.005212	-0.07	X
21	0.300000	0.060664	0.004662	0.239336	3.19	R
29	0.250000	0.060664	0.004662	0.189336	2.52	R
37	0.400000	0.082928	0.008107	0.317072	4.24	R
41	0.095238	0.110475	0.014468	-0.015237	-0.21	X
42	0.095238	0.110475	0.014468	-0.015237	-0.21	X
45	0.095238	0.110475	0.014468	-0.015237	-0.21	X
61	0.111111	0.110475	0.014468	0.000636	0.01	X
65	0.095238	0.110475	0.014468	-0.015237	-0.21	X
70	0.333333	0.082928	0.008107	0.250406	3.35	R
82	0.800000	0.110475	0.014468	0.689525	9.35	RX
113	0.095238	0.110475	0.014468	-0.015237	-0.21	X
123	0.250000	0.060664	0.004662	0.189336	2.52	R
128	0.285714	0.085331	0.008203	0.200383	2.68	R
131	0.000000	0.110475	0.014468	-0.110475	-1.50	X
132	0.047619	0.110475	0.014468	-0.062856	-0.85	X
150	0.095238	0.110475	0.014468	-0.015237	-0.21	X
151	0.200000	0.110475	0.014468	0.089525	1.21	X
152	0.000000	0.110475	0.014468	-0.110475	-1.50	X
154	0.300000	0.060664	0.004662	0.239336	3.19	R
158	0.047619	0.110475	0.014468	-0.062856	-0.85	X
179	0.058824	0.110475	0.014468	-0.051652	-0.70	X
187	0.250000	0.082928	0.008107	0.167072	2.24	R
190	0.333333	0.082928	0.008107	0.250406	3.35	R
207	0.250000	0.085331	0.008203	0.164669	2.20	R
223	0.047619	0.110475	0.014468	-0.062856	-0.85	X
224	0.047619	0.110475	0.014468	-0.062856	-0.85	X
227	0.047619	0.110475	0.014468	-0.062856	-0.85	X
240	0.125000	0.110475	0.014468	0.014525	0.20	X
244	0.285714	0.082928	0.008107	0.202787	2.71	R

```
250       0.058824  0.110475  0.014468  -0.051652     -0.70  X
289       0.095238  0.110475  0.014468  -0.015237     -0.21  X
299       0.190476  0.110475  0.014468   0.080001      1.08  X
300       0.190476  0.110475  0.014468   0.080001      1.08  X
328       0.047619  0.110475  0.014468  -0.062856     -0.85  X
329       0.095238  0.110475  0.014468  -0.015237     -0.21  X
353       0.500000  0.085331  0.008203   0.414669      5.55  R
371       0.300000  0.060664  0.004662   0.239336      3.19  R
394       0.047619  0.110475  0.014468  -0.062856     -0.85  X
406       0.047619  0.110475  0.014468  -0.062856     -0.85  X

R denotes an observation with a large standardized residual.
X denotes an observation whose X value gives it large influence.


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of length_of_max 2
length_of_max 2 = 1  subtracted from:

length_of_max 2     Lower   Center    Upper
2                0.007359  0.02611  0.04486

length_of_max 2  ----+---------+---------+---------+--
2                (---------------*--------------)
                 ----+---------+---------+---------+--
                   0.012     0.024     0.036     0.048


Tukey Simultaneous Tests
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of length_of_max 2
length_of_max 2 = 1  subtracted from:

                 Difference       SE of           Adjusted
length_of_max 2    of Means  Difference  T-Value   P-Value
2                   0.02611    0.009540    2.737    0.0062


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of ADT 2
ADT 2 = 1  subtracted from:

ADT 2     Lower   Center    Upper  ------+---------+---------+---------+
2      0.004955  0.02370  0.04245  (---------------*--------------)
                                   ------+---------+---------+---------+
                                       0.012     0.024     0.036     0.048


Tukey Simultaneous Tests
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of ADT 2
ADT 2 = 1  subtracted from:

       Difference       SE of           Adjusted
ADT 2    of Means  Difference  T-Value   P-Value
2         0.02370    0.009540    2.485    0.0130


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of length_of_max 2*ADT 2
```

```
length_of_max 2 = 1
ADT 2 = 1  subtracted from:

length_of_max 2  ADT 2      Lower   Center    Upper
1                2      -0.001741  0.02226  0.04627
2                1       0.000449  0.02467  0.04888
2                2       0.010794  0.04981  0.08883

length_of_max 2  ADT 2  --------+---------+---------+--------
1                2              (-----*------)
2                1              (------*------)
2                2                 (----------*----------)
                        --------+---------+---------+--------
                              0.000     0.035     0.070


length_of_max 2 = 1
ADT 2 = 2  subtracted from:

length_of_max 2  ADT 2     Lower    Center    Upper
2                1      -0.02720  0.002404  0.03201
2                2      -0.01502  0.027548  0.07012

length_of_max 2  ADT 2  --------+---------+---------+--------
2                1      (--------*-------)
2                2          (-----------*-----------)
                        --------+---------+---------+--------
                              0.000     0.035     0.070


length_of_max 2 = 2
ADT 2 = 1  subtracted from:

length_of_max 2  ADT 2     Lower   Center    Upper
2                2      -0.01755  0.02514  0.06783

length_of_max 2  ADT 2  --------+---------+---------+--------
2                2         (-----------*-----------)
                        --------+---------+---------+--------
                              0.000     0.035     0.070


Tukey Simultaneous Tests
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of length_of_max 2*ADT 2
length_of_max 2 = 1
ADT 2 = 1  subtracted from:

                        Difference       SE of           Adjusted
length_of_max 2  ADT 2    of Means  Difference  T-Value   P-Value
1                2         0.02226    0.009352    2.381    0.0808
2                1         0.02467    0.009435    2.614    0.0443
2                2         0.04981    0.015201    3.277    0.0058


length_of_max 2 = 1
ADT 2 = 2  subtracted from:

                        Difference       SE of           Adjusted
length_of_max 2  ADT 2    of Means  Difference  T-Value   P-Value
2                1        0.002404     0.01153   0.2084    0.9968
2                2        0.027548     0.01658   1.6611    0.3445
```

```
length_of_max 2 = 2
ADT 2 = 1  subtracted from:

                         Difference       SE of             Adjusted
length_of_max 2  ADT 2    of Means  Difference  T-Value    P-Value
2                2         0.02514     0.01663    1.512     0.4303
```

Results for: max span length less than 100 feet

Descriptive Statistics: individual deterioration rate

```
Variable          ADT 2    N  N*      Mean  SE Mean    StDev      Minimum
individual deter  1      260   0  0.06066  0.00377  0.06074  0.000000000
                  2       86   0  0.08293  0.00863  0.08007  0.000000000

Variable          ADT 2           Q1   Median       Q3  Maximum
individual deter  1      0.000000000  0.04762  0.09524  0.30000
                  2          0.04762  0.04762  0.10836  0.40000
```

Results for: max span length greater than 100 feet

Descriptive Statistics: individual deterioration rate

```
Variable          ADT 2   N  N*      Mean  SE Mean    StDev      Minimum
individual deter  1      84   0  0.08533  0.00847  0.07763  0.000000000
                  2      27   0   0.1105   0.0282   0.1467  0.000000000

Variable          ADT 2       Q1   Median       Q3  Maximum
individual deter  1      0.04762  0.04762  0.09524  0.50000
                  2       0.0476   0.0952   0.1053   0.8000
```

General Linear Model: individual deterioration rate versus continuity

```
Factor      Type   Levels  Values
continuity  fixed       2  1, 2


Analysis of Variance for individual deterioration rate, using Adjusted SS for
     Tests

Source       DF    Seq SS    Adj SS    Adj MS     F      P
continuity    1  0.008997  0.008997  0.008997  1.54  0.215
Error       455  2.649753  2.649753  0.005824
Total       456  2.658750


S = 0.0763127   R-Sq = 0.34%   R-Sq(adj) = 0.12%


Unusual Observations for individual deterioration rate

        individual
     deterioration
Obs           rate       Fit    SE Fit  Residual  St Resid
  7       0.250000  0.077207  0.005304  0.172793      2.27 R
 55       0.300000  0.077207  0.005304  0.222793      2.93 R
 98       0.300000  0.068293  0.004826  0.231707      3.04 R
```

122	0.300000	0.068293	0.004826	0.231707	3.04	R
133	0.285714	0.077207	0.005304	0.208507	2.74	R
139	0.800000	0.077207	0.005304	0.722793	9.49	R
140	0.333333	0.077207	0.005304	0.256126	3.36	R
163	0.300000	0.068293	0.004826	0.231707	3.04	R
191	0.285714	0.077207	0.005304	0.208507	2.74	R
196	0.333333	0.077207	0.005304	0.256126	3.36	R
199	0.250000	0.077207	0.005304	0.172793	2.27	R
233	0.250000	0.077207	0.005304	0.172793	2.27	R
289	0.400000	0.068293	0.004826	0.331707	4.36	R
328	0.230769	0.068293	0.004826	0.162476	2.13	R
329	0.230769	0.068293	0.004826	0.162476	2.13	R
342	0.222222	0.068293	0.004826	0.153929	2.02	R
343	0.222222	0.068293	0.004826	0.153929	2.02	R
418	0.500000	0.068293	0.004826	0.431707	5.67	R
422	0.250000	0.068293	0.004826	0.181707	2.39	R

R denotes an observation with a large standardized residual.

Tukey 95.0% Simultaneous Confidence Intervals
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of continuity
continuity = 1 subtracted from:

continuity	Lower	Center	Upper
2	-0.005179	0.008914	0.02301

```
continuity  ------+---------+---------+---------+
2           (----------------*-----------------)
            ------+---------+---------+---------+
                0.0000    0.0080    0.0160    0.0240
```

Tukey Simultaneous Tests
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of continuity
continuity = 1 subtracted from:

continuity	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	0.008914	0.007171	1.243	0.2139

General Linear Model: individual deterioration rate versus old or new

Factor	Type	Levels	Values
old or new	fixed	2	1, 2

Analysis of Variance for individual deterioration rate, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
old or new	1	0.015736	0.015736	0.015736	2.71	0.100
Error	455	2.643013	2.643013	0.005809		
Total	456	2.658750				

S = 0.0762156   R-Sq = 0.59%   R-Sq(adj) = 0.37%

Unusual Observations for individual deterioration rate

Obs	individual deterioration rate	Fit	SE Fit	Residual	St Resid	
7	0.250000	0.076230	0.004281	0.173770	2.28	R
55	0.300000	0.076230	0.004281	0.223770	2.94	R
98	0.300000	0.076230	0.004281	0.223770	2.94	R
122	0.300000	0.076230	0.004281	0.223770	2.94	R
133	0.285714	0.076230	0.004281	0.209484	2.75	R
139	0.800000	0.076230	0.004281	0.723770	9.51	R
140	0.333333	0.076230	0.004281	0.257103	3.38	R
163	0.300000	0.076230	0.004281	0.223770	2.94	R
191	0.285714	0.076230	0.004281	0.209484	2.75	R
196	0.333333	0.076230	0.004281	0.257103	3.38	R
199	0.250000	0.076230	0.004281	0.173770	2.28	R
233	0.250000	0.076230	0.004281	0.173770	2.28	R
289	0.400000	0.076230	0.004281	0.323770	4.25	R
328	0.230769	0.063501	0.006441	0.167268	2.20	R
329	0.230769	0.063501	0.006441	0.167268	2.20	R
342	0.222222	0.063501	0.006441	0.158721	2.09	R
343	0.222222	0.063501	0.006441	0.158721	2.09	R
418	0.500000	0.076230	0.004281	0.423770	5.57	R
422	0.250000	0.076230	0.004281	0.173770	2.28	R

R denotes an observation with a large standardized residual.

Tukey 95.0% Simultaneous Confidence Intervals
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of old or new
old or new = 1 subtracted from:

```
old
or
new      Lower   Center    Upper  --+---------+---------+---------+----
2    -0.002469  0.01273  0.02793  (--------------*--------------)
                                  --+---------+---------+---------+----
                                  0.000     0.010     0.020     0.030
```

Tukey Simultaneous Tests
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of old or new
old or new = 1 subtracted from:

old or new	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	0.01273	0.007734	1.646	0.0998

General Linear Model: individual deter versus average daily truck traffic 1 to 4

Factor	Type	Levels	Values
average daily truck traffic 1 t	fixed	4	1, 2, 3, 4

Analysis of Variance for individual deterioration rate, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
average daily truck traffic 1 t	3	0.035021	0.035021	0.011674	2.02	0.111
Error	453	2.623729	2.623729	0.005792		
Total	456	2.658750				

```
S = 0.0761045   R-Sq = 1.32%   R-Sq(adj) = 0.66%


Unusual Observations for individual deterioration rate

        individual
     deterioration
Obs           rate       Fit    SE Fit  Residual  St Resid
  7       0.250000  0.073451  0.009368  0.176549      2.34 R
 55       0.300000  0.083482  0.006035  0.216518      2.85 R
 98       0.300000  0.083482  0.006035  0.216518      2.85 R
122       0.300000  0.065357  0.006093  0.234643      3.09 R
133       0.285714  0.083482  0.006035  0.202233      2.67 R
139       0.800000  0.083482  0.006035  0.716518      9.44 R
140       0.333333  0.083482  0.006035  0.249852      3.29 R
163       0.300000  0.083482  0.006035  0.216518      2.85 R
191       0.285714  0.065357  0.006093  0.220357      2.90 R
196       0.333333  0.065357  0.006093  0.267976      3.53 R
199       0.250000  0.083482  0.006035  0.166518      2.19 R
233       0.250000  0.065357  0.006093  0.184643      2.43 R
289       0.400000  0.083482  0.006035  0.316518      4.17 R
328       0.230769  0.073451  0.009368  0.157318      2.08 R
329       0.230769  0.073451  0.009368  0.157318      2.08 R
418       0.500000  0.083482  0.006035  0.416518      5.49 R
422       0.250000  0.065357  0.006093  0.184643      2.43 R

R denotes an observation with a large standardized residual.


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of average daily truck traffic 1 t
average daily truck traffic 1 t = 1  subtracted from:

average
daily
truck
traffic
1 t         Lower    Center     Upper  ---------+---------+---------+-------
2        -0.04014  -0.01812  0.003889     (--------*--------)
3        -0.04838  -0.02114  0.006103  (----------*---------)
4        -0.03863  -0.01003  0.018573      (----------*----------)
                                       ---------+---------+---------+-------
                                            -0.025     0.000     0.025


average daily truck traffic 1 t = 2  subtracted from:

average
daily
truck
traffic
1 t         Lower     Center    Upper  ---------+---------+---------+-------
3        -0.03034  -0.003014  0.02431         (----------*----------)
4        -0.02059   0.008094  0.03678             (----------*----------)
                                       ---------+---------+---------+-------
                                            -0.025     0.000     0.025


average daily truck traffic 1 t = 3  subtracted from:
```

```
average
daily
truck
traffic
1 t         Lower   Center    Upper  ---------+---------+---------+-------
4        -0.02176  0.01111  0.04398           (------------*-------------)
                                     ---------+---------+---------+-------
                                           -0.025     0.000     0.025
```

Tukey Simultaneous Tests
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of average daily truck traffic 1 t
average daily truck traffic 1 t = 1 subtracted from:

average daily truck traffic 1 t	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	-0.01812	0.008576	-2.113	0.1488
3	-0.02114	0.010613	-1.992	0.1910
4	-0.01003	0.011144	-0.900	0.8048

average daily truck traffic 1 t = 2 subtracted from:

average daily truck traffic 1 t	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
3	-0.003014	0.01065	-0.2831	0.9921
4	0.008094	0.01118	0.7242	0.8874

average daily truck traffic 1 t = 3 subtracted from:

average daily truck traffic 1 t	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
4	0.01111	0.01280	0.8674	0.8217

General Linear Model: individual deterioration rate versus skew 1

Factor	Type	Levels	Values
skew 1	fixed	2	1, 2

Analysis of Variance for individual deterioration rate, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
skew 1	1	0.002409	0.002409	0.002409	0.41	0.521
Error	455	2.656341	2.656341	0.005838		
Total	456	2.658750				

```
S = 0.0764075   R-Sq = 0.09%   R-Sq(adj) = 0.00%


Unusual Observations for individual deterioration rate

        individual
     deterioration
Obs           rate       Fit    SE Fit  Residual  St Resid
  7       0.250000  0.074622  0.005049  0.175378      2.30 R
 55       0.300000  0.070030  0.005060  0.229970      3.02 R
 98       0.300000  0.074622  0.005049  0.225378      2.96 R
122       0.300000  0.070030  0.005060  0.229970      3.02 R
133       0.285714  0.074622  0.005049  0.211093      2.77 R
139       0.800000  0.070030  0.005060  0.729970      9.57 R
140       0.333333  0.074622  0.005049  0.258712      3.39 R
163       0.300000  0.070030  0.005060  0.229970      3.02 R
191       0.285714  0.074622  0.005049  0.211093      2.77 R
196       0.333333  0.074622  0.005049  0.258712      3.39 R
199       0.250000  0.074622  0.005049  0.175378      2.30 R
233       0.250000  0.074622  0.005049  0.175378      2.30 R
289       0.400000  0.070030  0.005060  0.329970      4.33 R
328       0.230769  0.070030  0.005060  0.160739      2.11 R
329       0.230769  0.070030  0.005060  0.160739      2.11 R
418       0.500000  0.074622  0.005049  0.425378      5.58 R
422       0.250000  0.070030  0.005060  0.179970      2.36 R

R denotes an observation with a large standardized residual.


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of skew 1
skew 1 = 1  subtracted from:

skew
1        Lower     Center     Upper  ---+---------+---------+---------+---
2     -0.01864  -0.004592  0.009456  (----------------*-----------------)
                                     ---+---------+---------+---------+---
                                     -0.0160   -0.0080    0.0000    0.0080


Tukey Simultaneous Tests
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of skew 1
skew 1 = 1  subtracted from:

skew  Difference       SE of           Adjusted
1       of Means  Difference  T-Value   P-Value
2      -0.004592    0.007148  -0.6423    0.5207
```

General Linear Model: individual deterioration rate versus Bar type

```
Factor    Type   Levels  Values
Bar type  fixed       2  1, 2


Analysis of Variance for individual deterioration rate, using Adjusted SS for
     Tests

Source     DF    Seq SS    Adj SS    Adj MS     F      P
Bar type    1  0.003136  0.003136  0.003136  0.54  0.464
Error     455  2.655614  2.655614  0.005837
```

```
Total     456  2.658750


S = 0.0763971   R-Sq = 0.12%   R-Sq(adj) = 0.00%


Unusual Observations for individual deterioration rate

        individual
     deterioration
Obs           rate       Fit    SE Fit  Residual  St Resid
  7       0.250000  0.074063  0.004284  0.175937      2.31 R
 55       0.300000  0.074063  0.004284  0.225937      2.96 R
 98       0.300000  0.074063  0.004284  0.225937      2.96 R
122       0.300000  0.074063  0.004284  0.225937      2.96 R
133       0.285714  0.074063  0.004284  0.211652      2.77 R
139       0.800000  0.074063  0.004284  0.725937      9.52 R
140       0.333333  0.074063  0.004284  0.259271      3.40 R
163       0.300000  0.074063  0.004284  0.225937      2.96 R
191       0.285714  0.074063  0.004284  0.211652      2.77 R
196       0.333333  0.074063  0.004284  0.259271      3.40 R
199       0.250000  0.074063  0.004284  0.175937      2.31 R
233       0.250000  0.074063  0.004284  0.175937      2.31 R
289       0.400000  0.074063  0.004284  0.325937      4.27 R
328       0.230769  0.068369  0.006480  0.162401      2.13 R
329       0.230769  0.068369  0.006480  0.162401      2.13 R
342       0.222222  0.068369  0.006480  0.153854      2.02 R
343       0.222222  0.068369  0.006480  0.153854      2.02 R
418       0.500000  0.068369  0.006480  0.431631      5.67 R
422       0.250000  0.068369  0.006480  0.181631      2.39 R

R denotes an observation with a large standardized residual.


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of Bar type
Bar type = 1  subtracted from:

Bar
type     Lower     Center     Upper    -+---------+---------+---------+-----
2     -0.02096  -0.005694  0.009572    (--------------*---------------)
                                       -+---------+---------+---------+-----
                                     -0.020    -0.010     0.000     0.010


Tukey Simultaneous Tests
Response Variable individual deterioration rate
All Pairwise Comparisons among Levels of Bar type
Bar type = 1  subtracted from:

Bar   Difference       SE of           Adjusted
type    of Means  Difference  T-Value   P-Value
2      -0.005694    0.007768  -0.7330    0.4636
```

Appendix D

Source Code for Programs Written for Project

D.1 Average Deterioration Rate Calculation Program (Visual Basic for Applications)

Note: When copying the source code into word, lines are wrapped to fit the page formatting. Be careful to place wrapped text back onto the original line or the program will function incorrectly

```
Option Explicit

Sub IndDetRate_NEW()
Dim Inline(22) As Double 'this variable will hold the current 23 cells read in
Dim i As Integer, j As Integer
i = 0
j = 0

Do Until IsEmpty(Cells(i + 2, 4))
    For j = 0 To 22
        Inline(j) = Cells(i + 2, j + 4)
    Next
    Cells(i + 2, 27).Value = calc_rate(Inline())
    i = i + 1
Loop

End Sub

Function calc_rate(Inline() As Double) As Double

Dim initial As Double, final As Double, date_placed As Double, EOSL As Double
Dim previous As Double, following As Double
Dim years1 As Double, years2 As Double, years3 As Double

Dim rate1 As Double, rate2 As Double, rate3 As Double
Dim i As Integer, det As Integer, early_fail As Integer, five_reached As Integer

Dim num As Double
rate1 = 0
rate2 = 0
rate3 = 0

initial = Inline(2)

date_placed = 1983

i = 0
det = 0
early_fail = 0
five_reached = 0

If Inline(i + 2) < 6 Then 'check to see if intial condition is five or below
    det = 1
    EOSL = 1983
    final = Inline(i + 2)
    five_reached = 1
    early_fail = 1
End If

Do While i < 20

    If det = 1 Then
        Exit Do
    End If

    previous = Inline(i + 2)
```

```
    final = Inline(i + 3)

    If i < 19 Then
    following = Inline(i + 4)
    End If

    If final < 6 Or i = 19 Then  'if deck condition reaches five, or the last
condition
        EOSL = 1983 + i + 1       'is reached then the current deck condition is the
last to be used in
        det = 1                   'calculating the deterioration rate
        If final < 6 Then
            five_reached = 1
            early_fail = 1
        End If
    End If
    If i < 19 Then
        If following - final > 1 Then 'if the deck condition improves by more than one
condition
        EOSL = 1983 + i + 1            'state that end of service life has been
reached since the
        det = 1                         'deck has been significantly improved or
repaired
        early_fail = 1

        End If
    End If
    i = i + 1
Loop


num = (initial - final)
If num < 0 Then 'If bridge has a negative deterioration rate, set rate equal to zero
num = 0         'since the bridge can't heal itself
End If

calc_rate = num / (EOSL - date_placed + 1) 'add one to include the year that
years1 = EOSL - date_placed + 1              'EOSL was reached
rate1 = calc_rate

If five_reached = 1 And i < 20 Then        'this section of code skips over the years
that the

    Do While i < 20                        'bridge was not repaired and was at a
condition state of five or below
    If Inline(i + 2) > 5 And Inline(i + 2) - final > 1 Then
        i = i - 1
        Exit Do
    End If
    i = i + 1
    Loop
End If

If early_fail = 1 And i < 20 Then ' if the deck failed early or received repairs,
calculate the deterioration rate for
det = 0                ' the next portion of its life span
date_placed = 1984 + i
initial = Inline(i + 3)
early_fail = 0
five_reached = 0

Do While i < 20
    If det = 1 Then
```

```
        Exit Do
    End If

    previous = Inline(i + 2)
    final = Inline(i + 3)

    If i < 19 Then
    following = Inline(i + 4)
    End If

    If final < 6 Or i = 19 Then 'if deck condition reaches five, or the last condition
        EOSL = 1983 + i + 1       'is reached then the current deck condition is the
last to be used in
        det = 1                 'calculating the deterioration rate
        If final < 6 Then
            five_reached = 1
            early_fail = 1
        End If
    End If
    If i < 19 Then
        If following - final > 1 Then 'if the deck condition improves by more than one
condition
         EOSL = 1983 + i + 1            'state that end of service life has been
reached since the
        det = 1                         'deck has been significantly improved or
repaired
        early_fail = 1

        End If
    End If
i = i + 1


Loop
'recalculate the deterioration rate to be the weighted average of the two seperate
linear deterioration
'rates that were calculated

num = initial - final
If num < 0 Then 'If bridge has a negative deterioration rate, set rate equal to zero
num = 0         'since the bridge can't heal itself
End If
years2 = EOSL - date_placed + 1
'MsgBox ("rate 1 = " & calc_rate * years1 / (years1 + years2) & "num = " & num & "
years1 = " & years1 & " years2 = " & years2)
If years2 <> 0 Then
    rate2 = num / years2
End If
calc_rate = rate1 * years1 / (years1 + years2) + rate2 * years2 / (years1 + years2)

End If




If five_reached = 1 And i < 20 Then        'this section of code skips over the years
that the
                                           'bridge was not repaired and was at a
condition state of five or below
    Do While i < 20
    If Inline(i + 2) > 5 And Inline(i + 2) - final > 1 Then
        i = i - 1
        Exit Do
```

```
    End If
    i = i + 1
    Loop
End If



If early_fail = 1 And i < 20 Then ' if the deck failed early or received repairs,
calculate the deterioration rate for
det = 0                ' the next portion of its life span
date_placed = 1984 + i
initial = Inline(i + 3)
early_fail = 0

Do While i < 20
 If det = 1 Then
        Exit Do
    End If

    previous = Inline(i + 2)
    final = Inline(i + 3)

    If i < 19 Then
    following = Inline(i + 4)
    End If

    If final < 6 Or i = 19 Then  'if deck condition reaches five, or the last
condition
        EOSL = 1983 + i + 1       'is reached then the current deck condition is the
last to be used in
        det = 1                 'calculating the deterioration rate
    End If
    If i < 19 Then
        If following - final > 1 Then 'if the deck condition improves by more than one
condition
        EOSL = 1983 + i + 1            'state that end of service life has been
reached since the
        det = 1                         'deck has been significantly improved or
repaired
        End If
    End If
i = i + 1


Loop
'recalculate the deterioration rate to be the weighted average of the two seperate
linear deterioration
'rates that were calculated

num = initial - final
If num < 0 Then 'If bridge has a negative deterioration rate, set rate equal to zero
num = 0         'since the bridge can't heal itself
End If
years3 = EOSL - date_placed + 1
'MsgBox ("rate 1 = " & calc_rate * years1 / (years1 + years2) & "rate 2 = " & num *
years2 / (years2 * (years1 + years2)) & "num = " & num & "years1 = " & years1 &
"years2 = " & years2)
If years3 <> 0 Then
    rate3 = num / years3
End If

calc_rate = rate1 * years1 / (years1 + years2 + years3) + rate2 * years2 / (years1 +
years2 + years3) + rate3 * years3 / (years1 + years2 + years3)
```

```
End If

End Function
```

D.2 Piecewise Linear Deterioration Curve Program (C++)

```
//This program implements the equations developed by Imad J. Abed-AlRahim and
//David W. Johnston for calculating the piecewise linear deterioration rates for
//bridge elements using inspection data such as that found in the NBI database.
//Their paper was published in the Transportation Research Record 1490 and is
//entitled "Bridge Element Deterioration Rates"

// note: this program uses a commercial overloaded matrix class
//If you want to run the program as is, you will have to purchase the class and install it
//in your compiler. Here is the information
//Matrix TCL Pro 2.12
//Copyright (c) 2000-2003 Techsoft Pvt. Ltd.
//TechSoft Pvt. Ltd.
//Email: matrix@techsoftpl.com
//Web: http://www.techsoftpl.com/matrix/

#include <cmatrix>

typedef techsoft::matrix<double> Matrix;

#include <iostream>

using std::cout;
using std::cin;
using std::endl;
using std::ios;
using std::left;
using std::right;

#include <fstream>

using std::ofstream;
using std::ifstream;
using std::istream;
#include <iomanip>

using std::setw;

#include <cmath>

#include <string>
using std::string;
using std::getline;

int main()
{

        int bridge_num, count, total,i,j;

        double place,zero,one,two,three,four,five,six,seven,eight,nine,ten
                        ,eleven,twelve,thirteen,fourteen,fifteen,sixteen,seventeen,eighteen
                        ,nineteen,twenty,twenty_one;
```

```
double r, n_decline, n_imp_one, n_imp,total_num, left, right,drop;
double AVGCHN[5];
double time[5];
int total_num_drops[5];

string title;

cout<<"Enter a title for the results"<<endl;
getline(cin,title);

cout<<"Enter the number of bridges in input file"<<endl<<endl;
cin>>bridge_num;

//declare array for data input using dynamic data allocation to
//make program more general

double *bridge_data= new double[bridge_num*21];

//declare Matrix object used to store data once it has been read in
Matrix data(bridge_num,21,0.0);

//read in data from file
ifstream text_stream("bridge.txt",ios::in);

;

count=0;
total=0;
while(text_stream>>place>>one>>two>>three>>four>>five>>six>>seven>>eight>>nine>>ten

>>eleven>>twelve>>thirteen>>fourteen>>fifteen>>sixteen>>seventeen>>eighteen
            >>nineteen>>twenty>>twenty_one)
{

      bridge_data[count]=one;
      bridge_data[count+1]=two;
      bridge_data[count+2]=three;
      bridge_data[count+3]=four;
      bridge_data[count+4]=five;
      bridge_data[count+5]=six;
      bridge_data[count+6]=seven;
      bridge_data[count+7]=eight;
      bridge_data[count+8]=nine;
      bridge_data[count+9]=ten;
      bridge_data[count+10]=eleven;
      bridge_data[count+11]=twelve;
      bridge_data[count+12]=thirteen;
      bridge_data[count+13]=fourteen;
      bridge_data[count+14]=fifteen;
      bridge_data[count+15]=sixteen;
      bridge_data[count+16]=seventeen;
      bridge_data[count+17]=eighteen;
      bridge_data[count+18]=nineteen;
      bridge_data[count+19]=twenty;
      bridge_data[count+20]=twenty_one;
```

```
		count=count+21;
		total++;
	}

	if(total!=bridge_num)
		cout<<"ERROR, NUMBER OF BRIDGES ENTERED DOES NOT EQUAL NUMBER IN
BRIDGE.TXT"<<endl;

	//transfer data from 1d array to 2d Matrix object
	count=0;
	for(i=0;i<bridge_num;i++)
		for(j=0;j<21;j++)
		{
			data(i,j)=bridge_data[count];
			count++;
		}


	count=0;
	for(r=9;r>4;r=r-1) //calculate deterioration rate for condition states
	{					//between 9 and 5

		total_num=0;
		one=0;
		two=0;
		three=0;
		four=0;
		five=0;
		n_decline=0;
		n_imp_one=0;
		n_imp=0;
		total_num=0;

		for(j=0;j<20;j++)
			for(i=0;i<bridge_num;i++) //for current r, loop through data
			{

				left=data(i,j);			//bridge condition from current year
				right=data(i,j+1);		//bridge condition from next year

				if(left==r)
				{
					total_num++;

					drop=left-right;

					if(drop>0)
						n_decline++;
					if(drop==0)
						zero++;
					if(drop==1)
						one++;
					if(drop==2)
						two++;
					if(drop==3)
						three++;
```

```
                    if(drop==4)
                        four++;
                    if(drop==5)
                        five++;
                    if(drop==-1)
                        n_imp_one++;
                    if(drop<-1)
                        n_imp++;

                }
            }
            //calculate the average change in condition rating
            AVGCHN[count]=(one*1+two*2+three*3+four*4+five*5+0.5*n_imp)/
                                (total_num-n_imp_one);
            //record the total number of drops that occured from the current condition rating
            total_num_drops[count]=(one+two+three+four+five);

            count++;
    }

    //calculate the time required on average for each drop in condition rating
    for(i=0;i<5;i++)
        time[i]=1/AVGCHN[i];

    //write the deterioration array to file
    ofstream out_results("rate.dat", ios::app );//open file for output

    out_results<<title<<endl<<endl;

    out_results<<"drop"<<setw(15)<<"8-7"<<setw(15)<<
                "7-6"<<setw(15)<<"6-5"<<setw(15)<<"5-4"<<endl<<endl;

    out_results<<setw(19)<<AVGCHN[1]<<setw(15)<<
            AVGCHN[2]<<setw(15)<<AVGCHN[3]<<setw(15)<<AVGCHN[4]<<endl<<endl;

    out_results<<"time"<<setw(15)<<"8-7"<<setw(15)<<
                "7-6"<<setw(15)<<"6-5"<<setw(15)<<"5-4"<<endl<<endl;

    out_results<<setw(19)<<time[1]<<setw(15)<<
            time[2]<<setw(15)<<time[3]<<setw(15)<<time[4]<<endl<<endl;

    out_results<<"total # dropping"<<endl<<endl;
    out_results<<setw(19)<<total_num_drops[1]<<setw(15)<<total_num_drops[2]<<setw(15)
                <<total_num_drops[3]<<setw(15)<<total_num_drops[4]<<endl<<endl;

    out_results<<"________________________________________________________________________"<
<endl<<endl<<endl;


    return 0;

}
```

D.3 Present Value Cost Analysis (Visual Basic for Applications)

Module 1

```
Option Explicit
Sub PresentValue()
'This program was coded by Justin Zimmerman, a graduate research assistant
'in structural engineering at the University of Minnesota in 2006

'this macro performs a present value cost analysis which considers
'several different strategies for repairing/replacing the bridge
'decks of this project (Economic Strategies for the Repair and
'Replacement of Low Slump Overlaid Concrete Bridge Decks)
'The user of this program will specify certain input parameters in
'the sheet labeled GUI (graphical user interface). This allows the
'user to enter project specific data/assumptions or to use default
'values. The data needed for the cost analysis resides in the sheet
'Bridge Data. The data from in this sheet is derived primarily from
'the NBI database. The output from this program is placed in the sheet
'labled Output, and if repairs were needed to keep a bridges NBI deck
'condition above Rmin, output is also placed in the sheet labeled "need_work".

'read in all data from sheet Bridge data and store in arrays
'place the structure numbers in one array, and the rest of the
'data in a seperate array.


Dim BrgData(492, 31) As Double
Dim StrucNum(492) As String
Dim opt(17)    'leave opt's as variants so that if an option is not valid
               'a string may be placed in the opt instead of cost
Dim GUI As Worksheet
Dim Bridge_data As Worksheet
Dim Output As Worksheet
Dim need_work As Worksheet

Set GUI = ActiveWorkbook.Worksheets("GUI")
Set Bridge_data = ActiveWorkbook.Worksheets("Bridge data")
Set Output = ActiveWorkbook.Worksheets("Output")
Set need_work = ActiveWorkbook.Worksheets("need_work")

Output.Range("A3", "S494").Clear    'clear the contents of the two output sheets
need_work.Range("A3", "W494").Clear

Dim i As Integer, j As Integer, v As Integer
i = 0
j = 0
v = 0

Do Until IsEmpty(Bridge_data.Cells(i + 3, 1))
  StrucNum(i) = Bridge_data.Cells(i + 3, 1)
  For j = 0 To 31
    BrgData(i, j) = Bridge_data.Cells(i + 3, j + 2)
  Next
  i = i + 1
```

```
Loop

'read in data from sheet GUI
Dim discount As Double
Dim inflation As Double
Dim options(17) As Integer
Dim ReOv As Double
Dim DeckRe As Double
Dim MillPat As Double
Dim CostCurve As Integer
Dim MillInc As Double
Dim OverInc As Double
Dim current_bridge As String
Dim widening As Double
Dim secondMill As Double
Dim secondOver As Double
Dim Rmin As Integer
Dim delam(2) As Double
Dim min_delam As Double
Dim four_just_reached As Double

'current_bridge = GUI.Cells(2, 2)
discount = GUI.Cells(22, 2)
inflation = GUI.Cells(23, 2)
options(0) = GUI.Cells(4, 2)
options(1) = GUI.Cells(5, 2)
options(2) = GUI.Cells(6, 2)
options(3) = GUI.Cells(7, 2)
options(4) = GUI.Cells(8, 2)
options(5) = GUI.Cells(9, 2)
options(6) = GUI.Cells(10, 2)
options(7) = GUI.Cells(11, 2)
options(8) = GUI.Cells(12, 2)
options(9) = GUI.Cells(13, 2)
options(10) = GUI.Cells(14, 2)
options(11) = GUI.Cells(15, 2)
options(12) = GUI.Cells(16, 2)
options(13) = GUI.Cells(17, 2)
options(14) = GUI.Cells(18, 2)
options(15) = GUI.Cells(19, 2)
options(16) = GUI.Cells(20, 2)
options(17) = GUI.Cells(21, 2)
ReOv = GUI.Cells(24, 2)
DeckRe = GUI.Cells(25, 2)
MillPat = GUI.Cells(26, 2)
MillInc = GUI.Cells(27, 2)
OverInc = GUI.Cells(28, 2)
widening = GUI.Cells(29, 2)
secondMill = GUI.Cells(30, 2)
secondOver = GUI.Cells(31, 2)
Rmin = GUI.Cells(32, 2)
delam(0) = GUI.Cells(33, 2)
delam(1) = GUI.Cells(34, 2)
delam(2) = GUI.Cells(35, 2)

four_just_reached = 0.2
```

```
If Rmin = 4 Then min_delam = 0.2    'these are the values used for percent delamination when a deck
If Rmin = 5 Then min_delam = 0.1    'just reaches a condition state
If Rmin = 6 Then min_delam = 0.04


CostCurve = 1 'this variable was set up so that if at a later point a non-linear
            'cost curve was desired, it could easily be incorporated

Dim k As Integer, need_work2 As Integer
need_work2 = 0
k = 0

Do Until IsEmpty(Bridge_data.Cells(k + 3, 1))
If GUI.Cells(2, 2) = "all" Then
   current_bridge = Bridge_data.Cells(k + 3, 1)
End If
If GUI.Cells(2, 2) <> "all" Then
   current_bridge = GUI.Cells(2, 2)
End If

Dim lctn As Integer 'stores location of current bridge in
                  'array StrucNum
i = -1
Dim found As Integer
found = 0 ' when the entry is located, found will be changed to 1
         ' to exit the loop
Do While i < 493 And found = 0
   i = i + 1
   If i < 493 Then
      If StrComp(StrucNum(i), current_bridge) = 0 Then 'strcomp returns zero if the two
         found = 1                                    'strings are equal
      End If
   End If
Loop
If found = 0 Then 'check to make sure the structure number was located
   MsgBox ("invalid structure number") 'alert the user that bridge was
   GoTo earlyquit2                     'not located, and go to end of
End If                                 'program

lctn = i

'perform preliminary calculations

Dim new_area As Double          'area of extra 6' deck widening
Dim area As Double              'area of deck currently - uses roadway width
Dim redeck_area As Double       'area of deck used for redeck calcs - uses out to out width
Dim future_deck As Double       'cost of redecking in 20 years
Dim current_deck As Double      'cost of redecking now
Dim current_overlay As Double   'cost of re-overlaying now
Dim current_millpatch As Double 'cost of mill & patch repairs now
Dim det_type As Integer
Dim redeck_possible As Integer
Dim higher_than7 As Integer

'determine which of the three deterioration curves is appropriate for
'particular bridge under consideration
```

```
'type 0 - combined cast in place concrete and long max span length high
'traffic
'type 1 - combined long span length low traffic and short span length
'high traffic
'type 2 - short span length low traffic

If BrgData(lctn, 3) = 1 Then 'cast in place
   det_type = 0
   GoTo end_det_curve 'length and ADT don't have to be considered for cast in place
End If                'so skip to end of det curve selection code

If BrgData(lctn, 8) = 2 And BrgData(lctn, 7) = 2 Then 'long high
   det_type = 0
End If
If BrgData(lctn, 8) = 1 And BrgData(lctn, 7) = 2 Then 'short high
   det_type = 1
End If
If BrgData(lctn, 8) = 2 And BrgData(lctn, 7) = 1 Then 'long low
   det_type = 1
End If
If BrgData(lctn, 8) = 1 And BrgData(lctn, 7) = 1 Then 'short low
   det_type = 2
End If

end_det_curve:

area = BrgData(lctn, 4) * BrgData(lctn, 5)
redeck_area = BrgData(lctn, 4) * BrgData(lctn, 31)

'when a deck is replaced, new bridge deck must be widened by 6 feet
new_area = BrgData(lctn, 4) * 6

'determine what intial NBI rating should be
Dim current_cond As Double
current_cond = BrgData(lctn, 30)
i = 0
found = 0
Do While i < 22 And found = 0
   i = i + 1
   If BrgData(lctn, 30 - i) <> current_cond Then
      found = 1
   End If
Loop
If i > 1 Then
   current_cond = initial_NBI(current_cond, i - 1, det_type)
End If


'Det_to_4.Cells(k + 1, 1) = current_bridge
'Det_to_4.Cells(k + 1, 2) = deterioration(current_cond, det_type, 1, 400, 4)
'GoTo earlyquit


current_deck = (redeck_area * DeckRe + new_area * widening)
future_deck = current_deck * (1 + inflation / 12) ^ 240
current_overlay = area * ReOv
```

```
'delam(0) = 0.075    'percent delamination for NBI deck condition of 5 ranges from
                     '5% to 10% - so use 7.5%
'delam(1) = 0.035    'percent delamination for NBI deck condition of 6 ranges from
                     '2% to 5% so use 3.5%
'delam(2) = 0.01     'percent delamination for NBI deck condition of 7 is less than
                     '2% so use 1%

higher_than7 = 0
If BrgData(lctn, 30) > 7 Then higher_than7 = 1 'this sets a flag so that repair
'will be limited for bridges with NBI deck conditions of 8 or above

'mill and patch is not a repair option if there is over 10% delamination. NBI deck
'condition of 4 has 10-25% delamination, so only ratings of 5 and above are valid
'conditions for mill & patch to be an option
If BrgData(lctn, 30) > 4 And higher_than7 = 0 Then
  current_millpatch = area * delam(BrgData(lctn, 30) - 5) * MillPat
End If
If current_cond = 4 Then 'for bridges that just reached a NBI deck condition of 4
  current_millpatch = area * four_just_reached * MillPat
End If

'for box girder bridges and T beam bridges, redecking is not possible, use this
'variable to skip over options that consider redecking
redeck_possible = 1
If BrgData(lctn, 9) = 4 Or BrgData(lctn, 9) = 5 Or BrgData(lctn, 9) = 6 Then
  redeck_possible = -1
End If

Dim cond1 As Double, cond2 As Double, cond_final As Double, years1 As Double, years2 As Double
Dim pres_val As Double, final_val As Double, years3 As Double
Dim redeck_cost As Double, overlay_cost As Double, mill_cost As Double, mill_cost2 As Double
Dim overlay_cost2 As Double, cheapest As Double, cheapest_opt As Integer



'check to see if any intervention is necessary

If GUI.Cells(2, 2) = "all" Then
  If BrgData(lctn, 30) > Rmin Then
    years1 = deterioration(current_cond, det_type, 1, 20, Rmin)
    If years1 = -1 Or years1 = 20 Then
      Output.Cells(k + 3, 2) = "Bridge will not deteriorate below Rmin in 20 years, final rating = "
      Output.Cells(k + 3, 3) = Round(deterioration(current_cond, det_type, 2, 20, 0), 1)
      Output.Cells(k + 3, 1) = current_bridge
      GoTo earlyquit
    End If
  End If
End If

If GUI.Cells(2, 2) <> "all" Then
  If BrgData(lctn, 30) > Rmin Then
    years1 = deterioration(current_cond, det_type, 1, 20, Rmin)
    If years1 = -1 Or years1 = 20 Then
      Output.Cells(3, 2) = "Bridge will not deteriorate below Rmin in 20 years, final rating = "
```

```
            Output.Cells(3, 3) = Round(deterioration(current_cond, det_type, 2, 20, 0), 1)
            Output.Cells(3, 1) = current_bridge
            GUI.Cells(12, 7) = 0
            GoTo earlyquit
        End If
    End If
End If

need_work2 = need_work2 + 1 'counts the number of bridges that actually will need
                        'intervention in the next 20 years

mill_cost = 0
cond1 = 0
cond2 = 0
cond_final = 0
years1 = 0
years2 = 0
pres_val = 0
final_val = 0
years3 = 0
redeck_cost = 0
overlay_cost = 0
'option #1 Redeck now
If options(0) = 1 Then
If redeck_possible = -1 Then
    opt(0) = "redeck not possible"
    GoTo begin_opt2
End If
cond1 = 9
cond_final = deterioration(cond1, det_type, 2, 20, 0)
final_val = cost_curve(cond_final, future_deck, 1)
opt(0) = current_deck - final_val * (1 + discount / 12) ^ (-240)
End If 'end option #1
begin_opt2:



mill_cost = 0
cond1 = 0
cond2 = 0
cond_final = 0
years1 = 0
years2 = 0
pres_val = 0
final_val = 0
years3 = 0
redeck_cost = 0
overlay_cost = 0
'option #2 Let deteriorate to Rmin then redeck
If options(1) = 1 Then
If redeck_possible = -1 Then
    opt(1) = "redeck not possible"
    GoTo begin_opt3
End If
If BrgData(lctn, 30) < Rmin + 1 Then
    opt(1) = "NAO"
```

```
    GoTo begin_opt3
End If
years1 = deterioration(current_cond, det_type, 1, 20, Rmin)
years2 = 20 - years1
cond_final = deterioration(9, det_type, 2, years2, 0)
final_val = cost_curve(cond_final, future_deck, CostCurve)
redeck_cost = current_deck * (1 + inflation / 12) ^ (12 * years1)
opt(1) = redeck_cost * (1 + discount / 12) ^ (-12 * years1) - final_val * (1 + discount / 12) ^ (-240)

End If 'end option #2
begin_opt3:




mill_cost = 0
cond1 = 0
cond2 = 0
cond_final = 0
years1 = 0
years2 = 0
pres_val = 0
final_val = 0
years3 = 0
redeck_cost = 0
overlay_cost = 0
'option #3 Reoverlay now, nothing else if rating stays above Rmin

If higher_than7 = 1 Then 'reoverlaying now doesn't make sense
    opt(2) = "NAO"       'for bridges with current NBI deck condition > 7
    opt(3) = "NAO"
    opt(4) = "NAO"
    opt(5) = "NAO"
    GoTo begin_opt7
End If

If options(2) = 2 And options(3) + options(4) + options(5) <> 6 Then
    MsgBox ("Invalid selection of options, select option 3 as well")
    GoTo earlyquit2
End If 'option three must be included for options 4,5,and 6 to function properly
If options(2) = 1 Then
cond1 = current_cond + OverInc
years1 = deterioration(cond1, det_type, 1, 20, Rmin)
If years1 = -2 Then
    opt(2) = "DLLE"
    opt(3) = "DLLE"
    opt(4) = "DLLE"
    opt(5) = "DLLE"
    GoTo begin_opt7
End If
If years1 <> -1 And years1 < 20 Then
    opt(2) = "DLLE"
    GoTo begin_opt4
End If
cond_final = deterioration(cond1, det_type, 2, 20, 0)
final_val = cost_curve(cond_final, future_deck, CostCurve)
```

```
opt(2) = current_overlay - final_val * (1 + discount / 12) ^ (-240)
opt(3) = "Redundant"
opt(4) = "Redundant"
opt(5) = "Redundant"
GoTo begin_opt7
End If
'end option #3
begin_opt4:


mill_cost = 0
cond1 = 0
cond2 = 0
cond_final = 0
years1 = 0
years2 = 0
pres_val = 0
final_val = 0
years3 = 0
redeck_cost = 0
overlay_cost = 0
'option #4 reoverlay now, and redeck when Rmin is reached
If options(3) = 1 Then
If redeck_possible = -1 Then
   opt(3) = "redeck not possible"
   GoTo begin_opt5
End If
cond1 = current_cond + OverInc
years1 = deterioration(cond1, det_type, 1, 20, Rmin) 'the number of years to reach Rmin
cond2 = 9
years2 = 20 - years1
cond_final = deterioration(cond2, det_type, 2, years2, 0)
final_val = cost_curve(cond_final, future_deck, CostCurve)
redeck_cost = current_deck * (1 + inflation / 12) ^ (12 * years1) 'determine cost of redecking in future
opt(3) = current_overlay + redeck_cost * (1 + discount / 12) ^ (-12 * years1) - final_val * (1 + discount / 12) ^ (-
240)
End If 'end option #4
begin_opt5:


mill_cost = 0
cond1 = 0
cond2 = 0
cond_final = 0
years1 = 0
years2 = 0
pres_val = 0
final_val = 0
years3 = 0
redeck_cost = 0
overlay_cost = 0
'option #5 Reoverlay now, reoverlay again when Rmin is reached
If options(4) = 1 Then
```

```
cond1 = current_cond + OverInc
years1 = deterioration(cond1, det_type, 1, 20, Rmin)
cond2 = Rmin + secondOver
years2 = 20 - years1
cond_final = deterioration(cond2, det_type, 2, years2, 0)
If cond_final < Rmin Then
   opt(4) = "DLLE" 'doesn't last long enough
   GoTo dlle5
End If
final_val = cost_curve(cond_final, future_deck, CostCurve)
overlay_cost = current_overlay * (1 + inflation / 12) ^ (12 * years1)
opt(4) = current_overlay + overlay_cost * (1 + discount / 12) ^ (-12 * years1) - final_val * (1 + discount / 12) ^ (-
240)
dlle5:
End If 'end option #5



mill_cost = 0
cond1 = 0
cond2 = 0
cond_final = 0
years1 = 0
years2 = 0
pres_val = 0
final_val = 0
years3 = 0
redeck_cost = 0
overlay_cost = 0
'option #6 reoverlay now, mill and patch when Rmin is reached
If options(5) = 1 Then
cond1 = current_cond + OverInc
years1 = deterioration(cond1, det_type, 1, 20, Rmin)
cond2 = Rmin + secondMill
years2 = 20 - years1
cond_final = deterioration(cond2, det_type, 2, years2, 0)
If cond_final < Rmin Then
   opt(5) = "DLLE" 'doesn't last long enough
   GoTo dlle6
End If
final_val = cost_curve(cond_final, future_deck, CostCurve)
mill_cost = area * min_delam * MillPat * (1 + inflation / 12) ^ (12 * years1)
opt(5) = current_overlay + mill_cost * (1 + discount / 12) ^ (-12 * years1) - final_val * (1 + discount / 12) ^ (-240)
dlle6:

End If ' end option #6
begin_opt7:



mill_cost = 0
cond1 = 0
cond2 = 0
cond_final = 0
```

```
years1 = 0
years2 = 0
pres_val = 0
final_val = 0
years3 = 0
redeck_cost = 0
overlay_cost = 0
'option #7, let deteriorate to Rmin, then reoverlay, do nothing else if rating stays above Rmin
If options(6) = 2 And options(7) + options(8) + options(9) <> 6 Then
   MsgBox ("Invalid selection of options, select option 7 as well")
   GoTo earlyquit2
End If 'option 7 must be included for options 8,9, and 10 to function properly
If options(6) = 1 Then
If BrgData(lctn, 30) < Rmin + 1 Then
   opt(6) = "NAO"
   GoTo begin_opt8
End If
years1 = deterioration(current_cond, det_type, 1, 20, Rmin)
cond1 = Rmin + OverInc
years2 = deterioration(cond1, det_type, 1, 20 - years1, Rmin)
If years2 = -2 Then
   opt(6) = "DLLE"
   opt(7) = "DLLE"
   opt(8) = "DLLE"
   opt(9) = "DLLE"
   GoTo begin_opt11
End If
If years2 <> -1 And years2 < 20 Then
   opt(6) = "DLLE"
   GoTo begin_opt8
End If
cond_final = deterioration(cond1, det_type, 2, 20 - years1, 0)
final_val = cost_curve(cond_final, future_deck, CostCurve)
overlay_cost = current_overlay * (1 + inflation / 12) ^ (12 * years1)
opt(6) = overlay_cost * (1 + discount / 12) ^ (-12 * years1) - final_val * (1 + discount / 12) ^ (-240)
opt(7) = "Redundant"
opt(8) = "Redundant"
opt(9) = "Redundant"
GoTo begin_opt11
End If
'end option #7
begin_opt8:


mill_cost = 0
cond1 = 0
cond2 = 0
cond_final = 0
years1 = 0
years2 = 0
pres_val = 0
final_val = 0
years3 = 0
redeck_cost = 0
overlay_cost = 0
'option #8 Let deteriorate to Rmin then reoverlay,then redeck
```

```
If options(7) = 1 Then
If redeck_possible = -1 Then
   opt(7) = "redeck not possible"
   GoTo begin_opt9
End If
If BrgData(lctn, 30) < Rmin + 1 Then
   opt(7) = "NAO"
   GoTo begin_opt9
End If
years1 = deterioration(current_cond, det_type, 1, 20, Rmin)
cond1 = Rmin + OverInc
years2 = deterioration(cond1, det_type, 1, 20 - years1, Rmin)
overlay_cost = current_overlay * (1 + inflation / 12) ^ (12 * years1)
cond2 = 9
cond_final = deterioration(cond2, det_type, 2, 20 - years1 - years2, 0)
final_val = cost_curve(cond_final, future_deck, CostCurve)
redeck_cost = current_deck * (1 + inflation / 12) ^ (12 * (years1 + years2))
opt(7) = overlay_cost * (1 + discount / 12) ^ (-12 * years1) + redeck_cost * (1 + discount / 12) ^ (-12 * (years1 +
years2)) - final_val * (1 + discount / 12) ^ (-240)
End If 'end option #8
begin_opt9:




mill_cost = 0
cond1 = 0
cond2 = 0
cond_final = 0
years1 = 0
years2 = 0
pres_val = 0
final_val = 0
years3 = 0
redeck_cost = 0
overlay_cost = 0
'option #9 let deteriorate to Rmin then reoverlay, let deteriorate to Rmin then reoverlay
If options(8) = 1 Then
If BrgData(lctn, 30) < Rmin + 1 Then
   opt(8) = "NAO"
   GoTo begin_opt10
End If
years1 = deterioration(current_cond, det_type, 1, 20, Rmin)
cond1 = Rmin + OverInc
years2 = deterioration(cond1, det_type, 1, 20 - years1, Rmin)
overlay_cost = current_overlay * (1 + inflation / 12) ^ (12 * years1)
cond2 = Rmin + secondOver
cond_final = deterioration(cond2, det_type, 2, 20 - years1 - years2, 0)
If cond_final < Rmin Then
   opt(8) = "DLLE" 'doesn't last long enough
   GoTo dlle9
End If
final_val = cost_curve(cond_final, future_deck, CostCurve)
overlay_cost2 = current_overlay * (1 + inflation / 12) ^ (12 * (years1 + years2))
opt(8) = overlay_cost * (1 + discount / 12) ^ (-12 * years1) + overlay_cost2 * (1 + discount / 12) ^ (-12 * (years1 +
years2)) - final_val * (1 + discount / 12) ^ (-240)
```

```
dlle9:
End If 'end option #9
begin_opt10:




mill_cost = 0
cond1 = 0
cond2 = 0
cond_final = 0
years1 = 0
years2 = 0
pres_val = 0
final_val = 0
years3 = 0
redeck_cost = 0
overlay_cost = 0
'option #10, Let deterioate to Rmin, then reoverlay, let deterioate to Rmin, then mill and patch
If options(9) = 1 Then
If BrgData(lctn, 30) < Rmin + 1 Then
   opt(9) = "NAO"
   GoTo begin_opt11
End If
years1 = deterioration(current_cond, det_type, 1, 20, Rmin)
cond1 = Rmin + OverInc
years2 = deterioration(cond1, det_type, 1, 20 - years1, Rmin)
overlay_cost = current_overlay * (1 + inflation / 12) ^ (12 * years1)
cond2 = Rmin + secondMill
cond_final = deterioration(cond2, det_type, 2, 20 - years1 - years2, 0)
If cond_final < Rmin Then
   opt(9) = "DLLE" 'doesn't last long enough
   GoTo dlle10
End If
final_val = cost_curve(cond_final, future_deck, CostCurve)
mill_cost = area * min_delam * MillPat * (1 + inflation / 12) ^ (12 * (years1 + years2))
opt(9) = overlay_cost * (1 + discount / 12) ^ (-12 * years1) + mill_cost * (1 + discount / 12) ^ (-12 * (years1 +
years2)) - final_val * (1 + discount / 12) ^ (-240)
dlle10:
End If
'end option #10
begin_opt11:




mill_cost = 0
cond1 = 0
cond2 = 0
cond_final = 0
years1 = 0
years2 = 0
pres_val = 0
final_val = 0
```

```
years3 = 0
redeck_cost = 0
overlay_cost = 0
'option #11, Mill and patch now, nothing else if rating stays above Rmin
If higher_than7 = 1 Then    'mill and patching now doesn't make sense for bridges
    opt(10) = "NAO"         'with current deck conditions above 7
    opt(11) = "NAO"
    opt(12) = "NAO"
    opt(13) = "NAO"
    GoTo begin_opt15
End If

If options(10) = 2 And options(11) + options(12) + options(13) <> 6 Then
    MsgBox ("Invalid selection of options, select option 11 as well")
    GoTo earlyquit2
End If 'option 11 must be included for options 12,13,and 14 to function properly
If options(10) = 1 Then
If current_cond < 4 Then 'mill and patch is not an option when the condition state is
    opt(10) = "NA0"              'less than 4 (must be less than 10% delamination)
    GoTo begin_opt12
End If
cond1 = current_cond + MillInc
years1 = deterioration(cond1, det_type, 1, 20, Rmin)
If years1 = -2 Then
    opt(10) = "DLLE"
    opt(11) = "DLLE"
    opt(12) = "DLLE"
    opt(13) = "DLLE"
    GoTo begin_opt15
End If
If years1 <> -1 And years1 < 20 Then
    opt(10) = "DLLE"
    GoTo begin_opt12
End If
cond_final = deterioration(cond1, det_type, 2, 20, 0)
final_val = cost_curve(cond_final, future_deck, CostCurve)
opt(10) = current_millpatch - final_val * (1 + discount / 12) ^ (-240)
opt(11) = "Redundant"
opt(12) = "Redundant"
opt(13) = "Redundant"
GoTo begin_opt15
End If
'end option #11
begin_opt12:


mill_cost = 0
cond1 = 0
cond2 = 0
cond_final = 0
years1 = 0
years2 = 0
pres_val = 0
final_val = 0
years3 = 0
redeck_cost = 0
```

```
overlay_cost = 0
'option #12 mill & patch now, redeck when Rmin is reached
If options(11) = 1 Then
If redeck_possible = -1 Then
   opt(11) = "redeck not possible"
   GoTo begin_opt13
End If
If current_cond < 4 Then 'mill and patch is not an option when the condition state is
   opt(11) = "NA0"             'less than 4 (must be less than 10% delamination)
   GoTo begin_opt13
End If
cond1 = current_cond + MillInc
years1 = deterioration(cond1, det_type, 1, 20, Rmin)
cond2 = 9
years2 = 20 - years1
cond_final = deterioration(cond2, det_type, 2, years2, 0)
final_val = cost_curve(cond_final, future_deck, CostCurve)
redeck_cost = current_deck * (1 + inflation / 12) ^ (12 * years1)
opt(11) = current_millpatch + redeck_cost * (1 + discount / 12) ^ (-12 * years1) - final_val * (1 + discount / 12) ^ (-
240)
End If 'end option #12
begin_opt13:




mill_cost = 0
cond1 = 0
cond2 = 0
cond_final = 0
years1 = 0
years2 = 0
pres_val = 0
final_val = 0
years3 = 0
redeck_cost = 0
overlay_cost = 0
'option #13 mill and patch now, mill and patch when Rmin is again reached
If options(12) = 1 Then
If current_cond < 4 Then 'mill and patch is not an option when the condition state is
   opt(12) = "NA0"           'less than 4
   GoTo begin_opt14:
   End If
cond1 = current_cond + MillInc
years1 = deterioration(cond1, det_type, 1, 20, Rmin)
cond2 = Rmin + secondMill
years2 = 20 - years1
cond_final = deterioration(cond2, det_type, 2, years2, 0)
If cond_final < Rmin Then
   opt(12) = "DLLE" 'doesn't last long enough
   GoTo dlle13
End If
final_val = cost_curve(cond_final, future_deck, CostCurve)
mill_cost = area * min_delam * MillPat * (1 + inflation / 12) ^ (12 * years1)
```

```
opt(12) = current_millpatch + mill_cost * (1 + discount / 12) ^ (-12 * years1) - final_val * (1 + discount / 12) ^ (-
240)
dlle13:
End If 'end option #13
begin_opt14:



mill_cost = 0
cond1 = 0
cond2 = 0
cond_final = 0
years1 = 0
years2 = 0
pres_val = 0
final_val = 0
years3 = 0
redeck_cost = 0
overlay_cost = 0
'option #14 mill and patch now, reoverlay when Rmin is reached
If options(13) = 1 Then
If current_cond < 4 Then 'mill and patch is not an option when the condition state is
   opt(13) = "NA0"            'less than 4 (must be less than 10% delamination)
   GoTo begin_opt15:
End If
cond1 = current_cond + MillInc
years1 = deterioration(cond1, det_type, 1, 20, Rmin)
years2 = 20 - years1
cond2 = Rmin + secondOver
cond_final = deterioration(cond2, det_type, 2, years2, 0)
If cond_final < Rmin Then
   opt(13) = "DLLE" 'doesn't last long enough
   GoTo dlle14
End If
final_val = cost_curve(cond_final, future_deck, CostCurve)
overlay_cost = current_overlay * (1 + inflation / 12) ^ (12 * years1)
opt(13) = current_millpatch + overlay_cost * (1 + discount / 12) ^ (-12 * years1) - final_val * (1 + discount / 12) ^ (-
240)
dlle14:
End If 'end option #14
begin_opt15:




mill_cost = 0
cond1 = 0
cond2 = 0
cond_final = 0
years1 = 0
years2 = 0
pres_val = 0
final_val = 0
years3 = 0
redeck_cost = 0
overlay_cost = 0
```

```
'option #15, Let deteriorate to Rmin, then mill and patch, nothing else if rating stays above R
If options(14) = 2 And options(15) + options(16) + options(17) <> 6 Then
   MsgBox ("Invalid selection of options, select option 15 as well")
   GoTo earlyquit2
End If 'option 15 must be included for options 16,17,and 18 to function properly
If options(14) = 1 Then
If BrgData(lctn, 30) < Rmin + 1 Then
   opt(14) = "NAO"
   GoTo begin_opt16
End If
years1 = deterioration(current_cond, det_type, 1, 20, Rmin)
cond1 = Rmin + MillInc
years2 = deterioration(cond1, det_type, 1, 20 - years1, Rmin)
If years2 = -2 Then
   opt(14) = "DLLE"
   opt(15) = "DLLE"
   opt(16) = "DLLE"
   opt(17) = "DLLE"
   GoTo end_opt
End If
If years2 <> -1 And years2 < 20 Then
   opt(14) = "DLLE"
   GoTo begin_opt16
End If
cond_final = deterioration(cond1, det_type, 2, 20 - years1, 0)
final_val = cost_curve(cond_final, future_deck, CostCurve)
mill_cost = area * min_delam * MillPat * (1 + inflation / 12) ^ (12 * years1)
opt(14) = mill_cost * (1 + discount / 12) ^ (-12 * years1) - final_val * (1 + discount / 12) ^ (-240)
opt(15) = "Redundant"
opt(16) = "Redundant"
opt(17) = "Redundant"
GoTo end_opt
End If
'end option #15
begin_opt16:



mill_cost = 0
cond1 = 0
cond2 = 0
cond_final = 0
years1 = 0
years2 = 0
pres_val = 0
final_val = 0
years3 = 0
redeck_cost = 0
overlay_cost = 0
'option #16, let deteriorate to Rmin, then mill and patch, then redeck when Rmin is reached
If options(15) = 1 Then
If redeck_possible = -1 Then
   opt(15) = "redeck not possible"
   opt(11) = "redeck not possible"
   opt(3) = "redeck not possible"
```

```
   GoTo begin_opt17
End If
If BrgData(lctn, 30) < Rmin + 1 Then
   opt(15) = "NAO"
   GoTo begin_opt17
End If
years1 = deterioration(current_cond, det_type, 1, 20, Rmin)
cond1 = Rmin + MillInc
years2 = deterioration(cond1, det_type, 1, 20 - years1, Rmin)
mill_cost = area * min_delam * MillPat * (1 + inflation / 12) ^ (12 * years1)
cond2 = 9
cond_final = deterioration(cond2, det_type, 2, 20 - years1 - years2, 0)
final_val = cost_curve(cond_final, future_deck, CostCurve)
redeck_cost = current_deck * (1 + inflation / 12) ^ (12 * (years1 + years2))
opt(15) = mill_cost * (1 + discount / 12) ^ (-12 * years1) + redeck_cost * (1 + discount / 12) ^ (-12 * (years1 +
years2)) - final_val * (1 + discount / 12) ^ (-240)
End If
'end option #16
begin_opt17:



mill_cost = 0
cond1 = 0
cond2 = 0
cond_final = 0
years1 = 0
years2 = 0
pres_val = 0
final_val = 0
years3 = 0
redeck_cost = 0
overlay_cost = 0
'option #17 let deteriorate to Rmin then mill&patch, mill&patch at Rmin again
If options(16) = 1 Then
If BrgData(lctn, 30) < Rmin + 1 Then
   opt(16) = "NAO"
   GoTo begin_opt18
End If
years1 = deterioration(current_cond, det_type, 1, 20, Rmin)
cond1 = Rmin + MillInc
years2 = deterioration(cond1, det_type, 1, 20 - years1, Rmin)
mill_cost = area * min_delam * MillPat * (1 + inflation / 12) ^ (12 * years1)
cond2 = Rmin + secondMill
cond_final = deterioration(cond2, det_type, 2, 20 - years1 - years2, 0)
If cond_final < Rmin Then
   opt(16) = "DLLE" 'doesn't last long enough
   GoTo dlle17
End If
final_val = cost_curve(cond_final, future_deck, CostCurve)
mill_cost2 = area * min_delam * MillPat * (1 + inflation / 12) ^ (12 * (years2 + years1))
opt(16) = mill_cost * (1 + discount / 12) ^ (-12 * years1) + mill_cost2 * (1 + discount / 12) ^ (-12 * (years2 +
years1)) - final_val * (1 + discount / 12) ^ (-240)
dlle17:
End If 'end option #17
begin_opt18:
```

```
mill_cost = 0
cond1 = 0
cond2 = 0
cond_final = 0
years1 = 0
years2 = 0
pres_val = 0
final_val = 0
years3 = 0
redeck_cost = 0
overlay_cost = 0
'option #18, Let deteriorate to Rmin, then mill and patch, let deteriorate to Rmin, then reoverlay
If options(17) = 1 Then
If BrgData(lctn, 30) < Rmin + 1 Then
   opt(17) = "NAO"
   GoTo end_opt
End If
years1 = deterioration(current_cond, det_type, 1, 20, Rmin)
cond1 = Rmin + MillInc
years2 = deterioration(cond1, det_type, 1, 20 - years1, Rmin)
mill_cost = area * min_delam * MillPat * (1 + inflation / 12) ^ (12 * years1)
cond2 = Rmin + secondOver
cond_final = deterioration(cond2, det_type, 2, 20 - years1 - years2, 0)
If cond_final < Rmin Then
   opt(17) = "DLLE" 'doesn't last long enough
   GoTo dlle18
End If
final_val = cost_curve(cond_final, future_deck, CostCurve)
overlay_cost = current_overlay * (1 + inflation / 12) ^ (12 * (years2 + years1))
opt(17) = mill_cost * (1 + discount / 12) ^ (-12 * years1) + overlay_cost * (1 + discount / 12) ^ (-12 * (years2 +
years1)) - final_val * (1 + discount / 12) ^ (-240)
dlle18:
End If
'end option #18
end_opt:


cheapest_opt = 0
cheapest = -1000000000
For i = 0 To 17 'put the most expensive option in cheapest
   If opt(i) > cheapest And options(i) = 1 And opt(i) <> "NAO" And opt(i) <> "DLLE" And opt(i) <> "Redundant"
And opt(i) <> "NA0" And opt(i) <> "redeck not possible" Then
      cheapest = opt(i)
      cheapest_opt = i + 1
   End If
Next


i = 0
For i = 0 To 17
   If options(i) = 2 Then
```

```
        opt(i) = "option not selected"
    End If
    If opt(i) < cheapest And options(i) = 1 Then
        cheapest = opt(i)
        cheapest_opt = i + 1
    End If
Next

If GUI.Cells(2, 2) = "all" Then
For i = 0 To 17
    need_work.Cells(v + 3, i + 2) = opt(i)
Next


need_work.Cells(v + 3, i + 2) = cheapest_opt
i = i + 1
need_work.Cells(v + 3, i + 2) = cheapest

need_work.Cells(v + 3, 22) = det_type

'place the options in the output sheet

Output.Cells(k + 3, 1) = current_bridge 'place the structure number for the current bridge
i = 0                               'in the output sheet
For i = 0 To 17
    If options(i) = 2 Then
        opt(i) = "option not selected"
    End If
    Output.Cells(k + 3, i + 2) = opt(i)

Next


need_work.Cells(v + 3, 1) = current_bridge 'place the structure number for the current bridge
'in the output sheet

need_work.Cells(v + 3, 23) = BrgData(lctn, 30)

v = v + 1 'variable is incremented only when a bridge needed work
End If

If GUI.Cells(2, 2) <> "all" Then
For i = 0 To 17
    need_work.Cells(3, i + 2) = opt(i)
Next


need_work.Cells(3, i + 2) = cheapest_opt
i = i + 1
need_work.Cells(3, i + 2) = cheapest

need_work.Cells(3, 22) = det_type

'place the options in the output sheet

Output.Cells(3, 1) = current_bridge 'place the structure number for the current bridge
```

```
i = 0                           'in the output sheet
For i = 0 To 17
    If options(i) = 2 Then
        opt(i) = "option not selected"
    End If
    Output.Cells(3, i + 2) = opt(i)

Next


need_work.Cells(3, 1) = current_bridge 'place the structure number for the current bridge
'in the output sheet

need_work.Cells(3, 23) = BrgData(lctn, 30)

If GUI.Cells(2, 2) <> "all" Then
    GUI.Cells(12, 7) = 1
End If

End If


earlyquit:

k = k + 1

Loop

earlyquit2:
If GUI.Cells(2, 2) = "all" Then
    GUI.Cells(12, 7) = need_work2
End If

End Sub
```

Module 2

```
Option Explicit

'this function uses deterioration curves calculated in the data analysis
'portion of the project to determine what the intial condition of the deck
'should be based on how many years it has been at it's present NBI deck
'condition state

Function initial_NBI(present As Double, years As Integer, det_type As Integer) As Double

Dim slopes(5, 5) As Double 'contains the data for the deterioration curves created in
                        'the data analysis portion of the project
                      'rows 0 and 1 are for type 0 deterioration
slopes(0, 0) = 2.89091  'years to drop from 9 to 8
slopes(0, 1) = 2.89091  'years to drop from 8 to 7
slopes(0, 2) = 7.83824  'years to drop from 7 to 6
slopes(0, 3) = 18.4     'years to drop from 6 to 5
slopes(0, 4) = 12.8571     'years to drop from 5 to 4
slopes(0, 5) = 12.8571     'years to drop from 4 to 3


slopes(1, 0) = 0.34591  'slope from 9 to 8 (in reality is negative)
slopes(1, 1) = 0.34591  'slope from 8 to 7
slopes(1, 2) = 0.12757  'slope from 7 to 6
slopes(1, 3) = 0.054347 'slope from 6 to 5
slopes(1, 4) = 0.077778 'slope from 5 to 4
slopes(1, 5) = 0.077778 'slope from 4 to 3

slopes(2, 0) = 4.34831  'rows 2 and 3 are for type 1 deterioration
slopes(2, 1) = 4.34831
slopes(2, 2) = 12.2238
slopes(2, 3) = 18.7273
slopes(2, 4) = 12.8571
slopes(2, 5) = 12.8571

slopes(3, 0) = 0.22997
slopes(3, 1) = 0.22997
slopes(3, 2) = 0.081807
slopes(3, 3) = 0.053397
slopes(3, 4) = 0.077778
slopes(3, 5) = 0.077778

slopes(4, 0) = 5.49688  'rows 4 and 5 are for type 2 deterioration
slopes(4, 1) = 5.49688
slopes(4, 2) = 17.5984
slopes(4, 3) = 30.7241
slopes(4, 4) = 12.8571
slopes(4, 5) = 12.8571

slopes(5, 0) = 0.18192
slopes(5, 1) = 0.18192
slopes(5, 2) = 0.056823
slopes(5, 3) = 0.032547
slopes(5, 4) = 0.077778
```

```
slopes(5, 5) = 0.077778

Dim present_place As Integer
If present = 9 Then
    present_place = 0
End If
If present = 8 Then
    present_place = 1
End If
If present = 7 Then
    present_place = 2
End If
If present = 6 Then
   present_place = 3
End If
If present = 5 Then
    present_place = 4
End If
If present = 4 Then
    present_place = 5
End If

Dim R_current As Double

initial_NBI = present - years * slopes(det_type * 2 + 1, present_place)

If initial_NBI < present - 0.75 Then 'limit decrease in condition to 3/4 a point. Some bridges may
    initial_NBI = present - 0.75      'be performing above average and therefore may remain at a given
End If                                'condition state longer than average. These bridges shouldn't have
                                     'inital conditions lower than 1 point below present conditions so
                                     'cutoff deterioration at 3/4 point to allow for this


End Function
```

Module 3

```
Option Explicit

'this function uses the deterioration curves calculated in the
'data analysis portion of the project to calculate the condition
'of a deck at some time in the future. It returns either the number
'of years to reach a specified NBI rating given an intial condition (an_type=1)
'or the condition of the deck given an intial condition and the number
'of years the deck is allowed to deteriorate. If years are being returned
'the number of years is rounded up or down to the nearest whole number

Function deterioration(condition As Double, det_type As Integer, an_type As Integer, num_years As Double,
rating_to_reach As Integer) As Double


Dim slopes(5, 5) As Double 'contains the data for the deterioration curves created in
                        'the data analysis portion of the project
                      'rows 0 and 1 are for type 0 deterioration
slopes(0, 0) = 2.89091  'years to drop from 9 to 8
slopes(0, 1) = 2.89091  'years to drop from 8 to 7
slopes(0, 2) = 7.83824  'years to drop from 7 to 6
slopes(0, 3) = 18.4     'years to drop from 6 to 5
slopes(0, 4) = 12.8571     'years to drop from 5 to 4
slopes(0, 5) = 12.8571     'years to drop from 4 to 3


slopes(1, 0) = 0.34591  'slope from 9 to 8 (in reality is negative)
slopes(1, 1) = 0.34591  'slope from 8 to 7
slopes(1, 2) = 0.12757  'slope from 7 to 6
slopes(1, 3) = 0.054347 'slope from 6 to 5
slopes(1, 4) = 0.077778 'slope from 5 to 4
slopes(1, 5) = 0.077778 'slope from 4 to 3

slopes(2, 0) = 4.34831  'rows 2 and 3 are for type 1 deterioration
slopes(2, 1) = 4.34831
slopes(2, 2) = 12.2238
slopes(2, 3) = 18.7273
slopes(2, 4) = 12.8571
slopes(2, 5) = 12.8571

slopes(3, 0) = 0.22997
slopes(3, 1) = 0.22997
slopes(3, 2) = 0.081807
slopes(3, 3) = 0.053397
slopes(3, 4) = 0.077778
slopes(3, 5) = 0.077778

slopes(4, 0) = 5.49688  'rows 4 and 5 are for type 2 deterioration
slopes(4, 1) = 5.49688
slopes(4, 2) = 17.5984
slopes(4, 3) = 30.7241
slopes(4, 4) = 12.8571
slopes(4, 5) = 12.8571
```

```
slopes(5, 0) = 0.18192
slopes(5, 1) = 0.18192
slopes(5, 2) = 0.056823
slopes(5, 3) = 0.032547
slopes(5, 4) = 0.077778
slopes(5, 5) = 0.077778

Dim column As Integer, i As Integer, j As Integer, num As Integer
Dim remainder As Double, partial_drop As Double, whole_drop As Double, total_years As Double
Dim final_slope As Double

If an_type = 1 Then

  If condition <= rating_to_reach Then 'first check to make sure that the current condition
    deterioration = -2          'of the bridge is higher than the rating that it is
    GoTo end_func               'deterioration to, and return -2 if its not
  End If
  If condition <= 9 And condition >= 8 Then
    column = 0
    remainder = condition - 8
    num = 8
  End If
  If condition < 8 And condition >= 7 Then
    column = 1
    remainder = condition - 7
    num = 7
  End If
  If condition < 7 And condition >= 6 Then
    column = 2
    remainder = condition - 6
    num = 6
  End If
  If condition < 6 And condition >= 5 Then
    column = 3
    remainder = condition - 5
    num = 5
  End If
  If condition < 5 And condition >= 4 Then
    column = 4
    remainder = condition - 4
    num = 4
  End If
  partial_drop = remainder / slopes(det_type * 2 + 1, column)


  i = column + 1
  j = 0
  whole_drop = 0
  Do While j < num - rating_to_reach
    whole_drop = whole_drop + slopes(det_type * 2, i)
    i = i + 1
    j = j + 1
  Loop
  total_years = partial_drop + whole_drop
  deterioration = Round(total_years) 'round total_years to integer before returning
  If (deterioration) > num_years Then
```

```
        deterioration = -1
    End If
    'debugging code
    i = 3
End If

Dim years_left As Double, check As Double, whole_condition As Double

If an_type = 2 Then

    If condition <= 9 And condition >= 8 Then
        column = 0
        remainder = condition - 8
        whole_condition = 8
    End If
    If condition < 8 And condition >= 7 Then
        column = 1
        remainder = condition - 7
        whole_condition = 7
    End If
    If condition < 7 And condition >= 6 Then
        column = 2
        remainder = condition - 6
        whole_condition = 6
    End If
    If condition < 6 And condition >= 5 Then
        column = 3
        remainder = condition - 5
        whole_condition = 5
    End If
    If condition < 5 And condition >= 4 Then
        column = 4
        remainder = condition - 4
        whole_condition = 4
    End If
    If condition < 4 And condition >= 3 Then
        column = 5
        remainder = condition - 3
        whole_condition = 3
    End If
    partial_drop = remainder / slopes(det_type * 2 + 1, column)

    If partial_drop > num_years Then
        deterioration = condition - num_years * slopes(det_type * 2 + 1, column)
        GoTo end_type_two
    End If

    years_left = num_years - partial_drop

    If column < 4 Then
        check = slopes(det_type * 2, column + 1)
    End If

    If column < 5 Then
        final_slope = slopes(det_type * 2 + 1, column + 1)
    End If
```

```
    If column = 5 Then
        final_slope = slopes(det_type * 2 + 1, column)
    End If

    i = column + 1

    Do While check < years_left And i < 5
        years_left = years_left - check
        i = i + 1
        check = slopes(det_type * 2, i)
        whole_condition = whole_condition - 1
        final_slope = slopes(det_type * 2 + 1, i)
    Loop


    deterioration = whole_condition - final_slope * years_left

end_type_two:

End If
end_func:

End Function
```

Module 4

```
Option Explicit
'this function calculates the final value of the bridge deck using either a linear(an_type =1)
'or a non-linear (an_type=2) technique depending on what the user specifies in GUI

Function cost_curve(current_cond As Double, complete_cost As Double, an_type As Integer) As Double

If an_type = 1 Then 'linear cost curve
    cost_curve = current_cond * complete_cost / 9
End If

If an_type = 2 Then

'add code here later if a non-linear cost curve is desired

End If

End Function
```