GEORGIA DEPARTMENT OF
TRANSPORTATION

Improving GDOT's Highway Pavement Preservation

Final Report

Project Name:
Improving GDOT's Highway Pavement Preservation
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Executive Summary

- **Background and Need**

Transportation agencies faces more and more severe challenge in preserving highway pavement with the current budget shortfalls in addition to the growing traffic volume and the loss of technical experts caused by personnel retirements. Efficient pavement management tools have become a must for most of the transportation agencies in the United States. The Georgia Department of Transportation (GDOT) has successfully implemented a Pavement Management System (PMS) under the Office of Maintenance (OM) and the Office of Material and Research (OMR). This system consists of several modules and programs including the Computerized Pavement Condition Evaluation System (COPACES), the Network-level Pavement Condition Analysis (Network module), the GIS-based Pavement Condition Analysis (GIS module), and the Annual Pavement Preservation Project Selection and Cost Estimation (ProjectSelection). With the use of these tools, GDOT has established a comprehensive pavement condition database covering Fiscal Year (FY) 1986 to FY 2008. The annual pavement condition survey and preservation project selection analysis has also been routinely performed using these tools and the resulting data are accumulating accordingly.

The established historical pavement condition data provides a solid foundation for GDOT to address some of the emerging needs that must be addressed under the constraints of the current stringent budget. These needs require the following actions:

1) **Evaluate the current statewide pavement performance**: Pavement performance is affected by several factors such as material, construction, traffic, environment, and maintenance. A comprehensive evaluation can help identify the relationship between pavement performance and the affected factors and improve future pavement construction and preservation.
2) **Predict the long-term pavement performance and identify the corresponding pavement preservation need**: It is crucial for GDOT to scientifically justify to the legislature the future funding need.

3) **Investigate the effectiveness of applying crack sealing**: Cracking sealing is one of the most economical maintenance treatments widely used by GDOT. It is important to know how effective it is, how to quantify its benefit, what is the best timing for the application of this treatment, and what is the need for crack sealing study.
4) **Study the usage of segment-level PACES data in pavement preservation**: Project-level PACES data is the aggregated pavement condition of all segments. Apparently, the localized pavement defects may be hidden by the aggregated project rating. It is meaningful to utilize more detailed segment-level PACES data to help identify the treatments that will improve GDOT's pavement preservation.
5) **Develop applications and functions to support the analyses and to improve the current pavement preservation activities.**

- **Objective and Proposed Research Program**

The objective of this research project is to perform analyses and to develop applications and functions to enhance GDOT's pavement preservation in addressing the aforementioned needs. The following list identifies the tasks to be conducted and developed in this research project.

1) Perform statewide pavement performance study by screening, processing, and analyzing the PACES data collected since FY 1986.
2) Predict GDOT statewide long-term pavement preservation funding need and the future pavement condition based on the existing insufficient funding levels. The potential impact of escalating construction cost on pavement condition is also analyzed.
3) Review the performance of crack sealing, one of the most popular pavement preservation methods, and recommend future research.
4) Study and compare the characteristics of segment-level and project-level PACES data that can be used for predicting pavement performance and for computing the associated ratings.
5) Develop the functions to re-define project termini.
6) Develop the functions to determine the localized pavement preservation need.

7) Develop the functions to reconstruct the historical pavement conditions based on customized project termini.
8) Develop the functions required for visualization of segment ratings on a selected route section that crosses into different counties.
9) Develop the functions necessary to generate pavement performance curves with or without the historical traffic volume (AADT and Truck percent).
10) Develop an application to query the existing pavement performance curves resulting from item 1).
11) Develop an application to predict and simulate the long-term pavement condition in supporting the analyses performed in item 2).

- **Major Findings and Developments**

The major findings resulting from the analyses are listed as follows:

1) By screening, processing and analyzing the historical PACES data from FY 1986 to FY 2007, the pavement performance curves are generated from 9,713 projects. These pavement performance curves are categorized into High, Medium and Low quality based on a systematic approach. 149 high quality performance curves are selected to perform the statewide analyses. The following are the major conclusions:
    a. The average statewide pavement resurfacing life (the time span of a new constructed pavement until the next resurfacing) is approximately 11 years.
    b. The average pavement resurfacing life varies among 7 working districts from 12 years in District 2 and 10.1 years in District 3.
    c. The relationship between pavement resurfacing life and traffic volume (AADT) shows that the pavement under High AADT (>10,000) has shorter resurfacing life (10.5 years) than Medium AADT (5,000 to 10,000) and Low AADT (<5,000) (11.7 years).
    d. The functional class of a pavement has certain effect on pavement resurfacing life. The average life for rural pavement is approximately 11.5 year; while it is 11 years for urban pavement.

e. The targeted PACES rating that triggers resurfacing is 70. However, through analyses, the actual average rating before resurfacing in GDOT is approximately 66, which indicates a delay before resurfacing. Approximately 68% of projects have been delayed for more than one year before resurfacing.
f. Among all pavement defects, load cracking, block cracking, rutting and patches/potholes are the four dominate distresses which contribute to pavement deterioration.

2) A Markovian-process-based model is developed to predict the long-term pavement performance utilizing the current budget level and different funding allocation strategies. The budget need is also identified by using an optimization formulation built on the Markovian-process-based model. The historical PACES data from FY 1986 to FY 2008 are used to construct the Markov Transition Probability Matrices (TPM). The actual expenditure on resurfacing for non-interstate highway from FY 1999 to FY 2007 is used to verify the accuracy of the developed model. At the current stage, only non-interstate highway is analyzed due to the availability of data. The following items summarize the major conclusions:
   a. Pavement preservation is very important to extend the pavement service life. Without any preservation, the pavement condition drops approximately 3 points in the composite PACES rating each year. In four years, (FY 2012), with FY 2008 as the initial year, the pavement composite rating will drop to 70. Correspondingly, the percent of pavement below 70 will increase to around 57%.
   b. If the current funding level and funding allocation remains the same in the following 10 years, the pavement condition still keeps dropping with around 2 point being lost each year. Around FY 2015, the composite rating will drop below 70 and the corresponding percentage will be 57%. The results indicate that the current funding level is insufficient to maintain the pavement network at a constantly serviceable level for a long-term period. Thus, more funding is needed in the future.

c. The comparison among three simulation strategies of “Worst First”, “User Specified” and “Optimization” shows that “Worst First” is the most inefficient strategy for pavement preservation while the “Optimization” strategy shows the best results. However, some factors such as user cost cannot be considered in the mathematical model due to the lack of support data. The “User Specified” strategy should be comparable to the “optimal” solution. The results from the “Optimization” strategy are still very useful as an upper bound in the process of decision-making.
d. The need analysis shows that the “85-10% requirements” are hard to achieve because there is $426.4 million shortfall in FY 2008, which is more than two times than the available budget (if the total available budget is $185.1 million, which is the projected funding for non-interstate highway). Considering the escalation rate of construction cost (it is assumed to be 18.1%), the needed funds will become $1.7 billion in FY 2017.
e. The escalating rate of construction cost has a direct impact on the pavement condition and pavement preservation need. The sensitivity study performed on three different Annual Average Escalating Rates (AAERs) (10%, 20% and 30%) shows that, in FY 2014, the difference in composite rating is around 1 point in comparison with the cases of 10% vs. 20%, and the cases of 20% vs. 30%. The difference increases to around 2 point in FY 2018. The corresponding percentages of pavement below 70 are 35%, 39% and 41% for cases of 10%, 20% and 30% respectively in FY 2014. The values increase to 53%, 60% and 67% in FY 2018. The increase in funding need is much faster than the increase of AAER. If the AAER remains 10% in the next 10 years, $880.3 million dollars will be needed to maintain the non-interstate highway network in FY 2018. With a double AAER of 20%, $1.9 billion will be needed in FY 2018, which is more than double the need with an AAER of 10%. If AAER increases to 30%, $4 billion is needed in FY 2018. Since construction costs are

difficult to forecast, the corresponding risk should be analyzed in the planning of pavement preservation.

f. The change of construction cost may be dramatic in the short term and will likely force transportation agencies to defer or cancel some planned pavement preservation projects. Thus, the long-term pavement performance will be adversely impacted. The preliminary sensitivity study illustrates the resulting pavement performance loss due to construction cost increases in 2009 of 50%, 100% and 150% respectively. With a 50% change, a 3.8% of Loss of Pavement Performance (LOPP) in the following 8 years is expected. With 100% and 150% changes, the LOPPs would be 7.8% and 10.4% in 8 years respectively.

3) Intensive literature review was performed on cracking sealing to evaluate its performance and the best timing of treatment. The investigation of cracking sealing by GDOT shows that the current available historical data may not support a viable study. Therefore, further effort is needed to improve the current data collection process. The following list gives the major conclusions:

   a. CALTRANS classifies cracks into working cracks and nonworking cracks. Cracking sealing is mainly applied on working cracks; while crack filling, a less expensive method, is applied on nonworking cracks.

   b. In terms of literature search, significant negative comments on applying crack sealing to asphalt pavement were not found. However, the Wisconsin Department of Transportation (WDOT) gave negative comments on applying crack sealing to Portland Cement Concrete (PCC) pavement.

   c. The study of benefit of cracking sealing in the literature shows certain variability. Pavement life can be extended by a) at least 2 years depending on the initial condition, environment, and traffic volume (Chong 1989; Ponniah and Kennepohl 1996); b) 2.5 years (Eltahan et al. 1999); c) 3 to 5 years (Pennsylvania DOT Local Technical Assistance Program (PennDOT LTAP) 2007); d) 3 years (Michigan DOT); and e) up to 8-9 years (CALTRANS).

d. The performance of crack sealing depends on the different sealant materials, construction practices, crack types, construction timing, temperature, and drainage conditions. There is a need for GDOT to perform an experimental study to evaluate the factors and practices that can result in the highest cracking sealing/filling performance based on Georgia's local roadway and temperature conditions.

e. The following items summarize GDOT's practice and experience:

    i. In GDOT, a liquefied asphalt emulsion is used for cracking filling; and a rubberized material is used for cracking sealing.

    ii. GDOT engineers agree that the rubberized material/operation is better and more effective, but there are no hard facts to back up this conjecture.

    iii. It is believed the pavement life can be extended for 5 years if the crack sealing/filling is performed at the right time, on the right distress, with the right construction, and the right material, However, there is no hard data to back this up.

    iv. A PACES rating between 75 and 85 is considered the best timing for cracking sealing according to GDOT General Office. However, due to the funding shortfall, the district offices often prioritize crack sealing/filling for projects with rating of 70 or below.

f. The preliminary study on using COPACES data shows the difficulty to scientifically and quantitatively measure the crack sealing performance. The reasons for missing and fluctuating data may result from a) no COPACES survey being performed when crack sealing was performed, b) the sample location was changed, c) different raters conducted the survey, and d) the COPACES deduct computations created inconsistencies.

4) Under current GDOT practice, the project-level PACES rating is used as a guide for determining pavement preservation. Therefore, since project-level PACES data is the average of all segment-level data in a project, it is needed to analyze and compare the characteristics and difference between these two levels of data.

The following list provides the major findings according to the intensive data analyses.

a. The historical segment ratings show large variation than the project ratings. If the pavement conditions are uniform, project-level COPACES data is more reliable to be used for pavement performance prediction.
b. The two methods for composite rating computation, the mean value and the length weighted average, produce almost similar results. These two methods are exchangeable for computing network composite rating.

The following functions and applications have been developed to support the above analyses and GDOT's pavement preservation activities:

1) The functions to re-define project termini were developed in COPACES. A project-level PACES rating is the aggregated pavement condition of all segments in the project. A project with uniform segment-level pavement condition is preferable and can result in more cost-effective pavement preservation strategies. However, some existing projects may not have a uniform segment condition. Some segments in a project may have significantly different ratings compared with other segments. In this case, it is proper to divide this project into two or more small projects with each project having segments of a similar condition. In another case, two adjacent projects may have similar condition. So, combining these two projects into a single project makes sense. The dividing and combining actions have been implemented in the new version of COPACES program.
2) The functions to determine the localized pavement preservation need were developed in the module of ProjectSelection. In GDOT, the current pavement preservation need is identified by using project-level PACES ratings in conjunction with the average distress deducts. The potential issue with the sole utilization of project-level data is that localized pavement defects may be "hidden" in the aggregated project rating when there is a significant variation of pavement conditions between the defective segment and other good segments. By using the developed functions, the localized pavement defects can be identified

and the corresponding preservation method can be applied based on pre-defined treatment criteria.

3) The functions to reconstruct the historical pavement condition are based on the customized project termini that were developed in the Network module. In OMR, it is often required to analyze the historical pavement condition for a programmed project which has termini as determined by the Pre-construction Division and thus these termini are different from the existing ones in the COPACE database. The developed functions facilitate the reconstruction of historical pavement project ratings that are re-computed based on the new project termini specified by the Pre-construction Division.
4) The functions to visualize the segment ratings on a selected route section that crosses into different counties were developed in the Network module. The current spatial definition of a project makes it difficult to visualize the continuous pavement condition on a selected route section when it crosses into different counties because the starting milepost on a route, identified by a route number, always starts from zero (0). Therefore, to visualize the sequential segment ratings on a selected route section that crosses into different counties, the county sequence needs to be determined. The HMMS database is used to construct the county sequence in the developed functions.
5) The functions to generate pavement performance curves with or without the historical traffic volume (AADT and Truck percent) were developed in the Network module. The generated pavement performance curves were used in the analyses of statewide pavement performance. The function is useful in future study when new pavement condition data becomes available.
6) The application for predicting and simulating the long-term pavement condition and the corresponding supporting analyses were developed (GDOT LP&S). Thus, four strategies were devised in the developed application: “Worst First”, “User Specified”, “Optimization” and “Need Analyses”. The first three strategies are used to predict the long-term pavement performance. With the “Worst First” strategy, a budget is allocated to the pavement projects in the worst condition. Under the “User Specified” strategy, the user can determine the allocation of

annual funding. The “Optimization” strategy applies linear programming to optimally allocate the available annual funding to achieve the maximum composite rating. Finally, the “Need Analyses” strategy is used to determine the future funding need to meet the user-defined requirements. In order to use this program, massive historical data and intensive analyses are required to develop the input parameters.

7) The application to query and analyze the pavement performance curves that were classified as High, Medium and Low quality resulting from the pavement performance analyses was developed (PaveLife). This application makes it convenient for users to query pavement life on the hundreds of selected projects.

- **Recommendations**

The following list gives the recommendations for future research and development based on the tasks performed in this research project.

1) The statewide pavement performance study provides a solid foundation for further project-level analyses. It is recommended to perform the following study at project level:
    a. Focused study is recommended on the projects with either long-life or short-life pavements. The contributing factors, e.g. timely pavement preservation for pavements with specific base materials, traffic volumes and designs, need to be identified for guiding the future pavement design and construction.
    b. Further study is needed on the high quality pavement performance curves to model the pavement deterioration at project level.
    c. The effectiveness of the current resurfacing strategy in GDOT needs to be further investigated.
    d. Alternative technologies need to be explored in order to perform the condition survey on an interstate highway. Due to the heavy traffic on these roads, there is a need to develop an automated condition survey system using computer vision and/or laser technology.

e. The historical pavement condition should be applied to develop a PACES data quality assurance program since the PACES data quality will strongly affect the pavement performance analysis results.

2) Pavement preservation is a complicated decision-making process. The study performed in this project demonstrated the capability of the developed models in predicting the long-term pavement performance and identifying the long-term budget need at the network level. However, further refinement and study is still needed to improve the accuracy and to extend the models to the level of project planning.

   a. A multi-year optimization model is needed to guarantee the optimal strategy in the entire analysis period. The current optimization model is annual-based and can only produce sub-optimal result.

   b. The following study is needed to improve the accuracy and reliability of the input parameters for the developed models, and thus improve the accuracy of the result.

      i. A more delicate method should be studied based on the theory of probability and stochastic process to create the Markov TPMs.

      ii. An evaluation of a non-homogeneous Markov model that can better capture the characteristics of the time-dependent pavement deterioration is recommended.

      iii. Further study of different price models and their impact on the long-term pavement performance and funding need is needed.

      iv. It is strongly suggested that an intensive study on the historical expense of pavement preservation should be performed. Thus, the accuracy of the unit prices of pavement Maintenance, Rehabilitation and Reconstruction (MR&R) activities can be improved.

      v. More study is needed to define finer MR&R activities and assign more alternatives to each pavement state.

   c. User cost should be included in the PMS models. Without the consideration of user cost, cheaper treatments are always the first selection by an optimization model, which in some cases make less sense in the transportation agencies' practice.

   d. It is recommended to further study the quantification of LOPP (Loss of Pavement Performance). Transportation agencies are greatly interested in the relationship between the investment loss and the pavement performance loss.
   e. It is of great value to do further study on a project-level PMS model. The current PMS model can be used for network-level planning. However, the detailed project-level programming cannot be handled by the current model.

3) Crack sealing is well-known one of the most cost-effective maintenance methods. With the current budget shortfall, it is of the special interest by transportation agencies. Based on the literature review and the preliminary study, the following recommendations are offered.
   a. There is a need for GDOT to perform an experimental study to evaluate the factors and practices that can result in the highest cracking sealing/filling performance based on Georgia's local roadway and temperature conditions.
   b. It is recommended that a large-scale crack sealing/filling experimental test be conducted in order to evaluate the most cost effective timing for treatment.
   c. An objective measurement method, such as using laser and vision technologies, is recommended to better quantify the crack sealing performance.
4) The study of pavement preservation is heavily dependent on data accuracy and availability. Through this research project, it is apparent that the data accuracy and availability largely limited the reliability and depth that the research can achieve. It is recommended to further improve the data quality and extend the necessary data recording by enhancing the current functions and applications and by developing new modules. Two examples are given below:

a. A more stringent data quality assurance and quality check (QA/QC) function should be added in the COPACES program.
b. Pavement maintenance method, timing, and cost should be recorded. In the current research project, the results of several research tasks were limited due to the lack of pavement maintenance information.

1 Introduction

Highway agencies, large and small alike, face challenges including: growing traffic volume, severe budget shortfalls, and loss of technical expertise caused by personnel retirements. When faced with shrinking budgets, Department of Transportation (DOT) managers must have the tools to effectively investigate cost-effective preservation alternatives and optimum strategies for maintaining pavements in a desirable performance condition.

The Georgia Department of Transportation (GDOT) has implemented a Pavement Management System (PMS) including many modules and programs, Among these, the Computerized Pavement Condition Evaluation System (COPACES), the Network-level Pavement Condition Analysis (Network Module), the GIS-based Pavement Condition Analysis (GIS Module), and the Annual Pavement Preservation Project Selection and Cost Estimation (ProjectSelection) models/programs have been successfully implemented by the Office of Maintenance (OM) and the Office of Material and Research (OMR) in support of GDOT's pavement management methods and processes. However, given the challenges mentioned above, there are needs to further improve the highway pavement preservation methodologies. The following section identifies the needs for the tools and analyses which will enhance GDOT's existing pavement preservation management and operation.

1.1 Research Need and Objective

- **Needs for analyses**

The number one question in GDOT is "*how long does the pavement last?*" In other words, "*what is the statewide pavement performance?*" "*Where are the pavements with a long life and where are the pavements with a short life*" would be the next questions. They can then be identified and labeled on a GIS map. This project focuses on the statewide level analyses and it will lay a good foundation to support the subsequent project-level study. The following questions can be answered in the project-level analyses. Why do some pavements have a short resurfacing life while others last very long and what are the contributing factors? Can we make the pavements in state of Georgia last longer or can we prevent short-life pavements?

GDOT is responsible for preserving and managing 18,000-centerline miles of state maintained roadways in Georgia. More than 95% of these roadways are constructed of asphalt. Therefore, the analyses performed in this study focus on asphalt pavement. GDOT has conducted its asphalt pavement condition evaluation using the Pavement Condition Evaluation System (PACES) since 1986. PACES has been further refined as the COPACES, developed by Georgia Tech, and utilized successfully by GDOT since 1998. This vast reserve of statewide, historical asphalt pavement performance evaluation data is available to support this study of pavement preservation which in turn requires a statewide pavement life study.

With the funding shortfall and escalating construction costs, GDOT has the needs: a) to forecast the statewide long-term pavement performance, b) to scientifically justify the highway pavement preservation funding needed to the legislature, c) to perform "what-if' analyses to evaluate the impacts of different funding levels and pavement preservation strategies, and d) to quantify the impact of escalating construction cost on GDOT long-term pavement preservation needs.

Crack sealing and filling, one of the most popular pavement preservation methods used by GDOT, was also studied in this project. Intensive literature review was performed and supplemented by PACES data analyses to answer the following questions:

1) Is crack sealing a cost-effective pavement preservation method?
2) Can we quantify the benefits of using crack sealing?
3) What is the optimal timing (e.g. rating and distresses, etc.) to apply crack sealing?

Another question which is asked and studied in this project is "Can we use PACES segment-level data to enhance the exiting pavement preservation in addition to the use of project-level PACES data?" In this report, we have compared the characteristics of both project-level and segment-level PACES data and have explored the use of segment-level data to support pavement preservation operations and management.

- **Needs for tools**

Besides the needs of the above analyses, there are also needs for developing the tools and functions to enhance the pavement preservation. These needs are identified below. GDOT currently determines pavement preservation needs based on pavement project-level ratings and distress deducts, that are the aggregated values obtained from individual segments of a project. However, it is difficult to identify the segments with low ratings and requiring local treatment as illustrated in Figure 1.1. Figure 1.2 illustrates the circumstances surrounding two adjacent pavement projects and their associated pavement condition survey ratings. If individual segment pavement conditions were used, these two old projects could be logically re-grouped into three new projects resulting in each project having a more uniform pavement condition and thus, more cost-effective treatment methods could be applied. Therefore, the following tools and functions utilizing segment-level pavement data to improve the exiting GDOT pavement preservation are identified. These tools are necessary to:

1) Enable OM to determine the logical treatment project termini containing uniform segment ratings and distress conditions, which can result in more cost-effective treatment strategies,
2) Enable the Office of Maintenance (OM) to identify individual roadway segments requiring localized treatment actions based on individual segment ratings and distresses, even though the overall project rating is greater than 70 and by GDOT policy does not require treatment actions,
3) Enable the Office of Material and Research (OMR) to reconstruct and recalculate the historical pavement project ratings for the new project termini specified by the programmed projects needed by the Pre-construction Division.
4) Visualize segment ratings on a selected route section that crosses into different counties.

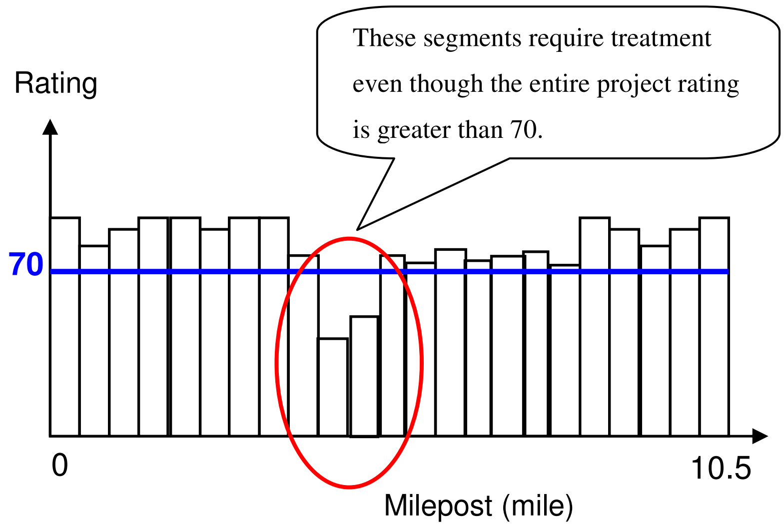


Figure 1.1 Identification of Segments that Need Localized Treatment

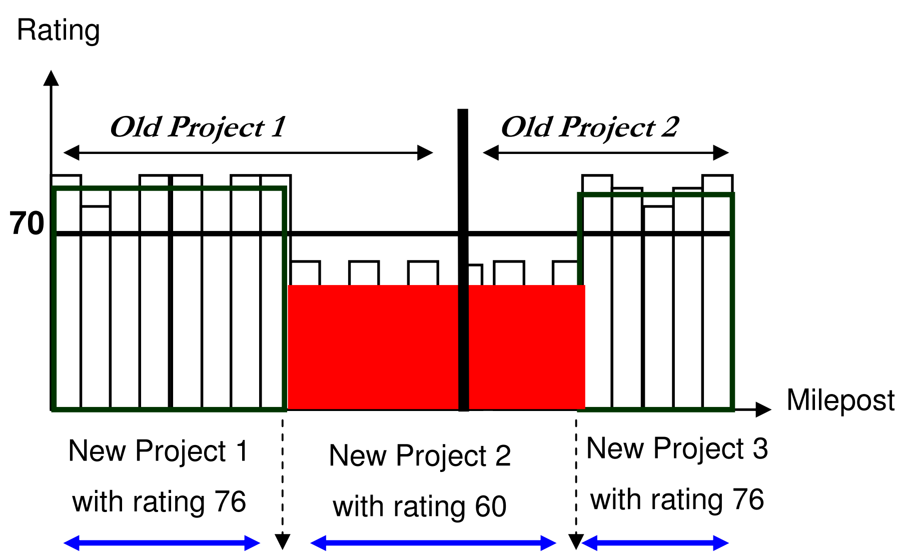


Figure 1.2 Reconstruct Project Termini with More Uniform Pavement Condition

In addition to the needs identified above (utilizing segment-level COPACES data), there are needs to develop pavement performance curves and to access the pavement life for the selected district and routes to support pavement design and preservation decisions.

These needs include:

1) Generating pavement performance curves with and without traffic volume.
2) Accessing Pavement Life data for the selected locations (e.g. district, route, etc.).

Besides the above analyses and application development, we have also carried out the following tasks in the course of this research project. These tasks include:

1) Preparing and populating historical traffic data (e.g. AADT and Truck percent) into GPAM Oracle database.
2) Providing technical support on the GPAM program since FY 2006.
3) Providing technical support of COPACES trainings since FY 2006.
4) Providing GPAM upgrades and installations.

With the needs identified above, the objective of this research project is to develop models, to perform analyses, and to develop applications and procedures to enhance GDOT. The following list identifies the analyses and applications/functions to be conducted and developed in this research project.

1) Perform statewide pavement performance study by screening, processing, and analyzing the PACES data collected since 1986. There are a total of 9,317 projects from FY 1986 to FY 2007. A systematic method is developed to quantify the pavement data quality for supporting creditable pavement performance study. Resurfacing life and 70 rating life are also analyzed.
2) Predict GDOT statewide long-term pavement preservation funding needs and the future pavement condition based on existing insufficient funding levels. The potential risk of escalating construction costs (impacting pavement preservation) is also analyzed.
3) The performance of crack sealing, one of the most popular pavement preservation methods, is critically reviewed. Intensive literature review is performed to quantitatively evaluate its performance and benefits, as well as the optimal timing of its application.
4) The characteristics of segment-level and project-level COPACES data for predicting pavement performance and computing ratings are studied and compared. Functions utilizing segment-level data to support pavement preservation operation and management are also recommended.
5) A function for re-defining project termini is developed.

6) A function for determining localized pavement preservation need is developed.
7) A function to reconstruct historical pavement conditions based on customized project termini is developed.
8) A function to visualize segment ratings on a selected route section that crosses into different counties is developed.
9) A function to generate pavement performance curves (by batching) with/without historical traffic volume (ADT and Truck percent) is developed.
10) A network-level long-term pavement performance prediction and simulation program (GDOT LP&S) is developed.
11) A program is developed to query the analyzed pavement performance curves (PaveLife).

1.2 Report Organization

This report is organized into seven chapters. They are briefly described below:

1) Chapter 1 **Introduction**. This chapter introduces the background and research needs, the objectives of this project, and the organization of the final report.

2) Chapter 2 **Study of Georgia's Network-level Asphalt Pavement Performance Using Historical PACES data**. Historical PACES data since 1986 are for the first time systematically screened, processed, and analyzed to evaluate Georgia's network-level asphalt pavement performance.

3) Chapter 3 **Long-Term Pavement Performance Forecasting and Need Assessment**. Probabilistic models are developed to simulate Georgia's long-term pavement preservation needs (based on Georgia's pavement deterioration rates determined from the historical PACES data) and to simulate the risk induced by funding shortfalls. The scientifically analyzed outcomes can be used to justify the funding need and to quantitatively address the agency risk induced by insufficient pavement preservation funding compounded by escalating pavement construction costs.

4) Chapter 4 **Exploration of Crack Sealing Performance Assessment**. Crack sealing is one of the popular pavement preservation methods used by GDOT.

This chapter performs a preliminary study on quantifying the benefit of crack sealing and on determining the optimal timing (rating and distress) for performing crack sealing that could result in the highest benefit for GDOT with the minimum cost. Further research is also identified in this study.

5) Chapter 5 **Utilization of Segment-level COPACES Data to Improve Pavement Preservation**. The characteristics of segment-level and project-level COPACES data are studied and compared in terms of their performance forecasting and rating computation applicability. Needs for utilizing segment-level data are also identified. Four applications are developed and presented in this Chapter. They include: a) Re-define project termini, implemented in the COPACES program, for the engineer in OM to determine the logical treatment project termini with "*uniform*" segment ratings and distress conditions, which can result in more cost-effective treatment strategies; b) Determine localized pavement preservation need, implemented in the ProjectSelection, to identify individual roadway segments requiring localized treatment actions based on individual segment ratings and distresses, (even though the overall project rating is greater than 70 and does not require treatment actions); c) Reconstruct historical pavement conditions based on customized project termini, implemented in GPAM Network module, in order to reconstruct and recalculate the historical pavement project ratings for the new project termini indicated by the programmed projects identified by the Pre-construction Division; d) Visualize segment ratings on a selected route section, implemented in Network module, to assist in the continuous visualization of the segment ratings even when the project crosses into different counties.

6) Chapter 6 **Utilization of Pavement Life Study for Improving Pavement Design and Preservation**. Two applications are developed and presented in this Chapter. They are: a) Generating pavement performance curves with and without traffic volume, (implemented in Network module), to plot pavement performance curves with or without corresponding traffic volume (ADT and truck%) in a pdf file format; and b) PaveLife stand-alone application, developed by processing historical PACES data from FY 1986 to FY 2007, to easily access the actual pavement resurfacing life for a selected region to support pavement design.

7) Chapter 7 Conclusions and Recommendations.

8) Appendixes. All supplementary documents are included in the Appendix I to XV.

2 Study of Georgia's Network-level Asphalt Pavement Performance Using Historical PACES Data

2.1 Objective

The number one question in GDOT is "how long does the pavement last?" This question can be answered by analyzing the historical pavement performance and determining the factors leading to different performance. This chapter focuses on the statewide network-level pavement performance study using COPACES data from FY 1986 to FY 2007. It is hoped that this study can establish a foundation for the subsequent in-depth study at project level.

The objective of this chapter is to perform two studies and to provide a logical presentation of the results of these studies for use by GDOT decision makers: 1) characterize and group the historical COPACES data; 2) study the time span (life) of asphalt pavements in Georgia. Additionally, the need and direction for additional research that can be performed with the data will be provided. In order to follow the process of analysis in this study, the following general outline is provided.

- COPACES Data Preparation:
  1) Prepare COPACES data from FY 1986 to FY 2007 and group the projects within a same project limit as established by buffering. This buffering approach is necessary because a fixed project query might not be able to group all of the appropriate projects since the query is based on MilepostFrom and MilepostTo and these two variables can change slightly from year to year. A detailed discussion of the buffering process is documented in Appendix I.
  2) Establish a systematic approach to evaluate the COPACES data quality and to determine the pavement life.
  3) Manually screen the historical projects and group only the projects with High/Medium/Low (H/M/L) quality to support the subsequent analysis. This process eliminates uncertain, incomplete and unacceptable data such as unclear

starting point (Starting Year) data or projects with three or fewer historical points. The detailed rules for establishing the High, Medium and Low Quality Projects are documented in Appendix II.

4) Perform a laborious manual review on each project's historical performance to determine the resurfacing life and life of 70 (70-Life) and the corresponding confidence (H/M/L). This process requires reviewing the completeness of the starting point, ending point, and trend of the historical data for each project under consideration. The overall confidence is the minimum confidence of the starting point, ending point, and trend variables. A strict or conservative set of rules was applied in this study because it is expected that the finalized high confidence level pavement project group should be used confidently to justify the pavement performance evaluation.

- Study of the statewide network-level pavement performance. In order to define the pavement performance, the following variables or combinations were examined.
  1) Statewide pavement life
  2) Resurfacing timing
     a. Resurfacing Life
     b. 70-Life
     c. Rating Before Resurfacing (RBR)
  3) Pavement life vs. different functional classes
  4) Pavement life vs. AADT
  5) Pavement life vs. GDOT working districts

- Preliminary study on pavement distress: An examination of the distresses was performed to determine the trends and distribution of distresses within projects. This examination included the following combinations.
  1) Trend of different distresses
  2) Distress distribution among different districts
  3) Distribution of dominate distresses
  4) Examination of different distress trends

- Preliminary study on where the long and short time span pavements occur. A geospatial examination of the location of the long and short life pavements was performed.

2.2 Data Preparation

COPACES data has multiple potential sources of error. Among these, human understanding of the written COPACES survey system, application of the survey system rules, measurement of the pavement distresses and logging of the survey information are pivotal to the accuracy and precision of the data. Since we typically have only the COPACES data for analysis, we must look at the consistency of the data to determine our confidence in the data. If we are working with a High Quality data group, we are more confident that this group is representative of all of the pavement projects with similar characteristics. Also, we are more confident in any relationships or correlations established between analysis variables. Therefore, the first step is to prepare the COPACES project data in order to establish the data quality.

The second part of this chapter deals with establishing the pavement life from the COPACES data. The most emergent need for GDOT is to extend the life of Georgia's pavements in an optimal cost-effective way. Thus, having a high quality source of data that can be utilized to define the life of pavements and to establish the relationships between the pavement life and deterioration causative variables (which reduce the life of the pavement) is a necessity. From these relationships, recommendations for pavement construction, pavement treatment and pavement treatment timing can be made. These recommendations will assist GDOT in making decisions that will help meet GDOT's goal of extending pavement life.

Within GDOT's 18,000-centerline mile roadway system, a logical division has been created in the form of the project. Projects are defined by GDOT for purposes of construction and maintenance and are approximately 10 miles in length on average. Utilizing these project definitions, GDOT developed the COPACES inspection system to determine the amount and type of surface distress on the pavement associated with a project. In order to quantify the pavement condition, definitions of distresses (Rut depth, Load cracking, Block Cracking, Reflection cracking, Patches & Potholes, Raveling, Edge Distress, Bleeding/Flushing, Corrugations/Pushing and Loss of Section) and appropriate levels of severity were established. The COPACES scheme requires that all visible pavement distresses be observed and documented for each one mile segment of the roadway. This measurement process is facilitated by taking a 100 foot sample section that is the most representative of the one mile segment under consideration. Proceeding with the COPACES process, a rating (based on maximum score of 100) is established for the project by taking the average extent and predominant severity level for each distress from the segments and determining the corresponding deduct values. These deduct values are summed and the result is subtracted from 100 giving the project rating. Since the project rating is established for every year, the rating versus year of inspection can be plotted and studied for examination of the behavior and time span or life of the pavement. A typical plot is provided in Figure 2.1 of this report.

A careful review of Figure 2.1 reveals a pavement life cycle (the yearly rating points for the YS (Starting Year) to the YE (Ending year)) that can be defined as the pavement resurfacing life. With no detectable surface distress, a new pavement or a newly resurfaced pavement will have a rating of 100 at the start of its life. (Note, for a pavement that is under construction, the rating is 105.) From this starting point, the pavement will continue to deteriorate until the point that resurfacing becomes necessary (unless a treatment or rehabilitation is performed). The end of the life of a pavement is essentially the point at which GDOT requires resurfacing. (GDOT currently has a goal of resurfacing pavements when the project rating falls below 70.) Thus, this definition of pavement life is well defined in concept and lends itself to the establishment of evaluation variables which can be used to establish the quality of the associated project data. These variables are determined by manual evaluation of the Project Rating vs. Year chart as seen in this example (Figure 2.1) and are further defined in the next section of this chapter.

The project rating continues to drop due to many factors which progressively cause deterioration of the pavement. Thus, we can observe this trend in our manual evaluation of the Project Rating vs. Year chart and we have defined this trend as the TM (Trend in the Middle). Since these three entities, YS, YE and TM are shown repetitively and are used to establish the life sequence of a pavement, their inherent definition and the observation of their relationships with each other are used to establish the quality of each of the three variables. In turn, the quality of the individual variables is evaluated to establish the quality for the pavement life. The establishment of rules to consistently apply the definitions and determine the relationships of the variables is necessary for maintaining the consistency of the project data quality.

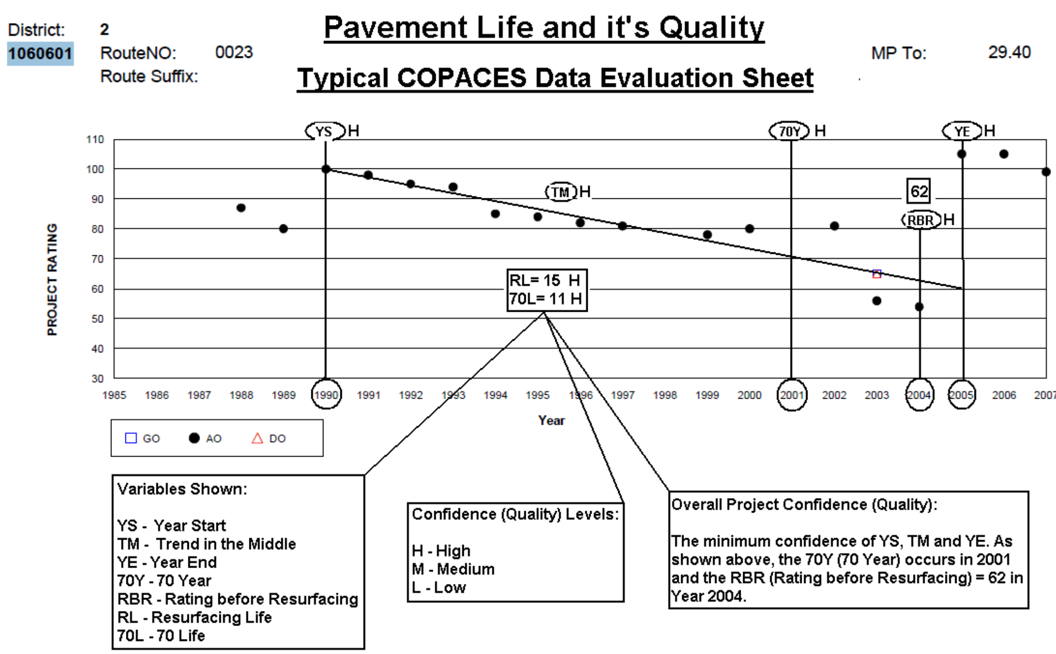


Figure 2.1 Pavement Life and Quality

In addition to the pavement life which is defined by the YE that varies significantly due to many factors including statewide and district budget constraints, another definition of pavement life, 70 Life, is also studied because this life has an ending point defined only by the evaluation of the GDOT rating (COPACES survey) and not by budget constraints or GDOT actions. The variable that defines the ending point of the 70 Life is the 70 Year (70Y). The 70Y is established manually along the trend line as the year closest to the 70 rating line. The value of the 70 life is having a basis for a system-wide comparison of the two life types in order to assist in evaluating the performance of GDOT's 70 rating-resurfacing policy.

Finally, as part of the confidence evaluation and for additional research on treatment impact, the Rating before Resurfacing (RBR) is manually established on the Project Rating vs. Year chart. The confidence of this variable is valuable since the RBR indicates how far the rating is allowed to decrease before resurfacing. In turn, knowing the system-wide RBR is a strong indicator of system-wide pavement maintenance performance.

Before the historical ratings of a project can be grouped as shown in Figure 2.1, an adjusted project limit buffer needs to be utilized. This was an essential step because the project limit can change slightly from year to year and with a fixed project limit, we may not be able to group all of the required projects because of the slight difference in the project limit (MilepostFrom and MilepostTo). A detailed discussion of the buffering process is documented in Appendix I.

The following table (Table 2.1) establishes the database field names for the seven variables that are being evaluated in association with project quality (confidence). The formal definitions of the variables are given in the next section.

Table 2.1 Pavement Life Variables Equivalency

Variable Description	Manual Variable Abbreviation	Database Variable Name
Resurfacing Life	RL	Life-Resurf
Year Start	YS	Yr-Start
Year End	YE	Yr-EndResurf
Trend in the Middle	TM	Trend in the Middle
70 Life	70L	70-Life
70 Year	70Y	70-Yr
Rating before Resurfacing	RBR	RBR

2.2.1 Definitions and Terms

- Terms associated with pavement life
  - **Life-Resurf**: Pavement Resurfacing Life - The time span from the establishment of a new pavement surface until the next pavement reconstruction/resurfacing
  - **Yr-Start**: Year Start - The Year Start is the beginning of a pavement life, and typically is identified by the first project rating of 100 (or 105) for the best pavement cycle trend which is selected. When the rating of 100 (105) is not indicated, a Year Start will be established according to the rules given with the appropriate confidence levels.
  - **Yr-EndResurf**: Year End - The Year End is the end of a pavement life. The Year End will be established according to the rules given with the appropriate confidence level.
  - **Trend in the Middle**: The Trend in the Middle are the data points and associated straight-line defined from the time period from the establishment of a new pavement surface (with a typical project rating of 100(or 105)) until the next pavement reconstruction/resurfacing (with a typical project rating of 100(or 105)). (i.e., from Yr-Start until Yr-EndResurf)
  - **70-Life**: Pavement Life to 70 - The time period from the establishment of a new pavement surface (with a typical project rating of 100(or 105)) until the pavement deteriorates to a rating of 70. (From Yr-Start until 70_Yr)
  - **70-Yr**: 70-Year - The 70-Year is the end of the Pavement Life of 70 and is determined as the year closest to the location of the intersection of the trend line and a horizontal line established at the 70 project rating level.
  - **RBR**: Rating Before Resurfacing - The Rating Before Resurfacing is generally established as the rating of the year before the year end. It may be a point on the trend line or it may represent the rating created by the intersection of a vertical year line and the trend line.

- Abbreviations associated with other terms used in pavement life analysis:
  - **AADT:** Average Annual Daily Traffic (Categories as Follows: **Low:** AADT < 5,000, **Medium:** 5,000< AADT <10,000, **High:** AADT >10,000)

- **AO:** Area Office – of the Georgia Department of Transportation
- **DO:** District Office - of the Georgia Department of Transportation
- **GO:** General Office - of the Georgia Department of Transportation
- **ESAL:** Equivalent Single Axle Load
- **COPACES:** Computerized Pavement Evaluation System
- **GDOT:** Georgia Department of Transportation
- **GIS:** Geographical Information System
- **Functional Class:** A roadway type designation assigned by GDOT based on planned or projected usage. (ex. FC 1: Principal Arterial – Interstate (Rural))

2.2.2 A Systematic Approach to Determine Data Quality

With the variables of pavement life analysis established, the need to have an organized way to classify these variables is evident. As a start after a preliminary evaluation, paper copies of the Project Rating versus Year charts were created for 455 projects by the preliminary selection from the 9,317 projects in the COPACES database. Initially the paper copies of the projects similar to Figure 2.1 were evaluated utilizing an initial rule set. From the initial work, it was decided to refine the rules and put them in table form for faster and more exact recognition of the requirements of the rules. There were approximately seven versions of the rules documented before deciding on the final set of rules as presented in this report. Some of the largest obstacles in the rule applications included the following:

- Establishing the Year Start where there was data missing at the beginning of the cycle but the cycle appeared very normal otherwise and should have some creditability.
- Establishing the Year End where there was data missing or the hierarchy of the GDOT offices indicated a significantly different value for the apparent Rating before Resurfacing.
- Establishing the Trend in the Middle in a consistent way caused a debate since the usual vertical variation from point to point generally precluded a good manual curve fitting technique. Thus, the straight-line approach was implemented using a

graphical best fit approach or holding the more important point according to the rules.

An organized approach evolved where the rules could be applied consistently by different individuals. The following basic steps were utilized:

- The rules to determine the confidence of the three variables which define pavement life were established and are presented in tables II-2, II-3 and II-4 respectively. These three variables are Yr-Start, Trend in the Middle and Yr-EndResurf. These rules establish a rating of High, Medium, Low, N/A (Not Acceptable), U (Unsure) or I (Incomplete) for each variable. Each of these ratings has a distinct definition based on the specific variable. However, the definitions for N/A, U and I are similar in meaning across the three variables.
- Based on the rules provided in Table 2.2 (also in table II-1) including the Lowest Level Rule and the results of the variable classification described in the step above, a confidence rating can be assigned to the Life-Resurf variable. In application, this rule set means that if any of the three variables has a rating of N/A, U or I, the Life-Resurf rating will be N/A, or U or I where N/A precedes U and U precedes I. If none of the variables has a rating of N/A or U or I, then the Lowest Level Rule will apply where the lowest confidence level from the three variables is selected. Thus, a rating of High, Medium, Low, Not Acceptable, Uncertain, or Incomplete is established.
- In a similar way to the Life-Resurf rating, the confidence of the 70_Life variable is established using the evaluation of the Yr-Start, Trend in the middle and the 70-Yr variable (instead of the Yr-EndResurf) as described in table II-5. These rules for each variable establish a rating of High, Medium, Low, N/A (Not Acceptable), U (Unsure) or I (Incomplete). Each of these ratings has a distinct definition based on the specific variable. However, the definitions for N/A, U and I are similar in meaning across the three variables. The rules for the confidence of the 70- yr variable are given in table II-6. Again, each rating level is defined for this distinct variable.

Table 2.2 Pavement Project Data Evaluation Rules for Pavement Life (Life-Resurf)

Pavement Life: (Life-Resurf)	**Definition:** The time period from the establishment of a new pavement surface (with a typical project rating of 100(105)) until the next pavement reconstruction/resurfacing (with a typical project rating of 100(105)). (From **Yr-Start** until **Yr-EndResurf**, respectively.)
Lowest level Rule:	**Rule:** If the project contains no **U** or **N/A** or **I** confidence levels, then, the overall Pavement Life confidence level is selected as the lowest confidence level (**Low, Medium or High**) of these three factors: 1. **Yr-Start*** 2. **Yr-EndResurf** * 3. **Trend in the middle*** *These factors and their related confidence levels will be defined in the tables that follow.
Factor Confidence Rating:	**Factor Confidence Rating Definitions and applications to Pavement Life:**
N/A	**N/A:** (Not Acceptable) The **N/A** rating means that the project data for these projects is not useful and that this data will not be used in the future. **N/A** has the highest priority in deciding the overall pavement life (**Life-Resurf**) confidence level. If any of the three decision factor ratings is **N/A**, the overall pavement life (**Life-Resurf**) confidence level will be **N/A**.
U	**U:** (Uncertain) The **U** rating means that the project data for these projects have potential to provide useful information after further investigation is completed. If any of the three decision factor ratings is **U** with no **N/A**, the overall pavement life (**Life-Resurf**) confidence level will be **U**.
I	**I**: (Incomplete) The **I** rating means that the project data for these projects is incomplete. If any of the three decision factor ratings is **I,** with no **U** or **N/A**, the overall level is **I**.

- Finally, the rules for the confidence of the RBR (Rating before Resurfacing) variable are established in table II-7. The typical manual selection of the variable is shown in Figure 2.1. The confidence rating of the RBR is typically the same as the Trend in the Middle since the trend or cycle line sets the value of the RBR in the year before Yr-End.

- It should be noted that some projects contained more than one pavement cycle. In this case, the strongest cycle in terms of apparent quality was selected for evaluation. However, the value of multiple cycle pavements is noted as they may prove extremely valuable in the study of the complete service life of pavement.
- As an example of the rules tables, Table 2.2 is given above. The complete set of the rules tables is given in Appendix II.

2.2.3 Project Classification Results

Based on the analysis for completeness and the application of the confidence rules as previously discussed, 455 projects were classified to be High, Medium or Low quality from 9,317 projects (in the COPACES database). The results are shown in Figure 2.2. The breakdown yielded 149 High Quality, 169 Medium Quality and 137 Low Quality projects.

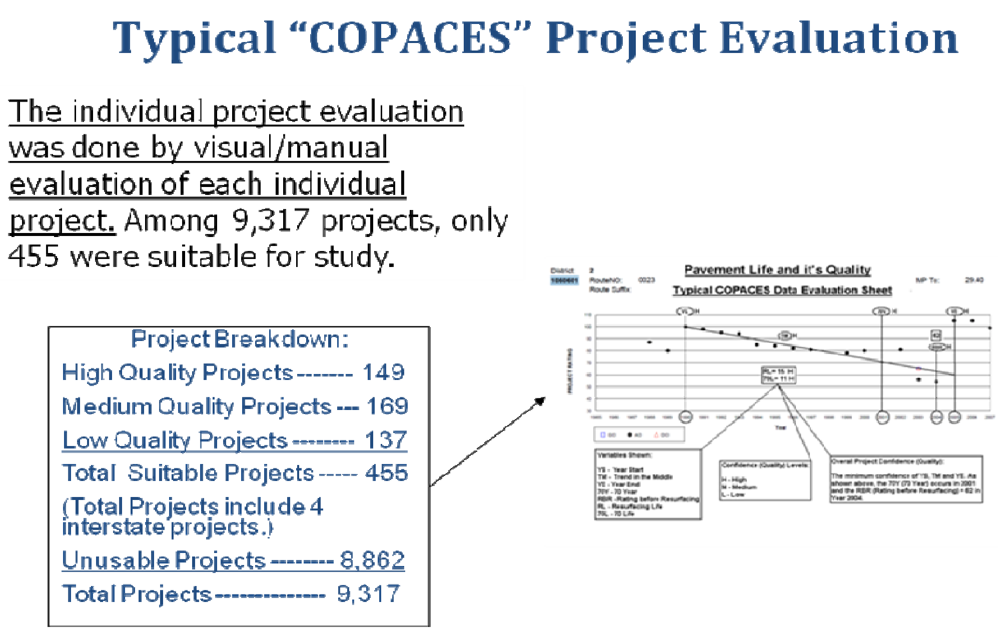


Figure 2.2 Project Evaluation and Classification

The yearly breakdown of the numbers for High, Medium, Low and Combined Projects is given in Figure 2.3. Variation in all categories of quality is apparent. The Year as shown on the horizontal axis in the figure is the Yr-EndResurf. The year 2002, had the largest number of High Quality projects and the largest number of Combined Quality projects (High, Medium and Low Quality projects) reaching the end of their pavement life for the cycle studied. The absence of data for the early years of PACES, 1986 through 1991, is primarily due to fact that most pavement cycles are 6 years or greater. Thus, no cycles were identified during this period.

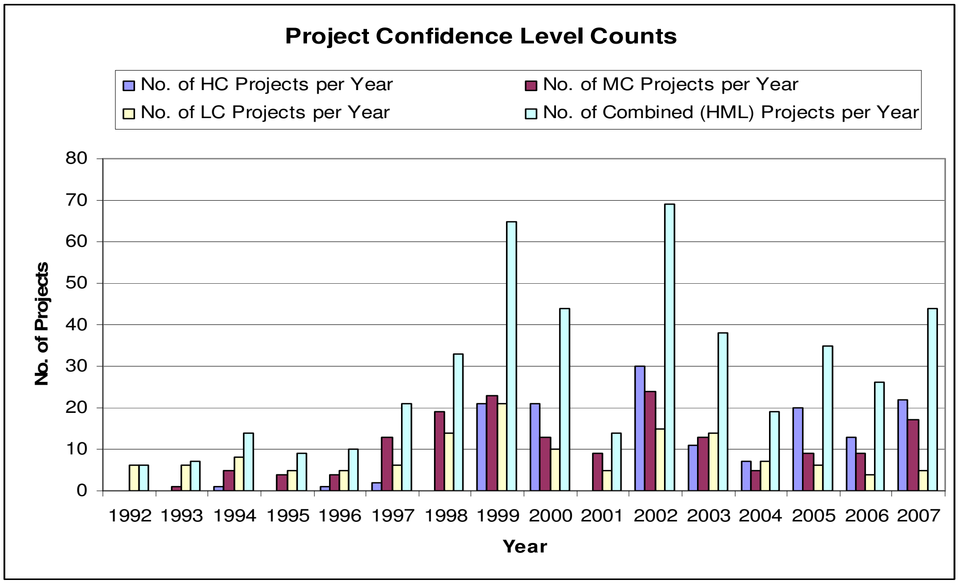


Figure 2.3 Yearly Project Classification Counts

In Figure 2.4, the accumulated number of High Quality projects is increasing by approximately 20 projects per year. To this point, we have completed the analysis of project quality and are prepared to look forward at project pavement performance.

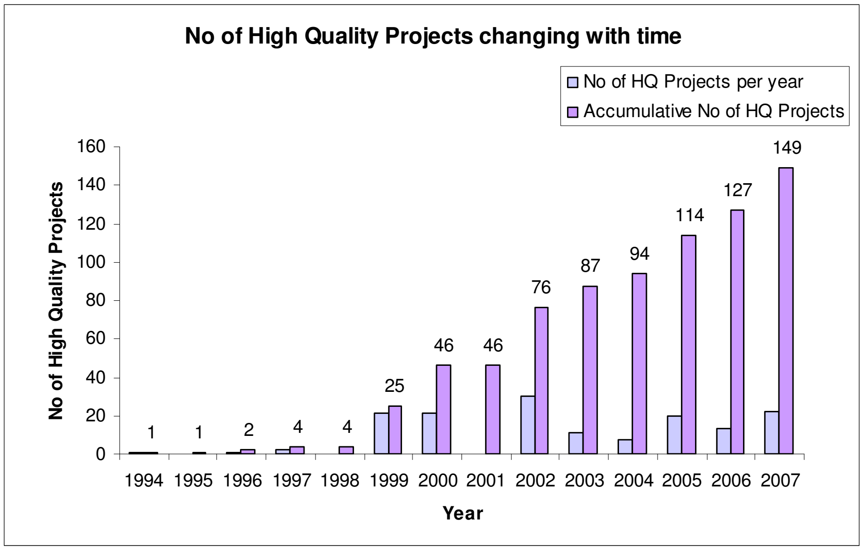


Figure 2.4 Yearly High Quality Project Counts

2.3 Statewide Pavement Performance

The Life-Resurf (Resurfacing Life) as shown in Figure 2.5 is important since the pavement life indicates the amount of service being obtained from the pavement. The average Life-Resurf for all projects (H/M/L) is around 11 years. It is noted that the standard deviation varies with the confidence level. The number of Interstate projects is too small to derive valid statistical results for the Life-Resurf. Based on the 5 Interstate projects, the average Life-Resurf is about 8.6 years.

It is recommended that efforts to improve the quality of the project data continue since it will result in more high quality projects which in turn will give a better indication of the average Life-Resurf of the system. Additionally, more attention should be given to Interstate highways, as they are very crucial for the whole highway system and the analysis result indicated a shorter pavement life of them.

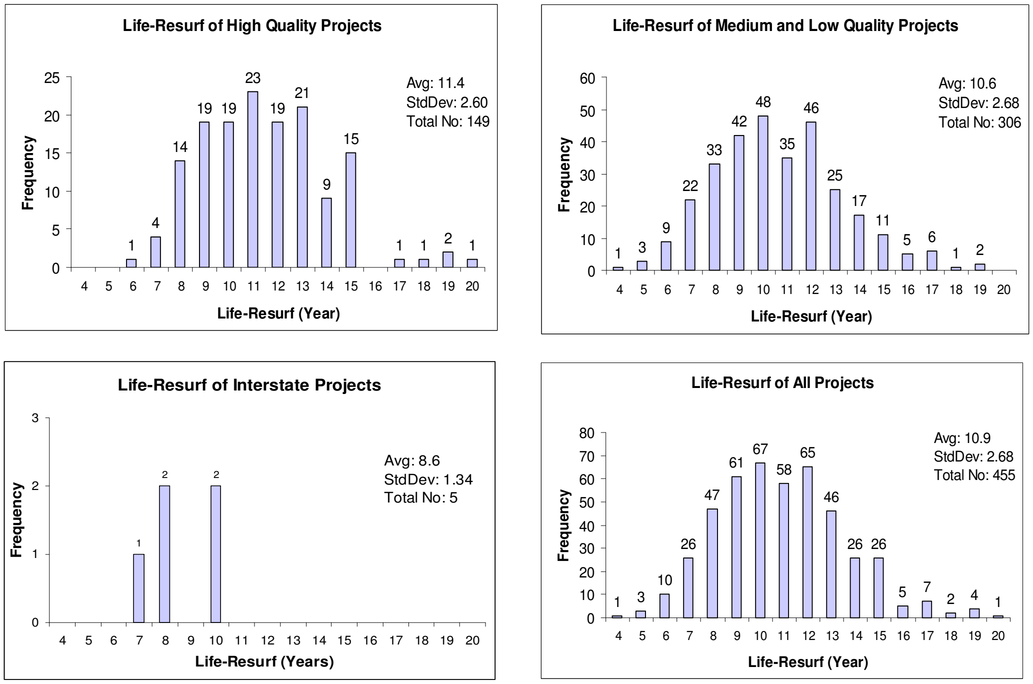


Figure 2.5 Resurfacing Life of Statewide Pavements

Figure 2.6 summarizes the average 70-Life, which is 9.4 years based on High Quality projects and 8.7 years in terms of all projects. This is shorter than the value of Life-Resurf, which means that the pavement resurfacing actually occurred 2 years later after the pavement rating reached 70. In other words, an average of 2 years delay on resurfacing is the current GDOT's practice. A complete examination of 70-life should be conducted in future research and should cover many of the same relationships identified for resurfacing life in this report. Also, a thorough examination of the components of the delay is warranted in order to determine if the individual time components are discretionary or mandatory. In conjunction with this effort, the timing of standard operating procedures by GDOT should be examined to determine how these procedures relate to the time components and do determine if a different order of procedures and/or further automation could reduce the delay.

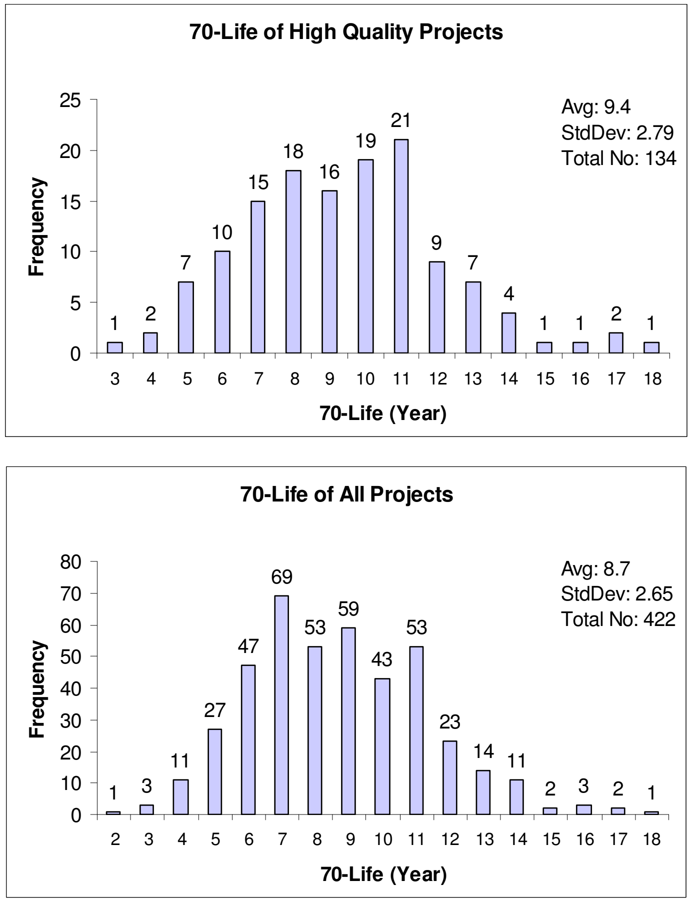


Figure 2.6 70-Life of Statewide Pavements

Figure 2.7 shows the difference between the Life-Resurf and the 70-Life for High Quality projects and all projects. As shown in the figures, “1 year” means that if the pavement rating dropped to 70, it was treated in the next fiscal year, and there was no delay. The result shown in Figure 2.7 indicates that approximately 68% of the projects are being delayed by more than one year.

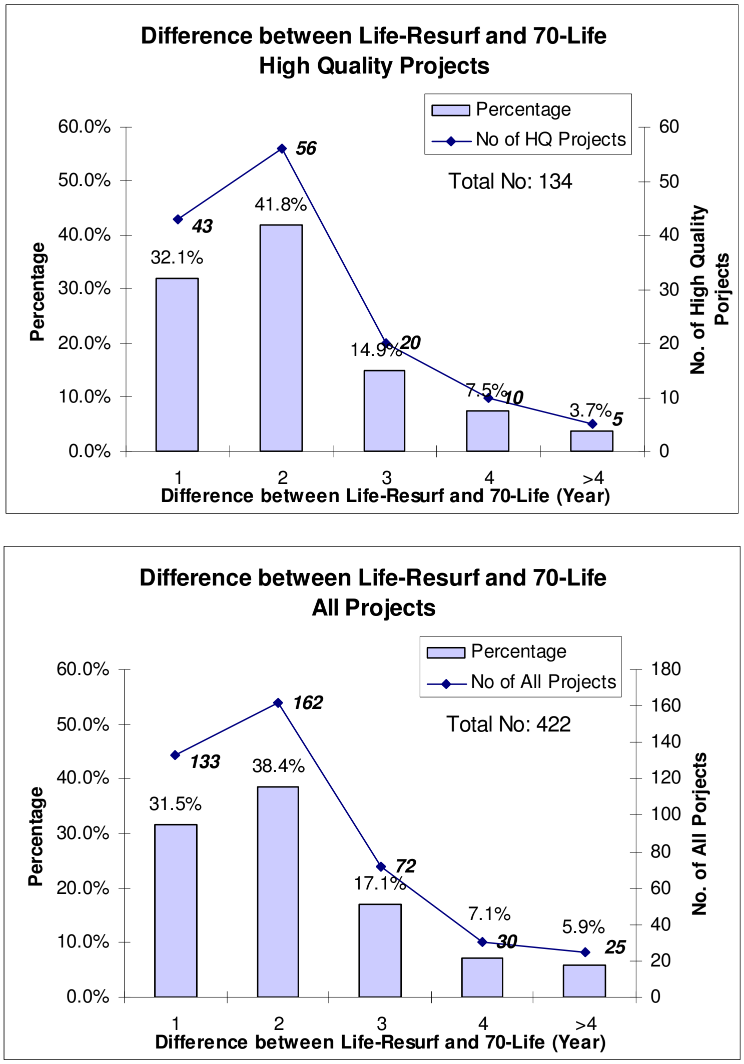
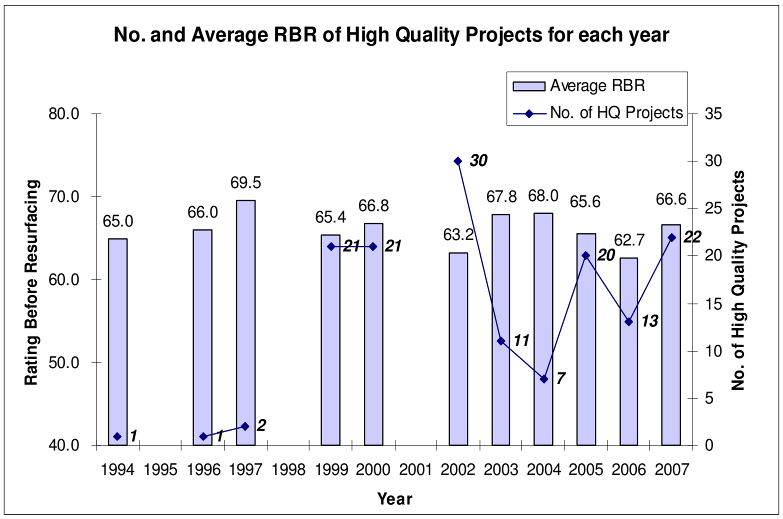


Figure 2.7 Difference between Life-Resurf and 70-Life

Based on the analysis of pavement life, it is apparent that the High Quality projects are generally representative of all projects. In the following sections, the High Quality projects will be emphasized. Also, note that the pavement life will be the resurfacing life. This choice was made since this work represents the intention in this report was to examine GDOT's current practices including actual resurfacing timing as a result of these practices.

2.4 Pavement Life vs. Rating before Resurfacing

In Figure 2.8, the Average Rating before Resurfacing (RBR) and the Number of Projects are plotted for each year for the High Quality projects and all projects. It can be examined through this figure the year to year variation in RBR which may indicates a budget or policy impact. Thus, it is anticipated that a trend in decreasing funding would indicate a corresponding trend of decreasing RBR values.



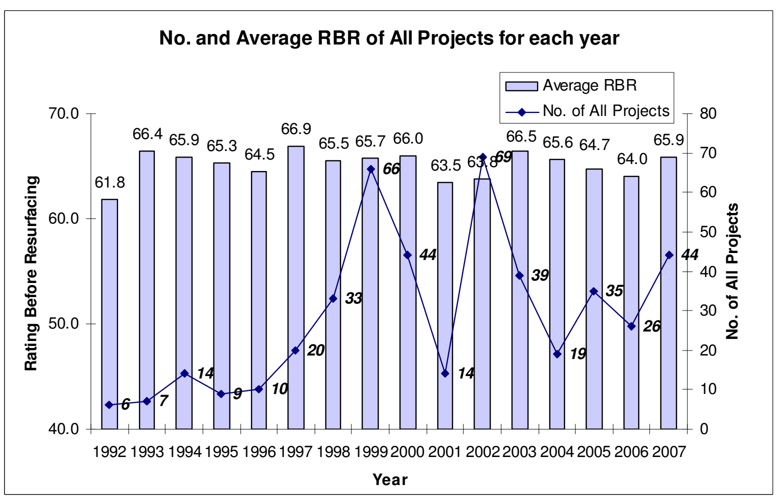
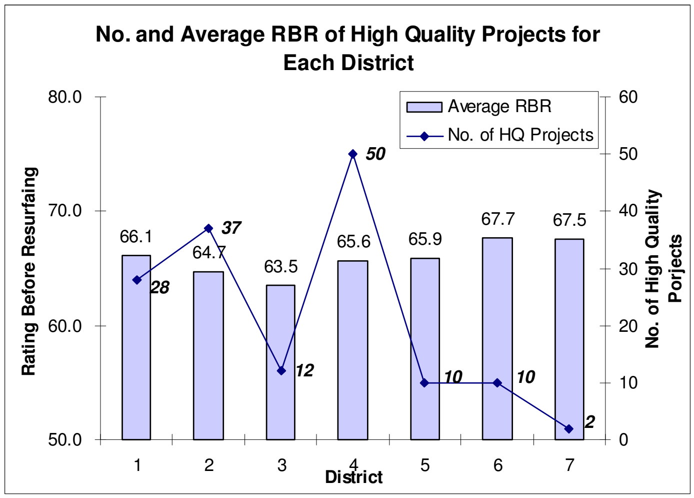


Figure 2.8 Yearly RBR and Project Counts

Figure 2.8 shows a void in several years for High Quality projects. However, starting in 2002, a number of High Quality projects are shown as substantiated by Figure 2.4. The graph of all projects appears almost cyclical in nature with the RBR being corrected and then allowed to drop for a 4 or 5 year period. Remembering that one of the stated goals of GDOT is to try to maintain a system level RBR as close to 70 as possible, it would be beneficial to determine if policy changes or standard operating procedures caused any portion of these changes.

In Figure 2.9, the average RBR and the Number of Projects are plotted for each GDOT working district for the High Quality projects and all projects. This can be used to examine the variability of RBR across districts.



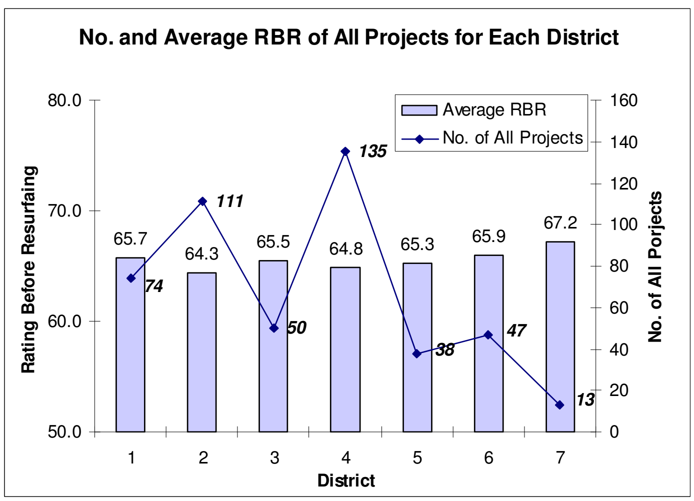


Figure 2.9 RBR and Project Counts for Each Working District

In Figure 2.9, note that comparing the High Quality projects to all projects shows that the RBR for High Quality projects is greater than the All Project RBR in every district except district 3. Since the RBR is selected from the project rating graph, there may be a slight difference in resurfacing policy for this district.

2.5 Pavement Life vs. Functional Class:

In this analysis, the High Quality projects were assembled according to their functional classes. The GDOT's functional classes are defined in Table 2.3.

Table 2.3 Classification of Functional Class

FC 1	PRINCIPAL ARTERIAL – INTERSTATE (RURAL)
FC 2	PRINCIPAL ARTERIAL – OTHER (RURAL)
FC 6	MINOR ARTERIAL (RURAL)
FC 7	MAJOR COLLECTOR (RURAL)
FC 8	MINOR COLLECTOR (RURAL)
FC 9	LOCAL (RURAL)
FC 11	PRINCIPAL ARTERIAL – INTERSTATE (URBAN)
FC 12	PRIN. ART.- OTHER FRWY/EXPRESSWY (URBAN)
FC 14	PRINCIPAL ARTERIAL – OTHER (URBAN)
FC 16	MINOR ARTERIAL (URBAN)
FC 17	COLLECTOR (URBAN)
FC 19	LOCAL (URBAN)

In Figure 2.10 below, the resurfacing life and the project counts are plotted while the different functional classes are presented. This graph can be used to observe the effect of Functional Class on the Resurfacing Life. The greatest number of High Quality projects occurs in the rural functional classes, F6 and F7.

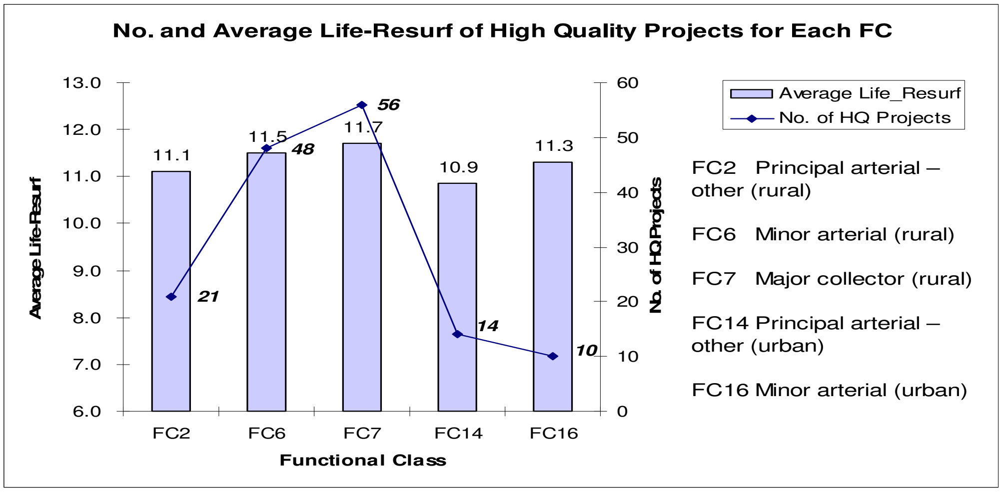


Figure 2.10 Resurf-Life vs. Functional Class

The average Life-Resurf of FC 2 (principal arterials – other), FC 6 (minor arterials) and FC 7 (major collectors) in rural area are 11.1, 11.5 and 11.7 years, respectively. The average Life-Resurf of FC 14 (principal arterials – other) and FC 16 (minor arterials) in urban area are 10.9 and 11.3 years, respectively.

From the analysis, it is noted that the projects in rural pavement functional classes generally have a longer pavement life than projects in urban pavement functional classes. At this point, the data for rural functional classes appears more reliable than that of the urban classes. The importance of Functional Class in the analysis cannot be overstated since the selection of the pavement design may have been based on Functional Class. The design of the pavement in turn influences the life of the pavement. The Functional Class should have been set by the function of the roadway and the anticipated traffic characteristics.

2.6 Pavement Life vs. AADT

To study the relationship between the Life-Resurf and AADT, high quality projects are divided in terms of AADT range, Low, Medium and High as follows:

Low: AADT < 5,000

Medium: 5,000< AADT <10,000

High: AADT >10,000

Figure 2.11, Figure 2.12 and Figure 2.13 are plots of Project Frequency vs. Life-Resurf based on the predefined AADT categories (Low, Medium and High). All three categories have a wide spread distribution: for the given High Quality projects, Life-Resurf varies from 7 years to 20 years for Low AADT; the range is 7 years to 18 years for Medium AADT; and 4 years to 18 years for High AADT. This wide spread may indicate the significant effect of other variables besides AADT. The Life-Resurf for Low and Medium AADT is 11.7 years; while it is 10.5 years for High AADT.

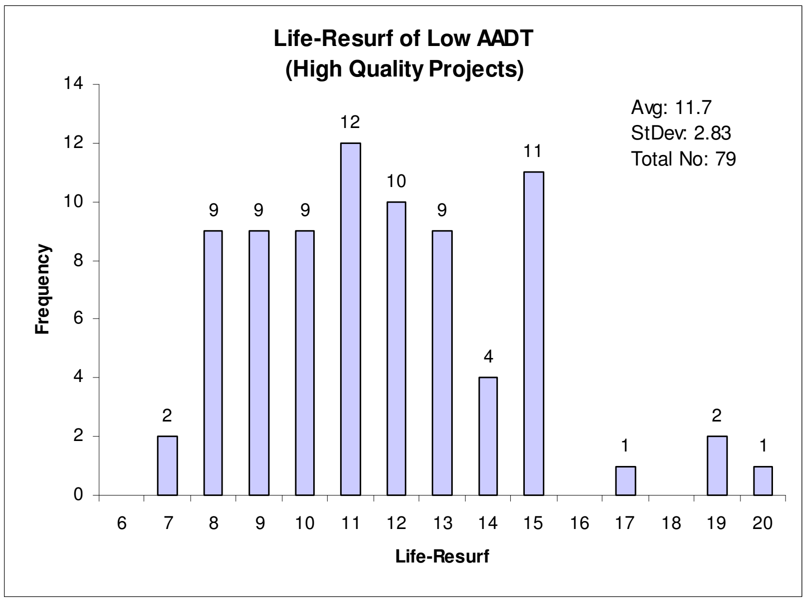


Figure 2.11 Resurf-Life and Project Count with Low AADT

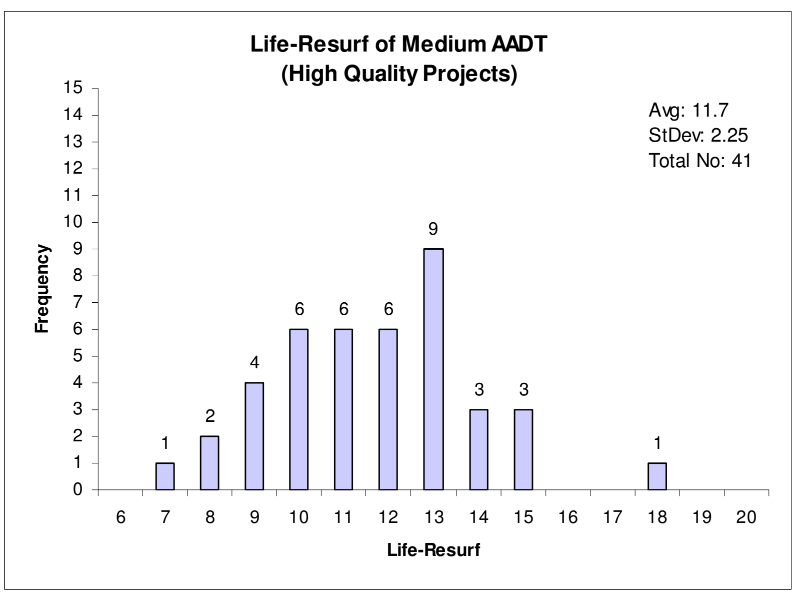


Figure 2.12 Resurf-Life and Project Count with Medium AADT

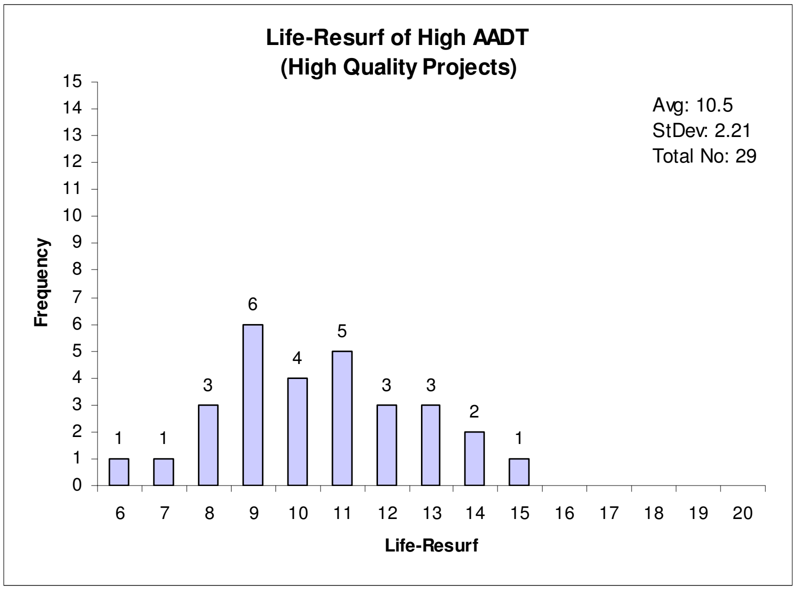


Figure 2.13 Resurf-Life and Project Count with High AADT

2.7 Pavement Life vs. Working Districts

In Figure 2.14, the number of projects and the average Life-Resurf are plotted for each working district. As can be seen, District 7 has the lowest number of High Quality projects while District 4 has 50 High Quality projects. This low number of High Quality projects may be an indication of the difficulty of performing the COPACES survey in the more urban environment of District 7 and may further indicate the need for a more automated system of data collection. District 2 has the longest Life-Resurf, which is 12.0 years; while the shortest one occurs in District 3, which is 10.1 years.

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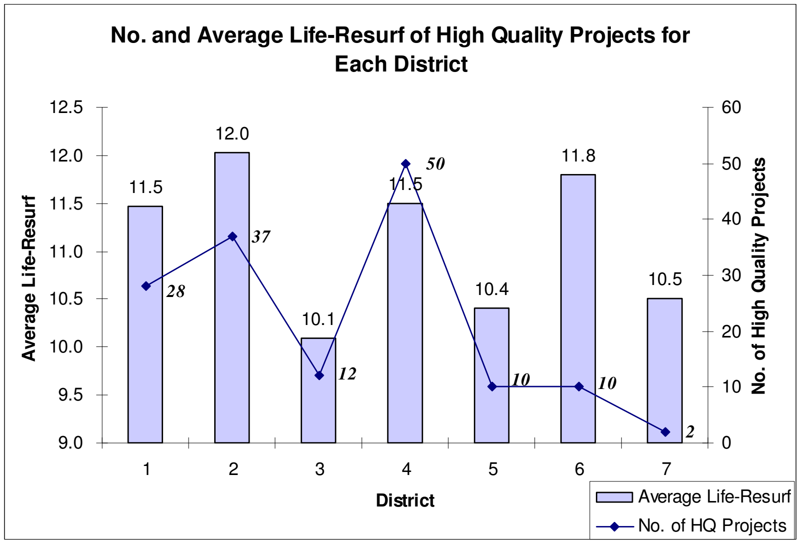


Figure 2.14 Resurf-Life and Project Count vs. Working Districts

2.8 Analysis on Pavement Distress

Pavement surface distress is an important indicator for pavement condition. In COPACES, the pavement rating is the combination of all presented distresses and their severity levels. In the section, the distress distribution will be investigated when a pavement needs resurfacing. The dominating distress will also be evaluated.

For all High Quality projects, the Average Length Weighted Deducts and the percentages are calculated for all distresses in the RBR Year. The procedures of data processing are as follows:

1) The distress deducts in each project for each distress are multiplied by the length of the project.
2) The average deduct of all projects for each distress is determined by dividing the value obtained in step 1 by the sum of the lengths of all projects for that particular distress. The result is called the "Average Length-Weighted Deduct".
3) The total deduct for each project is determined in the same way as given in step 2. Then, the average total deduct of all projects is calculated and called the "Average Length-Weighted Total Deduct".
4) The "Percentages on Total Deduct" = "Average Length-Weighted Deducts of each distress"/"Average Length-Weighted Total Deduct"*100%. (Note: The

Load_Deduct is the maximum load cracking deduct taken from the four severity levels.)

In Figure 2.15, the Average Length Weighted Deducts and the Percentage are plotted for each of the 10 Major Distresses for the High Quality projects. It can be seen that the dominate distresses are: Rutting, Load Cracking, Block Cracking and Patch/Pothole. Based on the discussion with engineers in OM, Reflection Cracking is likely to be categorized as Block Cracking if the underlying subbase material is unknown, which may increase the occurrence of Block Cracking. Further study is needed regarding this issue.

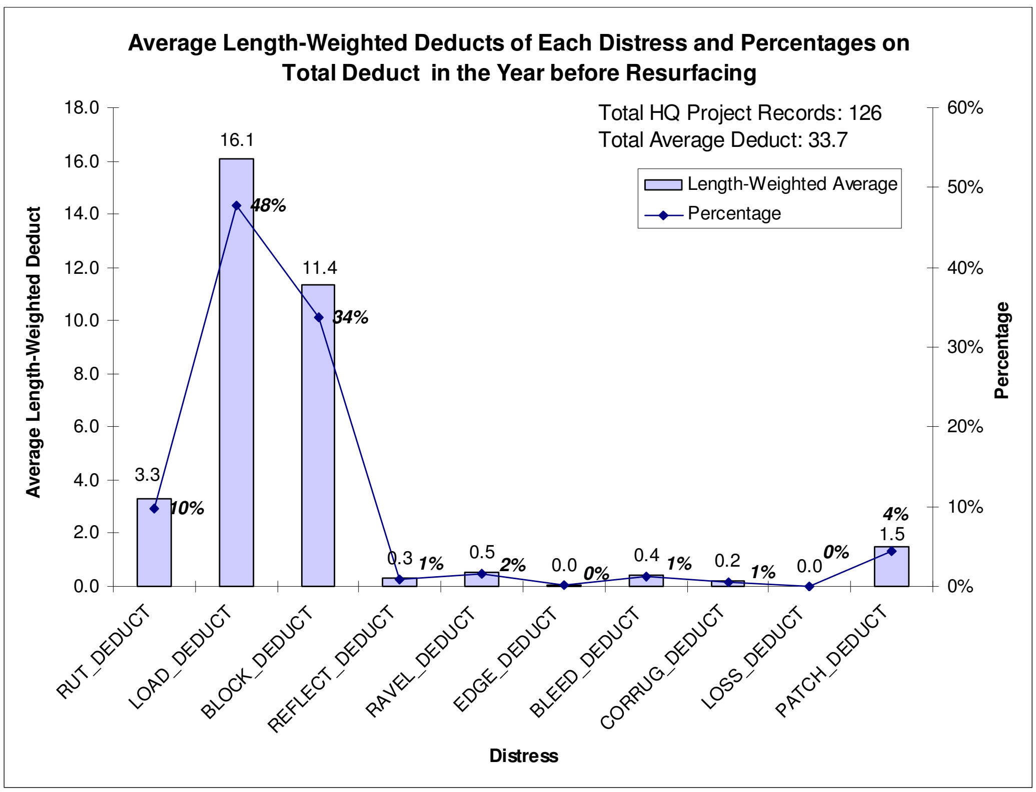


Figure 2.15 Distress Distribution in RBR Year

In Figure 2.16, the Average Length Weighted Deducts are plotted for each of the 10 Major Distresses (plotted horizontally) for the GDOT working districts using the High Quality projects. Note that District 7 was not included since there are no High Quality projects in it. As seen in Figure 2.16, distresses (Rutting, Load Cracking, Block Cracking and Patches/Potholes) are dominant among the different districts. Of the dominant distresses, Block Cracking appears to be the most uniform across districts. Among the 6 districts shown, District 5 has the highest average deduct for Load Cracking.

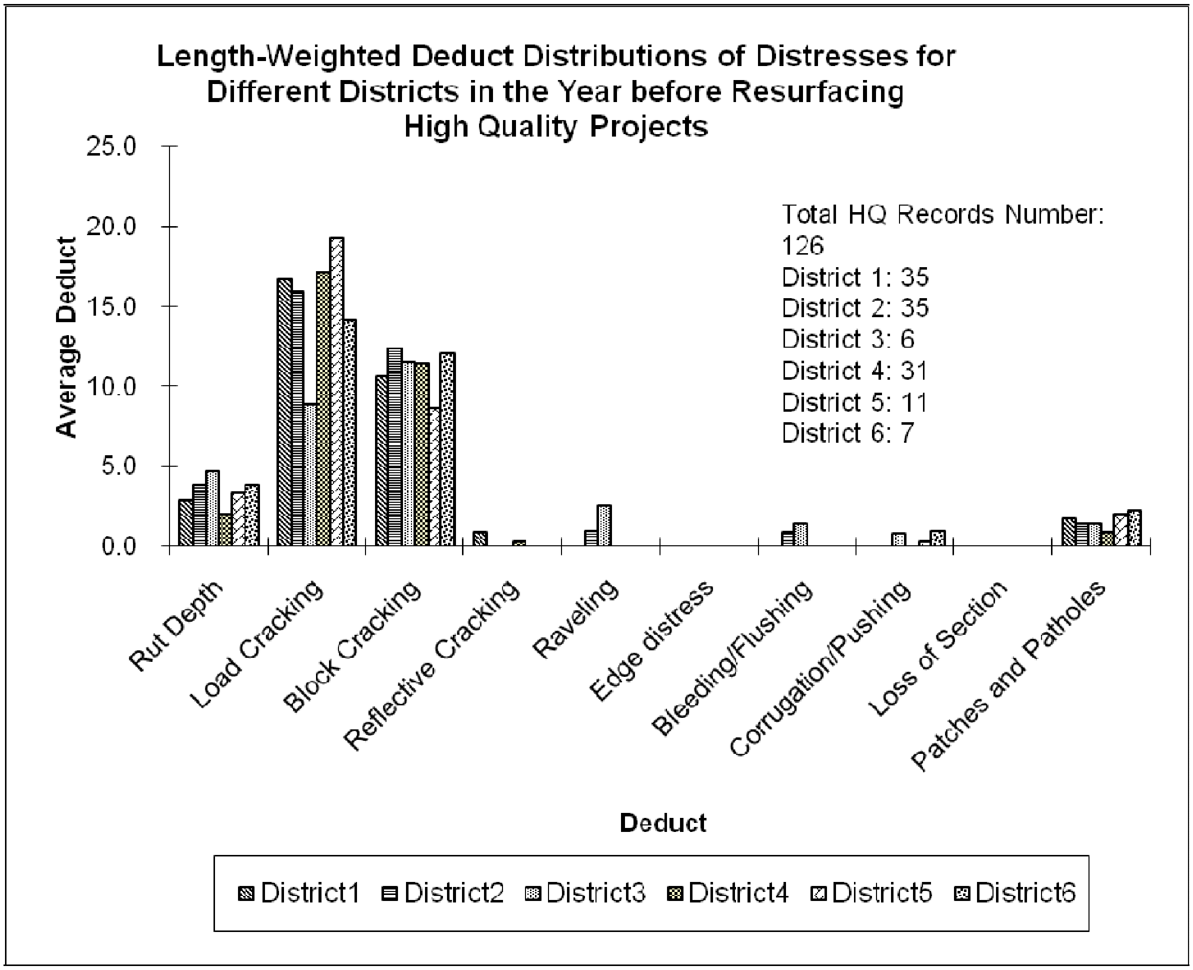
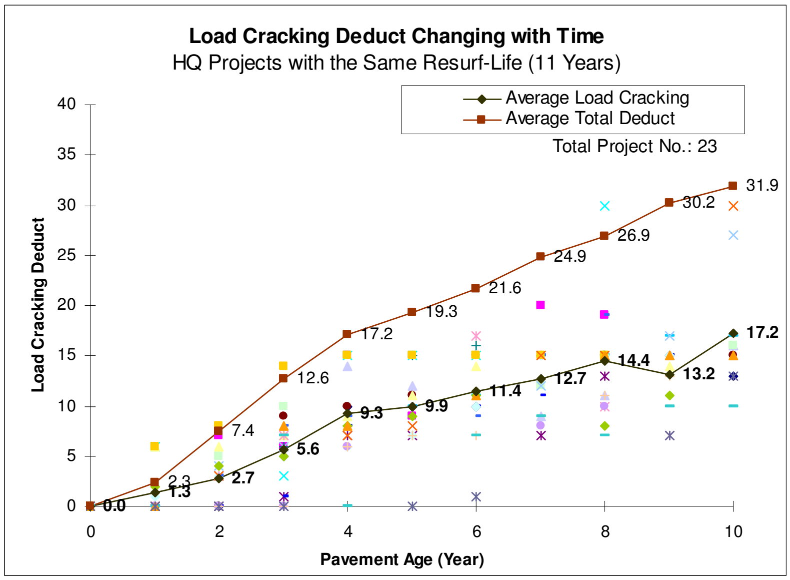


Figure 2.16 Distress Distribution in RBR Year in Working Districts

Figure 2.17 shows the development trends of load cracking and blocking cracking, which are two dominating distresses. The High Quality projects with the Life-Resurf of 11 years were chosen to do the analysis. In Figure 2.17, 23 projects are set to start with year zero. To maintain accuracy, duplicate records of the same project for the same year are deleted. For a specific project in a certain year, only one record which is most consistent with the trend is retained. Therefore, in any given year, there are 23 points at most. If in the second year, there are 20 points, this means that only 20 projects have survey data in the second year of this time cycle. The average for the second year means the average of the given 20 points.

In Figure 2.17, the trend for load cracking indicates a steeper assent for years 1-4 followed by a flatter slope for years 4-8 with a dip at year 9. The trend for block cracking shows a flatter slope than load cracking.



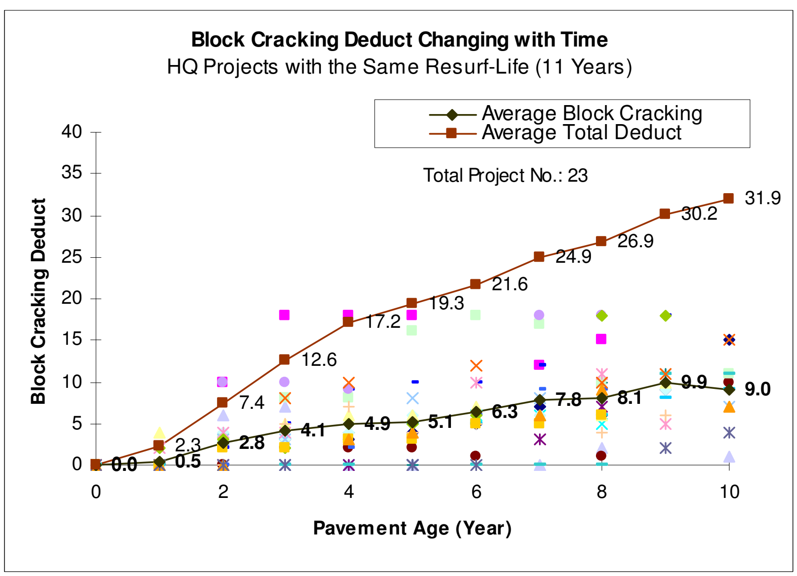


Figure 2.17 Development Trend of Load Cracking and Block Cracking

2.9 Mapping of Project Data

GIS is an intuitive way to display the spatial data. In this section, the High Quality projects categorized by life and AADT are plotted on the GIS Base Map with State Boundary, District Boundary, and Road Network.

Figure 2.18 shows the locations of the High Quality projects throughout the state and illustrates the capability of GIS to organize these projects into categories that provide important information for decision makers. ArcGIS was utilized with the establishment of the RCLink of each project for geospatial location. In terms of project life, data sets were established according to the ranges of Resurfacing Life. These ranges are shown in the legend of the GIS map and include the following: Short Life: 0 -7 Years, Medium Life: 8 – 11 Years and Long Life: 12 – 20 Years. Taking each data set individually, the AADT of the projects was categorized by three ranges as follows: (0 – 5000), (5001 – 10000) and (10001 and greater). These distinct ranges are illustrated by increasing line width as shown in the GIS map legend. Finally, the GDOT Districts and the state roadway network are included in the GIS map for reference purposes.

With the statewide mapping application in place, the distribution of the High Quality projects within the districts and the state can be visualized. Also, the location of projects with extremely short lives and projects with extremely long lives can be studied. Likewise, with the expansion of the GIS database, it is easy to see how other causative variables can be studied in future research.

In Figure 2.18, note the scattered distribution of Long-Life, high AADT pavements. With the void of projects in many areas, it is important to improve the data collection quality in future. In the meantime, further research is needed to recover those Medium Quality projects. With these efforts, the increased number of High Quality projects in conjunction with GIS functionality can be used to analyze and understand the pavement behavior and deterioration.

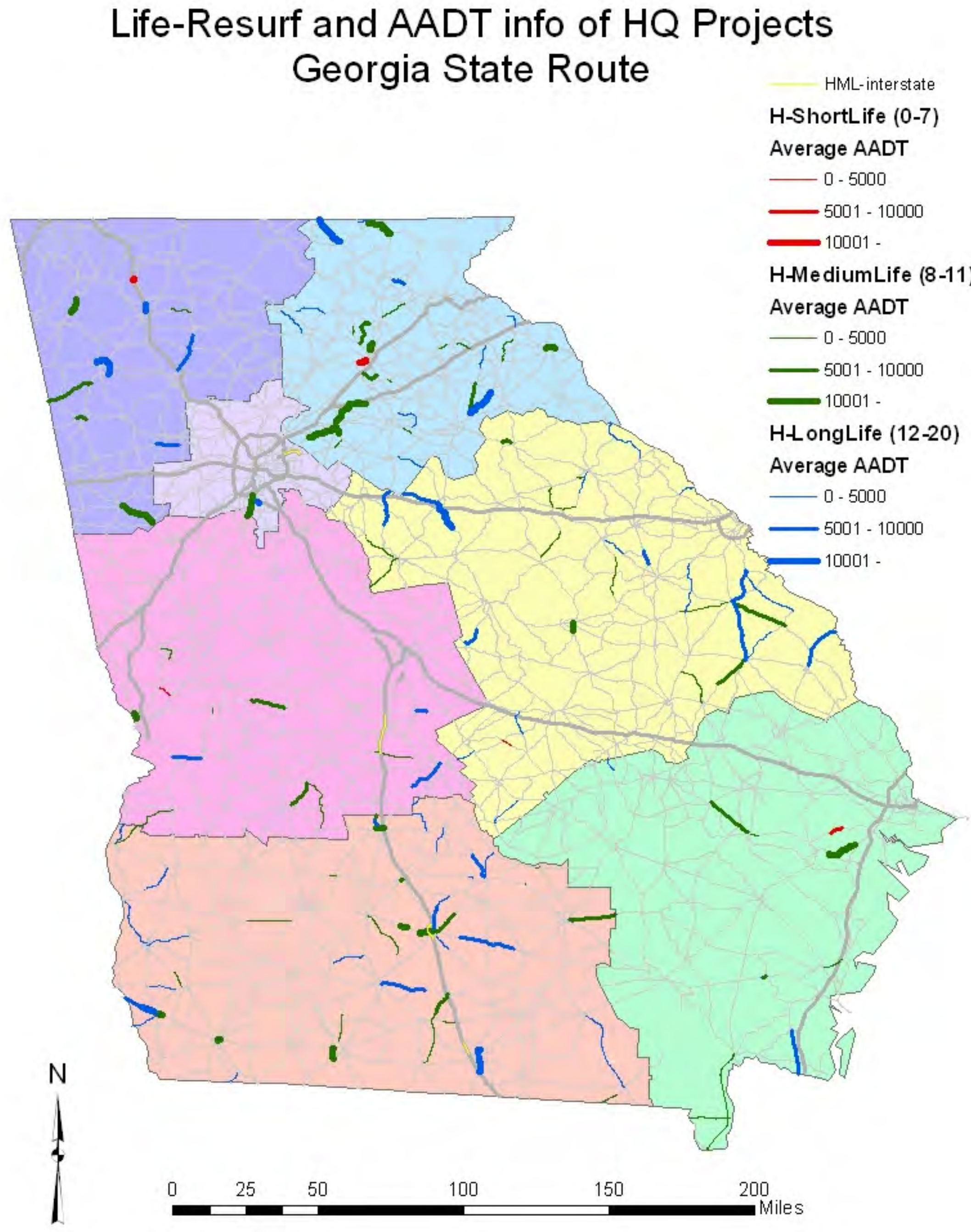


Figure 2.18 GIS Display of High Quality Projects Categorized by Life and AADT

2.10 Summary

Through the study on pavement life and the corresponding causative parameters, the following summarizes the findings and offers the recommendations for further research.

- **Findings:**

1) Categorizing projects based on the completeness and quality has resulted in manageable classification of projects. From 9,713 projects, 149 projects were categorized as High Quality; 169 Medium Quality; and 137 Low Quality.
2) The High Quality projects represent the best source of project data because they possess clear and complete data points for the start, end and middle of the pavement performance curve. Based on the descriptive statistical analysis of Resurfacing Life, dominate distresses and Rating before Resurfacing, it was determined that the High Quality project were used to do the analyses.
3) Having no interstate projects in the category of High Quality projects indicates that there is a challenge to perform the COPACES survey on the interstate due to the high traffic volume. Thus, there is a need to develop alternative condition assessment methods such as using computer vision or laser technology to perform automatic condition assessment.
4) The statistical analysis shows that the average resurfacing life of the GDOT projects is approximately 11 years. The average resurfacing life varies by district with the range from 10.1 years (District 3) to 12.0 years (district 2).
5) Comparing the pavement performance among different traffic volume categories (e.g. High, Medium, and Low), it shows a progressive decline in average resurfacing life as would be expected going from Medium AADT to High AADT.
6) Through the study on the relationship between pavement performance and different functional classes, the average resurfacing lives for the rural roads are higher than the urban road (11.5 years vs. 11.0 years).
7) The average Rating Before Resurfacing (RBR) is approximately 66 according to the statistical analysis. With the targeted 70 as the resurfacing trigger point, the average delay for resurfacing in GDOT is around 2 years. District 7 has the highest RBR, which might imply that District 7 has a more timely resurfacing

policy compared with other districts. Approximately 68% of projects have been delayed for more than one year before resurfacing.

8) The study on the distribution of pavement distress shows that the dominating distresses include Load Cracking, Block Cracking, Rutting and Patches/Potholes.
9) Mapping of the High Quality projects categorized by pavement resurfacing life and AADT illustrated the capability of GIS in displaying the spatial data, which is more intuitive and informative to decision makers. With more High Quality projects available in further, more in-depth spatial analysis can be performed to analyze the pavement performance and the corresponding geospatial parameters.

- **Recommendations:**

1) Further study can be performed to determine the most indicative variables that can be used to establish the most cost-effective treatment criteria and timing.
2) If data is available, more variables should be included in the analyses such as the pavement structure, materials, subgrade, environments and ESAL.
3) Further study can be performed on the long-life pavements especially pavements with multiple cycles in order to identify the pavement variables contributing to the extended life, e.g. timely pavement preservation for pavements with specific base materials, traffic volumes and designs. These types of pavements may last perpetually with only resurfacing if it is applied on a timely basis. The analysis of the multiple cycles should give insight into the modeling of the complete service life of the pavement.
4) Alternative technologies need to be explored in order to obtain the high quality survey data for Interstate highway. Due to the heavy traffic on these roads, there is a need to develop an automated condition survey system using computer vision and/or laser technology. Safety and technology should be the focus for acquiring more and better data for the interstate highways.
5) Using a pre-selected High Quality projects (10 – 20 projects), a detailed pavement performance analysis should be done. From this analysis, a model would be created which can:
   i. Adequately predict future pavement performance.

ii. Be adapted to incorporate the effect of pavement treatments.
iii. Allow for the projection of future pavement performance based on different treatment scenarios.
iv. Develop a cost model that includes reliability which follows the proposed treatment and timing scenario associated with future pavement performance.

6) Further study is needed to investigate the current GDOT strategy of using the rating of 70 before resurfacing. This study should examine the effectiveness of this strategy and look at a possible new model that allows for the aggregation of performance of various projects as a strategy. Also, the study should look at the impact of various treatment options for the pavement performance.
7) With more detailed data being available, a more in-depth study can be performed on the GIS platform to analyze the pavement performance and its relationship with other geospatial parameters such as materials, subgrade and environments.
8) The data quality for pavement condition survey needs further improvement. It is strongly suggested to implement a comprehensive data quality assurance module in the field data collection program (COPACES) and a data quality checking module in the Upload module. The historical pavement performance curve should be applied in the QA/QC procedures.

3 Long-Term Pavement Performance Forecasting and Need Assessment

3.1 Objectives

GDOT faces the current challenges of growing traffic volume and severe budget shortfalls. With the limited resource, decision makers must select and implement the most cost-effective maintenance and rehabilitation alternatives to provide and maintain the pavements in a serviceable condition.

There is an urgent need for GDOT to fulfill the following tasks in managing pavement maintenance and rehabilitation:

1) Effectively justify to the legislature highway pavement preservation funding needed.
2) Perform long-term network-level asphalt pavement performance forecasting.
3) Perform "what-if' analyses to evaluate the impacts of different funding levels and pavement preservation strategies.
4) Explore alternative pavement preservation strategies when funding becomes limited.

With the aforementioned needs, the objectives of this work task are to develop a network-level pavement performance forecasting and simulation model and a corresponding program that will facilitate the GDOT decision makers to effectively address these issues. A comprehensive literature review will be conducted first. Then, the historical PACES data and maintenance expenditure will be analyzed and combined with the engineering advice of the engineers in the Office of Maintenance (OM) to create a set of realistic input parameters (e.g. pavement condition categories, Markov transition probabilities, treatment methods and their unit costs and performance). Several cases are studied to explore the capability of the developed program, as well as to verify its reliability. The major findings of the research work described in this chapter has been published in the journal of Transportation Research Record (Wang, et al 2009)

3.2 Literature Review

After the Interstate Highway System (IHS) was completed early in the 1990s, the effort has been shifted to preserving and operating the one trillion dollars investment in highways and bridges. The concept of Asset Management was adopted to facilitate decision making in achieving the highest performance with the selection of policies among several alternatives covering an extended time horizon. Federal Highway Administration (FHWA) (FHWA 1999) defines an Asset Management as "*Asset management is a systematic process of maintaining, upgrading, and operating physical assets cost-effectively. It combines engineering principles with sound business practices and economic theory, and it provides tools to facilitate a more organized, logical approach to decision-making. Thus, asset management provides a framework for handling both short- and long-range planning*".

Pavement Management System (PMS) is an important branch and also an integral part of Asset Management, which typically involves complex decisions about how and when to apply pavement Maintenance, Rehabilitation and Reconstruction (MR&R) to keep the costs at a reasonable level. The following sections summarize the major findings in literature regarding building a PMS model.

3.2.1 Modeling on Pavement Deterioration

Pavement deterioration modeling is the most essential part of a PMS. The accuracy how a pavement deterioration model can achieve directly determines the applicability and reliability of a PMS regardless of how complicate and complete the optimization programming strategies are applied in it. Most deterioration models for rigid (PCC) pavements are fairly accurate because their failure follows a more typical structural pattern. In contrast, the deterioration of flexible (asphalt) pavements is more difficult to predict due to the visco-elastic characteristics of the asphalt (Ozbay and Laub 2001) as well as the complication of the involved factors such as traffic loading, environment, pavement structure, and maintenance & rehabilitation activities. That's why the literature on predicting flexible pavement performance are overwhelming. Accordingly, in this section only flexible pavement deterioration modeling is discussed.

3.2.1.1 Why Pavements Deteriorate?

The mechanism of pavement deterioration has been widely discussed and investigated. Basically, flexible pavement fails due to fatigue. Many factors contribute to pavement deterioration (a detail review can refer to (Shiyab 2007)).

- Traffic

  Traffic is considered as the most important factor affecting pavement performance. In pavement design, traffic configuration, magnitude and the number of repetition are normally considered as the basic traffic parameters (Huang 1993).

- Material properties and composition

  Properties of asphalt mix and subgrade highly affect pavement performance. These properties include durability, stability, flexibility, skid resistance, fatigue resistance, and impermeablity.

- Environment

  Environmental related factors include temperature, freeze and thaw, humidity and precipitation and ground water.

- Others

  Other factors include geometric features (longitudinal and cross slopes, provision of drainage facilities), design and construction factors such as pavement structure thickness, maintenance level, surface characteristics (micro and macro texture) and the quality of construction works including initial roughness level, and construction joints.

According to a case study, Day (1995) reveals three pavement concerns, which will affect pavement performance: an inadequate pavement section, seepage of water through the base material, and settlement of utility backfill.

3.2.1.2 Pavement Performance Indicators

Pavement performance can be defined from different perspectives. The well-known definition from American Association of State Highway Officials (AASHO) is the serviceability of a pavement over a design period of time. The serviceability of a pavement is defined as the ability to serve high-speed, high-volume automobile and truck traffic (AASHTO 1962).

Typically, there are four measurements those can be used to evaluate a pavement condition: roughness (or smoothness), surface distress, structural capacity, and skid resistance.

Surface distress indicates the pavement defects due to various factors such as traffic loading, environment, and others. Distress types and severity levels are surveyed by almost all transportation agencies following some well-known standard or their own distress identification manuals. The manual for flexible pavement distresses, developed by US Army Corps of Engineers, are known to be widely adopted worldwide. From this manual, there are 19 different distress types can be identified: alligator cracking, rutting, potholes, corrugation, depression, slippage cracking, edge cracking, patching, bleeding, block cracking, joint reflection cracking, swell, weathering and raveling, bumps and sages, lane shoulder drop off, polished aggregate, longitudinal and transverse cracking, and rail road crossing. Not all distresses are collected by transportation agencies. Also, the identification methods, measurement methods and unit can be different. The pavement condition can be rated by considering the combination of all occurring distresses. For example, in GDOT, PACES rating can be computed by deducting the sum of the observed distresses from score 100, when there are no visible surface distresses (GDOT 2007).

Rideability or serviceability is another commonly used indicator for pavement condition. The Present Serviceability Index (PSI) and the International Roughness Index (IRI) can be used for this purpose.

- PSI

  PSI is based on the original AASHO Road Test PSR (AASHTO 1962). The PSR was a ride quality rating that required a panel of observers to actually ride in an automobile over the pavement in question. Since this type of rating is not practical for large-scale pavement networks, a transition to a non-panel based system was needed.

  To transition from a PSR serviceability measure (panel developed) to a PSI serviceability measure (no panel required), a panel of raters during 1958 to 1960 rated various roads in the states of Illinois, Minnesota, and Indiana for PSR. This information was then correlated to various pavement measurements (such as slope variance (profile), cracking, etc.) to develop PSI equations. Further, the raters were asked to provide an opinion as to whether a specific pavement assessed for PSR was "acceptable" or "unacceptable" as a primary highway. Thus, although PSI is based on the same 5-point rating system as PSR it goes beyond a simple assessment of ride quality. About one-half of the panel of raters found a PSR of 3.0 acceptable and a PSR of 2.5 unacceptable. Such information was useful in selecting “terminal” or failure serviceability (PSI) design input for empirical structural design equations.

- IRI

  The international roughness index (IRI) was developed by the World Bank in the 1980s. IRI is used to define a characteristic of the longitudinal profile of a traveled wheeltrack and constitutes a standardized roughness measurement. The commonly recommended units are meters per kilometer (m/km) or millimeters per meter (mm/m). The IRI is based on the average rectified slope (ARS), which is a filtered ratio of a standard vehicle's accumulated suspension motion (in mm, inches, etc.) divided by the distance traveled by the vehicle during the measurement (km, mi, etc.). IRI is then equal to ARS multiplied by 1,000. Recently, many highway agencies worldwide start to use roughness as a trigger for pavement rehabilitation and reconstruction.

Other indicators such as structural number (SN), moduli (backcalculated from FWD (Falling Weight Deflectometer)) (Maina et al. 2000), and skid resistance can also be employed to evaluate pavement condition. In the most literature pertaining to pavement deterioration modeling, only one indicator was used. Shiyab (2007) proposed a new indicator (so called Overall Pavement Quality Index (OPQI)) combining four indicators: distress, roughness, structure, and skid resistance.

3.2.1.3 Approaches to Pavement Deterioration Modeling

The approaches to pavement deterioration modeling can fall into three categories: mechanistic, empirical and mechanistic-empirical. Mechanistic methods apply physical principles such as soil mechanics, material mechanics, and multilayer structural analysis techniques as well as limited experimental results. The advantage of mechanistic methods lies in the strict formulation deducing and tractable and explanatory results. Otherwise, the limitation of this type of approach is also obvious because many factors such as traffic loading, environment, and material properties can not be accurately obtained and duplicated with limited experiments. The empirical approach employs statistical techniques to analyze the historical pavement condition data. Thus, the relationship between pavement condition and time can be obtained. The advantage of this kind of methods is that all factors affecting pavement performance can be considered. The disadvantage is that the result, in most cases, is site specific and cannot be easily applied on a different site. In addition, empirical approach always needs large amount of historical data, which also limits its application. The mechanistic-empirical approach is the combination of the above two approaches. The mechanistic approach assists in determining pavement responses, structuring the explanatory variables and functional forms of empirical models. The final relationship between the response variables and pavement performance is developed with the statistical techniques adopted in the empirical approach. The coherent combination utilizes the advantages of both approaches and is expected to attain better performance models than the empirical approach only.

The early design guide developed by AASHTO (1993) is a good example of empirical method. To address some of the limitations of the empirically based design procedures of the AASHTO Guide, the NCHRP (National Cooperative Highway Research Program) 1-37 research project was initiated in 1998 to develop a guide that used existing mechanistic-based models and statistical results. This mechanistic-empirical method is gradually adopted by highway agencies nowadays.

Considering the methodology applied in the statistical analysis, pavement deterioration models can be further divided into deterministic and probabilistic models. In deterministic models, all variables are determined. In contrast, the result from probabilistic models is represented by probability.

3.2.1.3.1 Deterministic Model

The classic deterministic pavement deterioration model developed by AASHTO (1962) predicts the loss of the serviceability by considering the effects of traffic loadings, material characteristics, and environmental factors.

Garcia-Diaz and Riggins (1984) developed an empirical sigmoid curve model to accommodate the impact of the routine maintenance actions, which can provide more accurate long-term prediction. To overcome the shortage of empirical model that is lack of explanatory capability, Paterson (1987) proposed a series of incremental empirical models those consider more explanatory variables, such as pavement strength over different subgrades, environmental conditions, and maintenance actions, and different model structures based on the filed data.

Prozzi (2001) has developed a mechanistic-empirical pavement performance model by using a two-step approach. An initial incremental nonlinear pavement performance model was developed based on the AASHO Road Test data by using the random-effects estimation methods. Then, with the integration of the joint estimation method, the bias of the parameter estimation in the prediction model was corrected by incorporating the in-service pavement data sets.

Though deterministic model can fit the data quite well in some cases, it cannot capture the uncertainty in the process of pavement deterioration. To overcome this disadvantage, many other probabilistic models were developed.

3.2.1.3.2 Probabilistic Model

Li (2005) summarizes the classifications of probabilistic models as follows. There are three categories of probabilistic models: econometric models, Markov Chain models, and reliability analysis. Each category covers a range of more specific applications. With the interest of building a PMS model, only Markov chain models are reviewed.

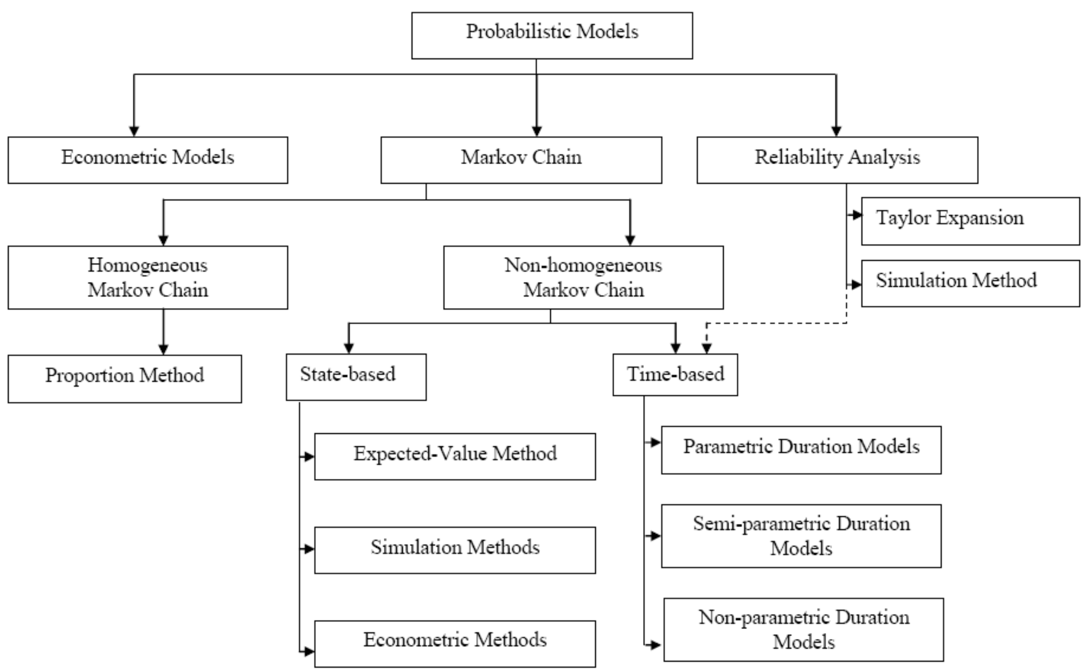


Figure 3.1 Classifications of Probabilistic Pavement Deterioration Models (Li 2005)

Markov model is the most popular probabilistic model for network level of management. Discrete Markov Model is the one used widely, in which the continuous performance indicator (such as PSI) is discretized into several conditions (or states). According to time-related factor, Markov models are classified into two categories: homogeneous and non-homogeneous Markov chain model.

1) Homogeneous Markov Chain Model

In homogeneous Markov chain model, the present condition state is only related to the previous state. In other words, the transition probabilities are constant throughout the analysis period.

In the development of Arizona Pavement Management System, Golabi et al. (1982) defined transition probabilities for each alternate maintenance actions ranging from routine maintenance to substantial corrective measures as $p_{ij}(a)$ which means the probability that the pavement condition changes from state i to j in one year with the action a applied. In this model, 120 states were discretized according to the combination of different level of pavement roughness, cracking, the change in cracking during the previous year, and the index to the first crack (which identify the difference of deterioration rate among different non-routine maintenance actions). A total of 17 alternate maintenance actions were defined for each state.

Butt et al. (1987) proposed a Markov process for pavement performance prediction, which was not implemented in a PMS and didn't consider maintenance actions. PCI was used to define pavement states (10 states were defined with equal 10-point interval). To estimate the transition probabilities, the Fletcher-Powell algorithm was used to solve an unconstrained nonlinear programming. The objective function was defined as

$$\text{Minimize } \sum_{t=1}^{N} \sum_{j=1}^{M(t)} \left| Y(t,j) - E\left[X(t,p)\right] \right|$$

Where

N = total number of duty cycles (age) for which PCI versus age data are available within each family;

$M(t)$ = total number of data points recorded at a duty cycle (age) t;

$Y(t, j)$ = PCI rating for each sample taken at a duty cycle (age) t;

$E[X(t, p)]$ = expected value in PCI at a duty cycle (age) t, as predicted by the current Markov values

In this model, to reflect non-homogeneous behavior of pavement deterioration, pavement ages were grouped into 5 time zones with 6 years in each zone. The transition among each time zone is non-homogenous, while the transition in each time zone is homogeneous.

2) Non-Homogeneous Markov Chain Model

Two types of Markov processes have been proposed according to different assumptions. The first is homogeneous Markov Chain process which assumes that the present condition state is only related to the previous state or the impact variables are constant during the analysis period (Golabi et al. 1982). In other words, the Markov Chain model has no memory of the entire past. On the other hand, the non-homogeneous Markov Chain models characterize the changes of the pavement deterioration rates over time. The Markov Chain models can be developed using the state-based or time-based models. The state-based models quantify the transition probabilities from one condition state to another in a predefined period of time, while the time-based models estimate the probability distributions of time it takes to change from one condition state to another (Mishalani and Madanat 2002).

The state-based models are widely developed in practice, because they require less frequency of data collection. The core of the state-based Markov Chain models is the development of Transition Probability Matrices (TPM). Research methods, varying from the simplest proportion method (Wang et al. 1994) and the expected-value method (Butt et al. 1987; Jiang et al. 1989) to the complicated econometric techniques (Madanat et al. 1995), were used to develop the TPMs. Since the deterioration rate is not constant in the whole deterioration process, non-homogeneous Markov Chain model is more proper to model this deterioration process.

The widely used non-homogeneous Markov Chain models were developed using the expected-value method in the 1980s. The expected-value method segments the pavements into different groups and then minimizes the differences between the expected values calculated using the TPMs and those obtained from the regression model with time as its explanatory variable. Another way of developing the state-based non-homogeneous Markov Chain model is the simulation approach which assumes design variables to follow different statistical distributions. The Monte Carlo simulation technique was used to produce the probability vectors representing the transition from one condition state to another, consisting of the TPMs. The calculated TPMs of pavement deterioration process determine the time-related non-homogeneous Markov Chain processes (Li 1996). This simulation method can save a significant amount of money and effort compared with the previously discussed proportion and expected-value methods, because the collection of multi-year performance data is not required.

3.2.2 Pavement M&R Planning

The final goal of a PMS is the M&R planning, i.e. to determine what M&R actions should be taken, given the current pavement conditions of the pavement sections within its jurisdiction, pavement deterioration behaviors, and the goals that would be met during a given time horizon. At the early stage before 1990s, the main focus was put on the best possible design of each individual project. And the network-level planning was simply formed by accumulating all projects for each year of the planning horizon. This type of "from the bottom up" approach worked quite well when funds are sufficient. With the aging pavement system deteriorates, the budget demand increases dramatically while the availability of budget is limited. The even worse situation is that the budget shrinkage is an unavoidable reality nowadays. Under this situation, the purely engineering oriented approach is not applicable. Economic analysis on network level must be considered in a PMS. This "from the top down" approach was prevalent in the past 10 years aiming to provide the best network-level result with the severe budget constraint (Gendreau and Soriano 1998).

3.2.2.1 Project-level Planning

Project-level and network-level planning are two commonly recognized planning strategies involved in a PMS, which address different concerns (Kher and Cook 1985; Gendreau 1987; Butt 1991).

Project-level planning deals with individual pavement section (project). Decision criteria based on the project related properties such as traffic, safety, inventory, and pavement condition are established to determine the optimum section M&R strategies. Alternative treatment strategies on the same pavement section will be also evaluated. The approaches to project-level planning include (Gendreau and Soriano 1998): (1) engineering judgment; (2) life-cycle cost analysis (LCCA); (3) dynamic programming; (4) expert system.

Engineering judgment on pavement M&R planning is widely used among highway agencies. It is easily implemented and requires less information. Engineer's experience plays an important role in this approach. Apparently, the disadvantage is that the result may vary well and not be the most cost-effective.

LCCA, in a broader Asset Management scale, is widely accepted as a useful project evaluation tool (FHWA 1999), while its application is not so widespread among transportation agencies. According to LCCA, the agency and user cost incurred over the life of a project can be evaluated, by which the analysis between or among various alternatives can be conducted. Though the idea is very sound, the implementation is not so straightforward due to the following open questions (Ozbay et al. 2004):

- *"Which costs should be included?*
- *Should benefits be included; if so, what type and in which form?*
- *What discount rate should be used?*
- *What is the reliability of the cost and benefit estimates?*
- *What is the length of the life cycle or the analysis period?*
- *What is the minimum acceptable or "trigger" level of serviceability of the infrastructure facility?"*

Academic literatures on LCCA include (Haas 1994; Kirk and Dell'Isola 1995; Papagiannakis and Delwar 2001; Reigle and Zaniewski 2002). National and international guidelines include (HDM-4; Office of Management and Budget 1992; FHWA 1996; Walls and Smith 1998). Ozbay et al. (2004) conducted a three-year survey on the use of

LCCA among all state departments of transportation in US. Figure 3.2 illustrates the gap between state-of-the-practice and state-of-the-art of LCCA.

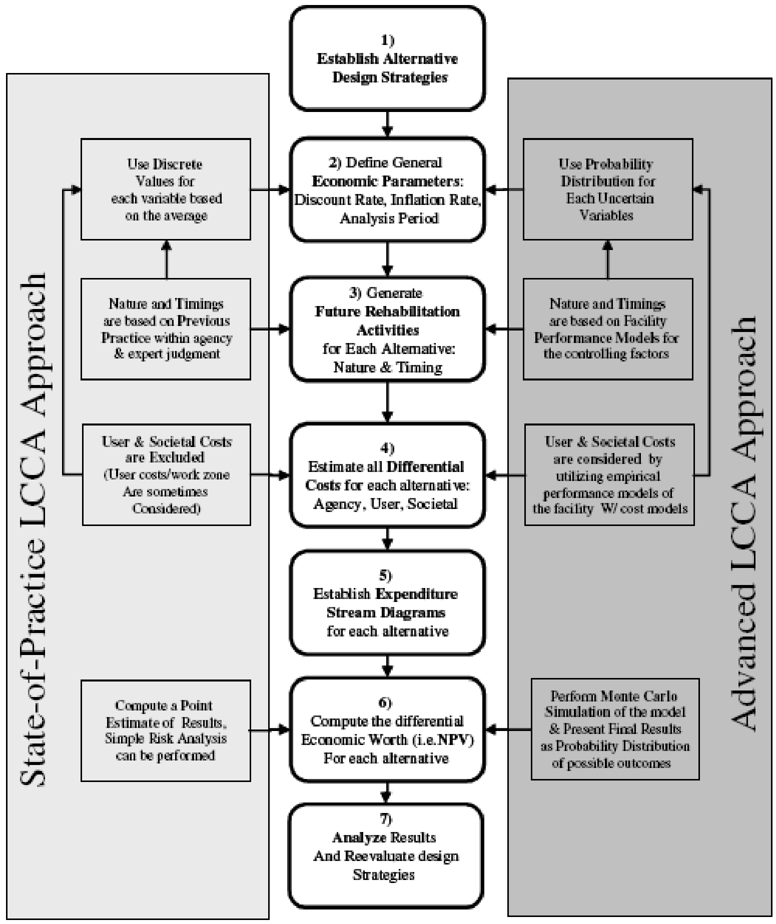


Figure 3.2 State-of-the-Practice vs. State-of-the-Art of LCCA (Ozbay et al. 2004)

3.2.2.2 Network-level Planning

While project-level planning deals with individual project, network-level planning, on the other hand, considers all pavement sections in a jurisdiction. The network-level planning intents to seek a solution to maintain the pavement network at a serviceable condition while respecting predetermined budgetary constraints. Project prioritization and optimization are two common approaches to solve network-level planning.

- **Project Prioritization**

Priority is to list all projects according to certain criteria, like highest benefit-cost ratio, least cost, largest benefit, safety gain etc. and select projects from high priority to low until reach the constraints. This belongs to the “from the bottom-up” philosophy of pavement management (Gendreau and Soriano 1998).

Priority approach could be separated into two steps, project evaluation and project selection. In terms of project evaluation, besides using certain index or combination of indexes, Fwa and Chan illustrated the feasibility of using neural network models for priority assessment of highway pavement maintenance needs (Fwa and Chan 1993).

- **Optimization**

Nowadays, the overwhelming literatures are focus on the optimization methodology for network-level planning. To form a set of mathematical programming models, two components must be determined: objective functions such as minimizing total costs and maximizing pavement performance; constraints such as annual budgets limitation, total budget limitation, network performance requirement, and other operational restrictions. Then, these models can be solved by one of several existing optimization techniques.

Based on the way how pavement network are formed, two different approaches can be found in all literatures: (1) pavement network are aggregated by all individual pavement sections (projects); (2) pavement network are divided into several families (or classes), each of which has the same characteristics (functional class, traffic, pavement type, etc). The following sections summarize their advantages and disadvantages.

1) Individual Project Model vs. Family Model

The planning results on individual project model are directly applied on each individual pavement sections over the whole planning horizon. Therefore, the suggested M&R program can be directly implemented with optimal network performance.

Mbwana and Turnquist (1996) presented a dynamic programming model which combines network-level with segment-level analysis. Variables were set on each section (Mbwana and Turnquist 1996). Ferreira et al. formed a mixed-integer optimization model, which used segment-level variables and identified maintenance actions taken on each segment

(Ferreira et al. 2002). The other is to aggregate them into families and analyze each group. Markov chain model falls into this category. Classification is based on different criteria. For example, network could be divided according to pavement structure, loading conditions (Abaza 2007). Grivas classified pavement sections into states that are defined on the basis of distress and non-distress factors, like pavement type, traffic, structural rating, surface rating and cracking rating (Grivas et al. 1993).

The first method has difficulty to deal with large-size problem while the second approach needs additional project selection process. To address this limit, one way is proposed by (Gendreau 1987), separate the whole problem into two complementary problems: a strategic problem (aggregated) to address the financial aspect and a tactical problem (detailed) to determine precise M&R program using the strategic solution as input. Additionally, heuristic optimization algorithms were used to solve large-size problem. The way to link project-level or segment-level analysis to network-level analysis needs further exploration.

2) Mathematical Programming

- Optimal control

The first trying is to solve M&R planning as an optimal control problem (Friesz and Enrique Fernandez 1979). Markow and Balta used optimal control to solve for the optimal timing of pavement rehabilitation (Markow and Balta 1995). As incontinuity of pavement performance curve caused by maintenance and rehabilitation activities, the optimal control problem is more complex. Solutions of only one rehabilitation case were provided. Solving optimal control problem is to choose one control and corresponding trajectory from all feasible solutions which optimizes certain objective function. If treatment times were determined and analysis period was limited, solving such kind of optimal control problem is like to enumerate all possible solutions and choose the best. One difficulty here is that treatment times or treatment frequency need to be predetermined. Therefore, this method was discarded.

In terms of mathematical optimization, linear programming, integer programming, non-linear programming and dynamic programming are applied.

- Linear programming

Golabi et al. (1982) developed a PMS for Arizona DOT used for the whole network system. Markovian process and LP model were used with the objective of minimize total cost. Decision variables are ‘fraction of network’.

Grivas et al. (1993) applied linear programming on network-level optimization problem. Pavement sections are classified into states that are defined on the basis of distress and non-distress factors, like pavement type, traffic, structural rating, surface rating and cracking rating. For each state and each treatment, state increment to occur is predicted based on historical data and empirical knowledge.

Abaza (2007) formulated a constrained linear optimization model with objective to maximize pavement condition improvement. Expected age donated the anticipated pavement condition improvement obtained by applying a specific treatment. It is used instead of complex pavement performance model. The whole network is divided into a number of systems with similar pavement structure and loading conditions. Maple 8 was used to get the optimal solutions.

- Integer programming

Al-Subhi et al. (1990) and Jacobs (1992) applied similar mixed-integer models to optimize long-term bridge deck rehabilitation actions. Jacobs set rehabilitation intensity as constant and the deterioration curve as piecewise linear and formed mixed-integer linear programming problem.

Ferreira et al. (2002) formed a mixed-integer optimization model, which linked segment-level analysis to network-level pavement management system, to identify maintenance actions taken on each segment. The objective is to minimize total discounted maintenance and rehabilitation cost. The model was solved by generic algorithm. After compared with branch-and-bound algorithm, problem size was still an issue for classic optimization approaches.

Ouyang and Madanat (2004) presented a mixed integer nonlinear programming model for optimal highway rehabilitation planning under multiple rehabilitation activities on multiple facilities. The model is aimed to minimize the life-cycle cost. A realistic empirical nonlinear pavement performance model was incorporated into the model. Branch-and-bound algorithm and a greedy heuristic algorithm were used to solve this model and got similar results. Heuristic approach is recommended for large scale problem in practice.

To solve integer programming problem, heuristic methods were used. Generic algorithm (Fwa et al. 1994; Fwa et al. 1996; Fwa et al. 2000; Ferreira et al. 2002) is one of the most popular. Besides that, greedy heuristic algorithm was also introduced (Ouyang and Madanat 2004).

- Dynamic programming

Feighan et al. (1987) used dynamic programming in conjunction with Markov chain model to obtain minimum cost maintenance strategies. Pavement sections were grouped into clusters with same properties, including surface type, distress modes and traffic levels. Dynamic programming is an optimization approach performed simultaneously on these classes.

Mbwana and Turnquist (1996) formed a network-level model for pavement management system. The model used each segment as decision variables and offered an easier way to link project-level and network-level analysis together. Also it considered both agency cost and user cost under traffic growth. Optimal long term M&R policies can be found by solving a dynamic programming problem. Improved policy iteration, successive approximation and conversion to an equivalent linear program were three available ways. Conversion to LP was chosen here.

Ouyang promoted a modeling framework for pavement resurfacing planning in network level. The objective is to minimize discounted life-cycle cost, including users' costs. It also considered the travelers' choices and pavement conditions simultaneously. Policy iteration together with a parametric function approximation technique was used to solve this problem (Ouyang 2007).

- Nonlinear programming

Abaza et al.(2004) presented a network-level optimization model combined with Markovian prediction model. Two objectives are optional, one is the nonlinear objective defined by proportions of sections in the five deployed condition states subject to budget constraints and the other minimizes M&R cost under requirement of pavement condition at the end of selected study period. Two methods are used in project selection, randomly selection and worst-first selection of projects within the same condition state. Therefore, penalty function method and uniform search method are used.

In terms of mathematical optimization, objective here is to either minimize cost under condition constraints or maximize facility conditions under financial limits. 'Cost' could be life-cycle cost, which may include users' costs. Despite of different optimization approaches used, differences of those models partly result from variables, deterioration models and treatment trigger criteria defined.

If using linear programming or mixed-integer linear programming, key problem is to express the nonlinear deterioration process in a linear way.

Dynamic programming is a promising approach to be used coupled with other optimization methods. Classify projects into groups, set each group as a sub problem and apply dynamic programming is a possible way to shrink problem size. Or set each analysis period as sub problem and run the optimization period by period is another feasible way to consider dynamic properties of deterioration process. For each sub problem, linear programming or integer programming could be used.

Nonlinear programming is gradually becoming a choice for pavement infrastructure scheduling. But there is still a question mark on how optimal the solution got via nonlinear programming.

3.3 Development of Network-Level PMS Models

In this section, a set of network-level PMS models are introduced. The widely used Markovian-process-based model is the core of the developed program, which is used to depict pavement deterioration over time. To facilitate the decision makers to perform different study, several pre-defined simulation strategies are developed, including Worst First, User Specified, Optimization (for each district and for all districts), and Need Analyses. The selection of a proper strategy depends on the problem to be solved.

In a Markovian-process-based PMS model, pavement conditions are categorized as several states according to the pre-defined rating ranges. The percentage of pavements in each state, along with the composite rating, is used to describe the pavement network condition. A Markov Transition Probability Matrix (TPM) is used to describe the behavior of pavement deterioration without MR&R activities. In each pavement state, there are several pre-defined MR&R alternatives and the associated performance probabilities. The final goal of a network-level PMS is to find a set of optimal MR&R activities to achieve the desired objectives. The following subsections describe each factor, input, and strategy in the developed network-level PMS program.

3.3.1 Pavement States and Markov Transition Probability Matrices

To implement a discrete-time Markovian-process-based model, it is necessary to define the pavement conditions in a finite set of states. Based on that, the historical data is analyzed and the Markov TPMs are created.

3.3.1.1 Pavement States

In the developed network-level PMS program, 5 states are defined for pavement conditions (see Table 3.1) according to the discussion with the engineers in OM.

Table 3.1 Definition of Pavement States

State	Minimum Rating	Maximum Rating
Excellent	91	100
Good	81	90
Fair	71	80
Poor	55	70
Bad	0	54

Throughout all the case studies in this chapter, the non-interstate highway pavement network is selected because the available data size for Interstate highway is limited and may affect the accuracy of the analysis. COPACES data from FY 1999 to FY 2008 is retrieved from the central database and analyzed.

Table 3.2 lists the pavement conditions of the non-interstate pavements from FY 1999 to FY 2008. Because the data in FY 2001 is incomplete, it is not included in the table.

Table 3.2 Non-interstate Highway Pavement Condition from FY 1999 to FY 2008

FY	Excellent	Good	Fair	Poor	Bad	Composite Rating
1999	39.35%	24.89%	21.51%	12.95%	1.30%	85.2
2000	36.45%	29.54%	22.37%	10.72%	0.92%	85.1
2002	40.04%	32.39%	19.49%	7.05%	1.02%	86.2
2003	34.77%	34.40%	22.33%	7.59%	0.91%	85.2
2004	31.96%	33.66%	22.73%	10.34%	1.31%	84.4
2005	31.96%	30.15%	24.35%	12.78%	0.75%	83.8
2006	32.18%	27.62%	24.41%	14.36%	1.43%	83.3
2007	31.57%	26.38%	25.12%	15.13%	1.80%	82.9
2008	32.39%	24.48%	26.01%	15.83%	1.28%	83.0

Note: Data in FY 2001 is incomplete and excluded.

3.3.1.2 Markov TPMs

A Markov TPM represents the behavior of pavement deterioration at network level. In the developed network-level PMS, time horizon is discretized at a one year interval, which means the Markov TPM represents the deterioration probabilities in a one-year period. Generally, a Markov matrix has the following definitions:

Table 3.3 Definition of Markov TPM

States *j* / *i*	**Excellent**	**Good**	**Fair**	**Poor**	**Bad**
Excellent	p_{11}	p_{12}	0	0	0
Good	0	p_{22}	p_{23}	0	0
Fair	0	0	p_{33}	p_{34}	0
Poor	0	0	0	p_{44}	p_{45}
Bad	0	0	0	0	1.0

In Table 3.3, the p_{ij} represents the percentage of total miles of pavements in state *i* that will shift to state *j* in next year. For example, p_{22} is the percentage of pavements in Good this year and will stay in the same state next year; while p_{23} is the percentage that will drop to Fair next year. Apparently, the sum of p_{22} and p_{23} is 1.0 (100%). As shown in Table 3.3, p_{55} is equal to 1.0 because Bad is the worst state and cannot shift to other states. For simplicity, we assume that in a one-year period, pavement can only deteriorate to the next consecutive state. Therefore, only 8 numbers need to be identified for the Markov matrix of a family (the definition of a family will be introduced later). Based on the nature of Markov chain, the following 3 rules will be applied on the matrix items:

Table 3.4 Rules of a TPM

	Rule
1	p_{11}, p_{12}, p_{22}, p_{23}, p_{33}, p_{34}, p_{44}, p_{45}, p_{55} should be a number between 0 and 1
2	All other items should be equal to 0
3	$p_{11} + p_{12} = 1$; $p_{22} + p_{23} = 1$; $p_{33} + p_{34} = 1$; $p_{44} + p_{45} = 1$; $p_{55} = 1$;

In general, the characteristics of pavement deterioration are determined by pavement structures, subgrade soils, materials, traffic and climate. An ideal TPM should be built for a family *f* (a group of pavements with the same deterioration characteristics) in terms of these factors. Otherwise, it is not practical because a) data is not always available; b) sample size is too small to apply probabilistic concept if too fine families are created. In this study, pavement surface type, working district and functional classes are used to create families. Because asphalt pavement is the focus, 14 families are formed in terms of 7 working district in each of which pavements are divided into Interstate and Non-interstate highway. Since the Georgia pavement network is divided into 7 districts and in each district there are interstate highway and non-interstate highway, 14 families are defined for the whole Georgia pavement network. Hence, 14 Markov TPMs are needed in the developed PMS models.

To determine the practical TPMs, we analyzed the COPACES survey data from FY 1999 to FY 2008 with data in FY 2001 excluded due to the aforementioned reason. The analysis procedures can be found in Appendix III. According to the analysis, about 46% to 66%of the surveyed interstate miles are filtered out and leave about 352 to 791 miles available in constructing the pavement deterioration matrix; about 37% to 57% of the surveyed non-interstate miles are filtered out, and a total of 7,700 to 13,567 miles is included in the study.

As mentioned above, a TPM depicts the behavior of pavement deterioration without treatment. To analyze it from historical survey data, only projects without treatment can be used. But, there is some difficulty in the current COPACES database because the treatment information was not recorded. Therefore, the analyzed transition probabilities for Fair to Poor and Poor to Bad are not accurate and cannot be directly used. Some adjustments are needed for these transition probabilities. In next section, the historical pavement conditions and resurfacing expenditure are used to calibrate these probabilities. As a summary, Table 3.5 lists all non-interstate TPMs (7 families) created through the analysis and calibration of the historical data.

Table 3.5 TPMs for Non-Interstate Highway in District 1 to 7

District 1					
	Excellent	**Good**	**Fair**	**Poor**	**Bad**
Excellent	0.62	0.38	0.00	0.00	0.00
Good	0.00	0.63	0.37	0.00	0.00
Fair	0.00	0.00	0.55	0.45	0.00
Poor	0.00	0.00	0.00	0.85	0.15
Bad	0.00	0.00	0.00	0.00	1.00
District 2					
Excellent	0.75	0.25	0.00	0.00	0.00
Good	0.00	0.65	0.35	0.00	0.00
Fair	0.00	0.00	0.55	0.45	0.00
Poor	0.00	0.00	0.00	0.85	0.15
Bad	0.00	0.00	0.00	0.00	1.00
District 3					
Excellent	0.77	0.23	0.00	0.00	0.00
Good	0.00	0.69	0.31	0.00	0.00
Fair	0.00	0.00	0.55	0.45	0.00
Poor	0.00	0.00	0.00	0.85	0.15
Bad	0.00	0.00	0.00	0.00	1.00
District 4					
Excellent	0.78	0.22	0.00	0.00	0.00
Good	0.00	0.62	0.38	0.00	0.00
Fair	0.00	0.00	0.55	0.45	0.00
Poor	0.00	0.00	0.00	0.85	0.15
Bad	0.00	0.00	0.00	0.00	1.00
District 5					
Excellent	0.72	0.28	0.00	0.00	0.00
Good	0.00	0.71	0.29	0.00	0.00
Fair	0.00	0.00	0.55	0.45	0.00

Poor	0.00	0.00	0.00	0.85	0.15
Bad	0.00	0.00	0.00	0.00	1.00
District 6					
Excellent	0.62	0.38	0.00	0.00	0.00
Good	0.00	0.67	0.33	0.00	0.00
Fair	0.00	0.00	0.55	0.45	0.00
Poor	0.00	0.00	0.00	0.85	0.15
Bad	0.00	0.00	0.00	0.00	1.00
District 7					
Excellent	0.67	0.33	0.00	0.00	0.00
Good	0.00	0.61	0.39	0.00	0.00
Fair	0.00	0.00	0.55	0.45	0.00
Poor	0.00	0.00	0.00	0.85	0.15
Bad	0.00	0.00	0.00	0.00	1.00

3.3.2 Treatments and Their Performance

As mentioned above, in each state there are several MR&R alternatives defined. For simplicity, only 3 main treatment categories are defined: Minor Preventive Maintenance, Major Preventive Maintenance and Major Rehab/Reconstruction. Table 3.6 summarizes the states and their associated treatments.

Table 3.6 Treatments and States

State	Treatments
Excellent	Do Nothing
Good	Do Nothing
Fair	Do Nothing, Minor Preventive Maintenance
Poor	Do Nothing, Major Preventive Maintenance
Bad	Do Nothing, Major Rehab/Reconstruction

Unit cost for each treatment and the escalating rate of construction cost over time are the important factors that need to be determined. Ideally, the historical MR&R expenditure and treated mileage should be analyzed to come up with the result. But, to this point, only data for resurfacing is available. The cost and treated mileage for minor preventive maintenance and major rehab/reconstruction is not retrieved yet.

With the help from GDOT's engineers, the annual funds spent on non-interstate highway resurfacing and the corresponding treated centerline miles are extracted from FY 1999 to 2007 (see Table 3.7). The unit cost for resurfacing can be estimated by dividing the total funds by the corresponding centerline miles. Furthermore, the escalation rate can be estimated by the average of yearly increasing rate. Because GDOT spent around 25% of total funding in major rehab/reconstruction, the annual total budgets is estimated by dividing the annual resurfacing cost by 75%.

Table 3.7 Historical Expense on Non-interstate Highway Resurfacing from FY 1999 to FY 2007

Year	1999	2000	2001	2002	2003	2004	2005	2006	2007
Funds (Million US $)	135.6	117.2	70.5	78.9	162.3	93.7	145.9	212.7	138.7
Centerline Mileage (Miles)	2175	1417	734	788	867	822	982	920	649
Projected Annual Funds (Million US $)	180.8	156.3	94.0	105.2	216.4	124.9	194.5	283.6	184.9
Unit Cost (US $)	62,344	82,730	96,049	100,182	187,195	114,005	148,557	231,241	213,784
Yearly Escalating Rate		32.7%	16.1%	4.3%	86.9%	-39.1%	30.3%	55.7%	-7.6%

Figure 3.3 shows the plot of the historical unit cost of pavement resurfacing in terms of Table 3.7. Apparently, the data for FY 2003 is exceptional high, which can be considered as an outlier. An adjustment has been made on the data point as shown in Figure 3.3.

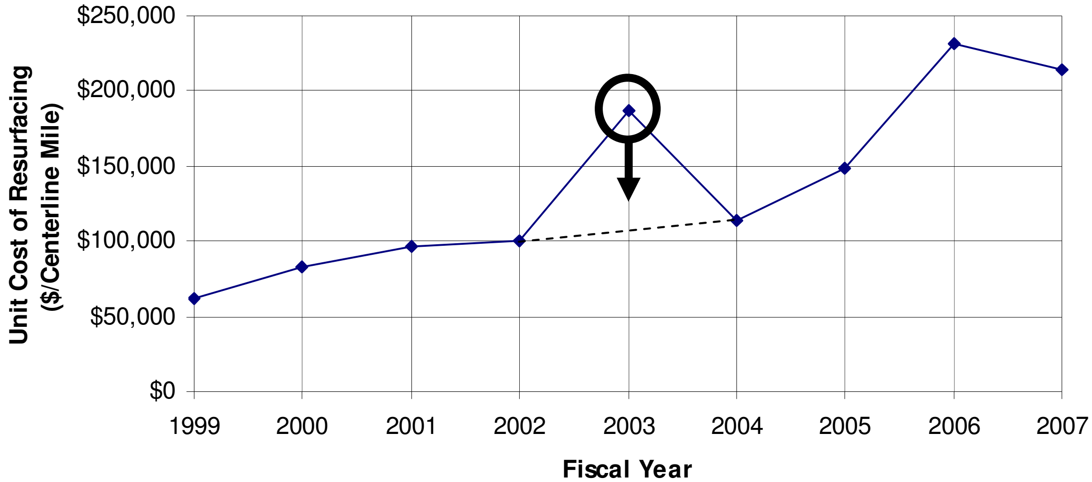


Figure 3.3 Historical Unit Cost of Resurfacing (Dollars per Centerline Mile)

Based on the adjusted historical unit cost of resurfacing as shown in Figure 3.3, the Annual Average Escalating Rate (AAER) of construction cost can be estimated by fitting the curve with equation 3.1.

$$C_t = C_0 \times (1 + AAER)^t \tag{3.1}$$

C_0 is the initial unit cost. C_t is the unit cost at t year. As shown in Figure 3.4, the AAER is 18.1% according to regression on the adjusted historical unit cost of resurfacing.

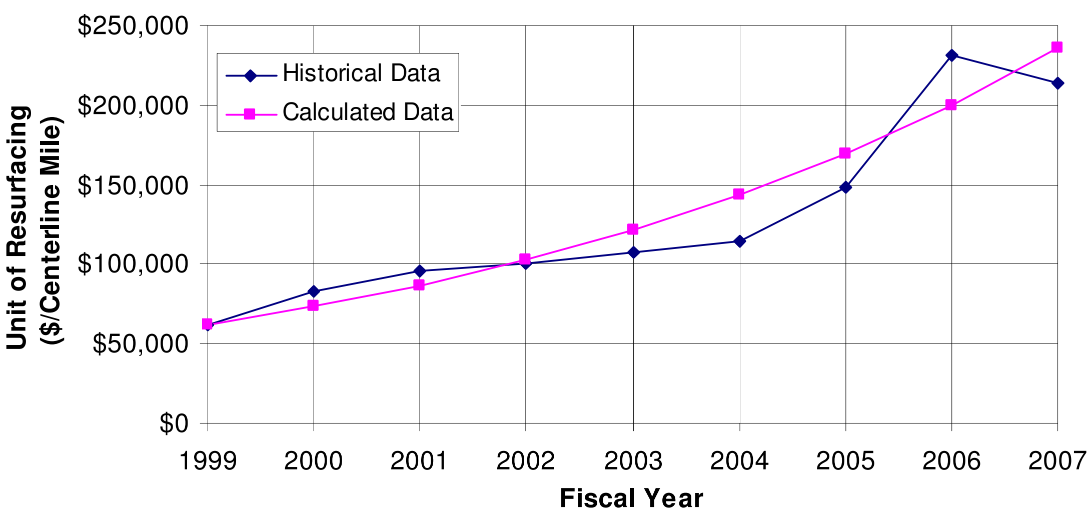


Figure 3.4 Regression of AAER (= 18.1%)

Because resurfacing is the major treatment in the category of Major Preventive Maintenance, its unit cost is used for this category. For Minor Preventive Maintenance and Major Rehab/Reconstruction, estimation is used by engineers in OM due to the lack of historical expenditure data. In FY 2007, the estimated unit cost for Minor Preventive Maintenance is $6,646 per centerline mile. For Major Rehab/Reconstruction, it is $553,805 per centerline mile. If AAER, 18.1%, is applied, their unit costs in FY 1999 are $1,756 and $146,338 respectively.

In the following sections, the historical data from FY 1999 to FY 2008 will be used to calibrate the proposed PMS models. And, a 10-year forecasting will be made from FY 2008. For this purpose, the unit cost for all treatments in FY 1999 and FY 2008 will be used in the computation. Table 3.7 only shows the data for FY 1999 and FY 2007. Other unit cost is estimated only for FY 2007. By using the 18.1% of AAER, the missed data are projected in Table 3.8.

Table 3.8 Unit Cost and Annual Funds Used in Calibration, Forecasting and Simulation

For Calibration (AAER = 18.1%)									
Year	1999	2000	2001	2002	2003	2004	2005	2006	2007
Annual Funds (Million US $)	180.8	156.3	94.0	105.2	216.4	124.9	194.5	283.6	185.1
Initial Unit Cost (US $)	1,756	← **Minor Preventive Maintenance**							
	62,344	← **Major Preventive Maintenance**							
	146,338	← **Major Rehab/Reconstruction**							

For Forecasting and Simulation (AAER = 18.1%)				
Year	**Funds (Million US $)**	**Unit Cost**		
		Minor Preventive Maintenance (US $)	**Major Preventive Maintenance (US $)**	**Major Rehab/Reconstruction (US $)**
2008	185.1 (million)	7,849	252,478	654,043

Each treatment can improve pavement condition at a certain level with a center probability. Accordingly, a Markov TPM can be established for each of them. Otherwise, it is difficult to obtain such kind of information in the COPACES database. Alternatively, engineer's knowledge is applied. Table 3.9 shows the performance of each treatment.

Table 3.9 Performance of Treatments

Treatment	Performance
Minor Preventive Maintenance	Pavement condition will stay at the same.
Major Preventive Maintenance	Pavement condition will increase to Excellent.
Major Rehab/Reconstruction	Pavement condition will increase to Excellent.

The treatment data discussed and analyzed above are all for non-interstate highway. For interstate highway, the same strategy can be applied when the historical data are available. Based on the discussion with the engineers in OM, in the developed program, a 1.8 of multiplication factor is used for interstate highway treatments in terms of the corresponding unit cost for non-interstate highway treatments.

3.3.3 Development of Formulations

There are 5 strategies defined in the proposed PMS models: Worst First, User Specified, Optimization on Each District, Optimization on All Districts and Need Analysis. All strategies are implemented using the Markovian-process-based methods. In addition, linear programming is also used for the last three strategies. In this section, a set of formulations are developed for purpose of implementation.

3.3.3.1 Notations

The following notations are used in the formulations.

1) Markov TPM without treatments. Since there are a total of 14 families defined for the pavements in Georgia, 14 matrices are needed. Matrix $\mathbf{P}^f$ is the TPM for family *f*, which is a 5×5 matrix (Eq. 1). The entry p_{ij}^f represents the probability that a pavement in state *i* will transit to stat *j* at the end of the current time period, i.e. the beginning of next time period. Each time period covers a 1-year cycle.

An assumption is made that each state cannot shift to more than the next adjacent state in one year.

$$\mathbf{P}^f = \begin{bmatrix} p_{11}^f & p_{12}^f & 0 & 0 & 0 \\ 0 & p_{22}^f & p_{23}^f & 0 & 0 \\ 0 & 0 & p_{33}^f & p_{34}^f & 0 \\ 0 & 0 & 0 & p_{44}^f & p_{45}^f \\ 0 & 0 & 0 & 0 & p_{55}^f \end{bmatrix}, \ f\text{=1, 2, …, 14} \qquad 3.2$$

$$\sum_{j=1}^{5} p_{ij}^f = 1$$

2) Treatment Transition Matrix (TTM). $\mathbf{P}'$ is defined for pavement performance under each M&R action. For simplicity, only one $\mathbf{P}'$ is constructed, which applies on the pavements for all families. For the states of Excellent and Good, no treatment will be applied, so the entries in the first two rows in the matrix are zeros.

$$\mathbf{P}' = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ p'_{31} & p'_{32} & p'_{33} & 0 & 0 \\ p'_{41} & p'_{42} & p'_{43} & p'_{44} & 0 \\ p'_{51} & p'_{52} & p'_{53} & p'_{54} & p'_{55} \end{bmatrix}, \ f\text{=1, 2, …, 14} \qquad 3.3$$

$$\sum_{j=1}^{5} p'_{ij} = 1$$

3) State vector. For each family, there is a state vector to define its pavement condition distribution. Since the computation is performed annually, $\mathbf{s}_t^f$ is defined as the initial state at the beginning of a one-year cycle. At the end of the cycle, the state will be changed, which is also the initial state of the next year's cycle.

$$\mathbf{s}_t^f = \left(s_t^{f1} \quad s_t^{f2} \quad s_t^{f3} \quad s_t^{f4} \quad s_t^{f5}\right), \ f = 1, 2, \ldots, 14, \ t = 1, 2, \ldots, T \qquad 3.4$$

4) Total mileage of each family l^f : , f=1, 2, …, 14

5) Total mileage of all families: $L = \sum_{f=1}^{14} l^f$

6) Initial unit cost: u_i, i =3, 4, 5. The initial unit cost is for the first year of the analysis time horizon. For following years, it is calculated in terms of the initial value, escalating rate.

7) AAER: r. It is the annual escalating rating of construction cost.

8) Unit cost matrix $\mathbf{U}_t$: This matrix is defined for purpose of the formulation in matrix form. It represents the current unit cost for each treatment. The 1s in it do not mean anything other than making its inverse meaningful.

$$\mathbf{U}_t = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & u_3 & 0 & 0 \\ 0 & 0 & 0 & u_4 & 0 \\ 0 & 0 & 0 & 0 & u_5 \end{bmatrix} \cdot (1+r)^t, \; t = 1, 2, \ldots, T \qquad 3.5$$

9) Funding allocation vector $\mathbf{X}_t^f$. They are defined as the funding spent for each family, each M&R action, and each time period.

$$\mathbf{X}_t^f = \begin{pmatrix} 0 & 0 & X_t^{f3} & X_t^{f4} & X_t^{f5} \end{pmatrix}, f=1, 2, \ldots, 14, t=1, 2, \ldots, T \qquad 3.6$$

10) Adjusted mean vector $\mathbf{m}^f$. The weighting factors m_j^f can be the middle point of a state or the mean value at the initial states of each family.

$$\mathbf{m}^f = \begin{pmatrix} m_1^f & m_2^f & m_3^f & m_4^f & m_5^f \end{pmatrix}, f = 1, 2, \ldots, 14 \qquad 3.7$$

11) Annual available funding: c_t (for year t)

12) Composite rating R_t. In GDOT, the network composite rating R_t, a weighted PACES rating, is used to identify the overall pavement conditions.

$$R_t = \left[\sum_{f=1}^{14} (\mathbf{s}_t^f \cdot \mathbf{m}^f) \cdot l^f \right] / \sum_{f=1}^{14} l^f, f=1, 2, \ldots, 14, \; t=1, 2, \ldots, T \qquad 3.8$$

3.3.3.2 Transition of States

With the concept of Markovian process, pavement conditions will deteriorate over time. If some pavement is treated, it will bring back to a better condition. Theoretically, the current pavement state vector $\mathbf{s}_{t+1}^{f}$ can be derived from its previous state vector $\mathbf{s}_{t}^{f}$. From equation 3.9, the current state vector consists of two parts: treated and untreated pavements.

$$\mathbf{s}_{t+1}^{f} = (\mathbf{s}_{t}^{f} - \mathbf{X}_{t}^{f}\mathbf{U}_{t}^{-1})\mathbf{P}^{f} + \mathbf{X}_{t}^{f}\mathbf{U}^{-1}\mathbf{P}', f=1, 2, \ldots, 14, \; t=1, 2, \ldots, T \qquad 3.9$$

Equation 3.9 is used for the strategies of Worst First and User Specified because the funding allocation is determined either by the worst condition or user defined proportion. It is also used in the formulations of linear programming for three optimization-based strategies.

3.3.3.3 Linear Programming for Strategy of "Optimization on Each District"

Because each district consists of interstate and non-interstate highway, this strategy comes up with optimal MR&R policy for them separately. The problem can be stated as "with the annual budget allocated for each family in each district, the optimal MR&R policy to achieve maximum composite rating for this family will be achieved". The optimization formulation will be solved for each family in each year. Users can use this strategy to evaluate the network problem for each individual family in each district.

The above problem can be formulated as the following linear programming:

$$\text{Max } R_{t+1}^{f} \qquad 3.10$$

$$\text{Subject to: } \sum_{i=1}^{5} \mathbf{X}_{t}^{f(i)} \le c_{t}^{f} \qquad 3.11$$

$$\mathbf{s}_{t}^{f} - \mathbf{X}_{t}^{f} \cdot \mathbf{U}_{t}^{-1} \ge 0 \qquad 3.12$$

$$\mathbf{X}_{t}^{f} \ge 0 \qquad 3.13$$

where c_{t}^{f} = annual budget for family f

Equation 3.11 is the constraint that annual total funds spent cannot exceed the annual budget. Equation 3.12 will guarantee that the treated pavements won't exceed the necessity. The equivalent scalar forms of the above formulations are as follows.

$$\text{Max } R_{t+1}^{f} = \sum_{i=3}^{5} a_t^{fi} X_t^{fi} + b_t^{f} \qquad 3.14$$

$$\text{Subject to: } \sum_{i=3}^{5} X_t^{fi} \le c_t^{f} \qquad 3.15$$

$$X_t^{fi} T_t^{fi} \le s_t^{fi},\ i = 3, 4, 5 \qquad 3.16$$

$$X_t^{fi} \ge 0,\ i=3, 4, 5 \qquad 3.17$$

$$\text{Where: } a_t^{fi} = T_t^{fi} \sum_{j=1}^{5} (p'_{ij} - p_{ij}^{f}) m_j^{f},\ i = 3, 4, 5 \qquad 3.18$$

$$b_t^{f} = \sum_{i=1}^{5} \sum_{j=1}^{5} s_t^{fi} p_{ij}^{f} m_j^{f} \qquad 3.19$$

$$T_t^{fi} = 1/(u_i \cdot (1+r)^t \cdot l^f),\ i = 3, 4, 5 \qquad 3.20$$

The output of this annual optimization will obtain the highest network composite rating with the given budget for each family. *T* times of linear programming will be solved throughout the analysis horizon.

3.3.3.4 Linear Programming for Strategy of "Optimization on All District"

The objective of this strategy is to maximize the annual composite rating throughout the analysis horizon with a given annual budget for the entire pavement network. This formulation can be used to predict long-term pavement performance with a given budget level and escalation rate of construction cost. The linear programming formulation is as follows.

$$\text{Max } R_{t+1} \qquad 3.21$$

$$\text{Subject to: } \sum_{f=1}^{14} \sum_{i=1}^{5} \mathbf{X}_t^{f(i)} \le c_t \qquad 3.22$$

$$\mathbf{s}_t^{f} - \mathbf{X}_t^{f} \cdot \mathbf{U}_t^{-1} \ge 0,\ f = 1, 2, \dots, 14 \qquad 3.23$$

$$\mathbf{X}_t^{f} \ge 0,\ f = 1, 2, \dots, 14 \qquad 3.24$$

where c_t = annual budget

Equation 3.22 is the constraint that annual total funds spent cannot exceed the annual budget. 3.23 will guarantee that the treated pavements won't exceed the necessity. The equivalent scalar forms of the above formulations are as follows.

$$\text{Max } R_{t+1} = \sum_{f=1}^{14}\sum_{i=3}^{5} a_t^{fi} X_t^{fi} + b_t \qquad 3.25$$

$$\text{Subject to: } \sum_{f=1}^{14}\sum_{i=3}^{5} X_t^{fi} \le c_t \qquad 3.26$$

$$X_t^{fi} T_t^{fi} \le s_t^{fi},\ f = 1, 2, \ldots, 14,\ i = 3, 4, 5 \qquad 3.27$$

$$X_t^{fi} \ge 0,\ f = 1, 2, \ldots, 14,\ i=3, 4, 5 \qquad 3.28$$

$$\text{Where: } a_t^{fi} = \left\{ l^f T_t^{fi} \sum_{j=1}^{5} (p'_{ij} - p_{ij}^f) m_j^f \right\} / \sum_{f=1}^{14} l^f,\ f = 1, 2, \ldots, 14,\ i = 3, 4, 5 \qquad 3.29$$

$$b_t = \sum_{f=1}^{14}\sum_{i=1}^{5}\sum_{j=1}^{5} s_t^{fi} p_{ij}^f m_j^f L^f / \sum_{f=1}^{14} l^f \qquad 3.30$$

$$T_t^{fi} = 1/(u_i \cdot (1+r)^t \cdot l^f),\ f = 1, 2, \ldots, 14,\ i = 3, 4, 5 \qquad 3.31$$

The output of this annual optimization will obtain the highest network composite rating with the given budget. *T* times of linear programming will be solved throughout the analysis horizon.

3.3.3.5 Linear Programming for Strategy of "Need Analysis"

The objective of this strategy in this formulation is to seek an annual least-cost preservation policy while maintaining the minimum performance requirements. It can be utilized to figure out the future funding needs to maintain the pavement conditions at a serviceable level as well as to identify the budget shortage.

The current GDOT requirements for network performance are that the annual composite rating is at least 85 and the percentage of pavements in Poor and Bad (less than or equal to 70) states is at most 10%. Using these requirements to minimize the total agency cost, the budget needs can be identified. Combing the results with the actual available funding, legislatures and stakeholders can further identify the budget shortage.

The optimization formulations are as follows:

$$\text{Min } c_t = \sum_{f=1}^{14}\sum_{i=3}^{5}\mathbf{X}_t^{f(i)} \qquad 3.32$$

Subject to: $R_{t+1} \ge 85$ 3.33

$$\left[\sum_{f=1}^{14}\left(\mathbf{s}_{t+1}^{f(4)} + \mathbf{s}_{t+1}^{f(5)}\right)\cdot l^f\right] / \sum_{f=1}^{14} l^f \le 10\% \qquad 3.34$$

$$\mathbf{s}_t^f - \mathbf{X}_t^f \cdot \mathbf{U}_t^{-1} \ge 0,\ f = 1, 2, \ldots, 14 \qquad 3.35$$

$$\mathbf{X}_t^f \ge 0,\ f = 1, 2, \ldots, 14 \qquad 3.36$$

Constraint 3.34 can be translated to the following scalar form. And others can be found the previous section.

$$\left\{\sum_{f=1}^{14}\sum_{i=4}^{5}\left[\sum_{j=1}^{5} s_t^{fj} p_{ji}^f + \sum_{j=3}^{5} X_t^{fj} T_t^{fj} (p'_{ji} - p_{ji}^f)\right] l^f\right\} / \sum_{f=1}^{14} l^f \le 10\% \qquad 3.37$$

The above two sets of formulations will be used in the next section to analyze the long-term pavement performance and budget needs for State of Georgia's non-interstate highway network.

3.3.4 Operation Flow of Forecasting and Simulation Strategies

3.3.4.1 Worst first

In this strategy, the program will assign the budget to each treatment based on the Worst First sequence. The pavements in Bad condition will be treated first. If budget is left, the pavements in Poor will be treated. Last, the pavement in Fair condition will be treated. Figure 3.5 illustrates the process.

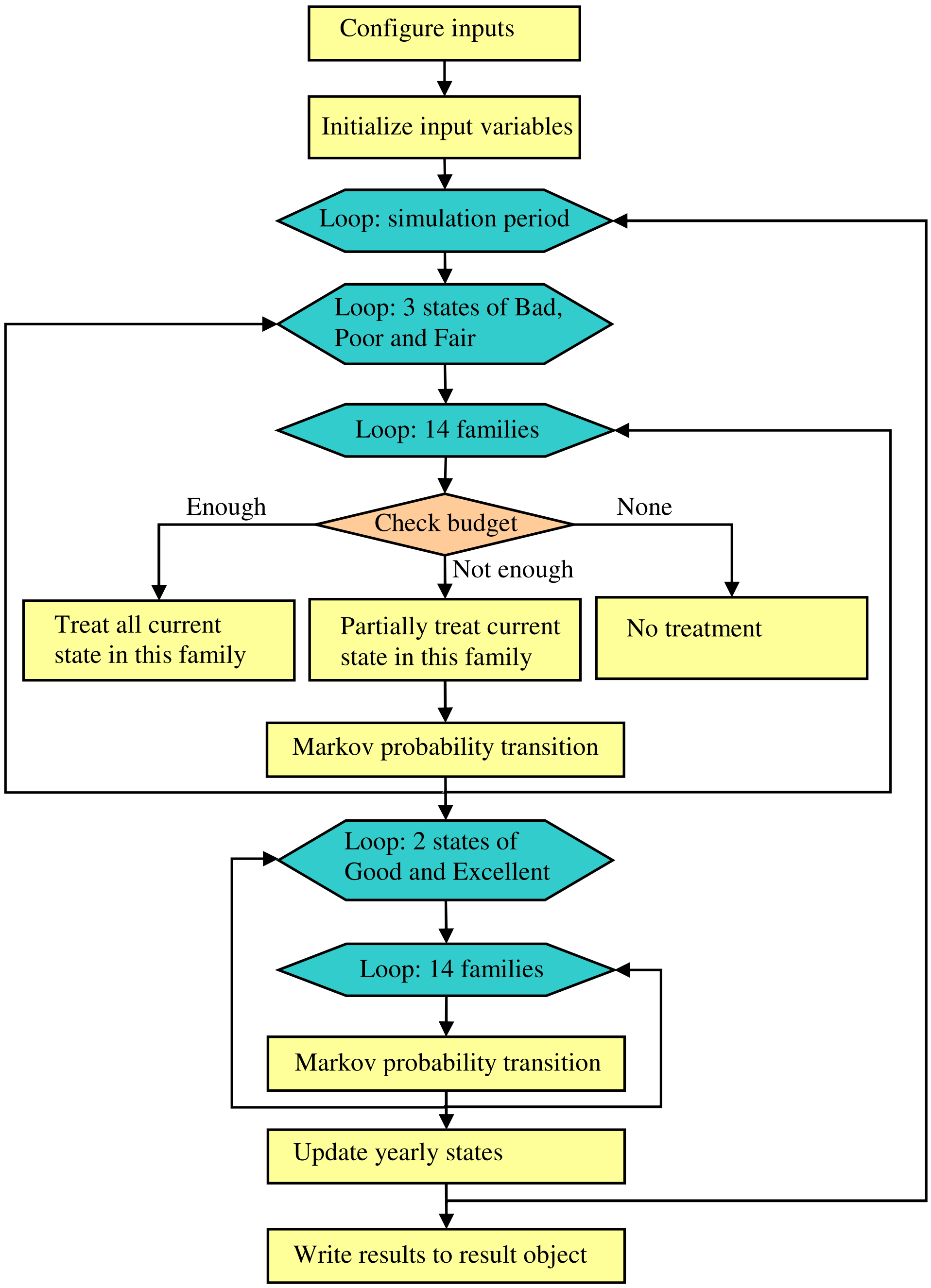


Figure 3.5 Flow Chart for 'Worst First' Strategy

3.3.4.2 User Specified

Under this simulation strategy, the annual budget for each family will be given, as well as the percentiles distributed among Bad, Poor, and Fair states. In each fiscal year for each family, according to the percentage of budget for the Bad state, the Bad state will be treated, followed by Poor and Fair. The algorithm is implemented according to the following flow chart:

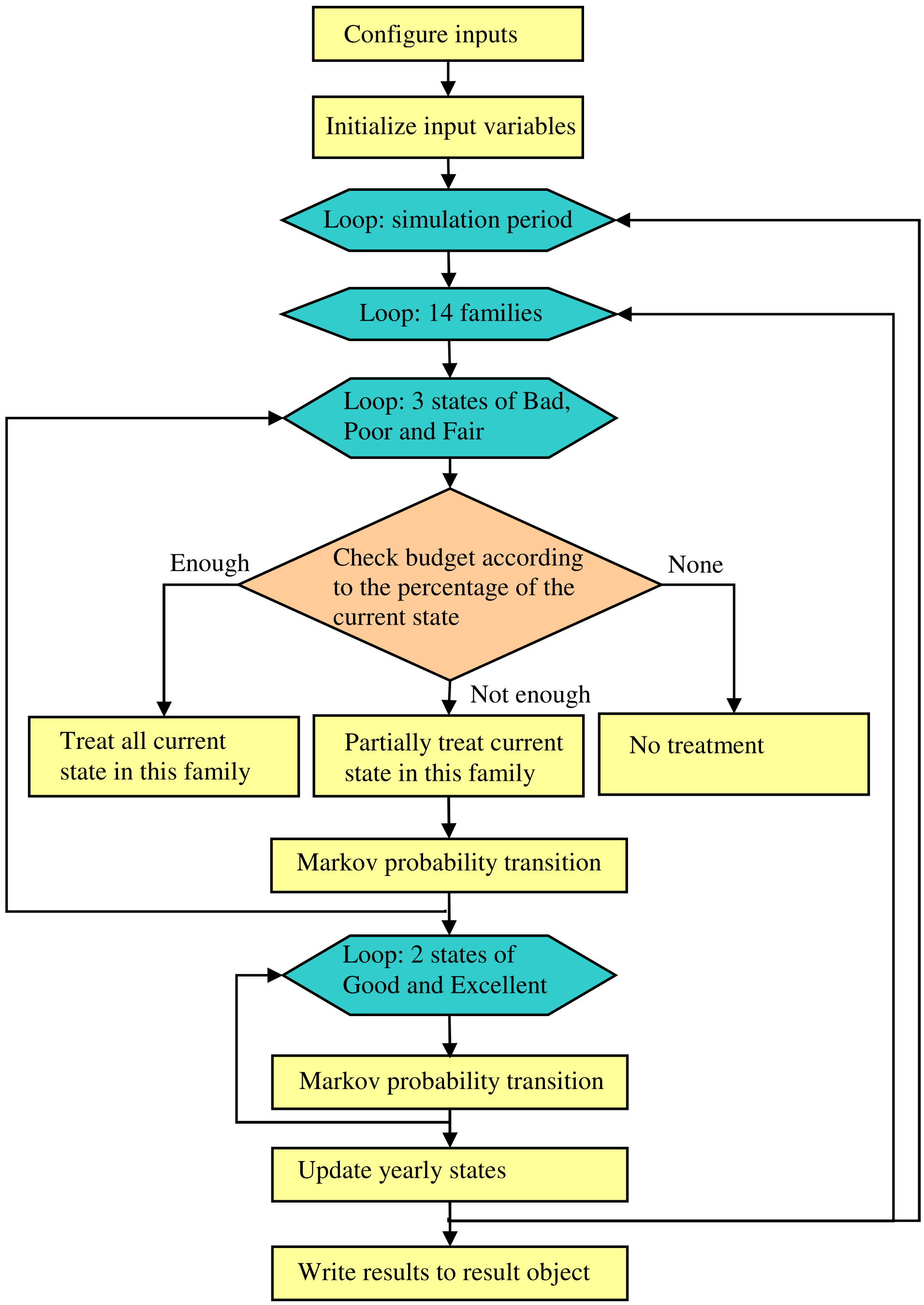


Figure 3.6 Flow Chart for 'User Specified' Strategy

3.3.4.3 Optimization on Each District

Under this simulation strategy, the annual budget for each family will be given. In each fiscal year for each family, linear programming will be executed to achieve the maximum composite rating for this family. The algorithm is implemented according to the following flow chart:

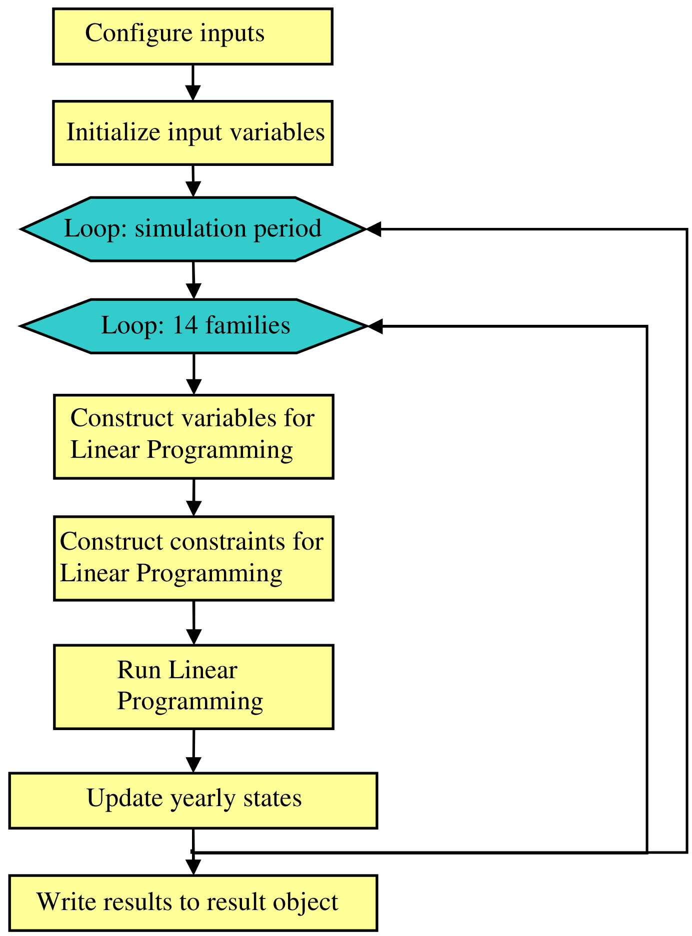


Figure 3.7 Flow Chart for 'Optimization on Each District' Strategy

3.3.4.4 Optimization on All Districts

Under this simulation strategy, the annual total budget will be given. In each fiscal year, the linear programming will be executed to achieve the maximum composite rating for all families. The algorithm is implemented according to the following flow chart:

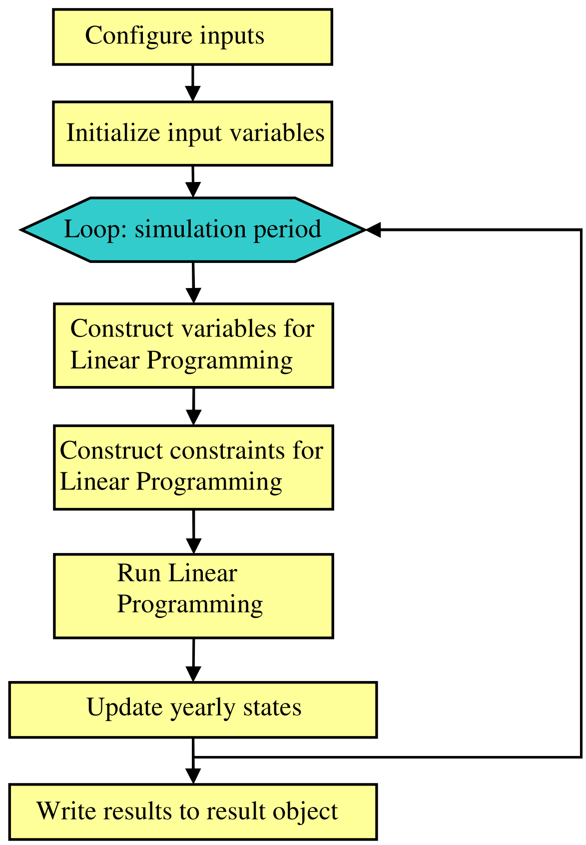


Figure 3.8 Flow Chart for 'Optimization on All Districts' Strategy

3.3.4.5 Need Analyses

Under this simulation strategy, the targeted network composition rating will be given, as well as the total percentile of Bad and Poor states. In each fiscal year, the linear programming will be executed to find the minimum budget needed to achieve the user defined goals.

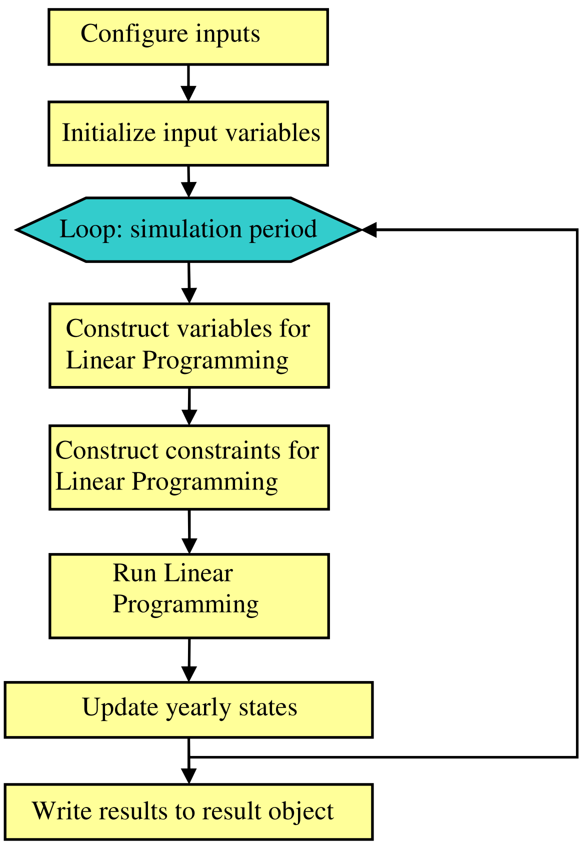


Figure 3.9 Flow Chart for 'Need Analyses' Strategy

3.4 Verification of Markov Models

The Markovian-process-based PMS models introduced in Chapter 3.2.2 has been implemented as a computer program (GDOT LP&S, the user's manual can be found in Appendix IV). Before the forecasting and simulation are to be performed, the correctness of the models and input parameters should also be verified. A comprehensive verification should be based on the historical pavement condition data and the MR&R expenditure. The completeness of the historical data is very important to the result of verification. However, at the current stage, there is some difficulty in obtaining all the necessary data from GDOT for purpose of model verification. Verification is only performed on non-interstate highway due to the following two reasons: 1) the size of samples used to generate the interstate highway Markov TPMs is too small to guarantee the accuracy; 2) the historical MR&R expenditure for interstate highway is not yet obtained from GDOT. Even for non-interstate highway, the available data is incomplete, too. First, to generate the Markov TPMs, the historical pavement condition data without treatment should be used. Because the treatment information is not systematically recorded in COPACES database in the past, it is very hard to separate the projects with or without treatment, especially for pavements in Fair, Poor and Bad states. Second, the historical treatment expenditure is incomplete. To this point, only the expense for resurfacing from FY 1998 to FY 2007 and the corresponding treated mileage are extracted. Under this situation, some work-around methods are used to fulfill the verification.

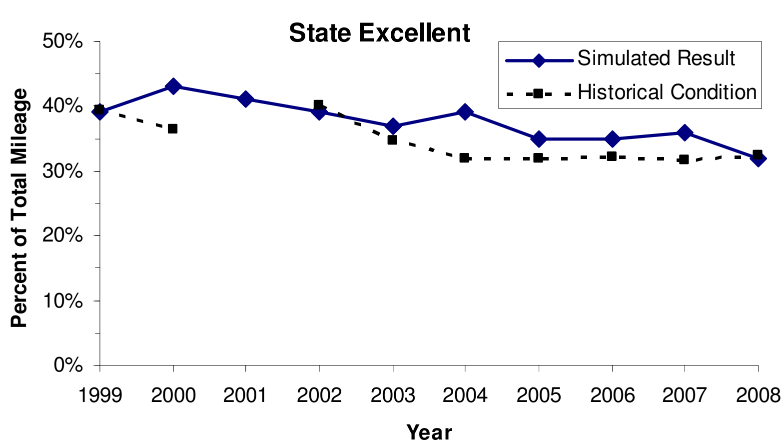
The following procedures are followed to verify the developed Markov models:

1) The Markov TPMs are developed based the historical COPACES data. Due to the lack of treatment information, the transition probabilities for Fair to Poor and Poor to Bad are adjusted (the generated Markov TPM can be found in Table 3.5).
2) Based on the historical expense on resurfacing from FY 1999 to FY 2007, the AAER for construction cost is estimated (18.1%). The annual funds are also projected (see Table 3.8).
3) With FY 1999 as the first year of analysis, User Specified strategy is used to forecast the pavement conditions from FY 2000 to FY 2008 based on the projected annual funds and the funding allocation proportion (75% for Major Preventive Maintenance and 25% for Major Rehab/Reconstruction). Minor Preventive Maintenance is not considered due to the lack of the expense information. In addition, based on engineers' knowledge, Minor Preventive Maintenance can not improve pavement condition. It can only last the current pavement condition for a period of time. If it is not considered, the result should be prone to be conservative.
4) Compare the forecasting result with the actual historical pavement condition from FY 2000 to FY 2008. If they are reasonably close to each other, the developed Markov models and the corresponding input parameters should be reliable and useable. Furthermore, the verified models and input parameters can be used for other forecasting and simulation tasks.

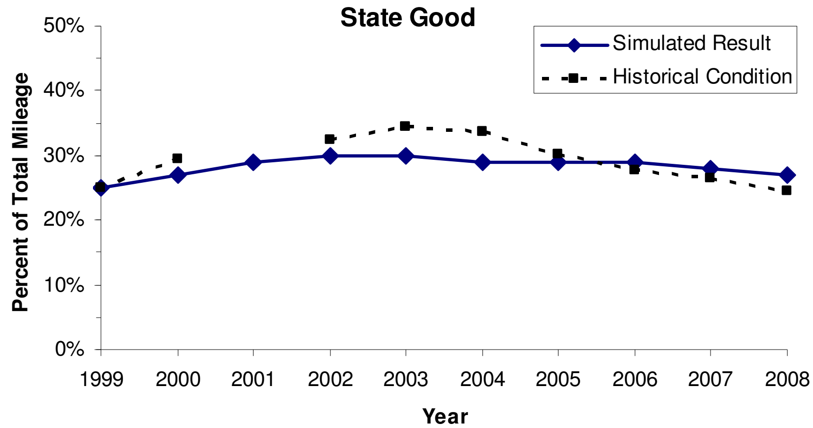
As shown in Figure 3.10, the simulated results labeled as the dotted lines are compared with the actual historical pavement performance data labeled as the solid lines. Because the historical data in 2001 is incomplete, it is not included in the charts. It shows that the simulated percentage of each state (Excellent, Good, Fair, Poor and Bad) are reasonably close to the historical pavement conditions as well as the network composite rating. Table 3.10 summarizes the differences of the simulated results and the historical data. The range of mean difference for each state is from 0.7% to 3.1%. And the standard deviation is 0.3% to 2.5%. For composite rating, the average difference is 0.9 and the standard deviation is 0.8.

Table 3.10 Verification of Markov Models (Statistics on Difference of Simulated Results and Historical Data)

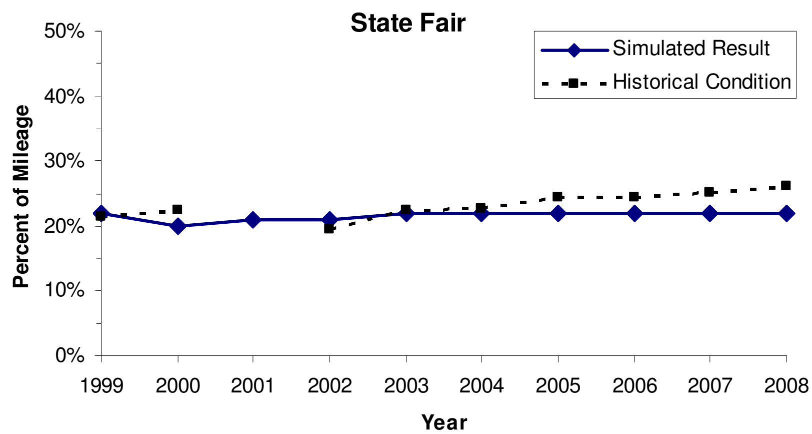
	Mean	Variance	Maximum
Excellent (%)	3.1	2.5	7.0
Good (%)	2.3	1.5	4.7
Fair (%)	1.9	1.3	4.0
Poor (%)	1.3	1.3	3.4
Bad (%)	0.7	0.3	1.3
Composite Rating	0.9	0.8	1.8



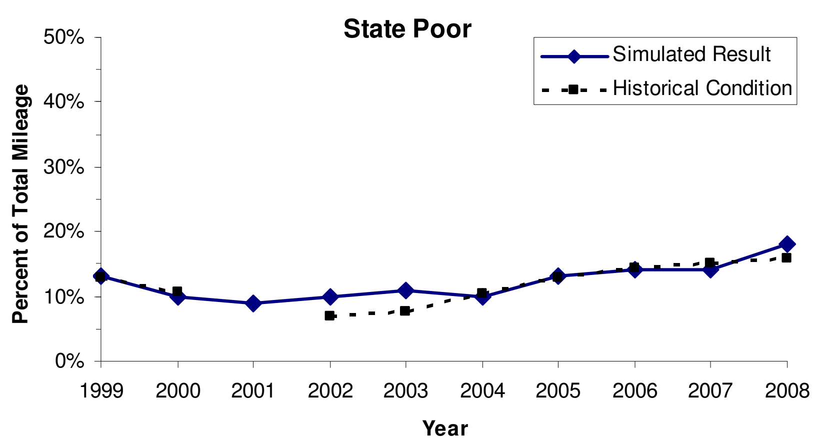
(a)


State Good
Simulated Result
Historical Condition
Percent of Total Mileage
50%
40%
30%
20%
10%
0%
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
Year

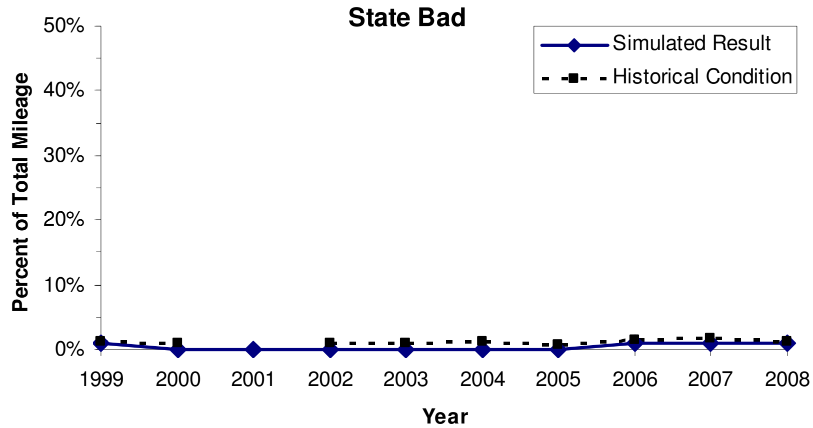
(b)


State Fair
Simulated Result
Historical Condition
Percent of Mileage
50%
40%
30%
20%
10%
0%
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
Year

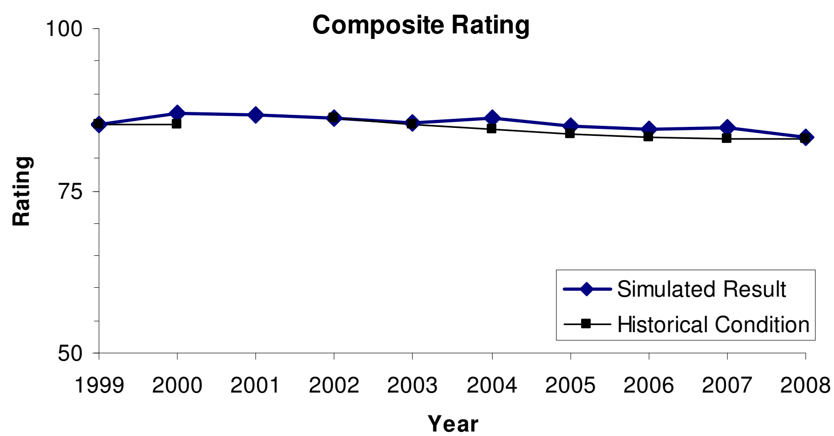
(c)


State Poor
Simulated Result
Historical Condition
Percent of Total Mileage
50%
40%
30%
20%
10%
0%
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
Year

(d)



(e)



(f)

Figure 3.10 Verification of Markov Models

The difference between the simulated result and the historical data comes from several sources. First, the model itself is not 100% accurate to depict the behavior of pavement deterioration. Some assumption has been made. For example, the stationary Markov process assumes the pavement deterioration probabilities are constant over time. In reality, the probability should be a variable dependent on time. Second, the data used in the simulation is not 100% accurate. The transition probability for Fair to Poor and Poor to Bad are manually adjusted in stead of being computed using the historical data. The annual funds are projected from the historical expense on resurfacing. The expense of Minor Preventive Maintenance and Major Rehab/Reconstruction are not extracted at the current stage. Nevertheless, the verification result shows that the proposed models and the corresponding input parameters capture the properties of pavement deterioration at the network level. They can be used to further forecast the future pavement performance and perform different what-if analyses.

3.5 Case Study

With the developed PMS models, users can run different algorithms to address their concerns on the pavement preservation at network level. In this section, several cases are studied and demonstrate the utilization and capability of the developed program. The following questions are addressed through the case study. As aforementioned, all case studies are performed on non-interstate highway.

1) How will the pavement perform in the following 10 years (FY 2009 to FY 2018) if no preservation is applied? How about if the current funding level will remain for the next 10 years? What's the best preservation strategy, Worst First, User Specified or Optimization?
2) Is the current funding level sufficient for pavement preservation? If not, how much funds are needed for the following 10 years?
3) How will the escalating rate of construction cost (AAER) affect the funding shortfall?
4) How will the sudden increasing cost affect the long-term pavement performance?

3.5.1 Pavement Performance Forecasting

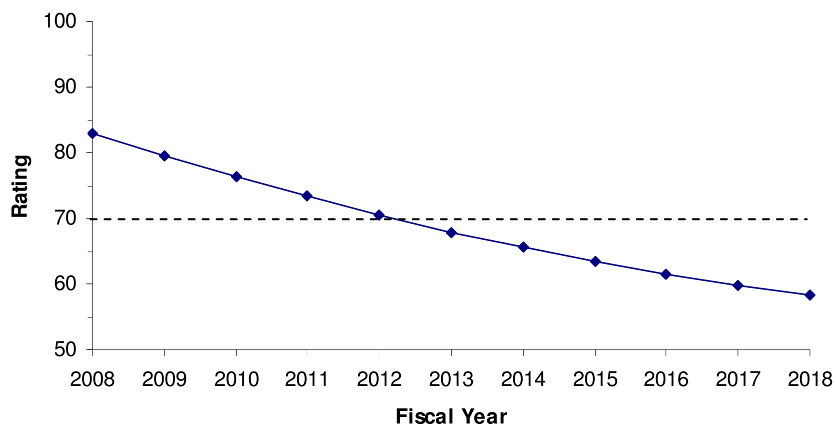
In this case study, a simulation is performed on non-interstate highway to forecast the pavement condition in the following 10 years with FY 2008 as the initial year. The input parameters can be found in Table 3.8.

Case I: Pavement Performance Forecasting without Preservation

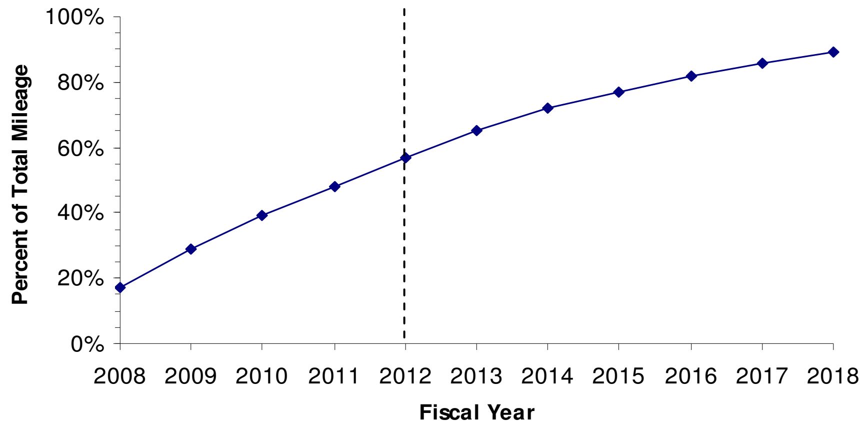
This case is to answer a question: how long will the current pavement network (non-interstate highway in this case) last if no preservation is applied in the following 10 years? Though this is not the real case, it can explore the pavement network's capability of the resistance to deterioration. From Figure 3.11 (a) and (b), the pavement composite rating in FY 2008 is 83 and the percent of pavement below 70 (Bad and Poor states) is 17%, which is already under the requirements defined by GDOT. In GDOT, the desirable pavement network condition should be the one with composite rating being greater than 85 and the percent of pavement below 70 being less than 10%.

Without any preservation applied, the pavement condition drops very fast, almost 3 point in composite rating being lost each year (see Figure 3.11 (a)). Four years later (around FY 2012), the pavement composite rating will drop to 70. In the meantime, the percent of pavement below 70 is around 57%. In FY 2018, the composite rating is 58. And, the percent of pavement below 70 is 89%, 54% of which is under 55 and needs Major Rehab/Reconstruction.

Though this case is not real, it is apparent that the current pavement condition will not last long with the desirable serviceability if no or insufficient preservation is applied



(a) Pavement Composite Rating vs. Fiscal Year



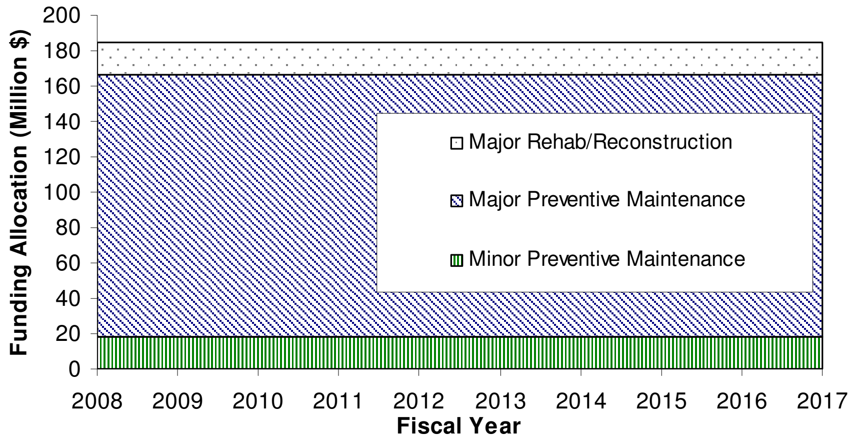
(b) Percent of Bad and Poor (below 70) vs. Fiscal Year

Figure 3.11 Pavement Performance Forecasting without Preservation

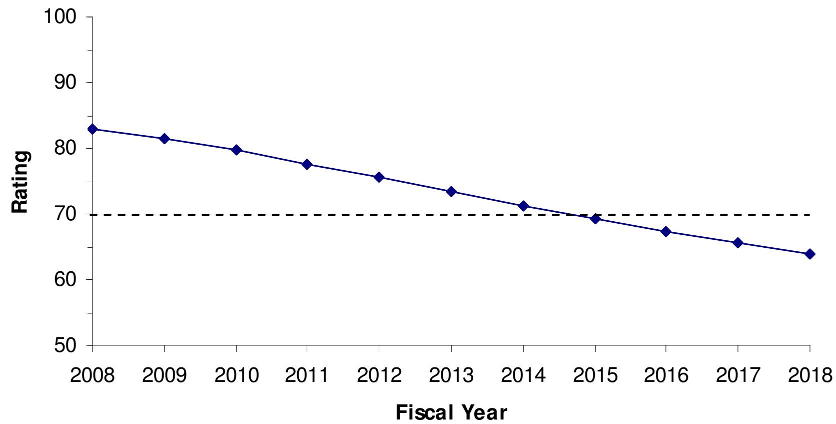
Case II: Pavement Performance Forecasting with Preservation

From Case I, there is no doubt that pavement needs sufficient preservation to remain its serviceability. In this case, another two questions are to be answered: 1) if the current funding level and funding allocation remain in the next 10 years, how will the pavement perform? 2) What is the best way to allocate funds, Worst First, User Specified or Optimization? The available budget is assumed to be the same as the one in FY 2007, which is $185.1 million (see Table 3.8).

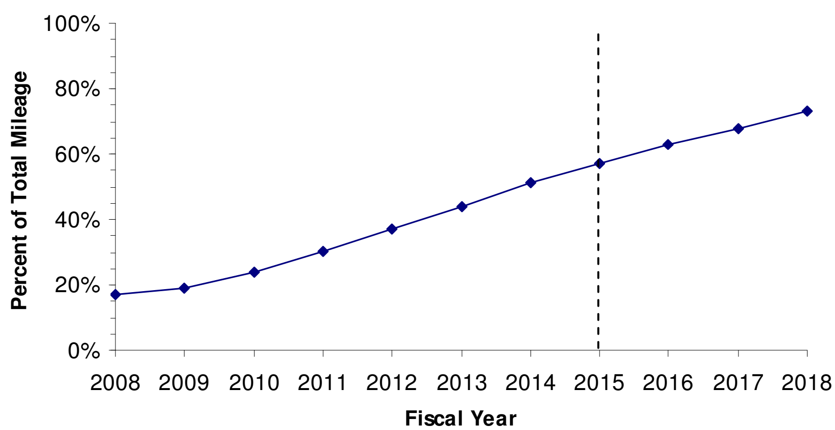
Figure 3.12 is the result of pavement performance forecasting with the current funding level and funding allocation. The funding allocation is assumed to be 10%, 80% and 10% for Minor Preventive Maintenance, Major Preventive Maintenance and Major Rehab/Reconstruction as seen in Figure 3.12 (a). If the current funding level remains same in the following 10 years, the pavement condition still keeps dropping as seen in Figure 3.12 (b), around 2 point being lost each year. Around FY 2015, the composite rating will drop to below 70 and the corresponding percentage is 57% (see Figure 3.12 (c)). In FY 2018, the composite rating is 64 and the percentage is 73%. From the result, it can be concluded that the current funding level is insufficient to maintain the current pavement condition.



(a) Funding Allocation vs. Fiscal Year



(b) Pavement Composite Rating vs. Fiscal Year



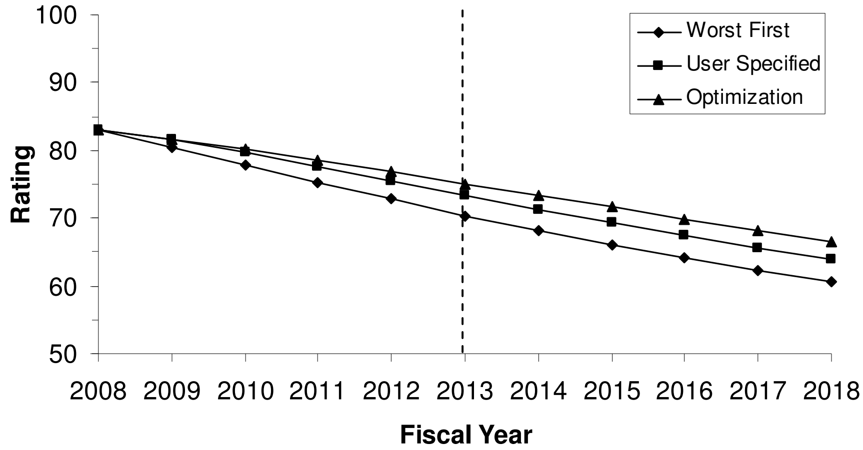
(c) Percent of Bad and Poor (below 70) vs. Fiscal Year

Figure 3.12 Pavement Performance Forecasting with Preservation

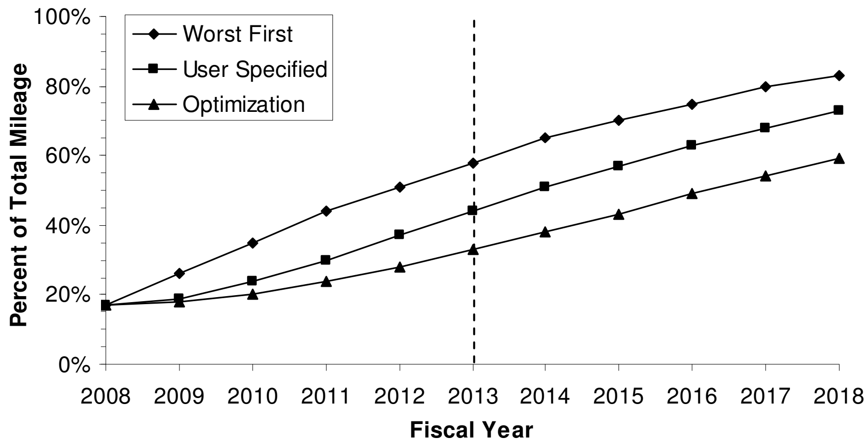
Different preservation strategy has different effect on pavement performance. In the developed PMS models, three strategies are developed for pavement performance forecasting: Worst First, User Specified and Optimization (on all districts). With Worst First strategy, the pavement in worst condition gets treated first. It has been observed and proved to be inefficient according to transportation agencies' practice. User Specified strategy allocates funds according to transportation agencies' experience. Otherwise, optimization-based strategy tries to optimally allocate funds in obtaining the maximal network composite rating. Figure 3.13 compares the results of different strategies with the same input parameters.

From Figure 3.13 (a), as expected, the composite rating drops fastest under Worst First strategy. Optimization strategy has the best result. User Specified strategy is close to Optimization in first 3 years. After that, the difference is obvious. As a comparison, the composite ratings are 70.4, 73.4 and 75.1 for Worst First, User Specified and Optimization respectively. The corresponding values for the percent of pavement below 70 are 58%, 43% and 33% (see Figure 3.13 (b)).

The reason causing the difference on pavement performance with different strategies can be explained from Figure 3.14. With Worst First strategy, after FY 2009, all funds are allocated for the expensive Major Rehab/Reconstruction because the funds are not enough to recover all Bad pavements (see Figure 3.14 (a)). While Optimization strategy always tries to do Minor Preventive Maintenance and Major Preventive Maintenance first because they are low cost compared to Major Rehab/Reconstruction (see Figure 3.14 (c)). If the maximal composite rating is the goal, Optimization strategy is the best one. In addition, an important conclusion can be drawn here: preventive maintenance is of the most importance to avoid the future expensive major rehab/reconstruction.



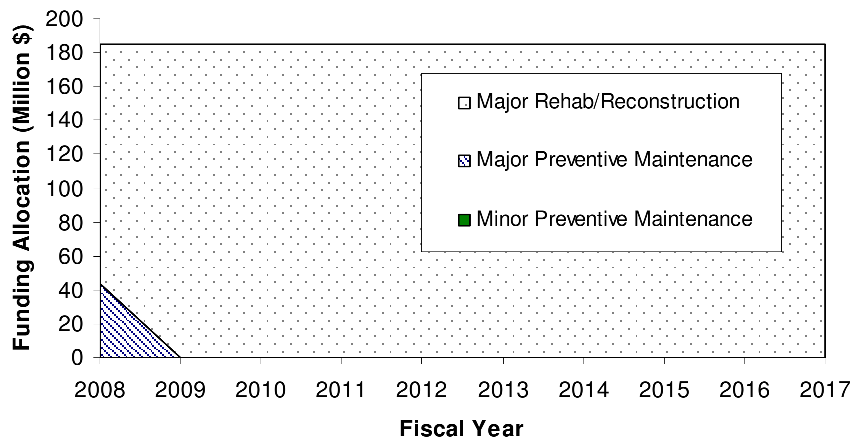
(a) Pavement Composite Rating vs. Fiscal Year



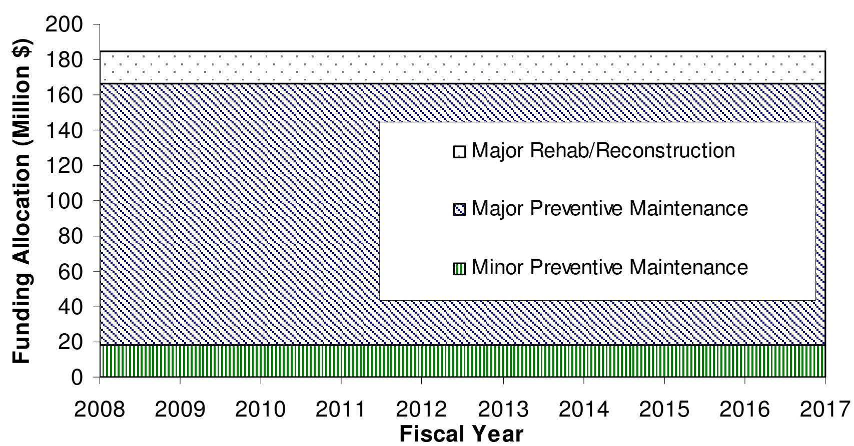
(b) Percent of Bad and Poor (below 70) vs. Fiscal Year

Figure 3.13 Pavement Performance Forecasting with Different Strategies

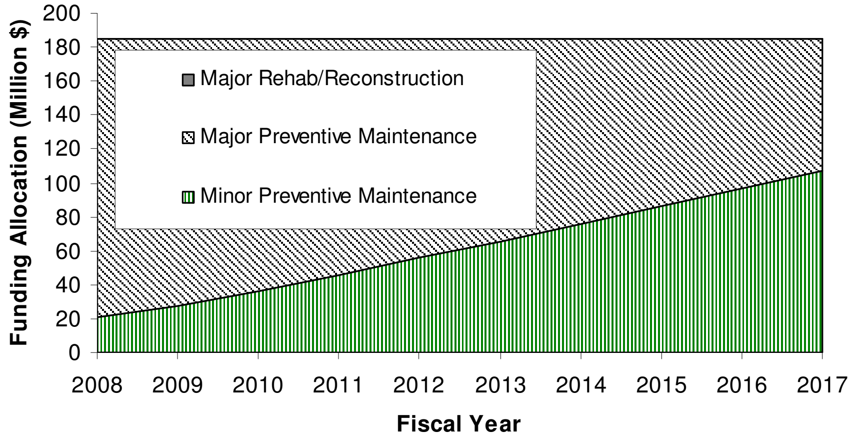
One question may be asked: in real-life pavement preservation, can we just simply follow the Optimization strategy because it can reach the maximal network composite rating? From Figure 3.14 (c), it can be found that the Major Rehab/Reconstruction has not been applied at all. Apparently, it makes less sense because it is not allowed that a pavement is too bad to be serviceable. Though the result from User Specified strategy has less composite rating, the bad pavement has the chance to be treated. Pavement preservation is a complicated decision-making process and it is impossible for a mathematical modal to fully handle that. In the current optimization model, user cost is not considered because it is very difficult to be quantified at the current stage. If the user cost is in consideration, the objective of the optimization model should also minimize the total user cost. Since the user cost increases while the pavement condition becomes worse, it is not allowed to keep the bad pavement always untreated. Of cause, it is not said that the problem will be solved if only user cost is considered. Many other factors also affect the accuracy of the simulation results such as the specific treatment method used, unit cost of each treatment, and the escalating rate of construction cost, etc. In a word, a mathematical PMS model can help making decision but itself can not make a decision.



(a) Worst First



(b) User Specified



(c) Optimization

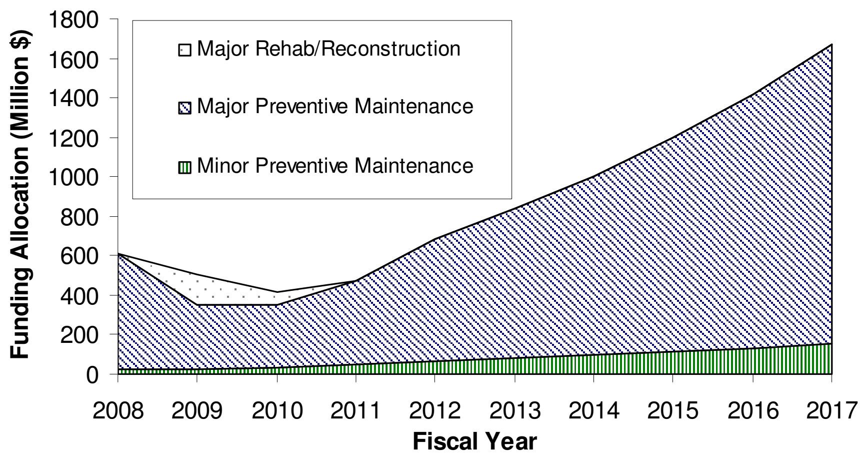
Figure 3.14 Funding Allocation

3.5.2 Analysis on Pavement Preservation Need

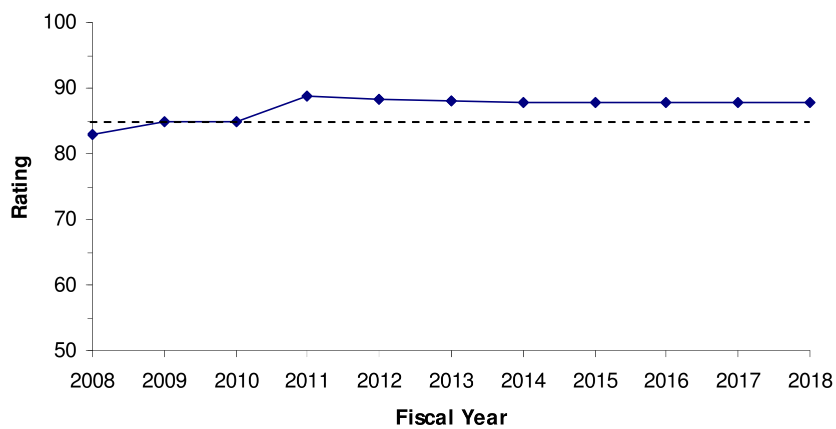
From the analysis in the above section, it is known that the current funding level is insufficient to maintain the pavement condition at a serviceable level. In this section, another question is to be answered: how much fund is needed in the following 10 years to maintain the pavement network (non-interstate highway)? In GDOT, a goal is set to maintain the pavement network condition with the composite rating being greater than 85 and the percent of pavement below 70 being less than 10% (in short, "85-10% requirements"). Apparently, the pavement condition in FY 2008 is already below these requirements, which are 83 and 17.11%. In this section, the funds needed for the "85-10% requirements" will be explored.

Case III: Pavement Preservation Need for "85-10% Requirements"

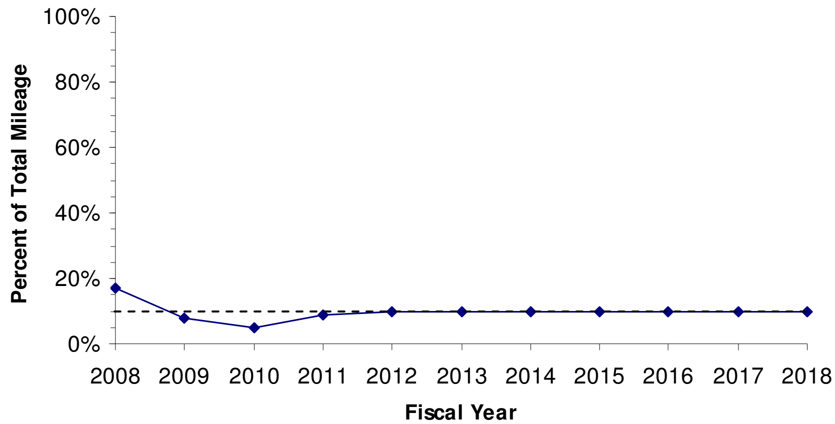
The objective of this case study is to figure out the annual funds that are needed to maintain the pavement condition meeting the "85-10% requirements". The initial year is still FY 2008 and the input parameters for Markov TPMs, treatment unit cost and AAER are same as Case I and II. The initial percent of pavement below 70 in FY 2008 is 17.11%. So, some pavements in Bad have been treated in FY 2009 and FY 2010 to decrease the percentage (see Figure 3.15 (a)). In result, the pavement composite rating increases to 85 in FY 2009 (see Figure 3.15 (b)) and the percent of pavement below 70 decreases below 10% (see Figure 3.15 (c)). From Figure 3.15, it is found that the trend for each figure becomes stable after FY 2012, which is called the steady status in a Markov Process. It means that after FY 2012, the pavement condition becomes stable with the unchanged percents of pavements in each state if the available funding and its allocation can meet the requirements. In Figure 3.15 (b), the actual stable composite rating is around 87 in stead of 85. It is because the composite rating and the percent of pavement below 70 are not independent of each other. In this case, if the maximal percent is met, the composite rating becomes above the minimal value.



(a) Funding Allocation vs. Fiscal Year



(b) Pavement Composite Rating vs. Fiscal Year



(c) Percent of Bad and Poor (below 70) vs. Fiscal Year

Figure 3.15 Pavement Preservation Need in 10 Years ("85-10% Requirements")

Table 3.11 lists the detailed annually needed funds. Apparently, the annual escalating rate after FY 2012 is close to 18.1% that is just the AAER applied in the case study. So, if no escalating rate is in consideration, the annual funds will also become stable. It can be seen that, to bring back the pavement condition to the requirements, $611.5 million is needed, which is $426.4 million shortfall compared to the assumed available $185.1 million. Due to accumulated construction cost increase, the needed funds become $1,668 million in FY 2017.

Table 3.11 Funds Needed to Meet the "85-10% Requirements" in 10 Years

Year	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Fund (Million $)	611.5	500.9	412.3	469.1	684.9	836.3	1,004.9	1,194.8	1,413.3	1,668.0

3.5.3 Impact of AAER on Pavement Condition and Budget Shortfall

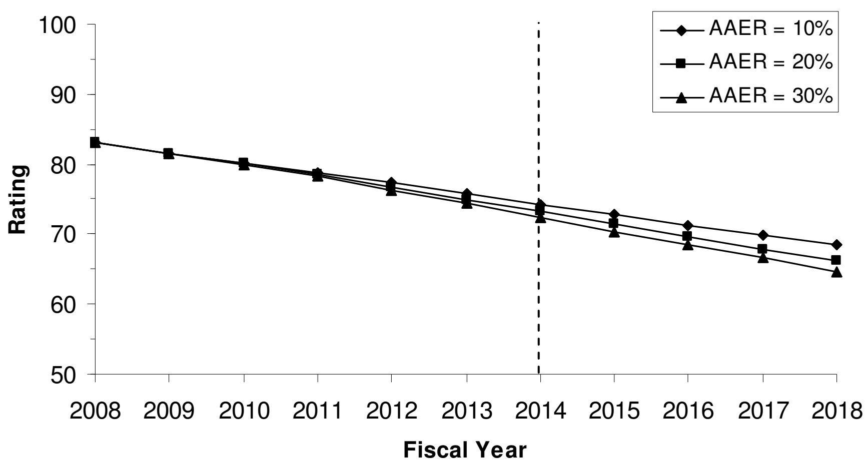
In the above study, the AAER is assumed to be 18.1% according to the analysis of the historical expenditure of resurfacing (see Figure 3.4). But, it is very unreliable to use this number for the pavement condition forecasting because construction cost changes dramatically and are far from a steady trend. It is very difficult and complicated to predict the trend of the construction cost.

With the budget shrinkage, it is very crucial for all highway agencies, legislatures and stakeholders to know how escalation rate affects the long term pavement conditions. In this section, a sensitivity study is performed to study a) the pavement conditions and b) the corresponding funding needs in 10 years with AAER. And it is assumed that the budget level of $185.1 million would not change in the next 10 years.

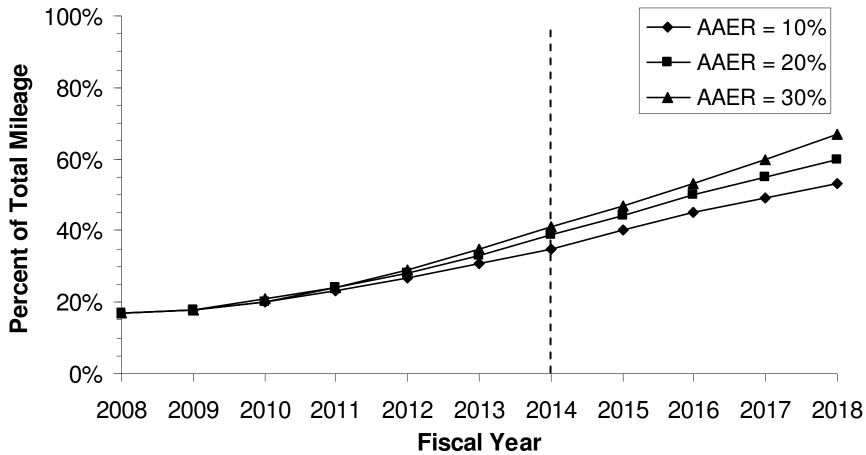
Case IV: Impact of AAER on Pavement Condition

In this case study, the pavement conditions are predicted with different AAERs of 10%, 20%, and 30%.

Figure 3.16 (a) and (b) shows the trends of pavement composite rating and the percent of pavements below 70 respectively with different AAERs of 10%, 20% and 30%. As expected, higher the AAER is, faster the pavement deteriorates. In FY 2014, the difference in composite rating is around 1 point in comparison with the cases of 10% and 20%, and the cases of 20% and 30%. The difference increases to around 2 point in FY 2018. The corresponding percents of pavement below 70 are 35%, 39% and 41% for cases of 10%, 20% and 30% respectively in FY 2014. The values increase to 53%, 60% and 67% in FY 2018.



(a) Pavement Composite Rating vs. Fiscal Year



(b) Percent of Bad and Poor (below 70) vs. Fiscal Year

Figure 3.16 Pavement Condition with Different Escalation Rates

Case V: Impact of AAER on Pavement Preservation Need

The needed funds for pavement preservation are directly affected by the AAER. In this case study, pavement preservation needs for the "85-10% requirements" are analyzed in terms of the different AAERs, 10%, 20% and 30%.

Figure 3.17 shows the budget needs with the different escalation rates in the next 10 years, which is roughly in a pattern of exponential increase over years. To recover the current pavement conditions to the 85 and 10% requirements, $611.5 million is needed in FY 2008, which means a shortage of $426.4 million for non-interstate pavements only. If the AAER remains 10% in the next 10 years, $880.3 million dollars is in the need to maintain the non-interstate highway network in FY 2018. With higher AAER, budget needed increases much faster in a nonlinear form. For example, with double AAER of 20%, $1.9 billion will be needed in FY 2018, which is more than double of the need with AAER of 10%. If AAER increases to 30%, $4 billion is needed in FY 2018.

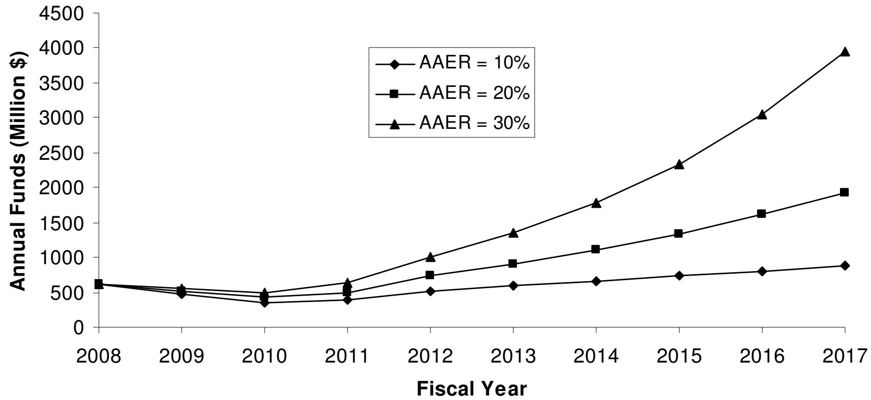
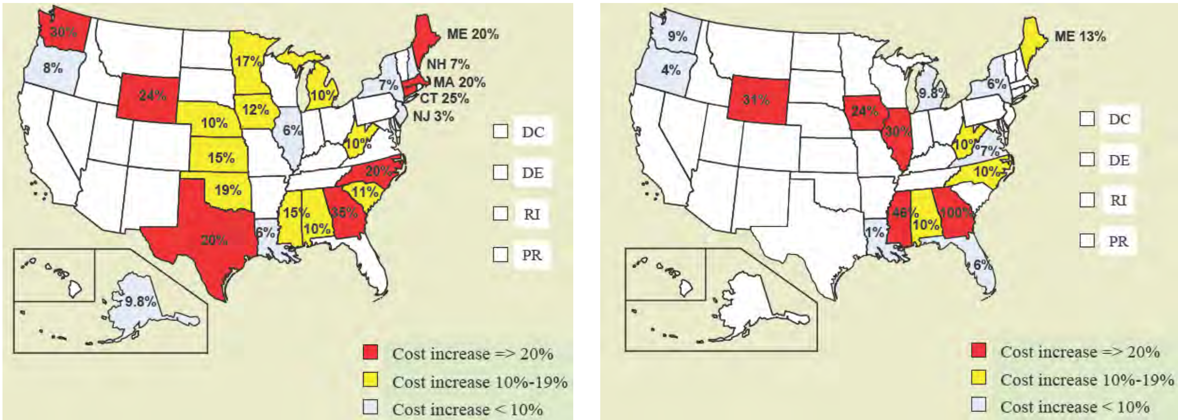


Figure 3.17 Funding Needs with Different Escalation Rates

The above analysis shows the severe situations confronting highway agencies, legislatures and stakeholders to maintain the highway pavements. To accurately predict the pavement performance and plan the future pavement preservations, further study is urgent to accurately predict the trend of construction cost.

3.5.4 Impact of Unexpected Construction Cost Increase on Pavement Performance

Pavement construction cost changes in an uncertain way. Sometimes, the change would be very dramatic. The unexpected changes in construction cost bring the difficulty to highway agencies in highway preservation because it may cause some planned projects being delayed or canceled. According to a survey conducted by the American Association of State Highway and Transportation Officials (AASHTO) on construction cost increases, state DOTs reported significant cost increases from 2005 to 2006. The Georgia Department of Transportation (GDOT) experienced the largest increase (35%; see Figure 3.18 (a)). Furthermore, construction costs have gone up as high as 100% from 2006 to 2007 (see Figure 3.18 (b)). How will the unexpected construction cost increase affect the long-term pavement performance? In this section, a sensitivity study is performed to answer this question.



(a) 2006 vs. 2005 **(b) 2007 vs. 2006**

Figure 3.18 Construction Cost Increases

Case VI: Impact of Unexpected Construction Cost Increase on Pavement Performance

In this case study, it is assumed that there is a sudden cost increase in FY 2009 by 50%, 100% and 150% and no extra budget is available. The AAER remains 18.1% after FY 2009.

To quantify the long-term loss, e.g. 10 years, due to this unexpected increase of construction costs, a LOPP (loss of pavement performance) is defined as shown in Figure 3.19, which is the ratio of the shaded area and the area surrounded by the vertexes O, A, B and C. The shaded area is surrounded by the normal pavement performance curve and the pavement performance curve after the unexpected change of construction cost at time T_C, which is above 70 of pavement rating. The computation of an LOPP can be expressed as the following equation.

$$\begin{aligned} LOPP &= 1 - \int_{T_c}^{T} (r_C(t) - 70)dt \Big/ \int_{T_c}^{T} (r_N(t) - 70)dt \\ r_C(t) &= 70, \text{if } r_C(t) < 70 \\ r_N(t) &= 70, \text{if } r_N(t) < 70 \end{aligned} \tag{3.38}$$

In which the normal pavement performance r_N and changed pavement performance r_C are all functions of time *t*.

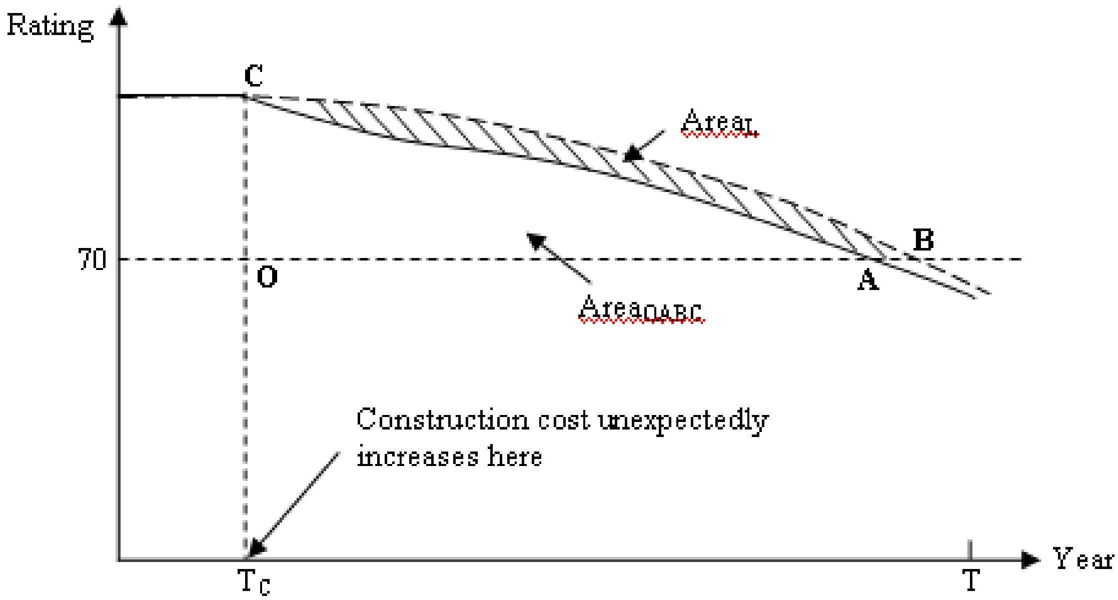


Figure 3.19 Definition of LOPP (Loss of Pavement Performance)

Figure 3.20 shows the pavement performance loss due to the construction cost increases in 2009 by 50%, 100% and 150% respectively. With 50% change, 3.8% of LOPP in the following 8 years is expected. With 100% and 150% changes, the LOPPs are 7.8% and 10.4% in 8 years respectively. It can be seen that although the construction cost change only happens in one year, the long term effect is still obvious. Further study is needed to quantify the corresponding loss in funds due the worse pavement conditions.

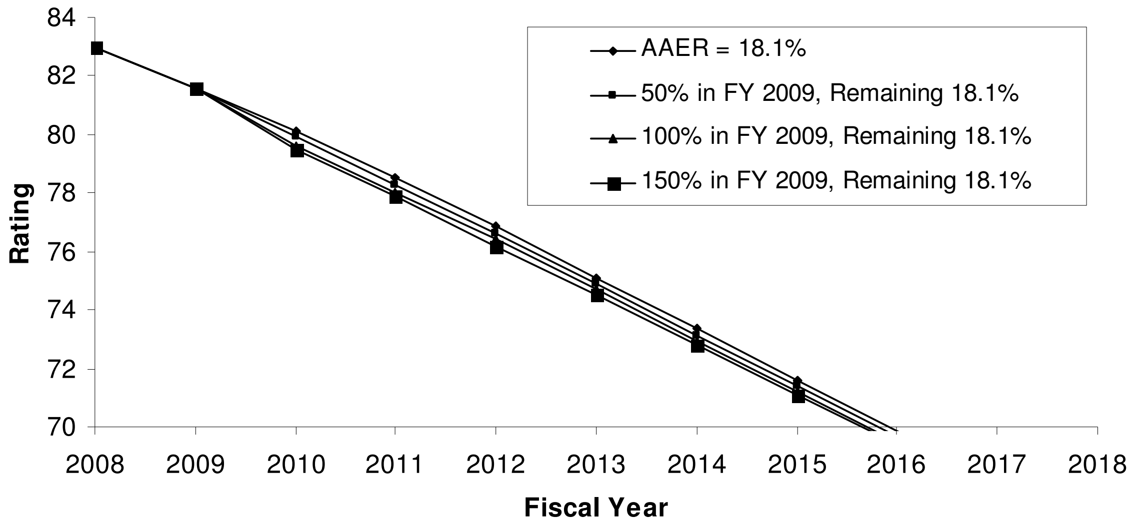


Figure 3.20 Loss of Pavement Performance

3.6 Summary

With the current stringent budget, there is an urgent need for GDOT to efficiently justify to the legislature the highway pavement preservation need. To fulfill this purpose, the long-term pavement conditions need to be forecasted with different funding level. The needed budget in sufficing the requirements on pavement conditions should also be scientifically predicted considering the escalation of construction cost. To assist the process of decision-making, a Markovian-process-based PMS model has been developed and implemented as a computer program. Several strategies for funding allocation were designed for different purpose:

1) The “Worst First” strategy is still widely used by agencies, which is also implemented in the developed program. But, it is not encouraged to be used because the simulation result shows its inferior efficiency.
2) The “User Specified” strategy can simulate GDOT’s current operation. By providing different funding allocation proportion, users can forecast pavement long-term performance under the different funding level. Users can make decision based on the comparison of different outcomes.
3) The “Optimization” strategy utilizes linear programming technique to find optimal funding allocation in achieving the optimal pavement composite rating.

The results coming from this strategy can be considered as an upper bound of the finally selected funding allocation.

4) The “Need Analyses” strategy predicts the annual minimum funding needed to maintain the pavement network in a satisfactory condition. Users can define different “satisfactory condition” by providing different values for the minimum composite rating and maximum percentage of pavements with ratings below 70. The what-if analysis using this strategy can help decision makers to identify the funding deficiency.

Other than the development of the PMS model, more efforts were spent on the analyses of the input parameters for the model including Markov TPMs, initial state vectors of pavements, unit cost of different MR&R activities, and the escalation rate of construction cost. The historical COPACES data from FY 1986 to FY 2008 were extracted and analyzed to generate the Markov TPMs and initial state vectors. Unit cost of different MR&R activities were obtained by the discussion with GDOT engineers because it is difficult to extract and analyze the historical expense on pavement preservation for each MR&R category at the current stage.

To validate the developed PMS model, the historical expenditure of resurfacing on non-interstate highway from FY 1999 to FY 2007 was extracted with the help of GDOT engineers. By analyzing the data, the unit cost and escalating rate has been established. In the meantime, the total annual funding from FY 1999 to FY 2007 was projected. Based on these input parameters, a simulation using “User Specified” strategy was performed to predict the pavement conditions from FY 2000 to FY 2008 with FY 1999 as the initial year. Based on the comparable results between the simulation and the historical pavement conditions, the developed PMS model and the corresponding input parameters have proven to be able to capture the characteristics of pavement deterioration and the effect of MR&R activities.

To illustrate the utilization of the developed PMS models and the program, six case studies were performed on the non-interstate highway. The following list the major findings:

1) Pavement preservation is very important to extend the pavement service life. Without any preservation applied, the pavement condition drops very fast, almost 3 points in composite rating being lost each year. Four years later (FY 2012) with FY 2008 as the initial year, the pavement composite rating will drop to 70. In the meantime, the percent of pavement below 70 is around 57%.
2) If the current funding level and funding allocation remains same in the following 10 years, the pavement condition still keeps dropping, around 2 point being lost each year. Around FY 2015, the composite rating will drop to below 70 and the corresponding percentage is 57%. In result, the current funding level is insufficient to maintain the pavement network at a constantly serviceable level in a long-term period. More funding is needed in the future.
3) The comparison among three simulation strategies of "Worst First", "User Specified" and "Optimization" shows that "Worst First" is the most inefficient strategy for pavement preservation. "Optimization" shows the best result. But, because some factors such as user cost cannot be considered in the mathematical model due to the lack of data support, "User Specified" should be comparable to a "optimal" solution. The result from "Optimization" strategy is still useful as a upper bound in helping the process of decision-making.
4) The need analysis shows that the "85-10% requirements" is hard to achieve because there is $426.4 million shortfall only in FY 2008, which is more than two times then the available budget (if the total available budget is $185.1 million). With the consideration of the escalation rate of construction cost (it is assumed 18.1% in this case), the needed funds become $1.7 billion in FY 2017.
5) The escalation rate of construction cost has the direct effect on the pavement condition and pavement preservation need. The sensitivity study performed on three different AAERs (10%, 20% and 30%) shows that, in FY 2014, the difference in composite rating is around 1 point in comparison with the cases of 10% vs. 20%, and the cases of 20% vs. 30%. The difference increases to around

2 point in FY 2018. The corresponding percentages of pavement below 70 are 35%, 39% and 41% for cases of 10%, 20% and 30% respectively in FY 2014. The values increase to 53%, 60% and 67% in FY 2018. The increase in funding need is much faster than the increase of AAER. If the AAER remains 10% in the next 10 years, $880.3 million dollars is in the need to maintain the non-interstate highway network in FY 2018. With double AAER of 20%, $1.9 billion will be needed in FY 2018, which is more than double of the need with AAER of 10%. If AAER increases to 30%, $4 billion is needed in FY 2018. Because construction cost is hard to be forecasted, the corresponding risk should be analyzed in the planning of pavement preservation.

6) The change of construction cost may be dramatic in short term. The unexpected change will force transportation agency to defer or cancel some planned pavement preservation projects. Thus, the long-term pavement performance will be adversely impacted. The preliminary sensitivity study shows the pavement performance loss due to the construction cost increases in 2009 by 50%, 100% and 150% respectively. With 50% change, 3.8% of LOPP in the following 8 years is expected. With 100% and 150% changes, the LOPPs are 7.8% and 10.4% in 8 years respectively.

Pavement preservation is a complicated decision-making process. The case study based on the developed PMS model and the computer program demonstrates the capability in helping the decision-making process. Otherwise, further refinement and study is still needed. The following summarize the suggestions for further research.

1) The current PMS optimization model uses annual-based linear programming. The results cannot guarantee the optimality during the entire analysis time horizon. For example, the annual funding need coming from the "Need Analysis" strategy is the minimum to meet the annual pavement condition requirements. But, the total funding need during the analysis period, say 10 years, is not guaranteed the minimum. To solve this issue, a multi-year optimization model is needed, which considers the funding allocation covering the whole analysis period.

2) The accuracy of the long-term pavement performance forecasting and funding need analysis largely depends on the accuracy of the input parameters of the computation model. The following research is needed to improve the accuracy and reliability of the input parameters.

    a. The current Markov TPMs were generated using the simple proportion methods. Due to the probabilistic feature of pavement condition, a more elaborate method should be studied based on the theory of probability and stochastic process.

    b. The homogeneous Markov model has some limitations in modeling pavement deterioration because the behavior of pavement deterioration is also dependent on time due to change of pavement material characteristics and traffic. Thought there is some difficulty in obtaining the necessary data support, it is valuable to evaluate the non-homogeneous Markov model.

    c. The constant price model, i.e. a single escalation rate of construction cost, used in the current PMS model lacks the capability to model the variation of construction cost. Though a case study was performance applying a different AAER in one year, the study is pretty rudimentary. Based on the study of LOPP, it is needed to further study the different price models and their impact on the long-term pavement performance and funding need.

    d. The accuracy of the unit prices of MR&R activities directly determine the buying power of money. Due to the project scope and resource limit, this study is very rudimentary at the current stage. It is strongly suggested to perform intensive study on the historical expense of pavement preservation.

    e. In the current PMS model, the classification of MR&R activities is very rough. Also, the alternative treatments are pre-set by engineers. More study is needed to define finer MR&R activities and assign more alternatives to each pavement state.

3) Without the consideration of user cost, cheaper treatments are always the first selection by an optimization model, which in some cases make less sense in transportation agencies' practice. Though there is some difficulty in quantifying the user cost at the current stage, the PMS model should include it for sensitivity study.
4) It is recommended to further study the quantification of LOPP. Transportation agencies are greatly interested in the relationship between the investment loss and the pavement performance loss
5) The current PMS model can be used for network-level planning and the detailed project-level programming cannot be handled. To link the project-level programming and the network-level planning, the so-called project-linked (or segment-linked) PMS model is needed. Though, in most cases, optimal solution for a project-level PMS optimization problem can not be achieved. But, with the use of some heuristic technique, the feasible solution can be efficiently found. Because the easy utilization of the result from a project-level PMS model, it is of great value to do further research on this topic.

4 Exploration of Crack Sealing Performance Assessment

4.1 Objective

Crack sealing is one of the popular pavement preservation methods performed by GDOT. Intensive literature review on crack sealing performance assessment was conducted in this chapter. The objective of this study is to analyze the benefit of crack seal treatment and identify the best practice (e.g. timing/condition) for crack sealing based on the previous studies. We also performed crack sealing performance evaluation using COPACES data. Although some data has begun to be recorded on when and where crack sealing treatments were done in the past few years, it was not done for the explicit purposes of a comparative study. Therefore, the existing data does not offer great potential to satisfy the objective, but analysis of the existing data will be discussed later in this chapter. It is hoped that this study can lead to a statewide experimental design to observe crack sealing treatments under different conditions in order to analyze the performance of crack sealing more scientifically. With the large-scale experimental tests, it can produce a set of guidelines based on the pavement distress conditions that will trigger preventive maintenance of pavements in order for GDOT to optimize their budget and to obtain the lowest cost for the longest serviceable pavement life.

4.2 Pavement Preservation

Zaniewski and Mamlouk (1999) reported that FHWA estimated the cost of maintaining the nation's pavement condition in 1993 would require $50 billion annually and the budget at that time was only $27 billion annually. To eliminate backlog requirements it would take an estimated $220 billion in 1993 dollars. To help alleviate this growing budget crisis, the use of pavement construction and rehabilitation money must be optimized in order to sustain the national pavement infrastructure system. The Strategic Highway Research Program (SHRP) as well as several other studies has demonstrated that preventive maintenance is cost-effective for roads in the National Highway System (Zaniewski and Mamlouk 1999). As a result, many agencies are putting more focus on maximizing the benefit of preventive maintenance. Some good examples of this emphasis are provided in this paper and in other research for Georgia's roads. The California Department of Transportation (CALTRANS) has created a Pavement Preservation Task Group (PPTG) that is an effort between local government and industry there to foster coordination and improvements in pavement preservation. More information on California's preservation program can be found at http://www.dot.ca.gov/hq/maint/PavePres/ppindex.htm where one can find additional information such as the Maintenance Technical Advisory Guide (MTAG) or one can review findings from the last forum, specifically the crack sealing sub-task group.

In evaluating the life-cycle of flexible pavement preventive maintenance, Labi and Sinha (2005) compared several different treatment scenarios that applied multiple preventive maintenance techniques at various times and then calculated cost-effectiveness on the basis of agency and user costs in years per million dollars. The ratios ranged from 13.09 to 40.48 with various treatment combinations versus the do-nothing-case which has a ratio of 0. In other words, the ratio of pavement life extension to treatment cost was positive for every scenario. However, it is also noted that there is an optimum preventive maintenance cost expenditure meaning the benefit is less for spending too little or too much on maintenance practices (Labi and Sinha 2005). Labi and Sinha (2005) also caveat that the cost-effectiveness for PM is the most for non-interstate system roads that are still part of the national highway system (NHS) because they generally carry larger volumes of traffic than local roads but may not be designed to high standards such as those for interstates highways (see Figure 2 in Labi and Sinha 2005 for more details).

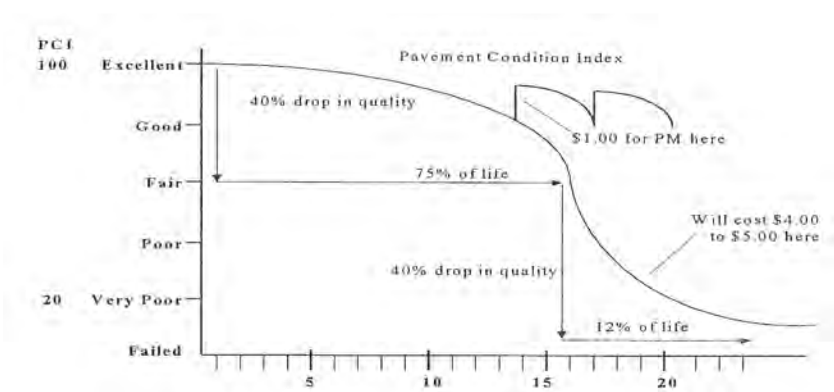


Figure 4.1 Typical Pavement Life-cycle (O'Brien 1989; Hicks et al. 1999)

As far as the timing and effectiveness of various PM treatments for flexible pavements, Hicks et al. (1999) provides an excellent summary of several factors to consider. Figure 4.1, originally from O'Brien (1989), shows the general trend of pavement deterioration and the increased cost to maintain pavement condition once it has reached the steep part of the curve. Therefore, PM treatments such as crack sealing, chip seals, slurry seals, fog seals, microsurfacing, and thin HMA overlays should all be applied while the pavement is still in good condition. Even within the arena of PM, some treatments are more long-term and may be applied later than other methods. Appendix V provides several more graphs and tables from Hicks et al. (1999) for assessing the most appropriate maintenance strategy for different types of distress, typical unit costs and life-expectancy of various PM treatments, guidelines for effective maintenance treatments, a conceptual relationship for timing for various maintenance and rehabilitation treatments, and an example showing equivalent annual costs based on the life of the treatment.

In evaluating the cost-effectiveness of PM treatments, Hicks et al. (1999) suggests using the equivalent annual cost (EAC) method because it is "relatively straightforward." EAC is the ratio of unit cost per expected life of the treatment in years (see tables in Appendix VII for examples). Despite the simplicity of the EAC method, Hicks et al. (1999) advocates using a combination of various factors of performance, constructability, and customer satisfaction for selecting the most appropriate PM treatment since using only EAC will always "skew the decision to the lowest cost product." These factors will be dependent on an agency's practices and will vary on a project specific basis. Finally, separate effectiveness calculations by Eltahan et al. (1999) showed the benefit over control sections (no maintenance performed) by average survival times for thin overlay, slurry seal, and crack seal lasting 3.1, 2.7, and 2.5 years longer respectively. The SPS-3 experiment designed under SHRP contract H-101 by the Texas Transportation Institute was the basis for these calculations.

4.2.1 Why Crack Sealing

Over time and constant cyclic loading from traffic and weather, roads develop distresses such as cracking and other detrimental effects that eventually lead to "failure" of the pavement and the need for new construction. Failure is mentioned in quotes because failure is relative based on the expectation of the road due to the amount of use or other limiting expectations set forth by the owner of the pavement. In general though, water intrusion into the pavement structure is the biggest factor that contributes to its deterioration (Christopher 2006). All of the harmful effects of water on soils (pavement base and subbase structure) are too complex and lengthy to go into here, but it is well known that water is the most destructive element to pavement. A figure from Cedergren (1987) shows that if the underlying structure of a pavement stays saturated 20% of the time (73 days a year) then the expected life reduces to 20% of the useful life; if it is saturated 50% of the time, the useful life drops to 10% of what it was designed for (Christopher 2006). AASHTO says that the detrimental effects of water include modulus reduction, loss of tensile strength, and loss of stiffness; (note, modulus is the key property in pavement design) (AASHTO 1993; Christopher 2006). Therefore, keeping water out of the pavement structure is the primary goal of the pavement maintenance practices of crack sealing and crack filling.

One of the most common methods of preventative maintenance is crack sealing because it is relatively easy to perform with an in-house work force, but its effectiveness has been debated. Ioannides et al. (2004) brings up the fact that crack sealing should be done in conjunction with pavements that have good drainage systems and routine inspections of these systems. It is known that crack sealing cannot keep 100% of surface water from getting into the pavement, either due to sealant degradation over time or new cracks forming and sealing not being done instantaneously, and thus a need for drainage of the water that does enter the structure. If drainage is not sufficient, crack sealing may be even more detrimental by trapping the water inside the structure.

Some engineers were also opposed to initial efforts to crack seal because sealant materials and construction practices contributed to poor performance, resulting in a waste of time and money. However, ineffective procedures and materials have been identified, and newer research has shown that filling or sealing pavement cracks properly to prevent water from entering the base and subbase will extend the pavement life by three to five years (PennDOT LTAP 2007). Ponniah and Kennepohl (1996) report at least a 2-year pavement life extension from crack sealing, and Michigan DOT reports that crack sealing can provide up to a 3-year life extension (Bausano et al. 2004). The CALTRANS even reports that crack sealing/filling can provide up to 8-9 years of service life based on research from the US Department of Transportation (Smith and Romine 1999b).

4.2.2 Variables that Affect Optimal Timing

One of the toughest challenges with this study is the number of variables associated with determining the optimum treatment material, timing, and method. The experiment will be largely guided by GDOT pavement engineers depending on current practices and availability of materials. One of the first questions to answer is whether to crack seal or crack fill? The next section will present the differences with these methods. The next variable is the type of crack sealant or filler to be used. CALTRANS lists several different options such as asphalt emulsion, asphalt cement, fiber-modified asphalt, polymer modified emulsion, various types of asphalt rubber, and silicone (CALTRANS 2003). The cost of each material, availability, and time to perform the process will need to be taken into consideration, as well as the performance of each material in order to perform a cost-analysis between them. Zimmerman and Peshkin (2004) talked about the limited number of studies that used control sections in which nothing was done to the pavement; a project study would certainly need to include a control section to see how the effects of all the different variables relate to the control section. Different crack sealing products and materials compared by Ioannides et al. (2004) would also need to be varied if money and time permits. Finally, but not all inclusive, the crack reservoir types and differences explored by Johnson et al. (2000) would need to be compared in this study as well.

Several agencies either use decision trees or pavement condition indexes to identify when to perform several preventive maintenance and rehabilitation projects. The Metropolitan Transportation Commission (MTC) in the San Francisco Bay area sets “treatment trigger levels” based on a standard deterioration curve (Zimmerman and Peshkin 2004). A PCI of 70 is the trigger value between preventive maintenance and light-to-moderate rehabilitation, and heavy rehabilitation occurs at a PCI of 50 (Smith 2002). Relating this to GDOT pavements, if a PCI of 70 is an unacceptable pavement, then an initial estimate for a trigger value for preventive maintenance may be somewhere around a PCI of 85-90 if cracks are developing at this point. This evaluation needs to be further linked to minimum crack widths before taking action. The Minnesota and Kansas DOT's have also taken several steps towards creating complex decision trees in order to incorporate and integrate preventive-maintenance treatments into their optimization analysis within a pavement management system (Zimmerman and Peshkin 2004). These departments should be contacted to see where they are at in the process and figure out why they make their decisions at the certain trigger values they have selected.

4.2.3 Crack Sealing versus Crack Filling

CALTRANS has also put together a comprehensive guide on several aspects of crack filling and crack sealing, and the following is a summary of Chapter 3 of their Maintenance Technical Advisory Guide, which also gains a lot of its material from FHWA 1999 manual on sealing and filling cracks (Smith and Romine 1999b). The ideas of crack sealing and crack filling are very similar. Both methods prevent water and incompressible materials from getting into cracks by placing generally flexible material either in or over the crack. Materials such as asphalt emulsions, polymer modified emulsions, asphalt rubber, and silicone sealants are used to fill or seal the crack and hopefully retain adhesion to the pavement, as well as flexibility, while also resisting wear from the traffic loads. The primary distinction between crack sealing and filling is what type of crack it is treating, whether it is working or nonworking and whether it is horizontal or longitudinal. A working crack means the crack is continuing to propagate relative to some criteria on how much it moves in a year. For example, CALTRANS criteria for a working crack is >6mm (1/4 in) of horizontal movement annually (CALTRANS 2003). Working cracks can be either horizontal or transverse, but most often are transverse. Crack sealing is used on working cracks, and crack filling is used for nonworking cracks or when cracks are closely spaced.

The advantage to crack filling is that it is less expensive because it is less time intensive to perform and generally the materials are cheaper. Crack sealing on the other hand requires thorough crack preparation and more expensive materials, but it is generally considered to be a longer term treatment than crack filling. The materials used for the filling or sealing, the placement method, traffic load, and quality of construction are the primary considerations on how effective and how long the preservation will be.

4.3 Crack Sealing Study

Although, there is not a study specific to Georgia's pavements, some other studies have been performed that are similar to the objective of this study. One of the most well known studies is from Ponniah and Kennepohl (1996) where they aimed to determine the cost-effectiveness of crack sealing through a life-cycle cost analysis. With proper crack preparation (including correct size, equipment, and cleaning) and material, results from 37 test sites in Canada showed that pavement life can be extended by at least 2 years depending on the initial condition, environment, and traffic volume. Crack growth was measured yearly and performance curves were created to compare types of sealants, route size, and the most beneficial time to apply the sealant (e.g. pavements with extensive cracking will not benefit from the treatment). Life-cycle cost analysis showed that crack sealing provides a 48% increase in cost-effectiveness over a more elaborate maintenance alternative. Conclusions from the study include the following: 1) a 40 x 10 mm routing of existing cracks promotes good sealant bonding; 2) not sealing cracks results in increased maintenance cost and decreased service life; 3) crack sealing can retard secondary crack growth; 4) a life-cycle cost analysis indicates that crack sealing is cost effective; and 5) a rout and crack seal program must be applied to suitable pavements, using acceptable materials, and at the correct time.

4.3.1 Crack Type

Zinke and Mahoney (2006) released a report comparing the two most common types of crack treatment (hot pour (crumb rubber or other additives heated to high temperatures) and cold pour (asphalt emulsions)). Part of their conclusions was that both materials performed better in longitudinal cracks than in transverse cracks. This may be attributed to two reasons: 1) transverse cracks are usually working cracks and continue to propagate thereby reducing the effectiveness of the sealed portion, and 2) longitudinal cracks are generally located between lanes or between a shoulder and a lane and as a result do not take as much direct traffic, whereas wheel loads are constantly passing over at least some point of a transverse crack. For both longitudinal and transverse cracks, the application methods were compared by using the same rating criteria for failed sealants as outlined in the SHRP crack treatment experiment report (Smith and Romine 1999a). Zinke and Mahoney (2006) concluded that the hot pour treatments outperformed the cold pour methods based on their data from field evaluations despite the fact that the hot-poured joints were two years older.

Yildirim et al. (2006) also compared 3 cold-pour sealants and 4 hot-pour sealants in four Texas DOT districts during a four-year study and came to the following conclusions. First, the cost of the sealants ranged from \$0.04 to \$0.13 per linear foot with the cold-pour treatments being the most expensive. Their study also found that hot-pour sealants performed better than cold-pour sealants over time and that the initial construction cost of hot-pour materials was also cheaper.

4.3.2 Type of Sealant Used and Construction Practices

The previous study focused on the general categories of sealants used, but there are other studies that also focused on comparing many different crack sealing materials and brands. In Montana, Johnson et al. (2000) compared nine different materials using both routed and nonrouted methods, as well as varied the size of the rout reservoir (Montana DOT typically uses "square" reservoirs but "shallow" or four-to-one reservoirs were also included due to their reported benefits). The square reservoirs were also filled using flush, recessed, or Band-Aid techniques. Finally, this study comments on the workmanship of the crack sealing performed at some of its test sites. All of these parameters were summarized in the following conclusions: 1) shallow reservoir and flush technique offers better performance than the square reservoir and flush technique; 2) Low Modulus, Polymer Modified and Polymer Modified, Rubberized Asphalt offered the best resistance to adhesion and cohesion failures; 3) Band-Aid and square reservoirs experienced the most failures after three years of service; 4) routing transverse cracks improved performance of sealants; 5) square reservoirs with recessed sealants did not perform well; 6) routing did not appear to be necessary for longitudinal cracks; 7) Band-

Aids appear to be less susceptible to snow plow pull-outs; and 8) higher failure rates of the sealants can be expected during the coolest months of the year when cracks are at their widest and the material is the most stiff. Finally, it is noted that the Tarkio site within the study included a control section for comparison to unsealed sections with all other factors the same (Johnson et al. 2000).

A similar joint sealant study was performed by Ioannides et al. (2004) on the Ohio Route 50 test pavement in which they tested 10 different sealant compounds on PCC pavements (4 silicone, 2 hot-applied, and 2 compression seals) and compared them to 4 unsealed sections over a three year period. Though different from flexible pavement cracks, some insight may be gained or reinforced from this study. In general, they found that compression seals outperformed the other sealants, and crew experience in sealant installation is a critical factor. More specifics can be found in the paper, but one thing that is worth noting here is that the brand names were mentioned and compared specifically and not just the sealant type. The various companies represented were Watson Bowman, Delastic, Techstar, Crafco, and Dow.

4.3.3 Climate and Temperature Effects

The studies reviewed varied widely in temperature, from very cold temperatures in Canada, Michigan and Connecticut, to more mild temperatures in Indiana and Ohio, to hot climates such as Texas. However, none of them specifically mention the performance of the sealants compared to other regions. The study by Johnson et al. (2000) in Montana did mention that as part of their method of evaluation they characterized the material by using a “coin test” to measure stiffness and resilience changes over time. The test involved pushing a quarter half way into the crack sealant and then measuring how much it recovered in 1 minute; the coin test was only performed when the temperature of the material was above 10ºC (50ºF). In mid-February 2007, the test track at the National Center for Asphalt Technology (NCAT) at Auburn University will be visited to take pictures and receive data on two different types of sealant that were placed there in longitudinal joints of flexible pavements for the Oklahoma DOT. This information will be for a climate that is the most similar to Georgia’s.

Hand et al. (2000) gives a synthesis of the practice of joint and crack sealing which includes a fairly exhaustive literature review on the issue and gives examples of non-supportive and supportive literature. Hand's paper will be supplemented by another paper to include the results of an extensive field study started in 2000 and was originally scheduled to only last 3 years. The paper is interesting because it aims at answering some of the same questions that GDOT has about crack sealing, primarily the following:

1) Does crack sealing improve the service life or serviceability of pavements?
2) If sealing does improve performance, is it cost effective and in what scenarios?

Hand et al. (2000) reviewed over 100 references after searching several databases on the topic and found that only 18 reports specifically addressed cost-effectiveness. This caused the authors to presume that since most of the papers focused on materials and procedures, the general perception in the pavement community is that sealing is cost effective. This was questioned primarily in a paper by Shober (1997) in which the Wisconsin DOT (WDOT) experienced little to no, or in some cases detrimental, effects from joint sealing portland cement concrete (PCC) pavements. WDOT's study resulted in suspending a previously $6 million crack seal program in 1990. This raises the primary questions posed above, but from mounds of other supporting literature and "some controversial and ambiguous research results" there is no justification for any other state to adopt a no-seal policy similar to WDOT (Hand et al. 2000). Finally, the research from WDOT and Shober's (1997) paper focused only on PCC pavements and does not give any conclusive evidence that sealing is not beneficial for flexible pavements, whereas many other papers such as Chong (1988), Ponniah and Kennepohl (1996), Evart and Bennett (1988), Sharaf and Sinha (1986) and Morian et al. (1997) do support crack sealing in asphalt pavements when performed at the proper time as a preventative maintenance treatment.

4.4 Measuring Cracks

Cracks in the pavement can be measured several ways, but many of these methods need improvement and do not currently measure all aspects of the crack that may be useful for treating it properly. Several methods currently being used or developed to measure cracks will be discussed first, and then the proposed idea for future research. The latter will include the future plans in which the research team at the Georgia Institute of Technology will pursue in developing a better, more robust crack measurement procedure. This information will then be integrated into the current pavement management system in order to improve the system by optimizing the time at which pavements are selected for crack sealing and other preventive maintenance treatments.

The primary categories in which cracks can be measured include manual, semiautomatic, and fully automatic methods (Offrell et al. 2005). In a test to compare the methods, Offrell et al. (2005) used traditional video based methods, line scan video, distance-measuring laser cameras, and manual windshield survey by different operators to assess the accuracy and repeatability of each. It is noted that automatic systems cannot generally recognize cracks thinner than 1-2 mm. The test was performed on a two-lane road in Sweden where the majority of cracks were longitudinal, which was considered difficult to measure. The laser had an especially difficult time recognizing vertical cracks because they only measure a single point horizontally and may either miss a longitudinal crack entirely or count a meandering longitudinal crack as multiple transverse cracks. Although single point lasers were used in this study, continuous line lasers are more common today and may be able to provide a better map of the cracked area by surveying the entire lane width along the entire driven route. To provide similar lighting situations for the video images, a strobe light bar was used so that ambient light would not affect the images. Other details can be found in Offrell et al. (2005). The ultimate results of the research project were the following: 1) road markings and texture changes affected the video image results; 2) texture changes that were not cracks also affected laser crack detections; 3) the repeatability of both automatic methods used was high; 4) repeatability of distance-measuring laser cameras was very high but a high number of crack registrations were from texture and not cracks; 5) windshield survey is strenuous on the rater and has low repeatability; and 6) automatic video images provide new possibilities for new crack measures.

Another important aspect of measuring cracks is organizing the various types of raw data such as crack width and length into more useful indicators that trigger some sort of action or provide more information about the cracking that is occurring. One of the goals of this research effort will be to determine what and how many parameters can be effectively measured in order to provide a clear picture of the causes, extent, and treatment of pavement cracking. It is desired to standardize the measurement technique and make it as objective as possible by automating the data collection and data analysis portions. Once the parameters to measure and the techniques to measure them are standardized, then the results can be incorporated into a pavement management system. By using previous data on the effective time to seal cracks and any new information discovered in this study, a threshold value can be determined that links the management system's decision recommendation for treatment to the standardized crack measurements.

During the literature review, one concept that is similar to what the current project proposes to include is the development of a crack type index from video images as proposed by Lee and Kim (2005). According to their paper, Lee and Kim (2005) say that the crack type index (CTI) can objectively determine the crack type as longitudinal, transverse or alligator cracking "with a very high level of accuracy." Their CTI method is based on a spatial distribution of image tiles rather than image pixels, which are analyzed vertically and horizontally and results in a single index. The tile grid reduces complex pixel-based computations and also helps to filter out noise. The description of the index calculations, though simple, is again beyond the scope of this paper and one should see Lee and Kim (2005) for more details. The main point is to apply the same type of concept when analyzing video images of pavement cracking. However, rather than just determining the type of cracking, which can easily be done visually by the manual rater, it is proposed by the current research that other meaningful data can be obtained from the crack images.

Two other papers reviewed that deal with different aspects of this study are "An Algorithm to Pavement Cracking Detection Based on Multi-Scale Space" by Liu and Li (2006) and "Experimental Evaluation of a Pavement Imaging System: Florida

Department of Transportation's Multipurpose Survey Vehicle" by Mraz et al. (2006). Liu and Li (2006) propose an algorithm to help combat the complexity of image processing, which "made the data processing and data analyzing come to the bottle-neck of the whole system" when gathering pavement data automatically. Liu and Li's conclusions were that the main advantages of the proposed method are accurate tiny crack detection even in noisy images and more efficient and accurate results. This research hopes to further improve algorithm methods of image processing. The other paper by Mraz et al. (2006) looks at testing the accuracy and repeatability of measuring pavement distresses at high speeds (moving in a vehicle) using a line scan camera. The paper notes that "to date there is a lack of standards regarding the accuracy and precision of imaging systems and guidelines for achieving optimum conditions for collecting reliable and accurate data" (Mraz et al. 2006). Conclusions from the paper are that results showed vehicle speed did not significantly affect the amount of noise in pavement images or the ability to recognize cracks accurately and artificial lighting systems may introduce significant noise under conditions in which natural light is sufficient. Mraz et al. (2006) concludes by saying that "the frontier of imaging technology lies in the development of software that can be used to accurately classify and quantify pavement distress on a real-time basis" and that is precisely what part of this research is trying to do.

4.4.1 Future Crack Growth Measurement

Since this study will focus on automatic detection methods using video or still camera images, it is agreed with Offrell et al. (2005) that new possibilities presented by automatic methods could eventually provide more suitable crack measures. Some of the parameters to be measured include but are not limited to the following suggested by Offrell e al. (2005):

1) Crack length
2) Accumulated crack extent either longitudinally or transverse
3) Position of the crack within the image or in the plane of the pavement lane
4) Direction
5) Shape of cracks

6) Percentage of cracked area

Other parameters not listed in the Offrell et al. (2005) paper that may be either critical or insightful to measure also include but are not limited to:

1) Crack width
2) Number of single-line cracks that connect to other cracks (another measure of extent)
3) Depth of cracks

Obviously some of these parameters will be more useful than others, and some measurements may not be able to be taken with a high level of accuracy or precision. Therefore, the measurements that will be the most repeatable, provide the best accuracy, and give some information about when to apply crack sealing will be targeted in the data collection. This will have to be determined partly by trial and error and partly by past experience from the field. It is worth mentioning here that the idea is not to make the problem as complex as possible but rather as quick and efficient as possible in order to make the information practical and useful.

From this point, the immediate next steps will be to set up one or more small scale lab experiments to try to accelerate crack propagation in a test pavement. From this lab experience, the objective will be to determine exactly what parameters from above or others that will be useful to measure in the field. Once the parameters are determined the computer science members of the research team will assist in creating algorithms to process digital photo and video images of the cracks to record the data.

4.5 Study of Crack Sealing on Georgia's Pavements

The following is a summary of GDOT crack sealing/filling site visit and the preliminary assessment of Georgia's crack sealing performance using COPACES data. There is a common consensus that crack sealing and crack filling are cost-effective and should continue to be used by the GDOT on Georgia's road network. However, there is no quantitative study on its effectiveness, or on the best application timing/condition along with the corresponding cost-effectiveness. There is a need to perform a full-scale research project to identify the cost-effectiveness of applying crack sealing/filling at different timings. This will enable GDOT to identify the optimum time to apply the most efficient material in order to prolong pavement life at the cheapest cost to the agency.

GDOT has been performing crack sealing and crack filling operations for several years now and it is encouraged to keep performing this practice as the majority of the literature suggests that preventive maintenance in the form of crack sealing does increase pavement life and also is cost-effective. This is especially true for asphalt cement concrete (ACC) pavements; there is more debate whether joint sealing for Portland cement concrete (PCC) pavements is cost-effective. The referenced special problem report above talks more about GDOT's current practices, which vary slightly by district, and consist mainly of "hot pour" rubberized asphalt material crack sealing operations and "cold pour" asphalt emulsion crack filling techniques. The literature suggests that hot pour techniques perform better than cold pour, and GDOT also prefers the hot pour technique as well. One advantage the cold pour asphalt emulsion treatment has over the hot pour rubberized material is its ability to seep in and fill much smaller cracks due to its much lower viscosity, and this may be a consideration if the optimum time to apply such treatments is pinpointed to a much smaller crack size than what the hot pour sealant can effectively be placed in. The following first look summarizes the crack sealing/filling site visit.

4.5.1 GDOT Crack Sealing/Crack Filling Site Visit

On 13 March 2007, Georgia Tech Research Team met with Terry Rutledge from the Georgia Department of Transportation (GDOT) to visit two crack sealing operations in north Georgia. The first operation visited was considered by GDOT to be crack filling and consisted of a liquefied asphalt emulsion, and the second site was considered to be crack sealing and consisted of a rubberized material that is melted and then spread over the cracks. Several questions and answers about the crack sealing operations and summarized below.

1) How are crack sealing projects selected? Basically the routes that are considered for crack sealing/filling are flagged by two questions in COPACES when the

pavement is rated. First, are the cracks greater than 1/4 of an inch? Second, if cracks have been sealed previously, is the sealant in good working condition or degraded severely? If the answer is yes to the first question, then it is a candidate for crack sealing. Terry said that cracks are rarely resealed in later years but indicated that this can and has been done. There is no set PCI or other trigger value to perform sealing other than the crack width. In the field, the raters generally use a separate criterion to determine if the crack is wide enough for the rubberized material to seal effectively; if the width of a quarter (coin) can fit into the crack then the rubberized material can be used. Terry mentioned that the liquid emulsion can get into smaller cracks and so this is somewhat subjective as to what pavements with cracks less than the width of a quarter (coin) get sealed.

2) Have the raters noticed good outcomes so far for the pavements that have been crack sealed? The answer was yes but GDOT wants to know how much benefit it is providing based on their costs. One negative comment that can be mentioned here is that in areas where the liquid emulsion is used occasionally citizens complain saying that it is visually unpleasing to have the dark crack seal lines amplified. Tracking (especially with the liquid emulsion) contributes to "the mess" as well as complaints from the emulsion splattering up onto vehicles. This can be minimized by not over-applying the emulsion, allowing maximum drying time before opening to traffic, and making sure that preventive measures such as applying sawdust over the top get applied sufficiently. In the liquid emulsion site visited, tracking appeared to be a problem and more saw dust could have been applied evenly. However, one section performed the day before appeared to have very little tracking compared to sections on either side of it; this offers some confusion of the exact conditions which produce more severe tracking. In every case though, the entire crack sealed section is opened to traffic in the evening of the same day when the workers go home for the night.

3) Does GDOT seal the pavements already in "bad" condition? The answer is that this is very seldom done. As a general rule, if the pavement has Severity Level 2 load cracking then crack sealing is not applied because it requires too much sealant (too expensive per lane mile), and the excessive sealant is a safety hazard

by lowering the skid resistance too much. Exceptions to this occur and a site was cited that had fairly severe block cracking and was scheduled for resurfacing but kept getting bumped. Crack sealing was applied late in the life of this pavement and has helped provide **5 years** onto the life until the resurfacing can eventually happen (hopefully very soon). A picture of this site is shown below, and it should be noted that the cracking is block cracking and therefore there is enough spacing in between the cracks to maintain skid resistance.

4) GDOT considers crack sealing to be physically effective but is unsure on the cost-effectiveness. Crack sealing is done by GDOT maintenance crews throughout the winter months when cracks are at their widest, and one of the foremen at the liquid emulsion site commented that they make an effort in their region to crack seal 100% of the roads in their part of the network every year that are considered candidates.
5) Drainage characteristics of a site are noted, but a poor drainage condition does not necessarily influence whether or not the pavement gets crack sealed. Other maintenance operations such as ditching are sometimes done in conjunction with operations such as crack sealing.
6) GDOT almost unanimously agrees that the rubberized material/operation is better and more effective, but there are no hard facts to back up this philosophy.

It is believed that if crack sealing/filling is performed at the right time, on the right distress, with the right construction, and the right material, it can prolong pavements as much as 5 years.

Site 1: Liquid Asphalt Emulsion

The first site visited was the liquid emulsion operation. Before actually observing the operation, we stopped and looked at some sealant/filler that was applied the previous day. The following photo shows that the procedure seemed to leave several cracks unsealed.

This can be attributed to poor workmanship and/or the emulsion sinking further into the crack and not enough being applied to seal the surface. Most of the cracks at this site were not wide enough to fit a quarter into, and therefore one advantage of the liquid is that it can get into tighter spaces and fill smaller cracks. One disadvantage of the less viscous material is that there is little control over where it flows even after placement. If there is a slight slope, the material is susceptible to running and not drying over the crack. The typical crew size for this operation is 8-10 people and consists of a driver pulling an air compressor in the front, two people blowing out or cleaning the cracks with the air compressor, a driver pulling the boiler with the emulsion, two people operating the wands that fill the cracks with the emulsion, a driver/operator for the sawdust spreader, two traffic control people, a foreman, and site superintendent. This operation is more complex in terms of the people and pieces of equipment required. Photos of the emulsion being applied are shown below (not shown are the air compressor in front and the spreader behind). The last photo is the final result after the sawdust is applied to try to help prevent tracking which occurred in the opposite lane after the previous day's operation in the left middle photo.

The operation can fill/seal approximately 2-3 lane miles per day. The emulsion in the boiler must be heated to about 150º F and variation in this temperature can have significant effects on the performance of the sealant. The COPACES report for this site is found in the Appendix but it had an overall PCI rating of 77 compared to 80 the previous year mostly due to Severity Level 1 load and block cracking. Even though this is not GDOT's preferred, it is "better than nothing" per Terry and will continue to be used to get the useful life out of the equipment that has already been purchased.

Site 2: Rubberized Asphalt Crack Sealing Material

This operation displayed the procedure that GDOT prefers for crack sealing. The primary machine or boiler costs $1.5k more ($32k versus $30.5k) than then the boiler for the liquid emulsion and the material is also more expensive, but GDOT still believes its performance is worth the extra cost. This operation seemed to be less cumbersome compared to Site 1 on the whole, but one immediate disadvantage is that this machine must heat up to about 450º F which can take 1-2 hours. Also, blocks of rubber equal to 3 gallons of product when melted, must be continually added throughout the operation. If these blocks are added too late, they may not have sufficient time to melt before extruding from the hose. This can cause clogging or insufficient spreading over the crack, therefore creating a raised bump that can be annoying the driver. One other disadvantage if the sealer is applied to thick is the susceptibility to pull-out from vehicles or snowplows. All of the crew is basically focused around the machine and truck which requires a minimum of three people to operate. The other crew members line up behind the personnel with the wand(s) and an interchange in operator is made every 10 minutes or so. This helps contribute to better quality work because there are frequent breaks and fresh eyes sealing the cracks. This procedure is also less “messy” because the material hardens to a very tacky material only minutes after it is applied and results in virtually no tracking when opened up to traffic. The machine can operate with two wands but the operation on this day only used one wand because the load cracking was primarily isolated to one wheel path. It is difficult to see in the photos, but the wand differs from the other machine in that it has a circular disc at the bottom to help spread the more viscous material and the wand arms in this machine are heated to help prevent the material from hardening in the lines. The maximum output is also roughly 2 lane miles per day. Following are some photos of this operation.

This particular site had a PCI rating drop from 95 to 79 in only one year and GDOT is trying to figure out why the site had such a severe drop in quality in such a short period of time. It is also worth noting that this site is a road right off an I-75 Interstate exit. See the COPACES reports in the Appendix for more details.

Final Comments

GDOT has not experimented with any other materials or procedures than the ones presented here and a more detailed description of the practices from the HMMS database can also be found in the appendix. In general, the operations seemed to be running smooth and efficiently, and GDOT believes that their crack sealing operations are contributing to extending pavement life.

4.5.2 Analyzing Current Crack Sealing Data

For the past few years, GDOT has been recording crack sealing maintenance activities in the Highway Maintenance and Management System (HMMS) database, but this data lacks a lot of distinguishing information that would allow proper assessment of the data. However, one of the next steps that will be taken is to select several projects that have been crack sealed recently and compare the Computerized Pavement Condition Evaluation System (COPACES) pavement condition ratings of these roads to other routes or segments nearby in similar starting condition before crack sealing. The COPACES ratings by project or segment have been plotted for all the selected routes in order to compare the deterioration trends between the sealed and unsealed pavements.

One of the main challenges of this specific task is the lack of historical data. GDOT has only been recording the application of crack sealants for a few years and, which may not have been enough time for the condition ratings to show a definitive trend. Also, the data does not distinguish whether the hot pour or cold pour technique was used, so there is no way to directly compare the two methods. However, this will give a starting point for identifying the initial hypothesis for how effective crack sealing is when the large-scale test project is performed. One critical aspect that will be compared in this initial look at the existing data is the difference in projects in the northern and southern parts of the state. Below the Fall Line (southern Georgia), the soils are typically more sandy in nature as the geology approaches the coastal plain whereas above the Fall Line the soils in Piedmont and Blue Ridge geologic formations tend to contain larger amounts of fines (more silty to clayey soils) due to significant weathering of the parent rock. Figure 4.2 below shows the distinction between these primary geologic regions.

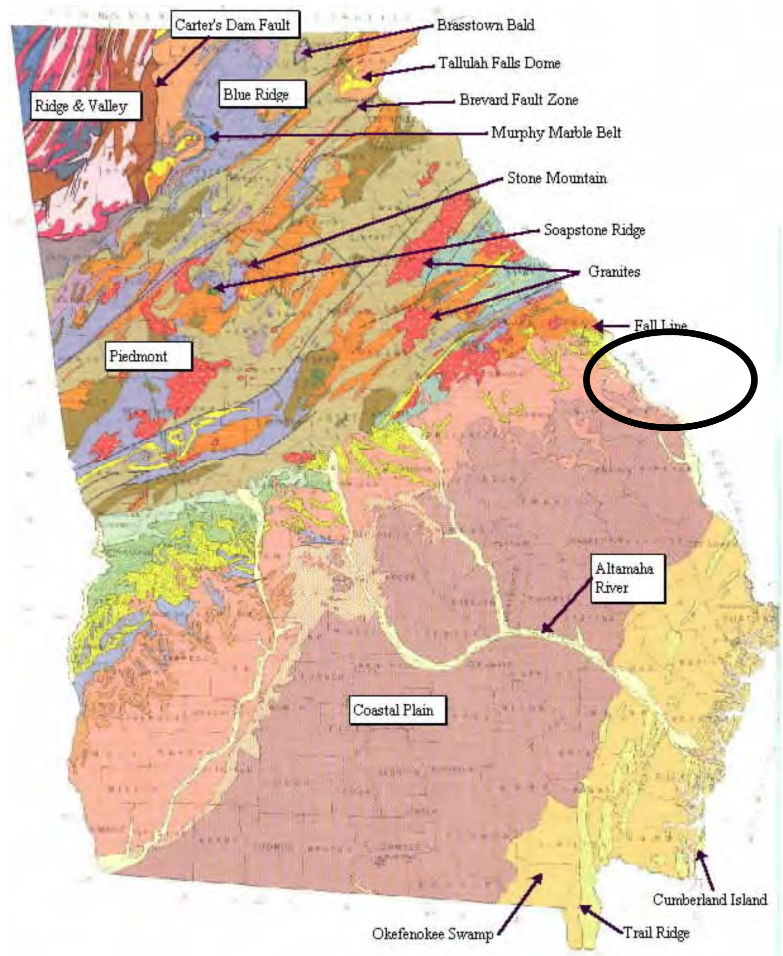


Figure 4.2 Georgia Geologic survey, 1977 (after David Lawton; Chuck and Rachel Cochran – http://home.att.net/~cochrans/geomap01.htm)

It is assumed that an overall trend will be observed in that the pavements that have been crack sealed will have outperformed their counterparts without the crack sealing treatment. However, due to the limited data, low number of years with data, and lack of specifics about the existing crack sealing data, it is presumed that the trend and improvement will be difficult to quantify. After analyzing approximately 200 crack sealing projects from the years 2000 to 2004, samples of the rating trends and comments on the sections are listed below.

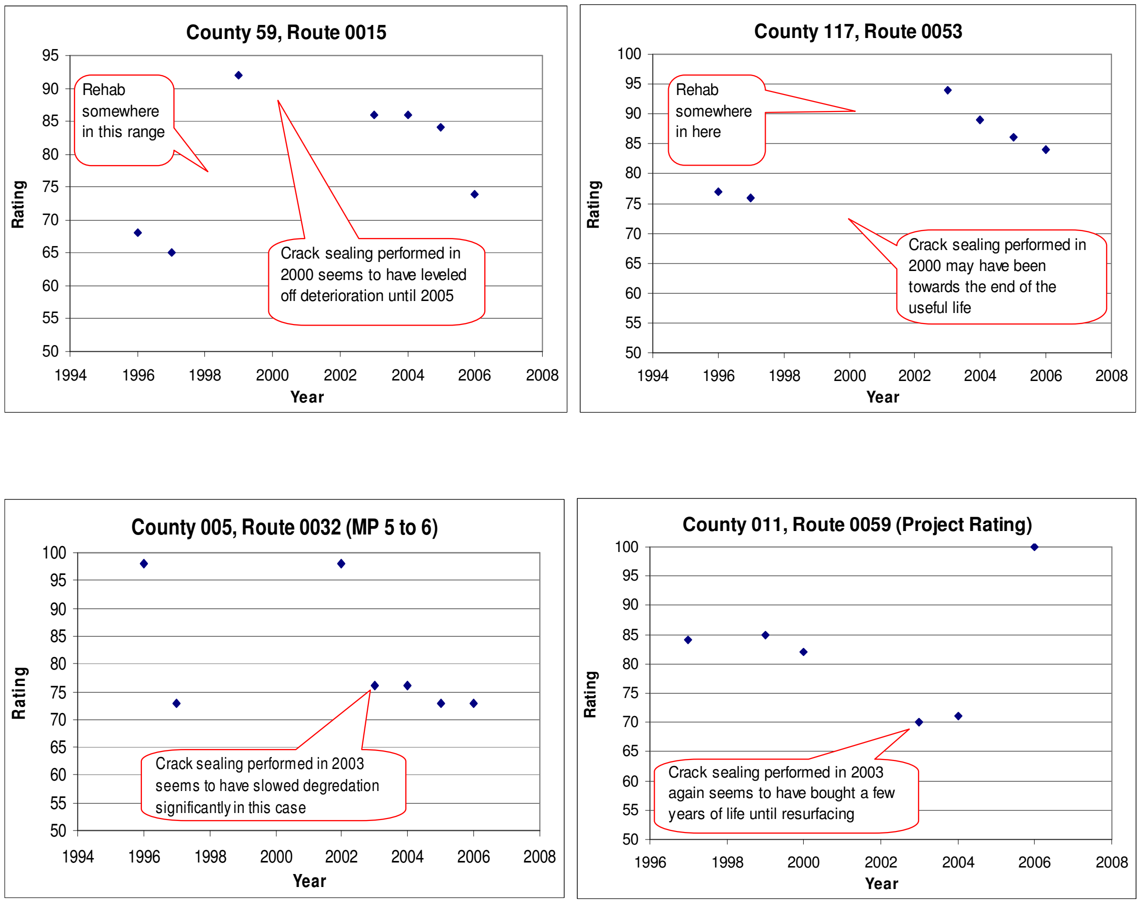


Figure 4.3 Examples of Condition Rating Trends

As shown in Figure 4.3, some data are missing and ratings are fluctuating. Thus, it is very difficult to objectively quantify the crack sealing performance. The following are some of the reasons causing the missing data and fluctuating ratings:

1) Missing data because no COPACES survey was performed. No detailed PACES ratings were recorded before 2004 for projects that were scheduled to be let the next year. (Note, the project may not actually have been let for several years due to budget constraints and there is no data available for these years.)
2) Rating fluctuation due to changing sample location. The 100-ft sample location at each segment (about 1 mile) varies yearly and it is difficult to compare the distresses at exact the same location.
3) Rating fluctuation due to different raters. Subjective and visual inspection was performed. Therefore, it is difficult to obtain a consistent measurement.

4) Rating variation due to COPACES deduct computation. There are micro level inconsistencies in the COPACES ratings (this means that it is possible for a more severe distress condition to actually have a higher project rating due to the way deduct values are applied—see example below). The following example shows the fluctuated rating trend caused by the PACES computation.

   *Take for example a pavement that only experiences **Load Cracking (LC) distresses**. In a certain year of the evaluation which we will call **Year 1**, the severity level (SL) and extent of the distresses are as follows: **20% SL 1, and 60% SL 2**. In **Year 2** the distress has become more severe and 20% of the SL 2 has now moved to SL 3 leaving **20% SL 1, 40% SL 2, and 20% SL 3**. The deduct values are calculated next from the charts or by plugging into the COPACES software.*

   Year 1 Deducts: SL 1 (20%) = **8** and SL 2 (60%) = **48** by extrapolation (chart only goes
   up to a deduct of **30** at 45% extent)

   Year 2 Deducts: SL 1 (20%) = **8,** SL 2 (40%) = **26**, and SL 3 (20%) = **28**

   Per Chapter 4, "Calculating Project Rating", from the PACES manual it says that for load cracking "only the largest load cracking deduct value is used." This means that for **Year 1 the value would be 48 (or 30) and for Year 2 it would be 28**. Now calculating the project rating by subtracting the deduct values from 100 gives **PCI = 52 (or 70) for Year 1 whereas PCI = 72 for Year 2**. Regardless of whether a rating of 52 or 70 is used for Year 1, the rating of 72 for Year 2 is higher than both even though the condition in Year 2 is worse.

Due to the reasons listed above, the average project rating may "cover up" localized distresses in various segments of an overall project rating and make it difficult to directly compare the benefits of portions of the road that have been crack sealed. Therefore, these inconsistencies unveil the need for a large-scale test project to be conducted in order to systematically compare various crack sealing parameters under field conditions such as, soil type, climate, sealant materials, various application times, construction practices, and others.

Also, a more accurate measurement technique is needed to objectively quantify all the pavement distresses instead of relying on subjective human opinions that actually rate only less than 2% (100 ft out 1 mile) of the total length of pavement assessed. There is a need to develop new technologies, such as computer vision analysis of pavement distress images. Computer image analysis offers the ability to quickly assess a large amount of data in the form of pavement images (video or still images) in order to quantify the severity and extent of different distress types with improved accuracy.

4.6 Summary

The following items summarize the findings in this chapter.

1) Based on the intensive literature review on crack sealing, it has shown:
    a. Crack sealing is used on working cracks, and crack filling is used for nonworking cracks or when cracks are closely spaced. CALTRANS criteria for a working crack is >6mm (1/4 in) of horizontal movement annually (CALTRANS 2003). Working cracks can be either horizontal or transverse, but most often are transverse. Crack filing is less expensive than crack sealing.
    b. Except for WDOT having negative comments on applying crack sealing on PCC, there are no negative comments on applying crack sealing to asphalt pavements.
    c. Based on Canada's study, it was shown that pavement life can be extended by at least 2 years depending on the initial condition, environment, and traffic volume (Chong 1989; Ponniah and Kennepohl 1996). Eltahan et al. (1999) showed that crack sealing can cause pavements to last 2.5 years longer in state of Texas. If drainage is not sufficient, crack sealing may be detrimental by trapping the water inside the structure. In addition,

ineffective construction procedures and materials can lead to poor performance. Research has shown that filling or sealing pavement cracks properly can prevent water from entering the base and subbase will extend the pavement life by 3 to 5 years (PennDOT LTAP 2007). Ponniah and Kennepohl (1996) report at least a 2-year pavement life extension from crack sealing, and Michigan DOT reports that crack sealing can provide up to a 3-year life extension (Bausano et al. 2004). The CALTRANS even reports that crack sealing/filling can provide up to 8-9 years of service life based on research from the US Department of Transportation (Smith and Romine 1999b).

d. A big variation of crack sealing performance as shown above is attributed to different sealant materials, construction practices, types of crack, timing of construction, temperature, and drainage conditions. There is a need for GDOT to perform an experimental study to evaluate the factors and practices that can result in the highest cracking sealing/filling performance based on Georgia's local roadway and temperature conditions.

2) Based on our crack sealing/filling site visit, the following findings are made.

v. Two sealant materials are used by GDOT. One is crack filling and consisted of a liquefied asphalt emulsion, and the other is considered to be crack sealing and consisted of a rubberized material that is melted and then spread over the cracks.

vi. In general, the operations seemed to be running smoothly and efficiently. GDOT engineers agree that the rubberized material/operation is better and more effective, but there are no hard facts to back up this conjecture.

vii. If the crack sealing/filling is performed at the right time, on the right distress, with the right construction, and the right material, it is believed the pavement life can be extended for 5 years. However, there is no hard data to back this up.

viii. The GDOT general office believes that the most cost-effective timing to perform crack sealing is when the COPACES rating is between 75 and 85. However, due to the funding shortfall, the district offices often prioritize crack sealing/filling for projects with COPACES ratings of 70 or below. Crack sealing/filling the worst pavements may be less cost-effective than treating the pavements with a rating between 75 and 85.

ix. A large-scale crack sealing/filling experimental test can be designed and performed to evaluate the cost effective timing to apply crack sealing/filling. This test will substantially benefit GDOT because it is the most inexpensive and popular pavement preservation method used by GDOT.

3) Based on the preliminary study of quantifying crack sealing performance using COPACES data, the following findings are made:
    a. Missing and fluctuating PACES rating data make it difficult to scientifically and quantitatively measure crack sealing performance. Reasons for missing and fluctuating data may come from the following situations: i) No COPACES survey was performed, ii) The sample location was changed, iii) Different raters were used, and iv) COPACES deduct computations created inconsistencies.
    b. An objective measurement method, such as using laser and vision technologies, is recommended to better quantify the crack sealing performance.
4) Based on the analysis performed in this chapter, the following suggestions are made for future study:
5) To design and implement a state-wide crack sealing performance experimental study. This study will help GDOT to determine the optimal timing, crack type, material, construction procedures, and regions to perform crack sealing/filling that will result in the highest benefit/cost ratio. The suggested research can also lead to the development of a practical GDOT optimal crack sealing/filling guideline.
    a. To develop an objective crack growth measurement technique. The existing subjective measurement technique may not be able to objectively quantify the performance of crack sealing. Therefore, there is a need to

develop the technologies such as computer vision or laser technologies to scientifically and objectively measure cracks.

5 Utilization of Segment-level COPACES Data to Improve Pavement Preservation

5.1 Needs for Using Segment-Level COPACES Data

In GDOT, the annual pavement condition survey is performed on each mile of its 18,000-centerline mile state highway, based on which the project-based pavement preservation can be programmed according to the pre-defined treatment criteria. Each project consists of several segments, each of which is typically one mile except for the beginning and ending segments. A project rating (COPACES rating) is calculated by deducting the aggregated distresses of all rated segments in it from 100. To this point, segment-level data is only used for the project rating calculation. However, segment-level COPACES data is apparently finer than a project-level data. Can it be directly utilized to improve the current pavement preservation? The following will identify the needs for GDOT to use the segment-level COPACES data.

- **Need 1**: Segment-level COPACES data reveals more detailed local pavement condition than project-level data. Can it perform better in analyzing pavement performance? In GDOT, a composite rating, the average length weighted project ratings, is used to indicate the overall pavement network performance. If segment-level data is used to compute the composite rating, how big the difference is it? These questions can be answered by analyzing the historical project-level and segment-level COPACES data, which will be performed in Section 5.2.
- **Need 2**: Pavement preservation is programmed at project level. A uniform project, in which all the segments have uniform segment ratings and distress conditions, is needed to make the treatment cost-effective. In some cases, it is needed for the engineer to re-define the project termini due to the condition variation among all segments in a project. The processing of project termini re-definition needs the combination of the existing segment-level COPACES data. Two functions have been developed in the program of COPACES to address this need. Further information can be found in Section 5.4.

- **Need 3**: Local pavement defect and treatment cannot be reliably identified by means of the project rating. In some cases, project rating may not meet the treatment criteria, but some segments in it need to be treated. This kind of localized pavement preservation need can only be determined by investigating the COPACES ratings and distress values of the individual roadway segments. Section 5.5 introduces the developed functions to address this need.
- **Need 4**: In the Pre-construction Division, the programmed projects often have the different project termini comparing with the ones defined in the COPACES database. As a part of project evaluation, it is required to investigate the historical pavement performance of the programmed project. Due the changed project termini, the original projects in the COPACES database need to be split or combined to form a new project with the customized project termini. **Need 2** can be considered as a basic operation in **Need 4** because it needs to be performed each year to form the history of the customized project. Section 5.6 gives the detailed information in addressing this need.
- **Need 5**: In evaluating a roadway condition, engineers often need to visualize the sequential segment ratings along a selected route section. Unlike a pre-defined project in the COPACES database, the selected route section may cross into different counties. This function needs to access the segment-level COPACES data and is further introduced in Section 5.7.

5.2 Comparison of COPACES Data: Project-Level vs. Segment-Level

In COPACES, a project rating is calculated by deducting the aggregated pavement distresses of all segments in it from 100. Ideally, all segments in a project should be uniform, i.e. in the same conditions. If so, the project rating should be the same as the segment rating. However, the conditions of the segments in a project vary in the real case.

- **Single Project Comparison**

Figure 5.1 shows the historical trend on ratings for a randomly selected project that consists of three segments. The variance among these three segments is obvious. The trend for the project ratings is much smoother than the segment ratings. According to PACES, some of the major pavement distresses such as load cracking, block cracking and reflection cracking are rated on a 100ft sample location for a segment. The selection of the sample location may vary among different raters and different visits. In addition, the understanding of the distress type and severity may also vary. These subjective factors bring in the variation of segment ratings. Statistically, project rating is more reliable provided that the conditions of all segments in a project are almost homogeneous. From Figure 5.1, it can be seen that the project rating is not same as the average of all segment ratings. The biggest difference (6^{th} year and 10^{th} year) is around 4 points.

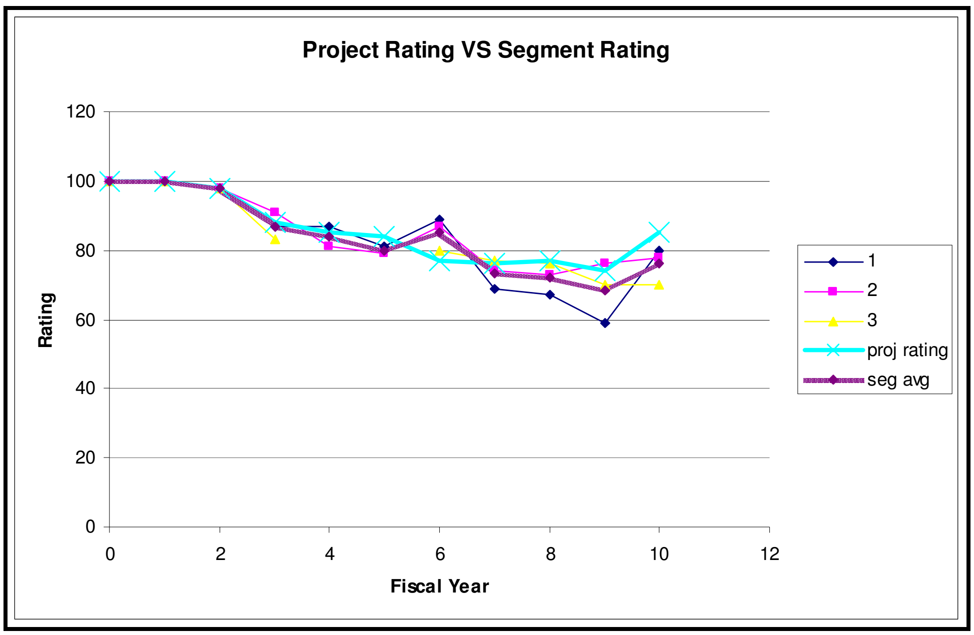


Figure 5.1 Comparison of Historical Trend: A Three Segment Project

From the above simple case, the segment-level COPACES data includes more subjective variations and may not be better than project-level data in predicting pavement performance. However, if the conditions of the segments in a project vary dramatically, the project rating may hide the actual pavement characteristics. Thus, as a preliminary conclusion, the project-level data with uniform segment conditions should be more reliable in modeling pavement performance.

▪ Network-level Comparison

Figure 5.2, Figure 5.3 and Figure 5.4 shown below illustrate the rating histories of High Quality projects with 11 years of service life. These projects were obtained from the work in Chapter 2 of this report. Figure 5.2 shows each project history and the average rating history of the projects. Figure 5.3 shows the history of each segment and the average rating history of the segments. Figure 5.4 compares the average of rating histories of the projects and segments. From Figure 5.2 and Figure 5.3, the variance of project ratings and segment ratings is obvious. Otherwise, the comparison in Figure 5.4 shows that the rating averages of project-level and segment-level data over 11 years of ratings are very close. Thus, at the network-level (this is a small network), the average ratings calculated from project-level and segment-level COPACES shows very good agreement.

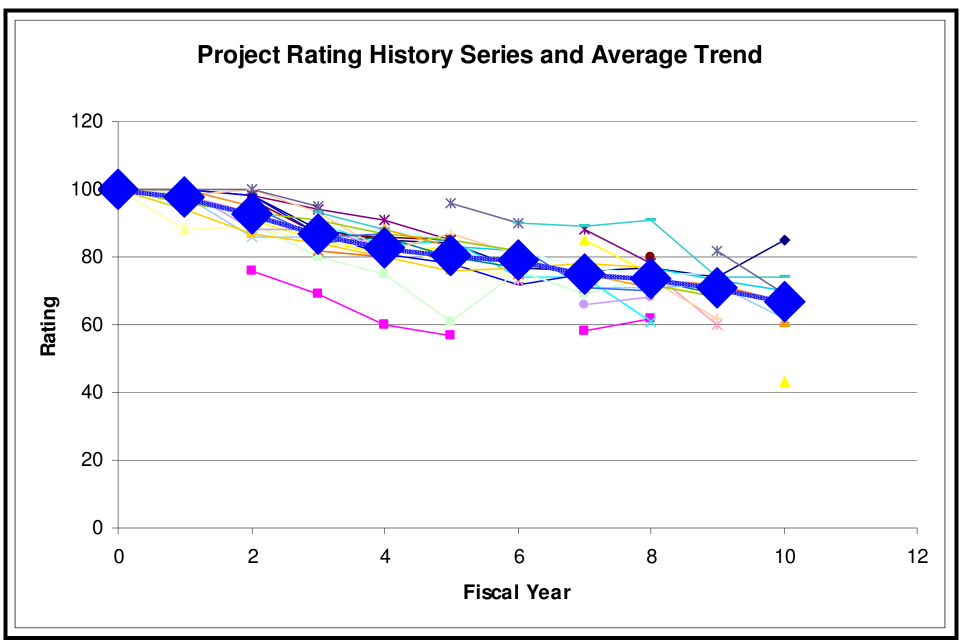


Figure 5.2 Project Rating History for High Quality Projects

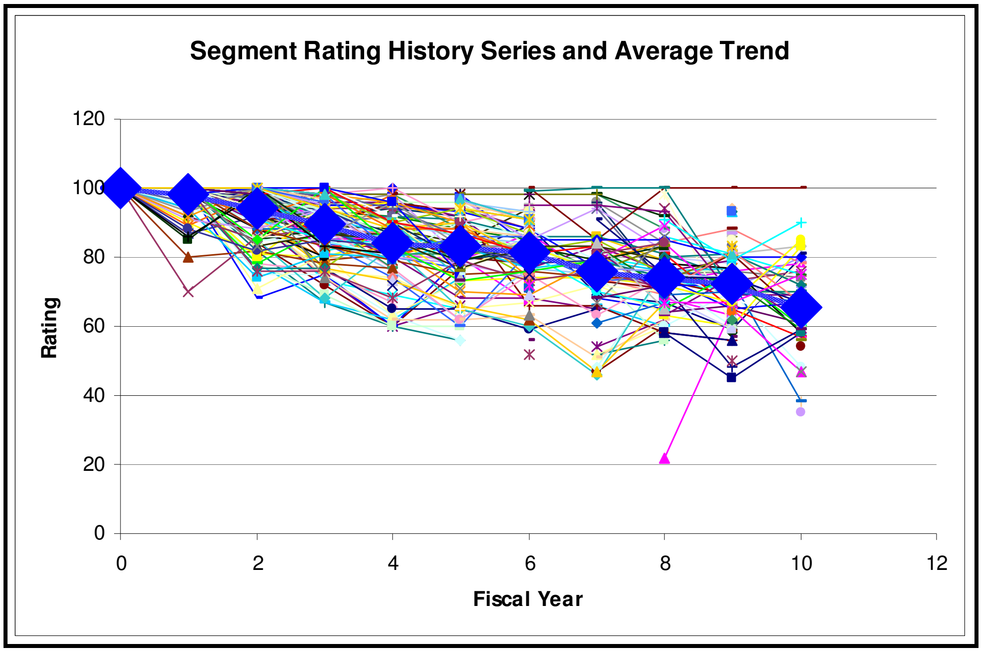


Figure 5.3 Segment Rating History for High Quality Projects

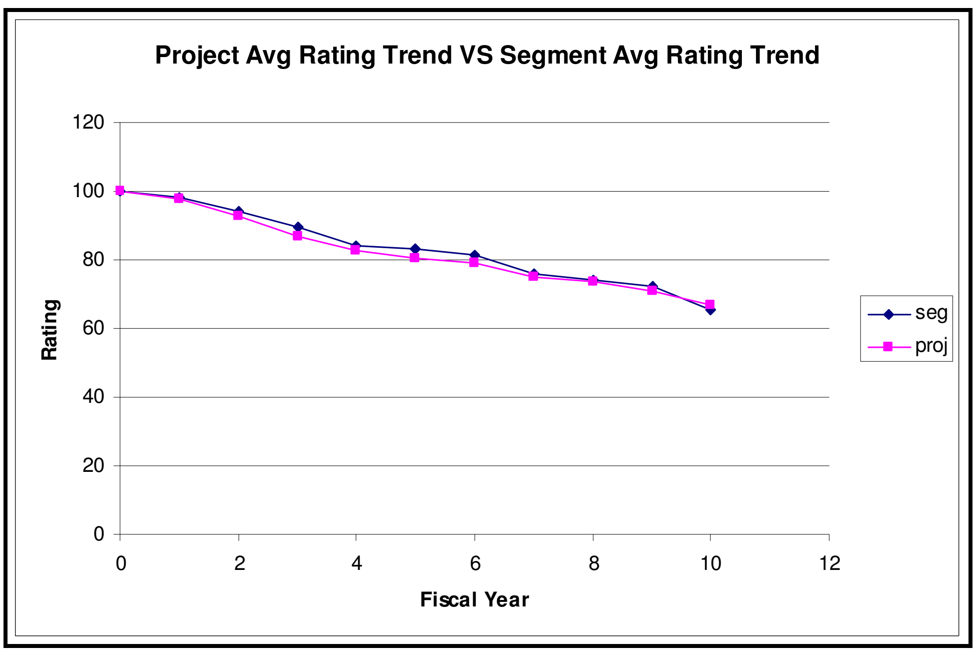


Figure 5.4 Comparison of Average Rating for Project-Level and Segment-Level Data

The following study will focus on a large-scale network. For this purpose, approximately 3,100 projects and 19,000 segments are selected from the COPACES database for FY 2006 and 2007. Note that only the Area Office (AO) data are included in the analysis.

Table 5.1 summarizes the comparison result. The average rating is calculated in two ways: 1) the mean, i.e. the sum of all ratings divided by total number of projects or segments; 2) the length weighted average, which is the sum of the product of rating and the corresponding project or segment length divided by the total length. In GDOT, the composite rating is a length weighted average of all project ratings, which is used to be a performance indicator of a pavement network. The results show that the average ratings calculated by using the two methods are essentially identical for projects and segments respectively. In addition, the difference between project-level and segment-level COPACES data is also very small. In FY 2006, the difference of average ratings at project-level and segment-level is less than 0.5 point. In FY 2007, it is less than 0.2 point.

Table 5.1 Comparison of Average Project and Segment Rating for FY 2006 and 2007 COPACES Data

Fiscal Year	No. of Projects	No. of Segments	Ave. Project Rating by Number	Ave. Project Rating by Length	Ave. Segment Rating by Number	Ave. Segment Rating by Length
2006	3060	18917	85.49	85.38	84.99	84.99
2007	3101	18966	84.94	84.90	84.74	84.75

The almost identical result from the two calculation methods can also be confirmed by Figure 5.5 and Figure 5.6, which are the project-level rating distributions using the number based and length based methods. The two curves in FY 2006 and 2007 show very good agreement. In result, the overall average should be very close.

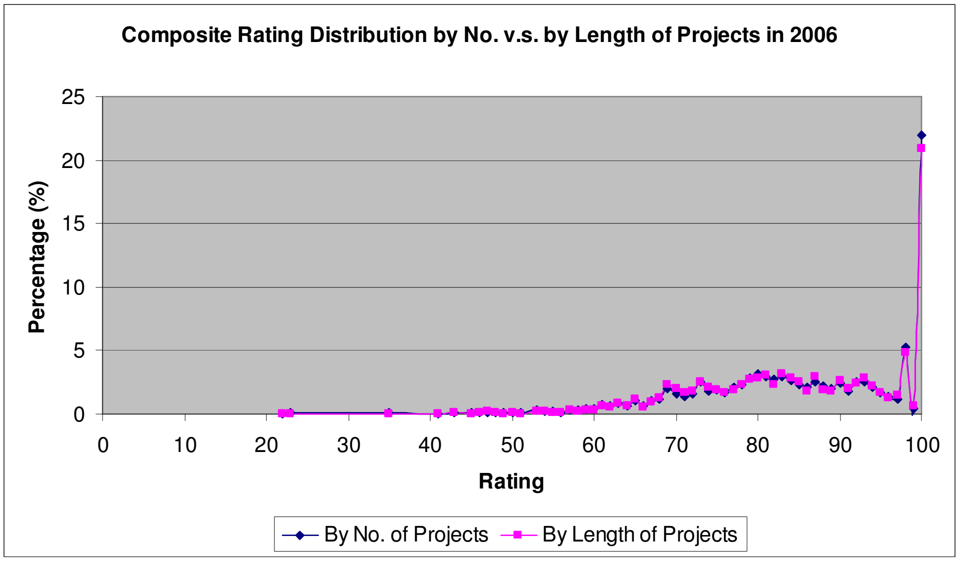


Figure 5.5 COPACES Rating Distribution for Projects in FY 2006

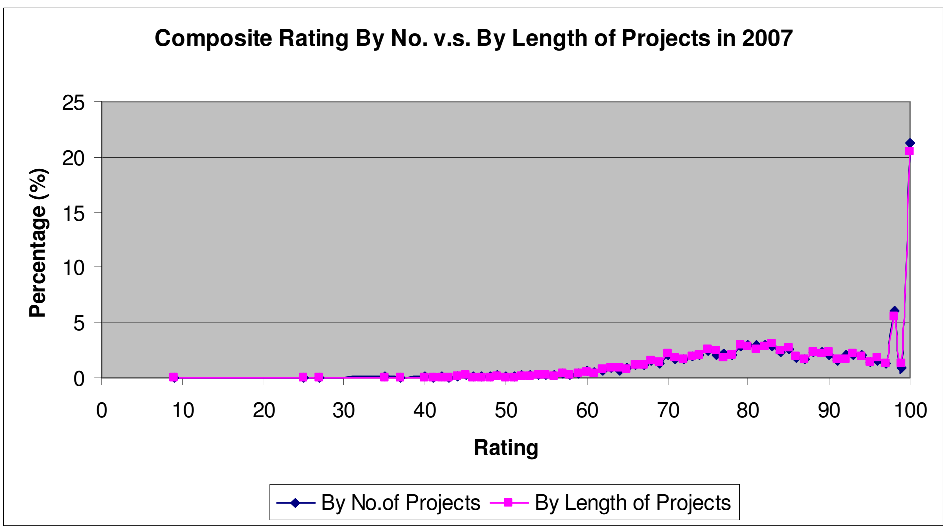


Figure 5.6 COPACES Rating Distribution for Projects in FY 2007

Figure 5.7 and Figure 5.8 further compare the difference of rating distributions between project-level and segment-level COPACES data. The two figures show that the pavement rating is concentrated between 50 and 100. Apparently, the segment-based rating distribution demonstrates larger oscillation; while the trend of both data source is almost identical. That's way the average ratings show good agreement as seen in Table 5.1.

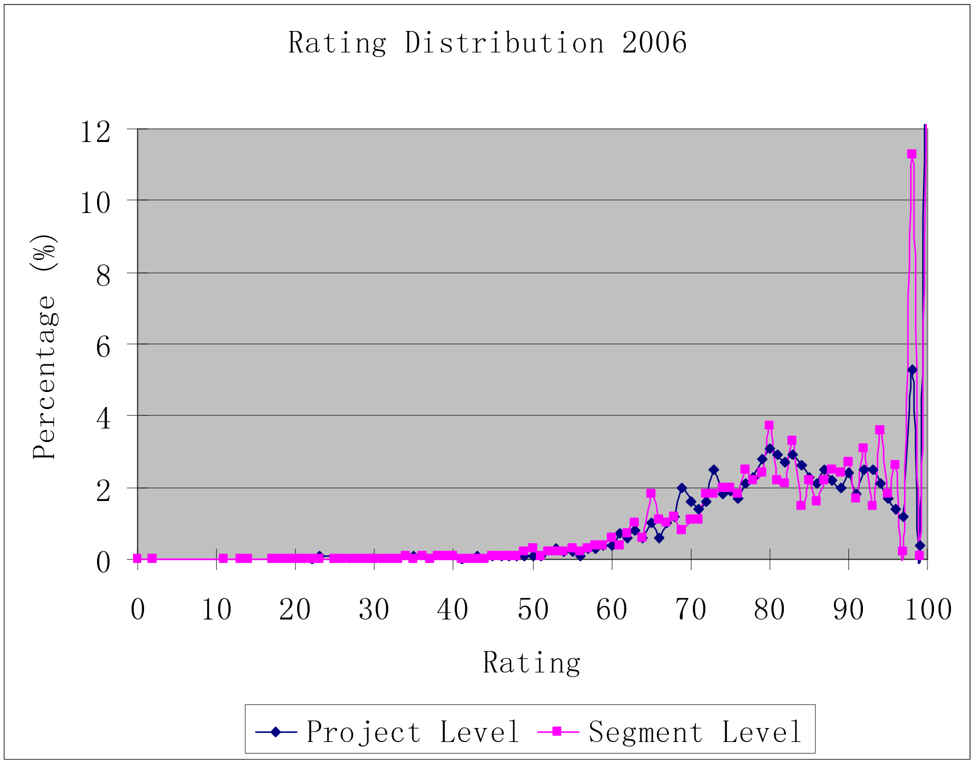


Figure 5.7 COPACES Rating Distribution for FY 2006

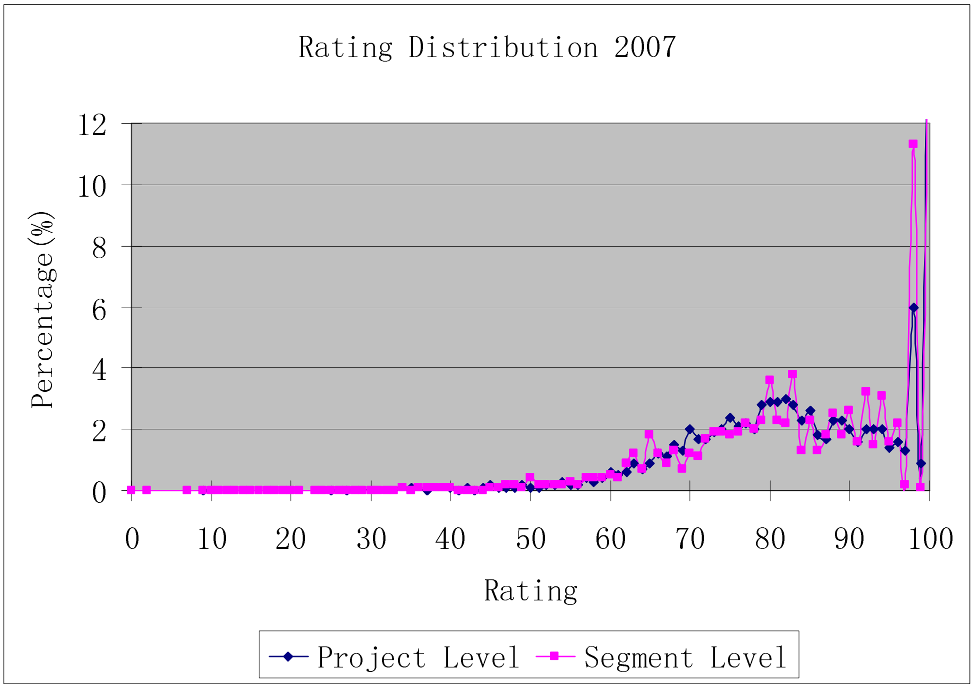


Figure 5.8 COPACES Rating Distribution for FY 2007

5.3 Challenges for using Segment-Level COPACES Data

Need 2, **4** and **5** introduced above requires the operations of splitting a project or combining several projects and re-calculating the project rating in terms of the corresponding segment-level COPACES data. The basic procedure is to query out all segments within the pre-defined spatial limits, and then combine them to a new project and re-calculate the project rating. In doing this, there exist several cases that need to be addressed, including overlapped data, missing data, and duplicate data. These cases are presented individually as following.

- **Segments that Partially Overlap with User Specified Project Termini**

Figure 5.9 illustrates the case that the New Project starting from 2.6 and the existing segment 2-4 is partially overlapped. Because a segment is the basic unit for pavement condition survey and there is no way to divide an existing segment into two parts. When the New Project is constructed, the segment 2-4 can be treated in two ways: 1) incorporate the segment 2-4 in the New Project, then the New Project starts from 2 instead of 2.6; 2) exclude segment 2-4 in the New Project, then the New Project starts from 4 instead of 2.6.

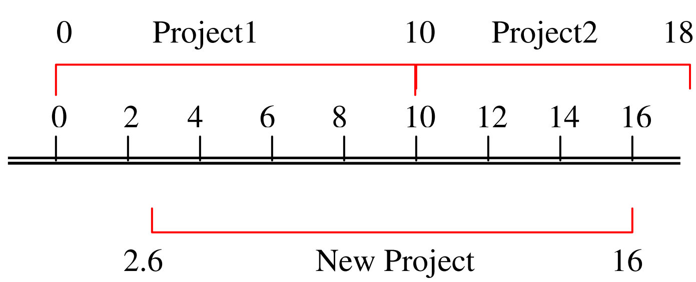


Figure 5.9 Project Overlapping Segment Data

Systematically, the rules can be described and extended as follows:

1) **Incorporate the segment only if it is fully within the user specified project limit**. Under this rule, the segment 2-4 in Figure 5.9 is not in the New Project.

2) **Incorporate the segment as long as it intersects with the user specified project limit**. Under this rule, the segment 2-4 is in the New Project because it intersects with the New Project.
3) **Incorporate the segment when the overlap is greater than a certain percentage (e.g. 50%)**. If 50% is used as the threshold, the segment 2-4 is in the New Project because the overlapping percentage is 70%.

In our development, Rule 1 was adopted.

- **Duplicate Segment Records**

In some cases, there is more than one survey on the same segment. In order to get a rational project rating, we need to confirm the rule for selecting segments when there are duplicates. Two methods are proposed as follows:

1) **Use the latest surveyed segments**. If there is more than one segment record in the same fiscal year, on the same location and from the same office, only the latest survey record will be used.
2) **Use the average of duplicate records**. If there is more than one segment record in the same fiscal year, on the same location and from the same office, use the average values of all those survey records.

In our development, the first method was adopted.

- **Missing Segment Records**

Figure 5.10 shows a case that some segment records are missed in re-constructing the history of a project with customized project termini. The customized project termini are between milepost 2 and 16. Two existing projects cover these milepost ranges. The first project is defined from milepost 0 to milepost 8 and has historical rating data from FY 1990 to FY 2005. The second project is defined from milepost 10 to 18 and does not have historical rating data in FY 2000 and FY 2003. Thus, the computation needs to consider the cases of the missed segment data.

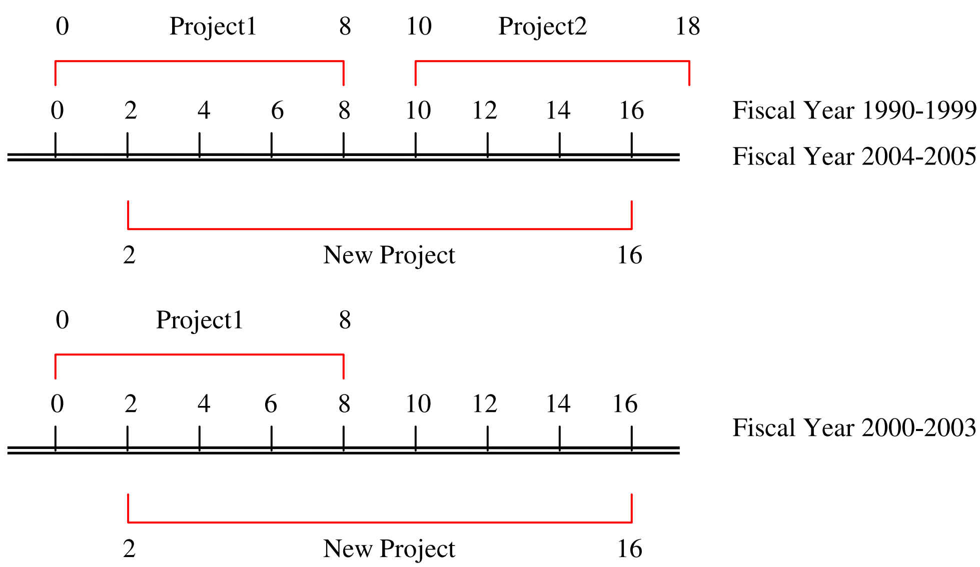


Figure 5.10 Missing Segment Data in Re-constructing Project

In order to handle the missing data, the methodology applied is to set the minimum requirement for rating computation. The total surveyed segments have to be greater than the pre-set percentage (e.g. 50%) of the user-specified project length in order to compute the rating. Otherwise, no rating will be calculated. This application implies that the missing segments have no effect on the project rating.

5.4 Re-definition of Project Termini

Each year, GDOT performs the COPACES evaluation survey on the state-wide roadway system. Based on the survey results, the pavement conditions of each project and each segment are made available, as shown in Figure 5.11. GDOT is currently using project-level pavement condition data only (e.g. 2,748 projects for FY 2005) to evaluate the pavement performance and to make the final treatment decisions. However, it is recognized that the pavement conditions of different segments within the same project may differ significantly. Therefore, when making decisions on treatment and maintenance, it would not be cost-effective to treat those segments with different conditions in the same way and at the same time by clustering all of those segments into the same project for letting by GDOT. Consequently, to cost-effectively utilize the limited funds, the existing projects may need to be re-defined by the re-clustering of segments where this re-clustering is based on a more localized assessment of condition. (See Figure 5.12)

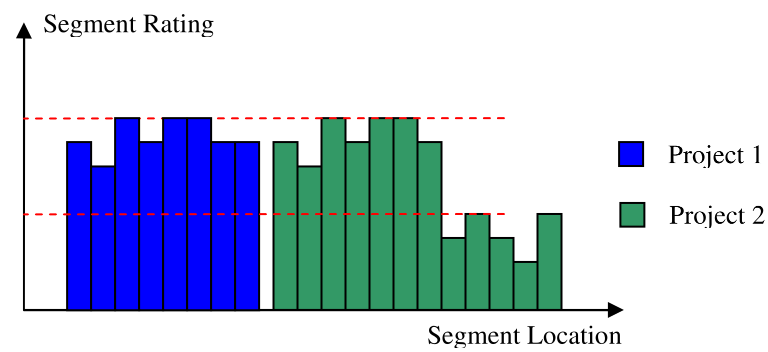


Figure 5.11 Segment Ratings of Two Adjacent Projects

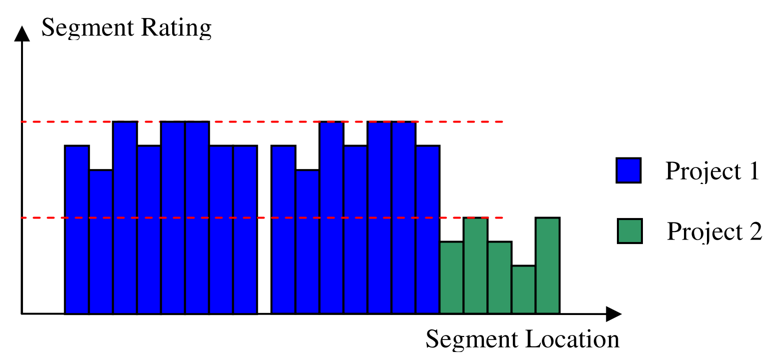


Figure 5.12 Re-definition of Project Termini

Apparently, two operations are needed in order to re-define the project termini: 1) split a project (Project 2 in Figure 5.11); 2) combine two projects (Project 1 and part of Project 2 in Figure 5.12). These two operations have been developed as two functions in the program of COPACES. The user's manual can be found in Appendix X. The following briefly introduce these two functions.

1) **Split Project Termini**: This function allows the users to split a particular project into two projects and determine the project rating of these two projects. It also allows the user to submit the new projects to the database, thus making them the

permanent projects in the system. This application also deletes the old project that was split once the Submit Changes step is executed.

2) **Merge Project Termini**: This function allows users to merge two projects into a new project, to determine the project rating of the new project and to submit the new project permanently into the system.

The general procedure to use this function is depicted in Figure 5.13. A more detailed examination of the process is explained in the section that follows.

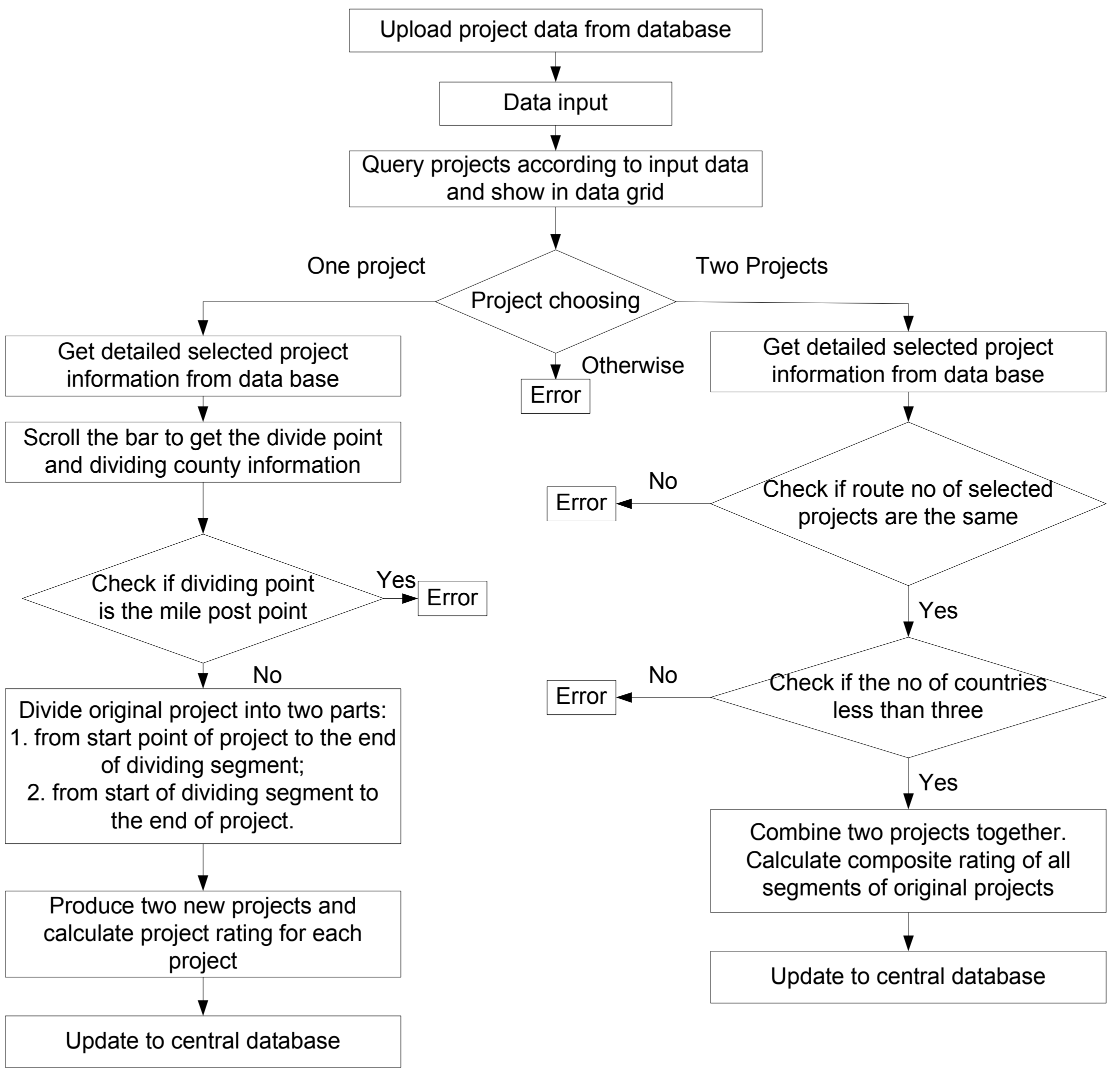


Figure 5.13 General Procedure of Changing Project Termini

5.5 Localized Treatment Determination

GDOT is currently using the project-level pavement condition data to evaluate the pavement performance and to make final treatment decisions. However, project-level COPACES data cannot be used to determine the localized pavement treatment need. In Figure 5.14, the project rating is above 70; while two segments in it are apparently lower than 70 and need treatment. A function was developed in the ProjectSelection to automatically identify the segments that need treatments. The user's manual can be found in the Appendix XI.

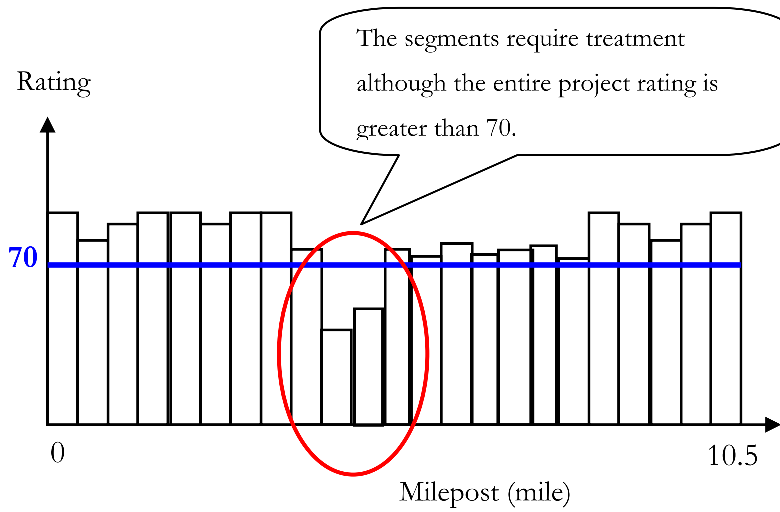


Figure 5.14 Segments Require Localized Treatment

Figure 5.15 illustrates the query form used for defining the searching criteria. Except for location information, users can specify the range of project rating and the difference between segment rating and project rating. The query result will list all projects satisfying the searching criteria and the suggested treatments.

With a selected project, the function provides a chart to display the project rating and the segment ratings (see Figure 5.16). Users can easily find the locations of segments that need treatments from this chart.

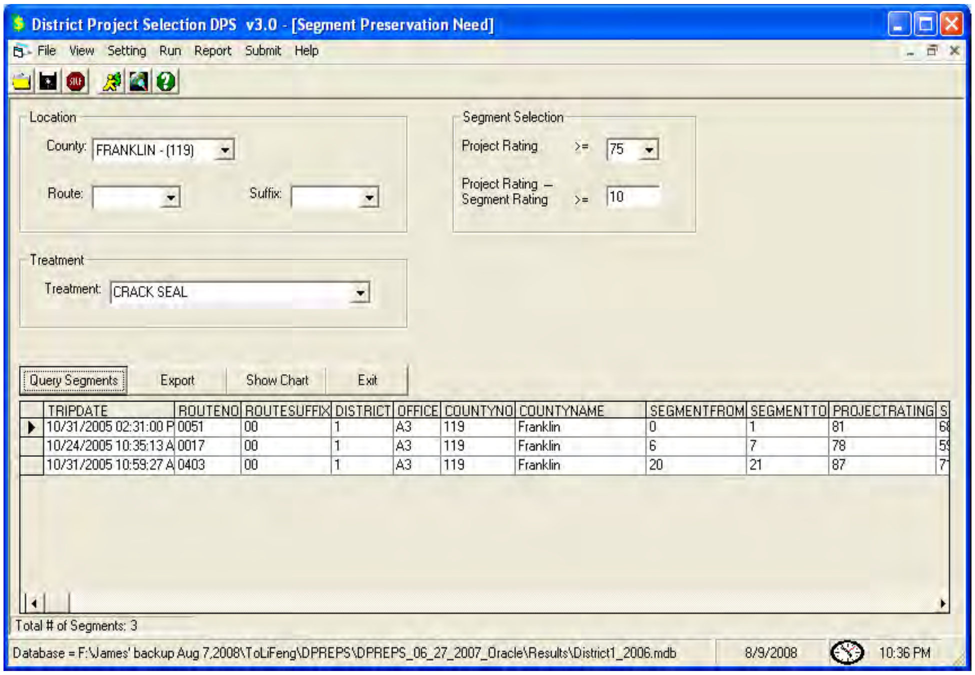


Figure 5.15 Query Localized Preservation Need

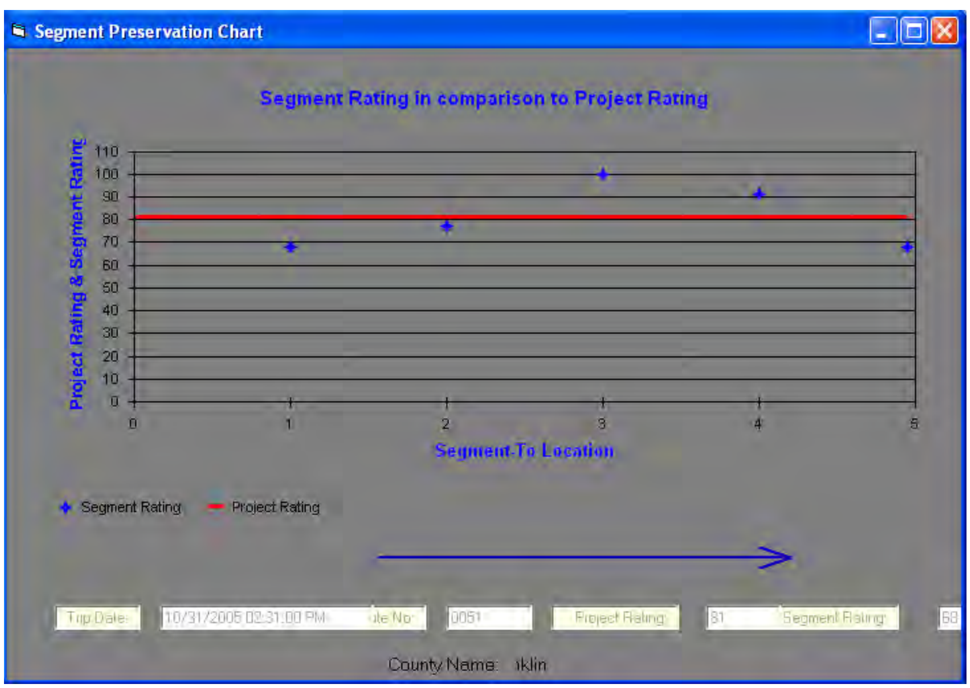


Figure 5.16 Segment Ratings vs. Project Rating

5.6 Re-construction of Historical Pavement Conditions with Customized Project Termini

In the Pre-construction Division, the programmed projects often have the different project termini comparing with the ones defined in the COPACES database. As a part of project evaluation, it is required to investigate the historical pavement performance of the programmed project. For this purpose, the new project with the customized project termini needs to be formed each year using the existing segment-level COPACES data. And, the new project ratings need to be re-calculated. A function to address this need has been implemented in the Network Module. The user's manual can be found in Appendix XII. The following will briefly introduce the procedures.

Step 1: Define the customized project termini. As shown in Figure 5.17, the new project can be part of the existing project or the combination of several existing projects.

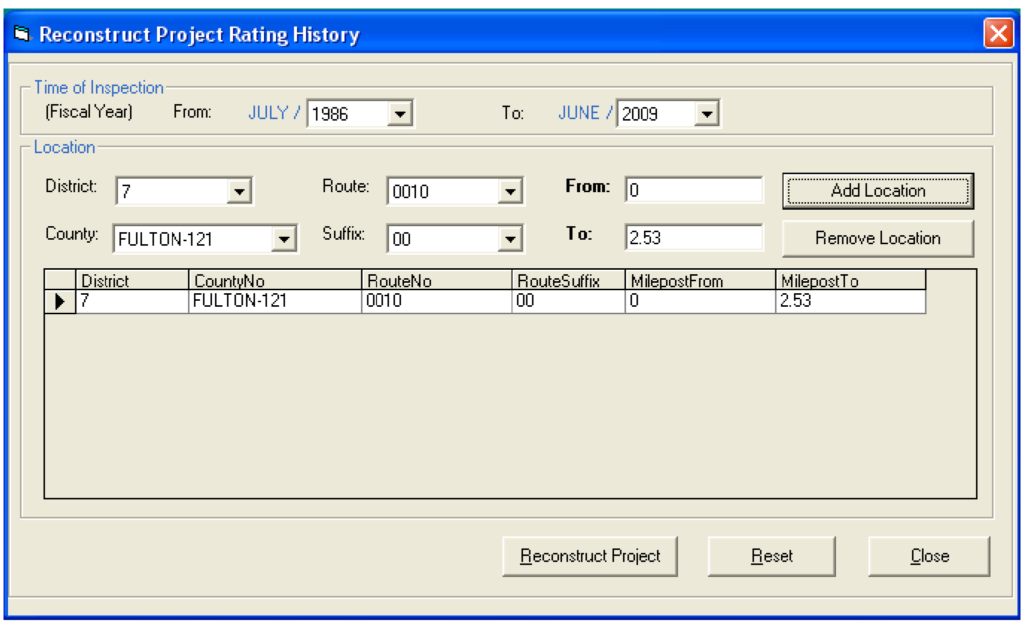


Figure 5.17 Define Customized Project Termini

Step 2: Based on defined project termini, all segments are queried out. And they are ordered by fiscal year and office.

Step 3: The segment records belonging to the same fiscal year and office are grouped and the project rating of each segment group is calculated, as described in Figure 5.18. Also, as can be seen in the Figure 5.18, the operation is required to loop on all segments. If the current segment record belongs to the same fiscal year and survey office with previous segment, it is going to be assigned into the same segment group as the previous one. Then, move to the next segment record and continue the loop.

If the current segment record does not belong to the same fiscal year and survey office as the previous segment, the end of this segment group is reached and the group project rating is calculated. After the end of one segment group, a new empty segment group is started.

Step 3: Finally, all new project ratings form the historical pavement conditions.

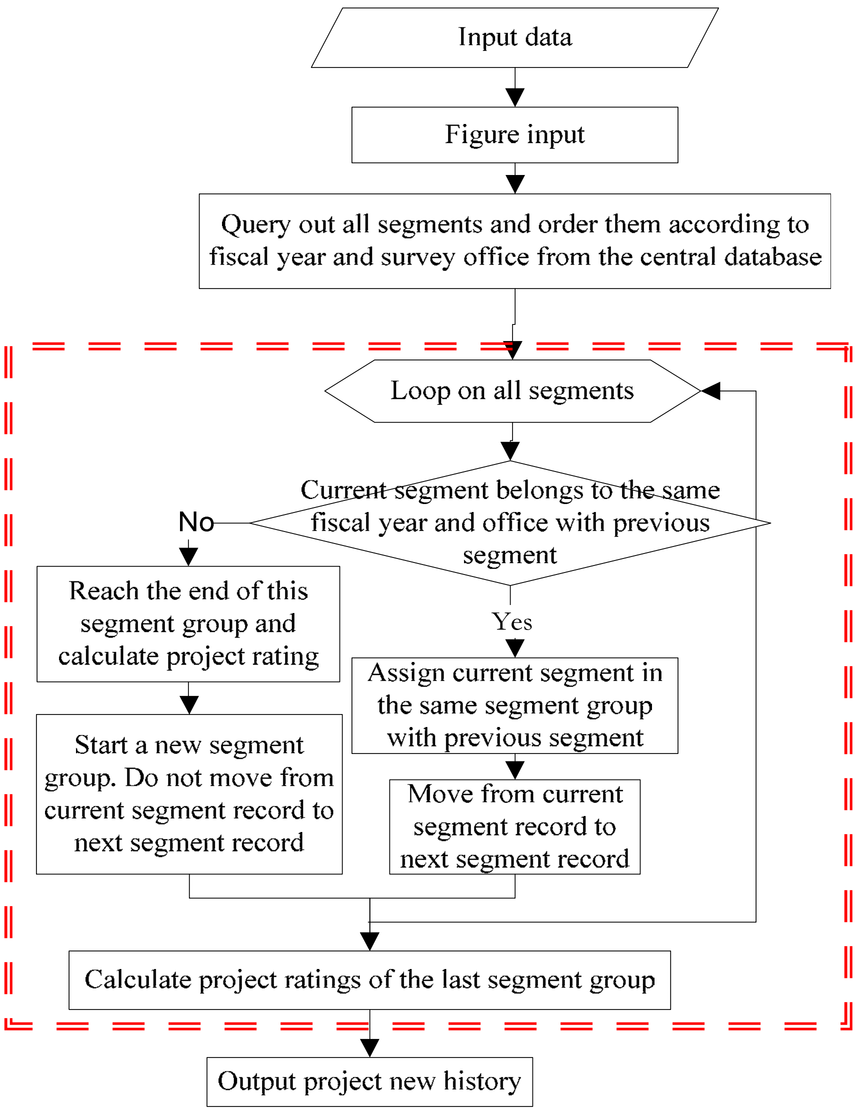


Figure 5.18 General Procedure of Reconstructing Historical PACES Rating

5.7 Visualization of Sequential Segment Ratings on Selected Route Section

In evaluating a roadway condition, engineers often need to visualize the sequential segment ratings along a selected route section. Unlike a pre-defined project in the COPACES database, the selected route section may cross into different counties. A function has been developed in the Network Module to address this need. The user's manual can be found in Appendix XIII.

The challenge in implementing this function is to sort the segments in a spatial sequence crossing several counties. In addition, the issues with duplicate segment data and segments on a divided highway have to be dealt with.

Figure 5.19 shows the general procedures to visualize the segment ratings on a selected route section.

Step 1: Input Data. Required inputs are route no., route suffix, county from and county to, inspection fiscal year and route direction.
Step 2: Check Input. After the initial data is input, an input data check is performed. It is required that route no. and route suffix should both be set; the inspection fiscal year should be input as well. The route direction is default as undivided positive.
Step 3: Query County Sequence along the Route. Query the county sequence along the route according to route no. and route suffix from the preset "RTE_SEG_SEQUENCE3" table. This table is obtained from the HMMS database provided by the Office of Information Technology.
Step 4: Loop on All Counties. First, query out all segments of each county on the route and order them by segment from and segment to. Then, according to the county sequences on the route section, assign a global segment (a milepost from and a milepost to) to each route segment in order to identify their relative locations.
Step 5: Output. Output and result and show the segment rating along this route.

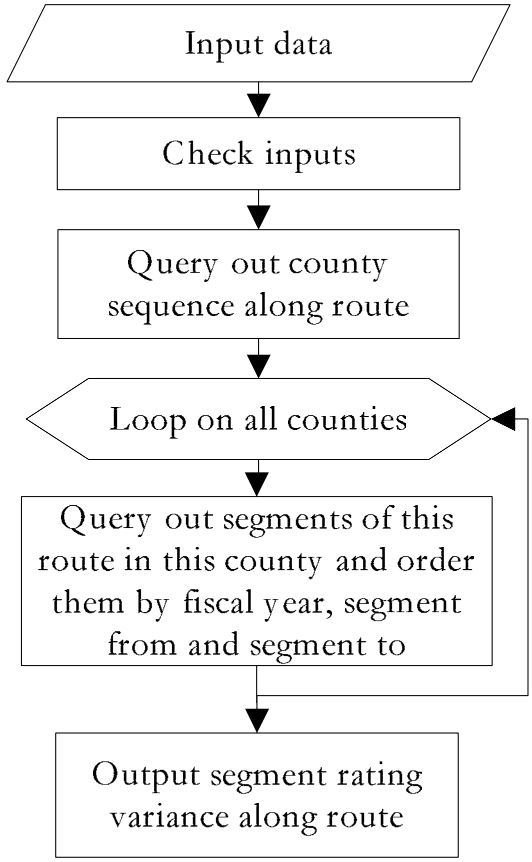


Figure 5.19 General Procedure of Visualizing Segment Rating on a Selected Route

5.8 Summary

This chapter focuses on the utilization of segment-level COPACES data in improving GDOT's pavement preservation. The needs for using segment-level data have been identified: 1) Evaluate the utilization of segment-level COPACES data in describing the historical pavement performance and the pavement network performance; 2) Re-define the project termini to achieve a uniform pavement condition, and thus to improve the cost-effectiveness of pavement preservation; 3) Determine the localized pavement preservation need; 4) Re-construct the historical pavement conditions with customized project termini; 5) Visualize the sequential segment rating on a selected route section.

Through the comparison of using project-level and segment-level COPACES data, the following conclusions can be drawn: 1) The historical segment ratings show large variation than the project ratings. If the pavement conditions are uniform, project-level

COPACES data is more reliable to be used for pavement performance prediction. 2) The two methods for composite rating computation, the mean value and the length weighted average, produce almost similar results. These two methods are exchangeable for computing network composite rating. 3) In the meantime, the results by using project-level COPACES data and segment-level data also show very good agreement.

Four functions were developed to address the Need 2, 3, 4 and 5. 1) The function to re-define the project termini was implemented in the program of COPACES, which can be used by engineers to define a project with uniform condition. 2) The function to determine the localized pavement preservation need was implemented in the ProjectSelection Module. 3) A function was developed in the Network Module to re-construct the historical pavement conditions with customized project termini. 4) Another function to visualize the sequential segment ratings on a selected route section was also developed in the Network Module. All these four functions are useful to further improve the pavement preservation.

6 Utilization of Pavement Life Study for Improving Pavement Design and Preservation

6.1 Objective

In Chapter 2, the asphalt pavement performance in Georgia has been analyzed based on the historical COPACES data from FY 1986 to FY 2008. In this Chapter, the function to generate the historical pavement performance curves along with the traffic data including AADT and percent of truck (Truck%) is introduced. By using this function, further pavement performance analyses can be performed when new data is available over time. In addition, based on the work in Chapter 2, the pavement performance curves were categorized as High, Median and Low quality according to the developed evaluation criteria, which are also useful for pavement design and preservation. To facilitate engineers to search and display these pavement performance curves, a standalone program was developed.

Pavement performance is influenced by many factors including pavement design, construction, materials, maintenance, weather, and traffic load. Traffic load is a very important factor because it is the direct cause of pavement damage. In the meantime, heavy vehicles contribute to most of pavement surface distress and structural capacity failure. Figure 6.1 is an illustration of the historical PACES rating of a project along with the AADT and Truck%, from which the pavement life of this project can be identified as well as the relationship with the traffic load.

The pavement life information is useful to evaluate the overall pavement performance, and the corresponding design and management quality of pavement. It also helps to analyze the factors influencing pavement life. In order to obtain the pavement life of each project in the roadway network, a standalone program was developed, from which user can query projects based on different criteria. It provides a convenient tool to display the pavement historical information of a specific project, as well as for the selected groups (e.g. each district). For example, for a project, user can obtain the project rating, pavement life information, and detailed project location information in each fiscal year; for a group of projects, user can also obtain the statistical data (i.e. max, min, mean pavement life) and the distribution for the selected spatial area, as shown in Figure 6.2.

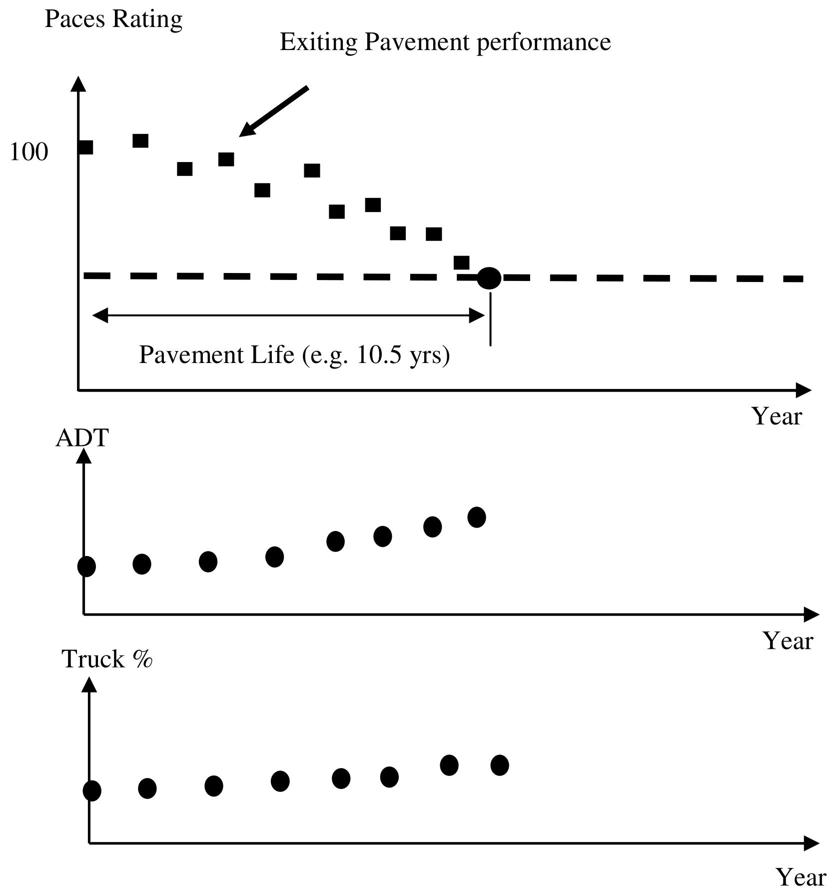


Figure 6.1 Historical Project Rating and the Corresponding AADT and Truck%

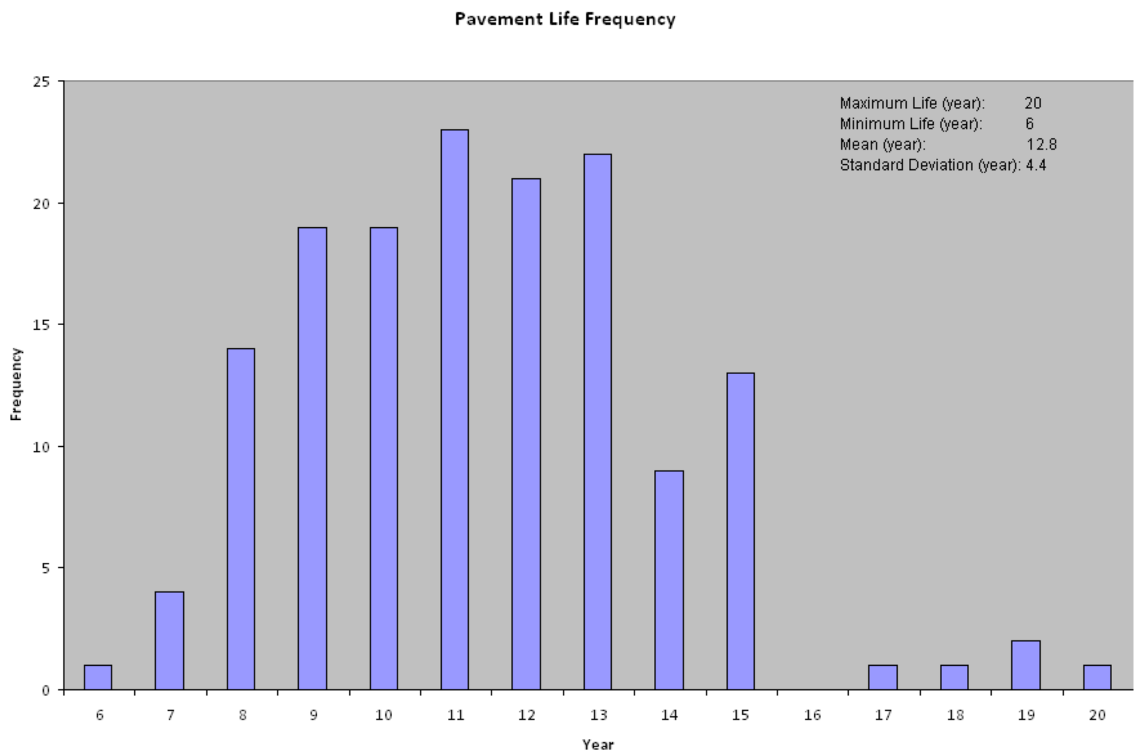


Figure 6.2 Pavement Life Distribution and Statistical Information

6.2 Methodology

The pavement life study can be described as three steps. The first step is plotting pavement historical performance curve with traffic data. The second step is generating pavement life from pavement performance curve. The third step is pavement lives query and management.

Step 1: Plotting the pavement historical performance curve with traffic data. Pavement historical performance curve is generated for individual project. Based on spatial criteria selection, pavement historical data including pavement rating, AADT, and percent of truck in each fiscal year are downloaded from the central database. Then, three charts are generated separately for each project to show project rating, AADT, and percent of truck in each fiscal year respectively. An example of such curve is shown in Figure 6.3.

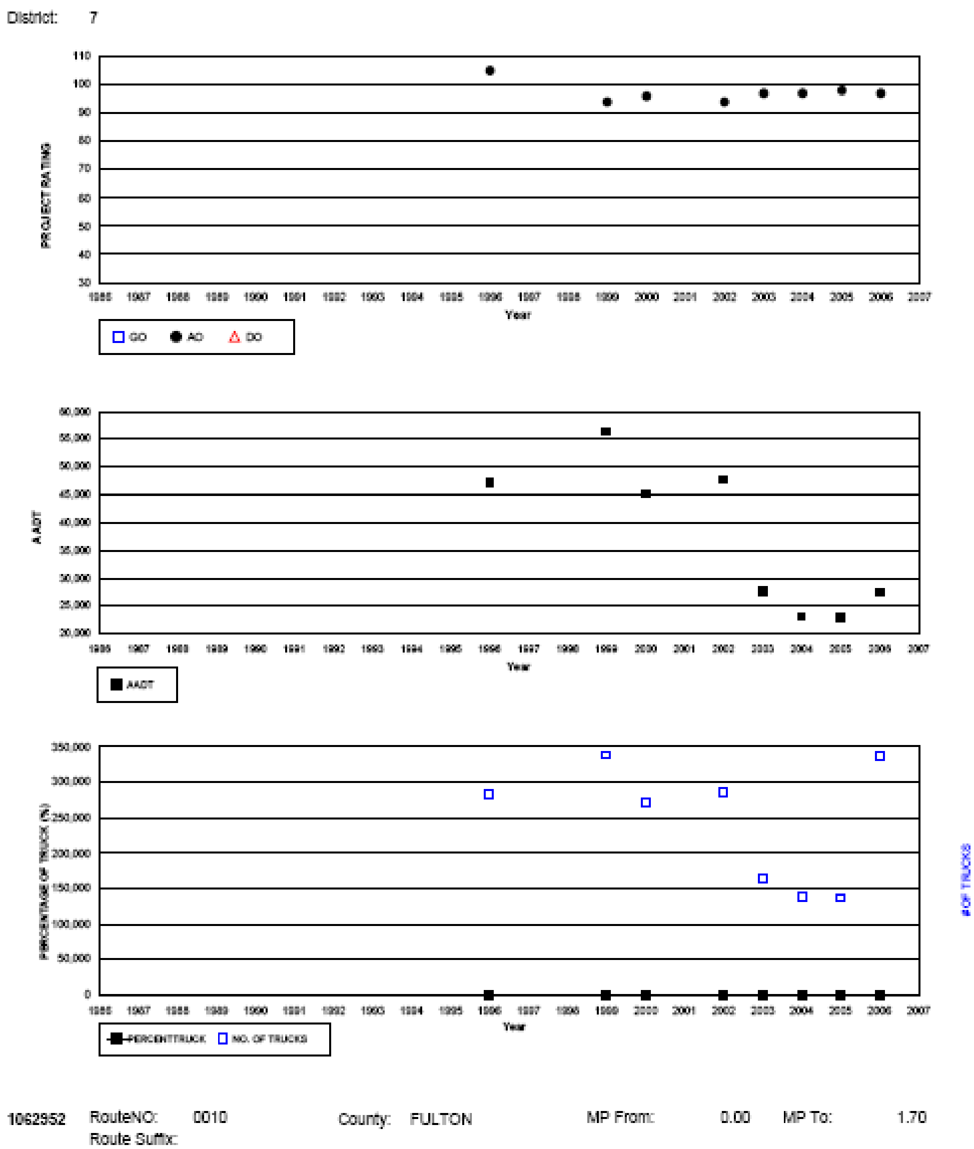


Figure 6.3 Pavement Historical Performance Curve with Traffic Data

Step 2: Generating Pavement life from pavement performance curve. Based on the pavement performance deterioration trend in pavement performance curve generated in the above step, various pavement lives can be defined as the duration of pavement life from the start year of pavement deterioration to the year of pavement resurfacing, or project rating decline to certain level. However, not all projects are suitable for pavement life analysis since some of them do not have desirable pavement deterioration curve. Therefore, visual or manual evaluation of each individual project is conducted based on the performance curve introduced in Chapter 2. 455 projects were selected from 9,317 projects. Selected projects are further classified into High, Median, and Low quality according to confidence level of pavement life parameters.

Step 3: Pavement life query. Pavement life information of 455 projects selected in the above step is stored in a Microsoft Access database. A life query program was developed to conveniently look up information in this database. The individual project life information along with the distress information can be queried out based on the searching criteria. In addition, user can also query out a group of projects and performance statistical analysis on the selected group.

The methodology of above three steps can also be described by the following flowchart.

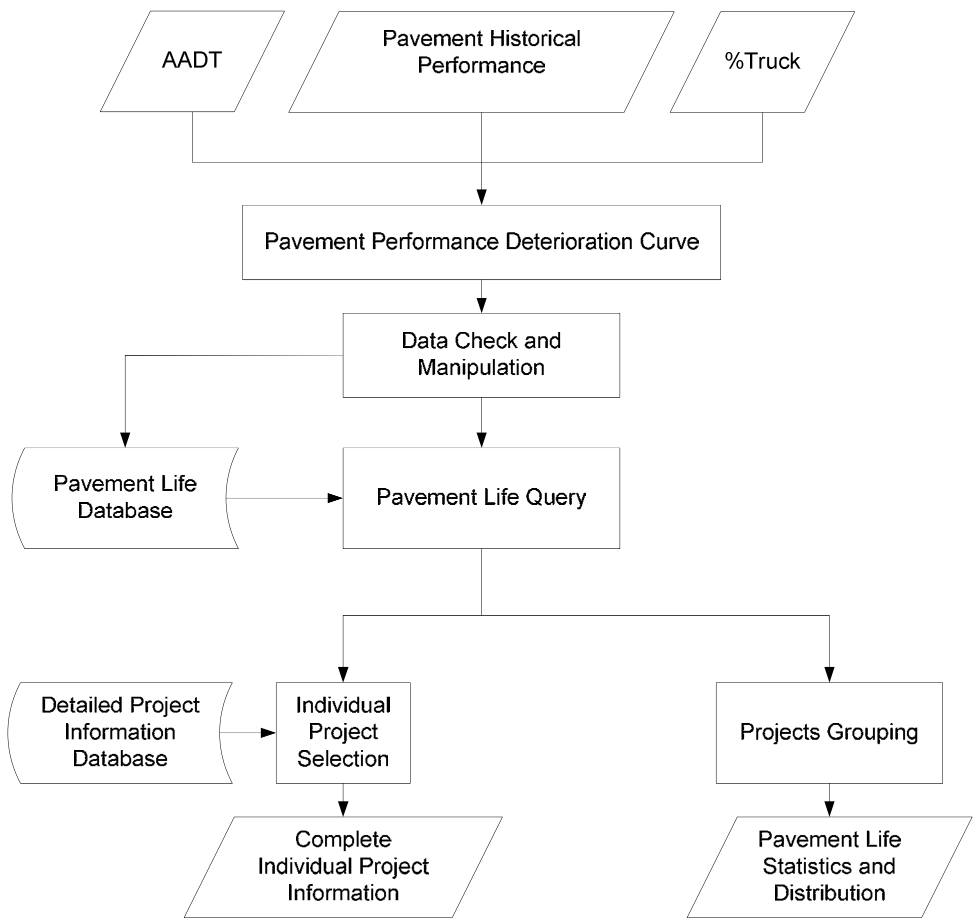


Figure 6.4 Framework Pavement Life Study

6.3 Introduction of Developed Functions and Program

Based on the above discussion, a function to generate the pavement historical performance curve with AADT and Truck% and standalone program to query the classified pavement lives, are developed for engineers to conveniently manage pavement historical performance and life data.

6.3.1 Generating Pavement Historical Performance Curve with AADT & Truck%

The objective of this task is to develop an automated procedures and functions to plot and report historical pavement rating along with AADT and Truck%. The detailed user manual can be found in Appendix XIV. The implementation of this function can be described by following steps:

Step 1: Definition of searching criteria. Firstly, users can query desired projects by setting certain criteria including "No. of points", "district", "county", "route no", and "route suffix". The projects meeting the query requirements will be retrieved and listed in a data grid as shown in Figure 6.5. The "No. of points" here means the minimum number of annual data in the database for each project. Those projects have less data than the "No. of points" do not meet the querying condition and will not be retrieved.

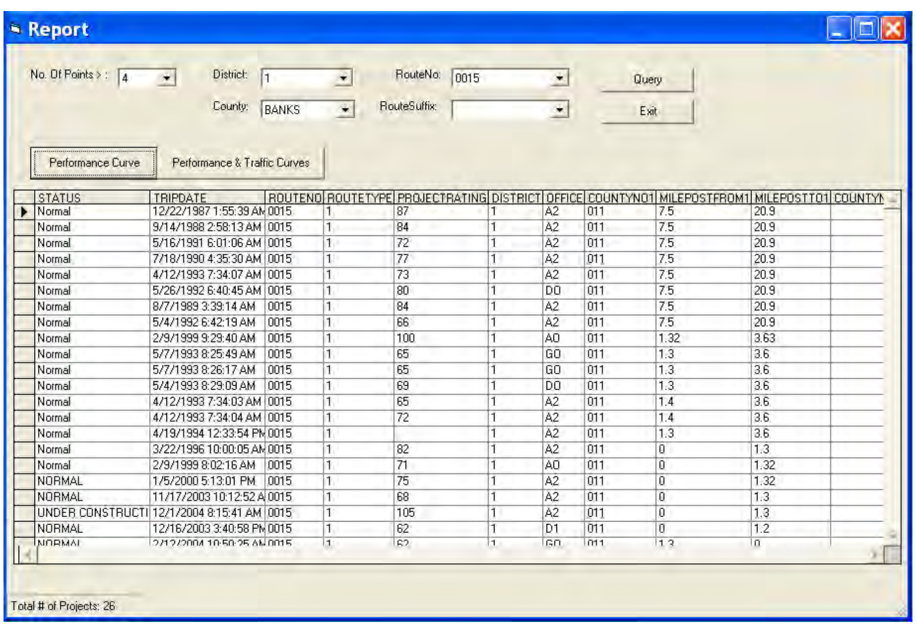


Figure 6.5 Query Form

Step 2: Generation of performance curves. Users can get the historical pavement performance curves by clicking **Performance Curve** button as shown in Figure 6.5.

Step 3: Generation of performance & traffic curves. The pavement performance data can also be plotted along with the traffic data (AADT, Percentage of Truck). The output information also include basic projects information like district, county, route no, route suffix, milepost from, and milepost to.

Step 4: Result output to Adobe PDF document.

The framework of this function can also be described as flow chart in Figure 6.6.

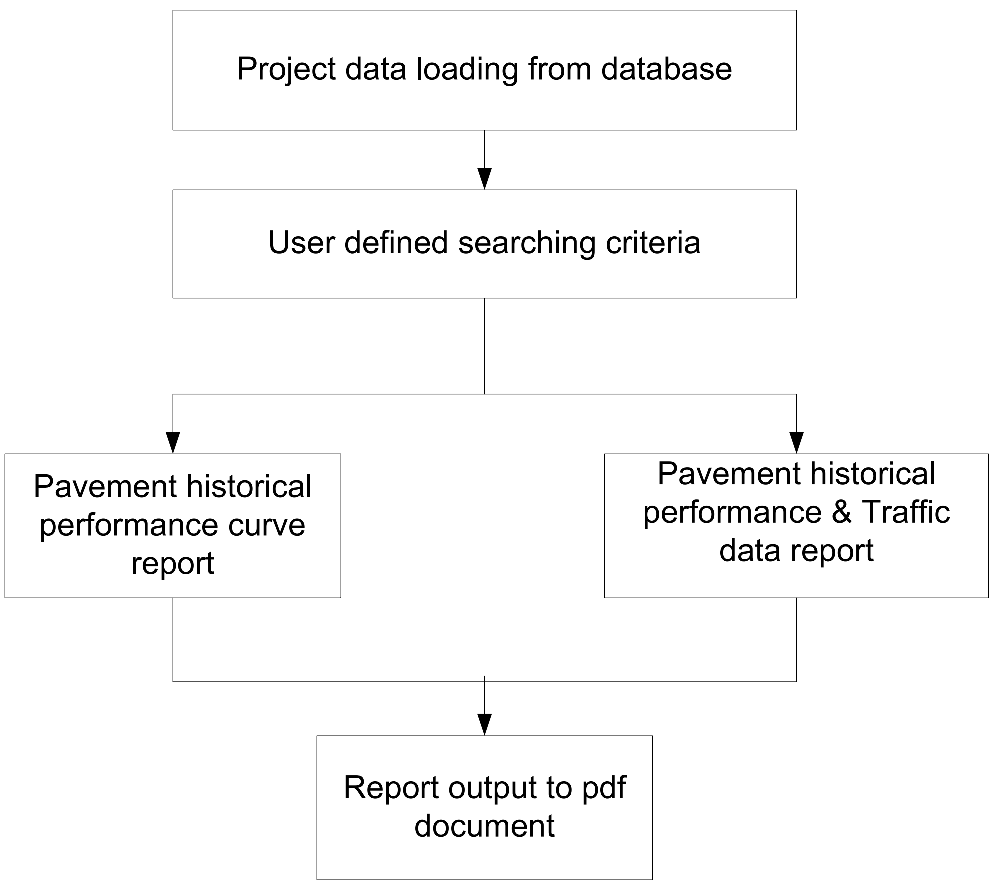


Figure 6.6 Framework of Pavement Historical Data Report Function

6.3.2 Pavement Life Query

The manual evaluation on pavement life curves performed in Chapter 2 is very time consuming. The classified projects with High, Medium and Low quality are very useful for pavement performance analysis. To facilitate the engineers to conveniently revisit the data, a standalone program was developed for data searching, display and analysis. The user manual of this program can be found in Appendix XV. The procedures are briefly described as follows:

Step 1: Load project information from pavement network database. The information mainly includes all of the district, county, route information in the state pavement network.

Step 2: Define searching criteria. Users can search projects based on district, county number, route number, route suffix, life start year, life end year, resurfacing life or 70_life, and confidence level (see Figure 6.7).

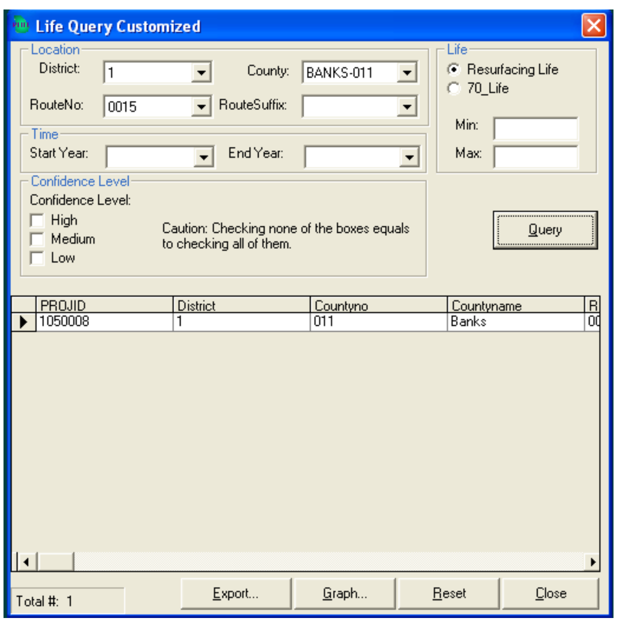


Figure 6.7 Query Form

Step 3: Query projects from database. Based on the searching criteria, the projects meeting the criteria will be retrieved and displayed in the data grid. The information for the selected projects shown in the grid include project ID, district, county no, county name, route no, and route suffix, milepost from, milepost to, pavement life start year, pavement life end year, resurfacing life, 70_life, resurfacing confidence level, average AADT, and average AADTT. Users can then choose one of project from the data grid and plot the historical rating data on a scatter chart.

Step 4: Display pavement life information. Based on the project selected from the data grid, the corresponding pavement life information of this project can be retrieved from the pavement life database. The pavement life information include district, county, route no, route suffix, pavement life start year, 70_year, pavement life end year, resurfacing life, 70_life, rating before pavement resurfacing, resurfacing confidence level, average AADT, and average AADTT, milepost from, and milepost. The "Pavement Rating vs. Fiscal Year" chart is also plotted. Figure 6.8 is an example.

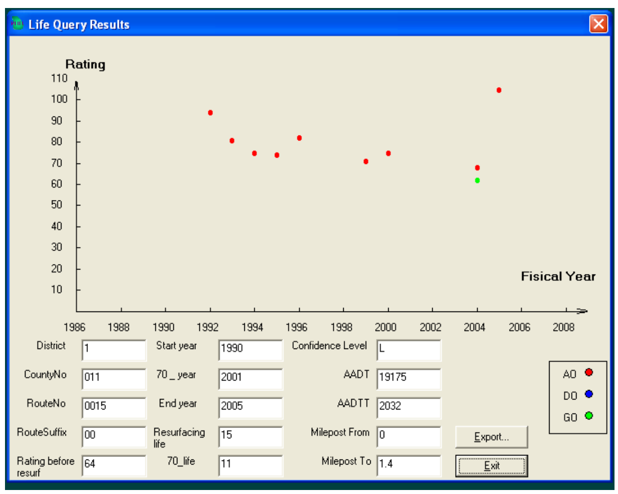


Figure 6.8 Pavement Historical Data and Life Information Display

Step 5: Output result to MS excel. After getting the pavement life and historical information, users can output the data and chart to a Microsoft Excel file. In the Excel report, a frequency chart is also plotted.

The framework of this program is also illustrated in Figure 6.9.

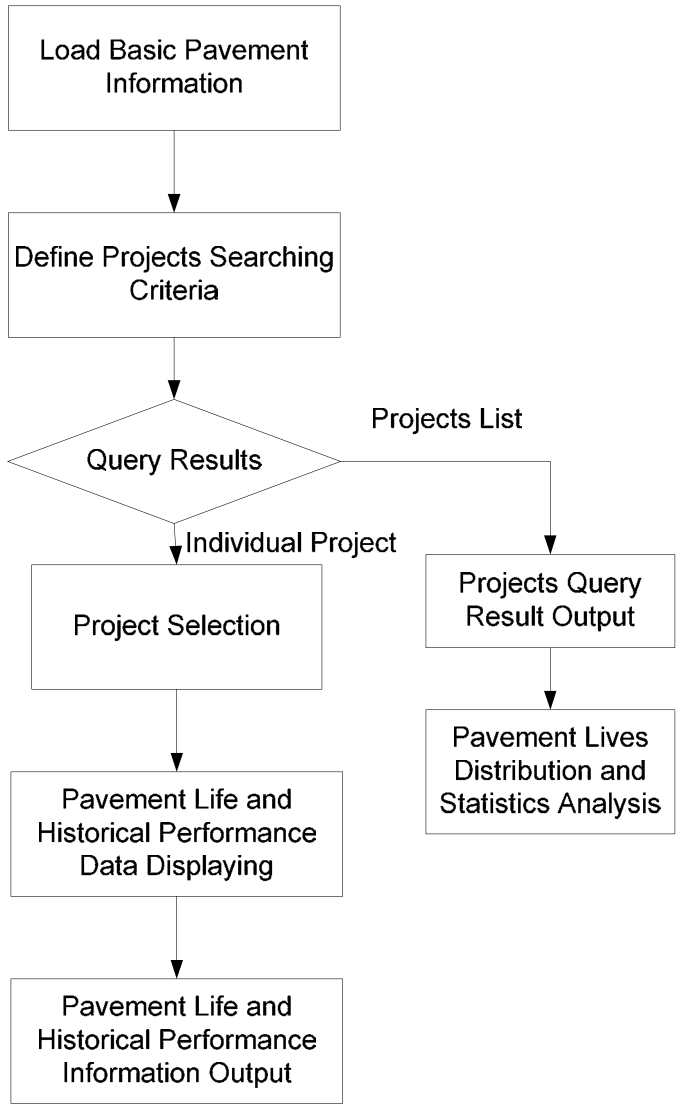


Figure 6.9 Framework of Pavement Life Query Function

6.4 Summary

The function to generate the historical pavement performance curves along with AADT and Truck% plays an important role in analyzing the statewide pavement performance. With new data is available, this function can be repeatedly utilized. However, the project grouping function is not implemented in the current Network Module, which is used to group the historical pavement condition data for a project. Based on the grouped project information, the pavement performance curves can be generated. It is suggested to automate this process in the future study.

The current pavement life query program is a tool for engineers to conveniently search, display and perform the statistical analysis on the manually classified project life information. The information stored in the database reflects the research result in the current project. It is suggested to extend this program in future to a pavement performance evaluation tool. The manual processing of data can become part of the function of this program.

7 Conclusions and Recommendations

This research project is to perform analyses and develop programs for GDOT to improve the pavement preservation, which is motivated by the challenge faced by transportation agencies due to the current budget shortfall, the growing traffic volume and the loss of technical experts caused by personnel retirements. GDOT has successfully implemented a PMS by OM and OMR including several modules and programs including COPACES, Network Module, GIS Module, and ProjectSelection. With the use of these tools, GDOT has established a comprehensive pavement condition database from Fiscal Year (FY) 1986 to FY 2008. The annual pavement condition survey and preservation project selection has also been routinely performed using these tools and the data are accumulated accordingly.

To further extend the current PMS and enhance GDOT's pavement preservation, the following objectives were set for this research project:

1) Perform statewide pavement performance study by screening, processing, and analyzing the PACES data collected since FY 1986. The relationship between pavement performance and other affected factors such as material, construction, traffic, environment, and maintenance is also studied.
2) Predict GDOT statewide long-term pavement preservation funding need and the future pavement condition based on the existing insufficient funding levels. The potential impact of the escalating construction cost on pavement condition is also analyzed.
3) Review the performance of crack sealing, one of the most popular pavement preservation methods. Research need for crack sealing study is recommended.
4) Study and compare the characteristics of segment-level and project-level PACES data for predicting pavement performance and computing ratings.
5) Develop the functions to re-define project termini.
6) Develop the functions to determine the localized pavement preservation need.
7) Develop the functions to reconstruct the historical pavement condition based on the customized project termini.

8) Develop the functions to visualize segment ratings on a selected route section that crosses into different counties.
9) Develop the functions to generate pavement performance curves with or without the historical traffic volume (AADT and Truck percent).
10) Develop an application to predict and simulate the long-term pavement condition in supporting the item 2).
11) Develop an application to query the existing pavement performance curves resulting from the item 1).

With the above objectives, data analyses and program developments have been conducted through this research project. The following summarize the major findings and the developed programs.

- **Major Findings on Data Analyses**

The statewide pavement life analyses were performed by screening, processing and analyzing the historical PACES data from FY 1986 to FY 2007. With a systematic approach, 9,713 projects were categorized in terms of their data quality. Among all projects, 149 high quality projects were used to perform the major analyses. The following are some findings:

1) The average statewide pavement resurfacing life (the time span of a new constructed pavement until the next resurfacing) is approximately 11 years.
4) The average pavement resurfacing life varies among 7 working districts from 12 years in District 2 and 10.1 years in District 3.
5) The relationship between pavement resurfacing life and traffic volume (AADT) shows that the pavement under High AADT (>10,000) has shorter resurfacing life (10.5 years) than Medium AADT (5,000 to 10,000) and Low AADT (<5,000) (11.7 years).
6) The functional class of a pavement has certain effect on pavement resurfacing life. The average life for rural pavement is approximately 11.5 year; while it is 11 years for urban pavement.

7) The targeted PACES rating that triggers resurfacing is 70. Otherwise, through analyses, the actual average rating before resurfacing in GDOT is approximately 66, which indicates a delay on resurfacing. Approximately 68% of pavement projects have been delayed for more than one year before resurfacing.
8) Among all pavement defects, load cracking, block cracking and rutting are three predominating distresses which contribute to the pavement deterioration.

To predict the long-term pavement performance and justify the future funding need to the legislatures, a Markovian-process-based PMS model is developed. The historical PACES data from FY 1986 to FY 2008 are used to construct the Markov Transition Probability Matrixes (TPM). The actual expenditure on resurfacing for non-interstate highway from FY 1999 to FY 2007 is used to verify the accuracy of the developed model. At the current stage, only non-interstate highway is analyzed due to the data availability. The following summarize the major conclusions through several case studies:

1) Without any preservation applied, the pavement condition drops approximately 3 points in composite PACES rating each year. If the current funding level and funding allocation remains same in the following 10 years, the pavement condition still keeps dropping, around 2 point being lost each year. Around FY 2015, the composite rating will drop to below 70 and the corresponding percentage is 57%. Therefore, the current funding level is insufficient to maintain the pavement network at a constantly serviceable level in a long-term period. More funding is needed in the future.
2) "Worst First" is the most inefficient strategy for pavement preservation. "Optimization" shows the best result. But, because some factors such as user cost cannot be considered in the mathematical model due to the lack of data support, "User Specified" should be comparable to an "optimal" solution. The result from "Optimization" strategy is still useful as an upper bound in helping the process of decision-making.
3) The need analysis shows that the "85-10% requirements" is hard to achieve because there is $426.4 million shortfall in FY 2008, which is more than two times then the available budget (if the total available budget is $185.1 million).

With the consideration of the escalation rate of construction cost (it is assumed 18.1%), the needed funds become $1.7 billion in FY 2017.

4) The escalation rate of construction cost has the direct impact on the pavement condition and pavement preservation need. The sensitivity study performed on three different Annual Average Escalating Rates (AAERs) (10%, 20% and 30%) shows that, in FY 2014, the difference in composite rating is around 1 point in comparison with the cases of 10% vs. 20%, and the cases of 20% vs. 30%. The difference increases to around 2 point in FY 2018. The corresponding percentages of pavement below 70 are 35%, 39% and 41% for cases of 10%, 20% and 30% respectively in FY 2014. The values increase to 53%, 60% and 67% in FY 2018. The increase in funding need is much faster than the increase of AAER. If the AAER remains 10% in the next 10 years, $880.3 million dollars is in the need to maintain the non-interstate highway network in FY 2018. With double AAER of 20%, $1.9 billion will be needed in FY 2018, which is more than double of the need with AAER of 10%. If AAER increases to 30%, $4 billion is needed in FY 2018. Because construction cost is hard to be forecasted, the corresponding risk should be analyzed in the planning of pavement preservation.
5) The change of construction cost may be dramatic in short term. The unexpected change will force transportation agency to defer or cancel some planned pavement preservation projects. Thus, the long-term pavement performance will be adversely impacted. The preliminary sensitivity study shows the pavement performance loss due to the construction cost increases in 2009 by 50%, 100% and 150% respectively. With 50% change, 3.8% of Loss of Pavement Performance (LOPP) in the following 8 years is expected. With 100% and 150% changes, the LOPPs are 7.8% and 10.4% in 8 years respectively.

Crack sealing and filling is one of the most popular preventive maintenance methods in GDOT. To evaluate its performance and the best timing of treatment, intensive literature review has been performed through this project. The exploration of cracking sealing in GDOT shows that the current available historical data hardly supports the sufficient study.

And further effort is needed to improve the current data collection process. The following list the major findings:

1) CALTRANS classifies cracks into working cracks and nonworking cracks. Crack sealing is mainly applied on working cracks; while crack filling, a less expensive method, is applied on nonworking cracks.
2) In terms of literature search, negative comments on applying crack sealing to asphalt pavement is hardly found, though Wisconsin Department Of Transportation (WDOT) has the negative comments on applying crack sealing on Portland Cement Concrete (PCC) pavement.
3) The study of benefit of cracking sealing in literature shows certain variability. Pavement life can be extended by "at least 2 years", "2.5 years", "3 to 5 years", "3 years", and "up to 8-9 years".
4) The performance of crack sealing depends on the different sealant materials, construction practices, crack types, construction timing, temperature, and drainage conditions. There is a need for GDOT to perform an experimental study to evaluate the factors and practices that can result in the highest cracking sealing/filling performance based on Georgia's local roadway and temperature conditions.
5) In GDOT, a liquefied asphalt emulsion is used for cracking filling; and a rubberized material is used for cracking sealing. GDOT engineers agree that the rubberized material/operation is better and more effective, but there are no hard facts to back up this conjecture. It is believed the pavement life can be extended for 5 years if the crack sealing/filling is performed at the right time, on the right distress, with the right construction, and the right material, However, there is no hard data to back this up. A PACE rating between 75 and 85 is considered the best timing for cracking sealing according to GDOT General Office. However, due to the funding shortfall, the district offices often prioritize crack sealing/filling for projects with rating of 70 or below.
6) The preliminary study on using COPACES data shows the difficulty to scientifically and quantitatively measure the crack sealing performance. The reasons for missing and fluctuating data may come from a) no COPACES survey

was performed, b) the sample location was changed, c) different raters conducted the survey, and d) COPACES deduct computations created inconsistencies.

In GDOT's practice, project-level PACES rating is used for determining pavement preservation need. While project-level PACES data is the aggregated pavement condition of all segment-level data in a project, it is needed to analyze and compare the characteristics and difference between these tow kinds of data source. The following are the major findings:

1) The historical segment ratings show large variation than the project ratings. If the pavement conditions are uniform, project-level COPACES data is more reliable to be used for pavement performance prediction.
2) The two methods for composite rating computation, the mean value and the length weighted average, produce almost similar results. These two methods are exchangeable for computing network composite rating.

- **Developed Functions and Applications**

To support the above analyses and provide tools for GDOT to enhance the pavement preservation, the following functions and applications have been developed:

1) The functions to re-define project termini were developed in COPACES. By using this function, a project can be divided into two new projects with more uniform segment rating distribution. In the meantime, two similar projects can be combined together. The project ratings for the new projects can be automatically calculated.
2) The functions to determine the localized pavement preservation need were developed in ProjectSelection. In GDOT, the current pavement preservation need is identified by using project-level PACES rating in conjunction with the distress deducts. The potential issue with the sole utilization of project-level data is the localized pavement defects may be "hided" in the aggregated value when the variation of pavement condition between the defected segment and other good segments. By using the developed functions, the localized pavement defects can

be found and the corresponding preservation method can be identified based on the pre-defined treatment criteria.

3) The functions to reconstruct the historical pavement condition based on the customized project termini were developed in the Network module. In OMR, it is often required to analyze the historical pavement condition for a programmed project which termini are determined by the Pre-construction Division and thus are different with the existing ones in the COPACE database. The developed functions make it convenient to reconstruct the project termini and generate the historical pavement condition with the recalculated project ratings.
4) The functions to visualize the segment ratings on a selected route section that crosses into different counties were developed in the Network module. The current spatial definition of a project make it difficult to visualize the continuous pavement condition on a selected route section when it crosses into different counties because the starting milepoint on a route, identified by a route number, always starts from 0. To visualize the sequential segment ratings on a selected route section that crosses into different counties, the county sequence need to be determined. The HMMS database is used to construct the county sequence in the developed functions.
5) The functions to generate pavement performance curves with or without the historical traffic volume (AADT and Truck percent) were developed in the Network module. The generated pavement performance curves were used in the analyses of statewide pavement performance. Though the analyses have been done, the function is still useful in future study when new pavement condition data is available.
6) The application to predict and simulate the long-term pavement condition in supporting the corresponding analyses was developed (GDOT LP&S). Four strategies are devised in the developed application: "Worst First", "User Specified", "Optimization" and "Need Analyses". The first three strategies are used to predict the long-term pavement performance. With "Worst First" strategy, budget is allocated to the pavement projects in the worst condition; with "User Specified" strategy, user can determine the allocation of annual funding;

"Optimization" strategy applies linear programming to optimally allocate the available annual funding to achieve the maximal composite rating. "Need Analyses" is used to determine the future funding need to meet the user-defined requirements. To use this program, massive historical data and intensive analyses are needed to provide the input parameters.

7) The application to query and analyze the pavement performance curves that were classified as High, Medium and Low quality resulting from the pavement performance analyses was developed (PaveLife). This application makes it convenient for users to re-visit and do further study on the hundreds of selected projects.

- **Recommendations**

The following are the recommendations for future research and development based on the tasks performed in this research project.

1) The statewide pavement performance study provides a solid foundation for further project-level analyses. It is recommended to perform the following study at project level:
   a. Further study is recommended on the long-life pavements. The contributing factors, e.g. timely pavement preservation for pavements with specific base materials, traffic volumes and designs, need to be identified for guiding the future pavement design and construction.
   b. Further study is needed on the high quality pavement performance curves to model the pavement deterioration at project level.
   c. The effectiveness of the current resurfacing strategy in GDOT needs to be further investigated.
   d. Alternative technologies need to be explored in order to perform the condition survey on an interstate highway. Due to the heavy traffic on these roads, there is a need to develop an automated condition survey system using computer vision and/or laser technology.

e. The pavement performance curve should be applied in the pavement condition survey as quality assurance criteria. In the study of the pavement performance, the data quality is an issue affecting the analysis result.

2) Pavement preservation is a complicated decision-making process. The study performed in this project demonstrated the capability of the developed models in predicting the long-term pavement performance and identifying the long-term budget need at network level. Otherwise, further refinement and study is still needed to improve the accuracy and extend the models to the level of project planning.

   a. A multi-year optimization model is needed to guarantee the optimal strategy in the entire analysis period. The current optimization model is annual-based and can only produce sub-optimal result.

   b. The following study is needed to improve the accuracy and reliability of the input parameters for the developed models, and thus improve the accuracy of the result.

      i. A more elaborate method should be studied based on the theory of probability and stochastic process to create the Markov TPMs.

      ii. It is valuable to evaluate the non-homogeneous Markov model that can better capture the characteristics of the time-dependent pavement deterioration.

      iii. It is needed to further study the different price models and their impact on the long-term pavement performance and funding need.

      iv. It is strongly suggested to perform intensive study on the historical expense of pavement preservation. Thus, the accuracy of the unit prices of pavement Maintenance, Rehabilitation and Reconstruction (MR&R) activities can be improved.

      v. More study is needed to define finer MR&R activities and assign more alternatives to each pavement state.

   c. User cost should be included in the PMS models. Without the consideration of user cost, cheaper treatments are always the first selection by an optimization model, which in some cases make less sense in transportation agencies' practice.

d. It is recommended to further study the quantification of LOPP. It is of great interest for transportation agencies to know the relationship between the investment loss and the pavement performance loss.
e. It is of great value to do further study on a project-level PMS model. The current PMS model can be used for network-level planning and the detailed project-level programming cannot be handled.

3) Crack sealing is well-known one of the most cost-effective maintenance methods. With the current budget shortfall, it is of the special interest in transportation agencies. Based on the literature review and the preliminary study, the following recommendations are offered.
    a. There is a need for GDOT to perform an experimental study to evaluate the factors and practices that can result in the highest cracking sealing/filling performance based on Georgia's local roadway and temperature conditions.
    b. It is recommended to conduct a large-scale crack sealing/filling experimental test in order to evaluate the cost effective timing for the treatment.
    c. An objective measurement method, such as using laser and vision technologies, is recommended to better quantify the crack sealing performance.
4) The study of pavement preservation is heavily dependent on the data accuracy and availability. Through this research project, it is apparent that the data accuracy and availability largely limited the reliability and depth that the research can achieve. It is recommended to further improve the data quality and extend the necessary data recording by enhancing the current functions and application and developing new modules. For example,
    a. A more stringent data quality assurance and quality check (QA/QC) function should be added in the COPACES program.

b. Pavement maintenance method, timing, and cost should be recorded. In the current research project, the result of several research tasks is limited due to the lack of pavement maintenance information.

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Appendix I: Spatial Grouping of Projects

The following explanation covers the process necessary to prepare COPACES data (from 1986 to 2007) and perform spatial grouping to cluster the projects within the adjacent location. In summary, the spatial clustering rules are: 1) the projects are at the same location (same county, route number, route suffix, and direction), and 2) the project limits are within certain buffer. The buffer length is set to be the minimum of 0.9 miles and 20 percent of the total project length after trial and error comparison. For example, a project beginning at mp 0 and ending at mp 10 would have a buffer of 0.2 miles. To be considered as spatially clustered, the projects should be within the adjusted project limit buffer and have the same county, route number, route suffix, and direction. Figure I-1 below shows how to determine the buffer and the adjacency of the projects. The MilepostFrom and MilepostTo should be within the buffers, (0 to 0.2) and (9.8 to 10.2), respectively.

Project A: County 001, Route no 0010, Suffix 00, MP 0 – 10

Buffer = min (0.2*10, 0.9)=0.2

Adjacent Projects: County 001, Route no 0010, Suffix 00, MP (0-0.2) to (9.8-10.2)

Project B: County 001, Route no 0010, Suffix 00, MP 0 – 9.85 (Clustered)

Project C: County 001, Route no 0010, Suffix 00, MP 0.1 – 10.2 (Clustered)

Project D: County 001, Route no 0010, Suffix 00, MP 0.1 – 11 (Not clustered)

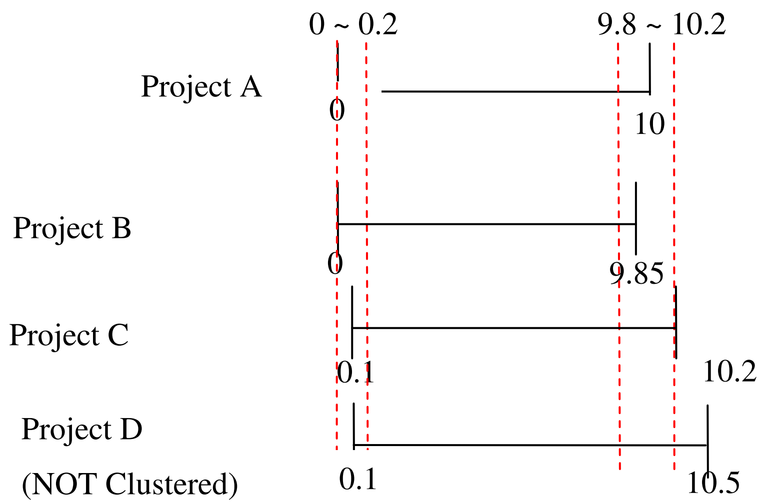


Figure I-1 Project Limit and Buffer

Before grouping the historical ratings into each individual project as shown in Figure I-1 to support pavement life analysis, a "spatial grouping" needs to be performed with the adjusted project limit buffer. This is an essential step because the project limit changes slightly along the year. With a fixed project limit query, we may not be able to group all project points because of the slight difference in project limits (MilepointFrom and MilepointTo). Therefore, the buffer for a project limit is necessary. However, too large of a buffer may cluster the project points that are not in the project. After a trial and error comparison, a buffer of the minimum of 20 percent of total project length or 0.9 miles was established as the individual project spatial clustering buffer.

Appendix II: Pavement Project Data Evaluation Decision Rules

Table II-1 Pavement Project Data Evaluation Decision Rules for Pavement Life (Life-Resurf)

Pavement Life: (Life-Resurf)	**Definition:** The time period from the establishment of a new pavement surface (with a typical project rating of 100(105)) until the next pavement reconstruction/resurfacing (with a typical project rating of 100(105)). (From **Yr-Start** until **Yr-EndResurf**, respectively.)
Lowest level Rule:	**Rule:** If the project contains no **U** or **N/A** or **I** confidence levels, then, the overall Pavement Life confidence level is selected as the lowest confidence level (**Low, Medium or High**) of these three factors: 1. **Yr-Start*** 2. **Yr-EndResurf** * 3. **Trend in the middle*** *These factors and their related confidence levels will be defined in the tables that follow.
Factor Confidence Rating:	**Factor Confidence Rating Definitions and applications to Pavement Life:**
N/A	**N/A:** (Not Acceptable) The **N/A** rating means that the project data for these projects is not useful and that this data will not be used in the future. **N/A** has the highest priority in deciding the overall pavement life (**Life-Resurf**) confidence level. If any of the three decision factor ratings is **N/A**, the overall pavement life (**Life-Resurf**) confidence level will be **N/A**.
U	**U:** (Uncertain) The **U** rating means that the project data for these projects have potential to provide useful information after further investigation is completed. If any of the three decision factor ratings is **U** with no **N/A**, the overall pavement life (**Life-Resurf**) confidence level will be **U**.
I	**I**: (Incomplete) The **I** rating means that the project data for these projects is incomplete. If any of the three decision factor ratings is **I,** with no **U** or **N/A**, the overall level is **I**.

Table II-2 Pavement Project Data Evaluation Decision Rules for Year Start (Yr-Start)

Year Start: (Yr-Start)	**Definition:** The **Year Start** is the beginning of a pavement life, and typically is identified by the first project rating of 100 (105) for the best pavement cycle trend which is selected. When the rating of 100 (105) is not indicated, a **Year Start** will be established according to the rules given with the confidence levels below.
Factor Confidence Rating:	**Factor Confidence Rating Definitions and applications to Year Start:**
High	**High:** A high confidence level for the **Year Start** is indicated by a project rating of 100 or 105 at the beginning of the selected pavement cycle trend. Sometimes the COPACES surveyors used a project rating of 105 to identify the project as being under construction at the time of survey. For project data with more than 2 project ratings of 100 (or 105) in subsequent years, the **Year Start** is selected as the year of the second 100 (or 105) from the right.
Medium	**Medium:** A Medium confidence level for the **Year Start** is indicated where the highest rating at the beginning of the selected pavement cycle trend falls between 90 and 100 and one of the following conditions apply: • Support data (additional ratings in the same year) is surveyed by more than one additional GDOT office (generally the District Office and/or the General Office) within a 4-year period before the high rating point. Then, the year following the year of the support data will be considered as the **Year Start**. • Support data (additional rating(s) in the same year) is surveyed by at least one GDOT office (generally the District Office or the General Office) within a 2-year period before the high rating point. The rating of the Support data must be at least 20 points lower than the rating of the highest rating point. Then, if the support data is the year before the highest point, the highest point will be considered as the **Year Start**. If the support data is two years before the highest point, the year before the highest point will be considered as the **Year Start**. In the case with no support data or where the support data occurs more than 2 years before, where the rating of the highest point of the beginning of the trend

	is between 95 and 100, the trend can be extrapolated backwards for one year. If this extrapolated point has a rating of 100 or higher, this point will establish the **Year Start** with a **Medium** confidence rating. The **Year Start** cannot overlap any previous trend data.
Low	**Low:** A Low confidence level for the **Year Start** is indicated where the rating data was collected in 1987 or earlier and the highest rating point is higher than 90 but less than 100. In this case, 1986 will be considered as the **Year Start**. In any case after 1987 without support data, where the rating of the highest point at the beginning of the trend is between 90 and 100, the trend can be extrapolated backwards for two years. If this extrapolated point has a rating of 100 or higher, this point will establish the **Year Start** with a Low confidence rating. Otherwise, for this case, the **Year Start** will be **U**-uncertain at the extrapolated point. The **Year Start** cannot overlap any previous trend data.
N/A	**N/A:** An **N/A** (Not/Acceptable) confidence level for the **Year Start** is indicated where the rating at the beginning of selected pavement cycle trend is lower than 80.
U	**U:** A **U** (Uncertain) confidence level for the **Year Start** is indicated where it is thought that future investigation will support the creation of a **Year Start** or where the beginning of the selected pavement cycle trend is 1986 or earlier and the rating at the beginning point is between 80 and 90.
I	**I**: An **I** (Incomplete) confidence level for the **Year Start** is indicated where the project data is considered too incomplete to create a **Year Start**.

Table II-3 Pavement Project Data Evaluation Decision Rules for Trend in the Middle

Trend in the middle	**Definition:** The **Trend in the middle** are the data points and associated straight-line defined from the time period from the establishment of a new pavement surface (with a typical project rating of 100(105)) until the next pavement reconstruction/resurfacing (with a typical project rating of 100(105)). (i.e., from **Yr-Start** until **Yr-EndResurf**) The **Trend in the middle** is selected as the best identifiable trend in the project survey history. In order to define the **Trend in the Middle** graphically, a straight line will be drawn between the known points (**Yr-Start** and the year before **Yr-EndResurf)** if available. If only one known end point is available, a combination of the known point and a weighted line position can be used. If both end points are unavailable, a weighted line position will be used. In the year before the Yr-EndResurf, if multiple points exist, the point defining the end of the trend line (for the Trend in the Middle) will be selected as the point which best supports the rest of the trend line.
Factor Confidence Rating:	**Factor Confidence Rating Definitions and applications to Trend in the middle:**
High	**High:** A high confidence level for the **Trend in the middle** is indicated by reasonable and sufficient data including more than 5 project rating points or more than half of the data points between the year after the **Year Start** point and the **Year End** point. (Whichever number is higher.) The trend must look reasonable in the selected life cycle.
Medium	**Medium:** A medium confidence level for the **Trend in the middle** is indicated by reasonable and sufficient data with five data points or at least half of the data points between the year after the **Year Start** point and **Year End** point. (Which ever number is greater.) The trend must look reasonable in the selected life cycle.
Low	**Low:** A low confidence level for the **Trend in the middle** is indicated by a minimum of four data points or one less than half of the data points between

	the year after the **Year Start** point and **Year End** point. (Which ever number of points is greater.) The trend looks somewhat reasonable in the selected life cycle.
N/A	**N/A:** An **N/A** (Not/Acceptable) confidence level for the **Trend in the middle** is indicated where there are fewer than 4 data points and/or the trend looks unreasonable. For example, if the trend curve is very flat or there is too much noisy data in the trend it is considered unworthy of further investigation.
U	**U:** A **U** (Uncertain) confidence level for the **Trend in the middle** is indicated where it is thought that future investigation will support the creation of a **Year Start**.
I	**I**: An **I** (Incomplete) confidence level for the **Trend in the middle** is indicated where the end year for the selected trend is incomplete and the rating on year 2007 is not surveyed by more than one office.

Table II-4 Pavement Project Data Evaluation Decision Rules for Year End (Yr-EndResurf)

Year End (Yr-EndResurf)	**Definition:** The **Year End** is the end of a pavement life. The Year End will be established according to the rules given with the confidence levels given below.
Factor Confidence Rating:	**Factor Confidence Rating Definitions and applications to Year End:**
High	**High:** A high confidence level for the **Year End** is indicated by a project rating of 100 or 105 for the next life cycle within 3 years after the best pavement cycle trend.
Medium	**Medium:** A Medium confidence level for the **Year End** is indicated where the highest rating at the beginning of the next pavement cycle trend falls between 100 and 90 and one of the following conditions apply: • Support data (additional ratings in the same year) is surveyed by more than one additional GDOT office (generally the District Office and/or the General Office) within a 4-year period before the high rating point. Then, the year following the year of the support data

	will be considered as the **Year End**. • Support data (additional rating(s) in the same year) is surveyed by at least one additional GDOT office (generally the District Office or the General Office) within a 2-year period before the high rating point. The rating of the Support data must be at least 20 points lower than the rating of the highest point. Then, the year right before the highest point will be considered as the **Year End**. Regardless of support data at the end of the trend, if the rating of the most appropriate end point is below 70, the year after the end point will be taken as the **Year End** with a Medium confidence level. Regardless of support data at the end of the trend, if the end point rating is above 70, the best pavement cycle trend can be extrapolated for one year to cross the 70 project rating level. The point closest to the crossing will be the **70_year** and the next year will be the **Year End** with a Medium confidence level. No overlaps into the next cycle are allowed.
Low	**Low:** Where there is no support data and the end point rating is above 70, the best pavement cycle trend can be extrapolated for two years to cross the 70 project rating level. The point closest to the crossing will be the **70_year** and the next year will be the **Year End** with a Low confidence level.
N/A	**N/A:** (Not Acceptable) The **N/A** rating means that the project data used in trying to establish a **Year End** is not acceptable.
U	**U:** A **U** (Uncertain) confidence level for the **Year End** is indicated where it is thought that future investigation will support the creation of a **Year End**.
I	**I**: An **I** (Incomplete) confidence level for the **Year End** is indicated where the best pavement cycle trend does not have a rating in year 2007 but still has a project rating in year 2006 with adequate trend supporting data.

Table II-5 Pavement Project Data Evaluation Decision Rules for Pavement Life to 70 rating (70_Life)

Pavement Life to 70: (70_Life)	**Definition:** The time period from the establishment of a new pavement surface (with a typical project rating of 100(105)) until the pavement deteriorates to a rating of 70. (From **Yr-Start** until **70_Yr**) (An extension of up to one year may be considered for 70_Life due to the decision lag period of GDOT.)
Lowest level Rule:	**Rule:** If the project contains no **U** or **N/A** or **I** confidence levels, then, the overall Pavement Life to 70 confidence level is selected as the lowest confidence level (**Low, Medium or High**) of these three factors: 1. **Yr-Start*** 2. **70_YR** * 3. **Trend in the middle*** *These factors and their related confidence levels will be defined in the tables that follow.
Factor Confidence Rating:	**Factor Confidence Rating Definitions and applications to Pavement Life to 70:**
N/A	**N/A:** (Not Acceptable) The **N/A** rating means that the project data for these projects is not useful and that this data will not be used in the future. **N/A** has the highest priority in deciding the pavement life to 70 (**70_Life**) confidence level. If any of the three decision factor ratings is **N/A**, the pavement life to 70 (**70_Life**) confidence level will be **N/A**.
U	**U:** (Uncertain) The **U** rating means that the project data for these projects have potential to provide useful information after further investigation is completed. If any of the three decision factor ratings is **U** with no **N/A**, the pavement life to 70 (**70_Life**) confidence level will be **U**.
I	**I**: (Incomplete) The **I** rating means that the project data for these projects is incomplete. If any of the three decision factor ratings is **I,** with no **U** or **N/A**, the overall level is **I**.

Table II-6 Pavement Project Data Evaluation Decision Rules for 70_YR

70_YR	**Definition: The 70_Year** is the end of the **Pavement Life of 70** and is determined as the year on the point at the 70 rating or the year closest to the location of the intersection of the trend line and a horizontal line established at the 70 project rating level. Confidence levels and rules for 7**0_YR** are given below.
Factor Confidence Rating:	**Factor Confidence Rating Definitions and applications to 70_YR:**
High	**High:** A high confidence level for the **70_YR** is indicated by the point at the 70 rating or on the best pavement cycle trend (with a **Trend in the Middle** confidence of High) crossing at the 70 project rating level.
Medium	**Medium:** A medium confidence level for the **70_YR** is indicated if the best pavement cycle trend (with a **Trend in the Middle** confidence of Medium) crossing at the 70 project rating level or the trend line can be extrapolated for one year to cross the 70 project rating level.
Low	**Low:** A low confidence level for the **70_YR** is indicated if the best pavement cycle trend (with a **Trend in the Middle** confidence of Low) crossing at the 70 project rating level or the trend line can be extrapolated for two years to cross the 70 project rating level.
N/A	**N/A:** (Not Acceptable) The **N/A** rating means that the trend information to be used in trying to establish the **70_YR** is not acceptable.
U	**U:** A **U** (Uncertain) confidence level for the **70_YR** is indicated where it is thought that future investigation will support the creation of an accurate **70_YR**.
I	**I:** An **I** (Incomplete) confidence level for the **70_YR** is indicated if the best

	pavement cycle trend does not cross the 70 project rating level but the rating data is complete up to year 2007.

Table II-7 Pavement Project Data Evaluation Decision Rules for Rating before Resurfacing

Rating before Resurfacing (RBR)	**Definition:** The **RBR-** Rating before Resurfacing is generally established as the rating of the year before the year end. It may be a point on the trend line or it may represent the rating created by the intersection of a vertical year line and the trend line. The confidence levels and rules for **RBR** are given below.
Factor Confidence Rating:	**Factor Confidence Rating Definitions and applications to RBR:**
High	**High:** A high confidence level for **RBR** is indicated by a point or where the rating is created by the trend line intersection and the **Trend in the Middle** has a high rating.
Medium	**Medium:** A medium confidence level for the **RBR** with no support data is indicated where the rating is created by the trend line intersection and the **Trend in the Middle** has a medium rating.
Low	**Low:** A low confidence level for the **RBR** is created by the trend line intersection and the **Trend in the Middle** has a low rating.
N/A	**N/A:** (Not Acceptable) The **N/A** rating means that the trend information to be used in trying to establish an **RBR** is not acceptable.
U	**U:** A **U** (Uncertain) confidence level for the **RBR** is indicated where it is thought that future investigation will support the creation of an accurate **RBR**.
I	**I:** An **I** (Incomplete) confidence level for the **RBR** is indicated if the Year End is rated as incomplete.

Appendix III: Historical Data Analysis for Markov Transition Probability Matrices

1 Pavement Condition Classification

The Markov Transition Probability Matrices (TPMs) are categorized by the route type, the working district, and the pavement condition. Different route types are considered to have different designs and traffic use. The working district represents the similarities in geographic locations. After discussing them with GDOT, the following are the finalized categories:

- Route type: Interstate
  Non-interstate
- Working district: there are seven working districts in Georgia.
- Pavement condition: [1] Excellent (100- 91)
  [2] Good (90-81)
  [3] Fair (80-71)
  [4] Poor (70-56)
  [5] Bad (<=55)

2 Data Description:

The historical PACES survey data stored in the GPAM database is the source for constructing the pavement performance matrices. The GPAM database contains the historical PACES survey data, dating back to 1986, and the data collected after the implementation of the COPACES in 1999. This study uses the data collected by the COPACES after 1999. Note that there is no data for 2001.

3 Data Pre-Processing Procedures:

The PACES survey projects from 1999 to 2006 were processed to construct the performance matrices for each category. Note that there is no data for 2001. The following are the steps used to process the data for every-two-year cycle (1999-2000, 2002-2003, 2003-2004, 2004-2005, 2005-2006):

1. Group the projects based on their locations.

The linear referencing system, a combination of RCLink and milepost, is used to determine the location of the project.

2. Filter out the projects with missing critical information, such as project rating.
3. Filter out the projects that are not surveyed by AO:

   PACES surveys are conducted by AO, DO, and GO. AO surveys all the state routes; the projects with low rating (less than 70) would be surveyed by DO and GO. The statewide statistics should be based on AO only due to the duplication of the DO and GO surveys.
4. Filter out the non-asphalt surface type projects.
5. Eliminate the projects with under-construction status.
6. Filter out the duplicated projects.

   After the projects grouping, each project is assigned with a project ID. There are cases that the multiple projects assigned by the same project ID. So, select the project with minimum RECORD NO among the projects with same ID to avoid the duplication.
7. Eliminate the projects with irrational deterioration trend.

   The pavement conditions are assumed to deteriorate over time, just as the project rating does. The project rating would improve under the following two cases:
   - When a project is rehabilitated, the pavement rating will be improved when compared with the previous year.
   - The project rating is improved, as perceived by raters, without actual rehabilitation

     The two cases above are removed from the data set, since the pavement deterioration matrix is before rehabilitation.

4 Data Pre-process

The data process and filter rules above were applied to the data for every-two-year cycle (1999-2000, 2002-2003, 2003-2004, 2004-2005, 2005-2006); Table 1 summarizes the results for data process in the different years. About 46% to 66%of the surveyed interstate miles are filtered out and leave about 352 to 791 miles available for constructing the pavement deterioration matrix. About 37% to 57% of the surveyed non-interstate miles are filtered out, and a total of 7,700 to 13,567 miles is included in this study. The 2005-2006 dataset contains the most of the available miles compared to other years.

Table 1: Data Process Results (unit: mile)

	Total	**Total of AO surveyed**	**Total after filtering out under-construction**	**Total after filtering out treated and irregular rating**
FY2005-2006				
Interstate				
D1	125.5	113.5	113.5	113.5
D2	169.8	105.8	24.5	24.5
D3	301.8	229.8	178.8	165.7
D4	142.9	124.4	59.8	46.5
D5	163.9	163.6	150.4	100.5
D6	255.9	235.3	235.3	163.8
D7	293.1	232.5	232.5	177.4
Sub-Total	1,452.9	1,204.8	994.9	791.8
Non-Interstate				
D1	2,890.2	2,373.7	2,018.0	1,642.6
D2	3,904.8	3,225.7	2,774.9	2,364.3
D3	4,126.5	3,289.6	2,852.5	2,508.1
D4	4,416.3	3,867.2	3,291.7	3,074.6
D5	2,726.9	2,493.2	2,132.0	1,724.7
D6	2,170.0	1,924.3	1,865.0	1,703.8
D7	1,096.7	852.0	813.6	549.6
Sub-Total	21,331.4	18,025.7	15,747.7	13,567.7
FY2004-2005				
Interstate				

D1	153.5	150.6	107.3	42.8
D2	86.6	75.6	70.6	24.0
D3	99.1	88.4	77.7	50.5
D4	141.1	141.1	46.5	46.5
D5	213.2	213.2	158.3	109.0
D6	255.2	255.2	241.2	46.2
D7	295.0	268.8	268.8	106.0
Sub-Total	1,243.6	1,192.8	970.3	425.1
Non-Interstate				
D1	2,284.5	1,787.7	1,586.1	1,168.0
D2	3,702.8	3,150.0	2,426.5	1,836.1
D3	2,750.3	2,258.5	2,103.4	1,546.6
D4	4,104.5	3,595.1	2,969.2	2,279.9
D5	2,787.1	2,425.3	2,074.6	1,541.8
D6	2,130.8	1,826.8	1,600.8	1,039.4
D7	963.5	830.1	830.1	369.3
Sub-Total	18,723.6	15,873.6	13,590.6	9,781.1
FY2003-2004				
Interstate				
D1	152.9	152.9	53.8	22.3
D2	131.7	92.7	91.1	35.6
D3	160.9	160.9	118.5	46.2
D4	75.9	75.9	46.5	46.5
D5	166.2	166.2	147.3	100.6
D6	254.2	254.2	254.2	162.9
D7	403.3	392.1	392.1	160.6
Sub-Total	1,345.1	1,294.9	1,103.5	574.7
Non-Interstate				
D1	2,389.0	1,898.4	1,654.5	850.6
D2	3,461.5	3,163.1	2,487.0	1,763.5

D3	3,376.6	2,966.5	2,617.7	1,586.5
D4	4,385.8	3,849.8	2,938.4	2,230.7
D5	2,681.7	2,381.4	1,972.7	1,404.9
D6	1,731.2	1,694.1	1,570.6	1,131.8
D7	979.6	867.4	867.4	619.6
Sub-Total	19,005.5	16,820.7	14,108.1	9,587.6
FY2002-2003				
Interstate				
D1	96.9	96.9	53.6	52.1
D2	116.6	44.8	44.8	55.8
D3	199.2	178.0	127.1	69.8
D4	99.2	99.2	21.4	
D5	55.0	55.0	55.0	27.0
D6	223.3	221.2	221.2	44.0
D7	157.9	156.3	156.3	109.1
Sub-Total	948.1	851.3	679.4	357.8
Non-Interstate				
D1	1,980.1	1,850.3	1,676.1	1,214.9
D2	3,458.6	2,639.5	2,498.3	1,670.8
D3	2,942.5	2,556.7	2,341.0	1,582.6
D4	4,048.7	3,592.3	2,709.8	2,170.8
D5	2,305.3	2,040.8	1,727.5	1,142.3
D6	1,684.5	1,641.7	1,581.1	1,103.3
D7	727.6	688.0	688.0	548.6
Sub-Total	17,147.2	15,009.4	13,221.8	9,433.4
FY1999-2000				
Interstate				
D1	173.0	168.6	168.6	92.0
D2	171.5	15.6	15.6	
D3	103.6	95.4	95.4	69.4

D4	120.6	120.6	120.6	96.0
D5	50.7	50.7	50.7	26.8
D6				
D7	319.5	248.2	248.2	68.4
Sub-Total	939.0	699.1	699.1	352.6
Non-Interstate				
D1	2,638.6	1,739.7	1,739.7	1,196.2
D2	3,568.9	2,701.4	2,701.4	1,989.5
D3	2,323.5	1,784.7	1,784.7	709.3
D4	4,266.6	3,305.6	3,305.6	2,212.8
D5	2,574.5	1,991.6	1,991.6	1,034.6
D6	1,169.3	602.9	602.9	303.8
D7	1,004.3	606.4	606.4	262.2
Sub-Total	17,545.6	12,732.2	12,732.2	7,708.5

5 Initial States

The initial state used in the model was estimated based on the AO survey data (Step 3). The miles, percentage of miles, and composite rating in each pavement condition states in the different working districts are summarized in Tables 2 to 6. The pavement condition for non-interstates is fairly stable over the years. District 7 has the lowest percentage, about 24%, of the excellent state (rating greater than 90) among all the districts. Table 7-1 shows the averaged initial state condition. Note that the miles for interstates are much fewer than the total miles on the interstate system and cannot represent the interstate system. Due to the insufficient data, the initial miles for Interstates are estimated based on RC files instead of the surveyed PACES projects. Table 7-2 shows the miles in each district based on RC files. Table 7-3 shows the averaged mileage distribution in each pavement condition state.

Table 2: Initial State for FY1999

District	State	Interstate			Non-Interstate		
		Miles	Percentage	Composite Rating	Miles	Percentage	Composite Rating
1	1	62.9	37.30%	98.6	579.4	33.30%	97.7
1	2	20.0	11.86%	88.5	521.2	29.96%	84.3
1	3	67.7	40.16%	75.7	456.7	26.25%	76.1
1	4	18.0	10.68%	67.0	172.2	9.90%	64.4
1	5	0.0	0.00%	0.0	10.3	0.59%	53.8
2	1	15.6	100.00%	97.9	1346.9	49.86%	98.3
2	2	0.0	0.00%	0.0	682.6	25.27%	85.0
2	3	0.0	0.00%	0.0	475.2	17.59%	76.0
2	4	0.0	0.00%	0.0	180.6	6.69%	66.1
2	5	0.0	0.00%	0.0	16.0	0.59%	50.5
3	1	69.4	72.73%	98.0	605.4	33.92%	98.5
3	2	15.5	16.27%	87.0	434.7	24.36%	85.2
3	3	10.5	11.00%	75.0	354.5	19.87%	76.1
3	4	0.0	0.00%	0.0	371.3	20.81%	64.9
3	5	0.0	0.00%	0.0	18.7	1.05%	52.3
4	1	36.4	30.19%	100.0	1252.7	37.90%	97.7
4	2	65.2	54.06%	83.6	633.6	19.17%	84.9
4	3	0.0	0.00%	0.0	786.5	23.79%	75.9
4	4	12.6	10.45%	67.5	555.9	16.82%	65.2
4	5	6.4	5.31%	51.0	76.9	2.33%	47.4
5	1	38.1	75.13%	97.5	720.8	36.19%	97.2
5	2	0.0	0.00%	0.0	505.5	25.38%	85.5
5	3	12.6	24.87%	80.0	429.2	21.55%	75.7
5	4	0.0	0.00%	0.0	286.3	14.37%	66.8
5	5	0.0	0.00%	0.0	49.8	2.50%	48.9
6	1	0.0	0.00%	0.0	321.2	53.28%	99.0

6	**2**	0.0	0.00%	0.0	109.9	18.22%	85.2
6	**3**	0.0	0.00%	0.0	134.6	22.33%	77.0
6	**4**	0.0	0.00%	0.0	35.8	5.94%	66.9
6	**5**	0.0	0.00%	0.0	1.4	0.23%	32.0
7	**1**	158.9	64.01%	96.3	172.5	28.45%	97.2
7	**2**	37.6	15.14%	84.2	287.6	47.42%	85.9
7	**3**	21.7	8.76%	77.7	107.0	17.65%	77.2
7	**4**	30.0	12.09%	63.9	39.3	6.48%	67.5
7	**5**	0.0	0.00%	0.0	0.0	0.00%	0.0

Table 3: Initial State for FY2002

		Interstate			**Non-Interstate**		
District	**State**	**Miles**	**Percentage**	**Composite Rating**	**Miles**	**Percentage**	**Composite Rating**
1	**1**	95.4	98.47%	96.9	561.8	30.36%	97.4
1	**2**	1.5	1.53%	89.0	547.0	29.56%	85.6
1	**3**	0.0	0.00%	0.0	507.4	27.42%	75.6
1	**4**	0.0	0.00%	0.0	195.8	10.58%	66.7
1	**5**	0.0	0.00%	0.0	38.4	2.07%	51.7
2	**1**	22.8	50.86%	94.4	1156.1	43.80%	96.9
2	**2**	22.0	49.14%	87.0	885.7	33.55%	85.0
2	**3**	0.0	0.00%	0.0	364.4	13.81%	76.2
2	**4**	0.0	0.00%	0.0	226.8	8.59%	66.1
2	**5**	0.0	0.00%	0.0	6.6	0.25%	49.2
3	**1**	78.0	43.82%	99.3	1176.0	46.00%	96.9
3	**2**	55.5	31.16%	89.5	654.4	25.60%	85.0
3	**3**	33.9	19.07%	77.5	514.2	20.11%	76.2
3	**4**	10.6	5.95%	62.0	155.3	6.08%	66.4
3	**5**	0.0	0.00%	0.0	56.7	2.22%	47.6

4	**1**	99.2	100.00%	99.5	2007.9	55.89%	98.1
4	**2**	0.0	0.00%	0.0	871.7	24.27%	85.7
4	**3**	0.0	0.00%	0.0	511.6	14.24%	76.4
4	**4**	0.0	0.00%	0.0	184.7	5.14%	67.0
4	**5**	0.0	0.00%	0.0	16.4	0.46%	49.6
5	**1**	55.0	100.00%	100.0	1028.5	50.39%	96.9
5	**2**	0.0	0.00%	0.0	699.7	34.29%	85.2
5	**3**	0.0	0.00%	0.0	220.1	10.79%	75.2
5	**4**	0.0	0.00%	0.0	75.9	3.72%	65.5
5	**5**	0.0	0.00%	0.0	16.6	0.82%	49.8
6	**1**	178.3	80.60%	96.7	968.3	58.98%	96.6
6	**2**	42.9	19.40%	87.3	415.7	25.32%	85.6
6	**3**	0.0	0.00%	0.0	195.8	11.93%	76.1
6	**4**	0.0	0.00%	0.0	61.9	3.77%	67.6
6	**5**	0.0	0.00%	0.0	0.0	0.00%	0.0
7	**1**	103.8	66.37%	94.4	159.0	23.11%	97.6
7	**2**	46.7	29.88%	87.6	219.4	31.88%	85.2
7	**3**	0.0	0.00%	0.0	278.6	40.49%	75.6
7	**4**	5.9	3.75%	68.3	31.1	4.51%	67.8
7	**5**	0.0	0.00%	0.0	0.0	0.00%	0.0

Table 4: Initial State for FY2003

District	State	Interstate			Non-Interstate		
		Miles	Percentage	Composite Rating	Miles	Percentage	Composite Rating
1	1	140.8	92.06%	97.9	626.3	32.99%	97.8
1	2	0.0	0.00%	0.0	614.9	32.39%	85.3
1	3	12.1	7.94%	79.0	454.9	23.96%	76.7
1	4	0.0	0.00%	0.0	202.3	10.66%	65.3
1	5	0.0	0.00%	0.0	0.0	0.00%	0.0
2	1	53.3	57.48%	96.2	1586.9	50.17%	97.5
2	2	39.4	42.52%	87.2	910.0	28.77%	85.3
2	3	0.0	0.00%	0.0	470.2	14.87%	76.3
2	4	0.0	0.00%	0.0	154.1	4.87%	65.5
2	5	0.0	0.00%	0.0	41.9	1.33%	53.8
3	1	102.7	63.84%	97.9	1240.4	41.81%	97.4
3	2	27.1	16.87%	90.0	934.8	31.51%	85.1
3	3	31.0	19.29%	74.5	537.1	18.11%	75.9
3	4	0.0	0.00%	0.0	195.9	6.60%	66.4
3	5	0.0	0.00%	0.0	58.4	1.97%	43.9
4	1	75.9	100.00%	97.3	2071.2	53.80%	98.0
4	2	0.0	0.00%	0.0	831.5	21.60%	85.6
4	3	0.0	0.00%	0.0	683.0	17.74%	75.8
4	4	0.0	0.00%	0.0	249.0	6.47%	64.8
4	5	0.0	0.00%	0.0	15.1	0.39%	48.7
5	1	166.2	100.00%	100.0	1076.1	45.19%	97.4
5	2	0.0	0.00%	0.0	790.9	33.21%	85.7
5	3	0.0	0.00%	0.0	366.6	15.39%	76.3
5	4	0.0	0.00%	0.0	130.5	5.48%	67.3
5	5	0.0	0.00%	0.0	17.4	0.73%	49.2

6	**1**	125.7	49.44%	97.1	802.1	47.35%	96.7
6	**2**	128.5	50.56%	89.5	529.6	31.26%	86.1
6	**3**	0.0	0.00%	0.0	299.1	17.66%	77.2
6	**4**	0.0	0.00%	0.0	59.3	3.50%	67.8
6	**5**	0.0	0.00%	0.0	4.0	0.24%	52.0
7	**1**	155.8	39.74%	94.7	189.0	21.79%	97.2
7	**2**	162.9	41.54%	84.4	256.1	29.53%	83.7
7	**3**	29.8	7.61%	76.4	335.0	38.62%	74.9
7	**4**	8.7	2.21%	68.0	74.6	8.60%	67.0
7	**5**	34.9	8.91%	38.5	12.7	1.46%	51.0

Table 5: Initial State for FY2004

		Interstate			**Non-Interstate**		
District	**State**	**Miles**	**Percentage**	**Composite Rating**	**Miles**	**Percentage**	**Composite Rating**
1	**1**	149.1	99.02%	98.3	502.1	28.09%	97.4
1	**2**	1.5	0.98%	88.0	524.8	29.36%	85.0
1	**3**	0.0	0.00%	0.0	419.8	23.48%	75.8
1	**4**	0.0	0.00%	0.0	320.9	17.95%	65.3
1	**5**	0.0	0.00%	0.0	20.1	1.12%	49.5
2	**1**	55.3	73.13%	97.1	1454.1	46.16%	97.8
2	**2**	20.3	26.87%	86.4	871.4	27.66%	85.2
2	**3**	0.0	0.00%	0.0	567.0	18.00%	77.4
2	**4**	0.0	0.00%	0.0	211.3	6.71%	66.5
2	**5**	0.0	0.00%	0.0	46.3	1.47%	49.8
3	**1**	61.2	69.29%	96.2	877.8	38.87%	97.0
3	**2**	0.0	0.00%	0.0	675.0	29.89%	84.8
3	**3**	27.1	30.71%	79.0	517.4	22.91%	76.8
3	**4**	0.0	0.00%	0.0	172.0	7.62%	66.8

3	**5**	0.0	0.00%	0.0	16.4	0.73%	46.5
4	**1**	124.1	87.99%	99.0	1879.8	52.29%	98.1
4	**2**	17.0	12.01%	88.0	768.5	21.38%	85.6
4	**3**	0.0	0.00%	0.0	455.3	12.66%	76.7
4	**4**	0.0	0.00%	0.0	424.3	11.80%	65.3
4	**5**	0.0	0.00%	0.0	67.3	1.87%	51.2
5	**1**	213.2	100.00%	98.9	1020.6	42.08%	98.1
5	**2**	0.0	0.00%	0.0	805.0	33.19%	85.6
5	**3**	0.0	0.00%	0.0	416.2	17.16%	76.8
5	**4**	0.0	0.00%	0.0	155.7	6.42%	65.2
5	**5**	0.0	0.00%	0.0	27.7	1.14%	45.2
6	**1**	88.2	34.55%	95.5	718.1	39.31%	96.7
6	**2**	167.0	65.45%	88.1	730.1	39.97%	85.6
6	**3**	0.0	0.00%	0.0	333.2	18.24%	76.9
6	**4**	0.0	0.00%	0.0	45.5	2.49%	66.4
6	**5**	0.0	0.00%	0.0	0.0	0.00%	0.0
7	**1**	148.2	55.12%	95.1	153.6	18.51%	97.9
7	**2**	89.7	33.37%	86.1	200.0	24.09%	85.5
7	**3**	30.9	11.51%	76.5	391.2	47.12%	76.3
7	**4**	0.0	0.00%	0.0	85.3	10.28%	65.1
7	**5**	0.0	0.00%	0.0	0.0	0.00%	0.0

Table 6: Initial State for FY2005

District	State	Interstate			Non-Interstate		
		Miles	Percentage	Composite Rating	Miles	Percentage	Composite Rating
1	1	112.1	98.70%	95.7	701.9	29.57%	97.6
1	2	1.5	1.30%	90.0	623.6	26.27%	84.7
1	3	0.0	0.00%	0.0	695.5	29.30%	76.2
1	4	0.0	0.00%	0.0	345.1	14.54%	64.5
1	5	0.0	0.00%	0.0	7.6	0.32%	51.1
2	1	96.2	91.00%	99.7	1,420.0	44.02%	97.9
2	2	4.8	4.50%	85.0	799.7	24.79%	85.7
2	3	4.8	4.50%	80.0	632.2	19.60%	76.0
2	4	0.0	0.00%	0.0	339.1	10.51%	65.8
2	5	0.0	0.00%	0.0	34.7	1.08%	48.7
3	1	106.1	46.16%	96.8	1,395.1	42.41%	96.8
3	2	51.2	22.27%	84.8	761.3	23.14%	84.7
3	3	72.6	31.57%	76.4	688.4	20.93%	75.6
3	4	0.0	0.00%	0.0	423.4	12.87%	65.9
3	5	0.0	0.00%	0.0	21.4	0.65%	46.3
4	1	94.1	75.66%	98.5	1,960.6	50.70%	98.4
4	2	17.0	13.63%	88.0	944.5	24.42%	85.0
4	3	0.0	0.00%	0.0	612.0	15.83%	75.8
4	4	13.3	10.71%	69.0	338.3	8.75%	66.8
4	5	0.0	0.00%	0.0	11.9	0.31%	48.9
5	1	161.6	98.78%	97.7	1,004.8	40.30%	97.8
5	2	0.0	0.00%	0.0	680.1	27.28%	85.4
5	3	2.0	1.22%	75.0	561.3	22.51%	76.4
5	4	0.0	0.00%	0.0	224.7	9.01%	64.3
5	5	0.0	0.00%	0.0	22.3	0.90%	47.3

6	**1**	203.1	86.32%	93.9	651.0	33.83%	96.7
6	**2**	19.9	8.46%	87.2	711.2	36.96%	85.5
6	**3**	11.6	4.93%	78.0	346.0	17.98%	77.0
6	**4**	0.7	0.30%	64.0	216.0	11.23%	66.3
6	**5**	0.0	0.00%	0.0	0.0	0.00%	0.0
7	**1**	0.0	0.00%	0.0	178.9	21.00%	98.1
7	**2**	113.9	48.98%	94.2	215.3	25.27%	84.7
7	**3**	90.0	38.71%	85.9	306.2	35.94%	75.4
7	**4**	28.6	12.31%	76.6	129.8	15.24%	65.9
7	**5**	0.0	0.00%	0.0	21.7	2.55%	41.9

Table 7-1: Averaged Pavement Condition

Distric t	**State**	**Interstate**			**Non-Interstate**		
		Mile s	**Percentag e**	**Composit e Rating**	**Miles**	**Percentag e**	**Composit e Rating**
1	**1**		85.11%	97.501	769.3	30.86%	97.573
1	**2**		3.92%	88.875	735.7	29.51%	85.001
1	**3**		24.05%	77.332	650.1	26.08%	76.086
1	**4**		10.68%	67	317.3	12.73%	65.258
1	**5**		0.00%	0	25.7	1.03%	51.532
2	**1**		74.49%	97.044	1648. 4	46.80%	97.676
2	**2**		30.76%	86.408	986.6	28.01%	85.26
2	**3**		4.50%	80	590.7	16.77%	76.358
2	**4**		0.00%	0	263.1	7.47%	66.001
2	**5**		0.00%	0	33.1	0.94%	50.4
3	**1**		59.17%	97.656	1472. 3	40.60%	97.337
3	**2**		21.64%	87.826	975.5	26.90%	84.945

3	**3**		22.33%	76.481	739.1	20.38%	76.123
3	**4**		5.95%	62	391.3	10.79%	66.089
3	**5**		0.00%	0	47.9	1.32%	47.313
4	**1**		78.77%	98.861	2127.2	50.12%	98.073
4	**2**		26.57%	86.526	940.9	22.17%	85.38
4	**3**		0.00%	0	715.2	16.85%	76.107
4	**4**		10.58%	68.25	415.9	9.80%	65.815
4	**5**		5.31%	51	45.4	1.07%	49.187
5	**1**		94.78%	98.834	1285.9	42.83%	97.479
5	**2**		0.00%	0	920.8	30.67%	85.502
5	**3**		13.05%	77.5	524.8	17.48%	76.07
5	**4**		0.00%	0	234.2	7.80%	65.802
5	**5**		0.00%	0	36.6	1.22%	48.068
6	**1**		62.73%	95.793	1030.6	46.55%	97.139
6	**2**		35.97%	88.001	672.0	30.35%	85.609
6	**3**		4.93%	78	390.3	17.63%	76.85
6	**4**		0.30%	64	119.3	5.39%	66.981
6	**5**		0.00%	0	5.1	0.23%	42
7	**1**		56.31%	95.149	241.2	22.57%	97.628
7	**2**		33.78%	87.294	338.1	31.64%	85.016
7	**3**		16.65%	79.122	384.3	35.97%	75.874
7	**4**		7.59%	69.186	96.4	9.02%	66.676
7	**5**		8.91%	38.5	21.5	2.01%	46.45

Table 7-2: Interstate Miles from RC file

District	Two-way Centerline Miles (Asphalt)	Two-way Centerline Miles (Total)
1	219.7	342.0
2	76.0	384.8
3	258.8	557.3
4	121.2	210.4
5	176.5	385.7
6	236.0	309.5
7	363.7	549.9
Total	1,451.9	2,739.7

Table 7-3: Averaged Pavement Condition on Interstates

State	Percentage	Composite Rating
1	67.23%	97.22
2	21.46%	86.63
3	8.10%	76.87
4	2.49%	53.31
5	0.72%	17.90

6 Markov TPM Calculations

The TPM for each working district for each fiscal year was computed by

$$p_{ij} = \frac{\text{total project mileage of condition } j \text{ in year } (t+1)}{\text{total project mileage of condition } i \text{ in year } t}$$

and the final TPMs for all working districts were obtained by averaging the matrices generated for all duty year study. The computations are based on these steps (take 2005-2006 as an example):

1. Filter the original data as described in Section 3;
2. Match the 2005 projects and 2006 projects by the same project ID;
3. Separate the matched data by interstate and non-interstate route type;
4. For either route type:
5. Compute the total mileage of all 5 pavement conditions, respectively, in year 2005 for all 7 working districts;
6. Compute the total mileage of all 5 pavement conditions respectively in year 2006 for all 7 working districts;
7. For each working district, put the pavement conditions and corresponding total mileages of 2005, pavement conditions, and corresponding total mileages of 2006 together
8. Apply the formula above to compute each p_{ij}, where $1 \le i \le j \le 5$.

The TPMs for all working districts in different years were estimated and summarized in Tables 8 to 14.

Table 8: Non-Interstate TPM - District 1

1999-2000					
	Excellent	**Good**	**Fair**	**Poor**	**Bad**
Excellent	60.65%	39.35%	0.00%	0.00%	0.00%
Good	0.00%	64.66%	35.34%	0.00%	0.00%
Fair	0.00%	0.00%	76.91%	23.09%	0.00%
Poor	0.00%	0.00%	0.00%	96.25%	3.75%
Bad	0.00%	0.00%	0.00%	0.00%	100.00%
2002-2003					
Excellent	60.96%	39.04%	0.00%	0.00%	0.00%
Good	0.00%	65.70%	34.30%	0.00%	0.00%
Fair	0.00%	0.00%	66.47%	33.53%	0.00%
Poor	0.00%	0.00%	0.00%	100.00%	0.00%

Bad	0.00%	0.00%	0.00%	0.00%	100.00%
2003-2004					
Excellent	65.21%	34.79%	0.00%	0.00%	0.00%
Good	0.00%	59.95%	40.05%	0.00%	0.00%
Fair	0.00%	0.00%	70.28%	29.72%	0.00%
Poor	0.00%	0.00%	0.00%	100.00%	0.00%
Bad	0.00%	0.00%	0.00%	0.00%	100.00%
2004-2005					
Excellent	55.00%	45.00%	0.00%	0.00%	0.00%
Good	0.00%	59.18%	40.82%	0.00%	0.00%
Fair	0.00%	0.00%	78.21%	21.79%	0.00%
Poor	0.00%	0.00%	0.00%	100.00%	0.00%
Bad	0.00%	0.00%	0.00%	0.00%	100.00%
2005-2006					
Excellent	69.92%	30.08%	0.00%	0.00%	0.00%
Good	0.00%	63.50%	36.50%	0.00%	0.00%
Fair	0.00%	0.00%	66.29%	33.71%	0.00%
Poor	0.00%	0.00%	0.00%	87.42%	12.58%
Bad	0.00%	0.00%	0.00%	0.00%	100.00%

Table 9: Non-Interstate TPM - District 2

1999-2000					
	Excellent	**Good**	**Fair**	**Poor**	**Bad**
Excellent	80.17%	19.83%	0.00%	0.00%	0.00%
Good	0.00%	64.80%	35.20%	0.00%	0.00%
Fair	0.00%	0.00%	80.85%	19.15%	0.00%
Poor	0.00%	0.00%	0.00%	100.00%	0.00%
Bad	0.00%	0.00%	0.00%	0.00%	100.00%
2002-2003					
Excellent	80.50%	19.50%	0.00%	0.00%	0.00%
Good	0.00%	58.50%	41.50%	0.00%	0.00%
Fair	0.00%	0.00%	65.62%	34.38%	0.00%
Poor	0.00%	0.00%	0.00%	84.89%	15.11%
Bad	0.00%	0.00%	0.00%	0.00%	100.00%
2003-2004					
Excellent	76.93%	23.07%	0.00%	0.00%	0.00%
Good	0.00%	67.20%	32.80%	0.00%	0.00%
Fair	0.00%	0.00%	71.10%	28.90%	0.00%
Poor	0.00%	0.00%	0.00%	40.40%	59.60%
Bad	0.00%	0.00%	0.00%	0.00%	100.00%
2004-2005					
Excellent	66.17%	33.83%	0.00%	0.00%	0.00%
Good	0.00%	66.27%	33.73%	0.00%	0.00%
Fair	0.00%	0.00%	68.25%	31.75%	0.00%
Poor	0.00%	0.00%	0.00%	97.82%	2.18%
Bad	0.00%	0.00%	0.00%	0.00%	100.00%
2005-2006					
Excellent	72.16%	27.84%	0.00%	0.00%	0.00%
Good	0.00%	69.30%	30.70%	0.00%	0.00%
Fair	0.00%	0.00%	65.30%	34.70%	0.00%

Poor	0.00%	0.00%	0.00%	90.13%	9.87%
Bad	0.00%	0.00%	0.00%	0.00%	100.00%

Table 10: Non-Interstate TPM - District 3

1999-2000					
	Excellent	**Good**	**Fair**	**Poor**	**Bad**
Excellent	72.83%	27.17%	0.00%	0.00%	0.00%
Good	0.00%	77.69%	22.31%	0.00%	0.00%
Fair	0.00%	0.00%	46.22%	53.78%	0.00%
Poor	0.00%	0.00%	0.00%	45.55%	54.45%
Bad	0.00%	0.00%	0.00%	0.00%	100.00%
2002-2003					
Excellent	78.27%	21.73%	0.00%	0.00%	0.00%
Good	0.00%	65.22%	34.78%	0.00%	0.00%
Fair	0.00%	0.00%	63.03%	36.97%	0.00%
Poor	0.00%	0.00%	0.00%	100.00%	0.00%
Bad	0.00%	0.00%	0.00%	0.00%	100.00%
2003-2004					
Excellent	77.07%	22.93%	0.00%	0.00%	0.00%
Good	0.00%	72.03%	27.97%	0.00%	0.00%
Fair	0.00%	0.00%	86.81%	13.19%	0.00%
Poor	0.00%	0.00%	0.00%	94.02%	5.98%
Bad	0.00%	0.00%	0.00%	0.00%	100.00%
2004-2005					
Excellent	80.45%	19.55%	0.00%	0.00%	0.00%
Good	0.00%	62.46%	37.54%	0.00%	0.00%
Fair	0.00%	0.00%	66.05%	33.95%	0.00%
Poor	0.00%	0.00%	0.00%	100.00%	0.00%
Bad	0.00%	0.00%	0.00%	0.00%	100.00%
2005-2006					

Excellent	77.81%	22.19%	0.00%	0.00%	0.00%
Good	0.00%	67.44%	32.56%	0.00%	0.00%
Fair	0.00%	0.00%	66.68%	33.32%	0.00%
Poor	0.00%	0.00%	0.00%	83.04%	16.96%
Bad	0.00%	0.00%	0.00%	0.00%	100.00%

Table 11: Non-Interstate TPM - District 4

1999-2000					
	Excellent	**Good**	**Fair**	**Poor**	**Bad**
Excellent	69.77%	30.23%	0.00%	0.00%	0.00%
Good	0.00%	49.18%	50.82%	0.00%	0.00%
Fair	0.00%	0.00%	62.66%	37.34%	0.00%
Poor	0.00%	0.00%	0.00%	95.59%	4.41%
Bad	0.00%	0.00%	0.00%	0.00%	100.00%
2002-2003					
Excellent	77.98%	22.02%	0.00%	0.00%	0.00%
Good	0.00%	65.60%	34.40%	0.00%	0.00%
Fair	0.00%	0.00%	68.63%	31.37%	0.00%
Poor	0.00%	0.00%	0.00%	100.00%	0.00%
Bad	0.00%	0.00%	0.00%	0.00%	100.00%
2003-2004					
Excellent	78.83%	21.17%	0.00%	0.00%	0.00%
Good	0.00%	58.70%	41.30%	0.00%	0.00%
Fair	0.00%	0.00%	43.25%	56.75%	0.00%
Poor	0.00%	0.00%	0.00%	91.48%	8.52%
Bad	0.00%	0.00%	0.00%	0.00%	100.00%
2004-2005					
Excellent	77.74%	22.26%	0.00%	0.00%	0.00%
Good	0.00%	75.47%	24.53%	0.00%	0.00%
Fair	0.00%	0.00%	70.35%	29.65%	0.00%

Poor	0.00%	0.00%	0.00%	100.00%	0.00%
Bad	0.00%	0.00%	0.00%	0.00%	100.00%
2005-2006					
Excellent	84.51%	15.49%	0.00%	0.00%	0.00%
Good	0.00%	60.35%	39.65%	0.00%	0.00%
Fair	0.00%	0.00%	60.69%	39.31%	0.00%
Poor	0.00%	0.00%	0.00%	95.16%	4.84%
Bad	0.00%	0.00%	0.00%	0.00%	100.00%

Table 12: Non-Interstate TPM - District 5

1999-2000					
	Excellent	**Good**	**Fair**	**Poor**	**Bad**
Excellent	69.23%	30.77%	0.00%	0.00%	0.00%
Good	0.00%	71.45%	28.55%	0.00%	0.00%
Fair	0.00%	0.00%	77.72%	22.28%	0.00%
Poor	0.00%	0.00%	0.00%	86.39%	13.61%
Bad	0.00%	0.00%	0.00%	0.00%	100.00%
2002-2003					
Excellent	51.55%	48.45%	0.00%	0.00%	0.00%
Good	0.00%	67.37%	32.63%	0.00%	0.00%
Fair	0.00%	0.00%	52.42%	47.58%	0.00%
Poor	0.00%	0.00%	0.00%	82.84%	17.16%
Bad	0.00%	0.00%	0.00%	0.00%	100.00%
2003-2004					
Excellent	74.40%	25.60%	0.00%	0.00%	0.00%
Good	0.00%	78.90%	21.10%	0.00%	0.00%
Fair	0.00%	0.00%	77.44%	22.56%	0.00%
Poor	0.00%	0.00%	0.00%	79.39%	20.61%
Bad	0.00%	0.00%	0.00%	0.00%	100.00%
2004-2005					

Excellent	81.99%	18.01%	0.00%	0.00%	0.00%
Good	0.00%	70.45%	29.55%	0.00%	0.00%
Fair	0.00%	0.00%	78.92%	21.08%	0.00%
Poor	0.00%	0.00%	0.00%	98.79%	1.21%
Bad	0.00%	0.00%	0.00%	0.00%	100.00%
2005-2006					
Excellent	84.94%	15.06%	0.00%	0.00%	0.00%
Good	0.00%	65.97%	34.03%	0.00%	0.00%
Fair	0.00%	0.00%	67.63%	32.37%	0.00%
Poor	0.00%	0.00%	0.00%	73.05%	26.95%
Bad	0.00%	0.00%	0.00%	0.00%	100.00%

Table 13: Non-Interstate TPM - District 6

1999-2000					
	Excellent	**Good**	**Fair**	**Poor**	**Bad**
Excellent	51.45%	48.55%	0.00%	0.00%	0.00%
Good	0.00%	51.86%	48.14%	0.00%	0.00%
Fair	0.00%	0.00%	84.26%	15.74%	0.00%
Poor	0.00%	0.00%	0.00%	0.00%	0.00%
Bad	0.00%	0.00%	0.00%	0.00%	100.00%
2002-2003					
Excellent	72.74%	27.26%	0.00%	0.00%	0.00%
Good	0.00%	61.39%	38.61%	0.00%	0.00%
Fair	0.00%	0.00%	77.41%	22.59%	0.00%
Poor	0.00%	0.00%	0.00%	100.00%	0.00%
Bad	0.00%	0.00%	0.00%	0.00%	100.00%
2003-2004					
Excellent	60.84%	39.16%	0.00%	0.00%	0.00%
Good	0.00%	76.80%	23.20%	0.00%	0.00%
Fair	0.00%	0.00%	90.39%	9.61%	0.00%

Poor	0.00%	0.00%	0.00%	100.00%	0.00%
Bad	0.00%	0.00%	0.00%	0.00%	100.00%
2004-2005					
Excellent	62.77%	37.23%	0.00%	0.00%	0.00%
Good	0.00%	72.35%	27.65%	0.00%	0.00%
Fair	0.00%	0.00%	71.65%	28.35%	0.00%
Poor	0.00%	0.00%	0.00%	100.00%	0.00%
Bad	0.00%	0.00%	0.00%	0.00%	100.00%
2005-2006					
Excellent	60.35%	39.65%	0	0	0
Good	0.00%	74.90%	25.10%	0.00%	0.00%
Fair	0.00%	0.00%	66.91%	33.09%	0.00%
Poor	0.00%	0.00%	0.00%	100.00%	0.00%
Bad	0.00%	0.00%	0.00%	0.00%	100.00%

Table 14: Non-Interstate TPM - District 7

1999-2000					
	Excellent	**Good**	**Fair**	**Poor**	**Bad**
Excellent	54.62%	45.38%	0.00%	0.00%	0.00%
Good	0.00%	85.83%	14.17%	0.00%	0.00%
Fair	0.00%	0.00%	96.21%	3.79%	0.00%
Poor	0.00%	0.00%	0.00%	100.00%	0.00%
Bad	0.00%	0.00%	0.00%	0.00%	100.00%
2002-2003					
Excellent	49.81%	50.19%	0.00%	0.00%	0.00%
Good	0.00%	60.66%	39.34%	0.00%	0.00%
Fair	0.00%	0.00%	80.71%	19.29%	0.00%
Poor	0.00%	0.00%	0.00%	100.00%	0.00%
Bad	0.00%	0.00%	0.00%	0.00%	100.00%
2003-2004					

Excellent	60.26%	39.74%	0.00%	0.00%	0.00%
Good	0.00%	47.31%	52.69%	0.00%	0.00%
Fair	0.00%	0.00%	73.13%	26.87%	0.00%
Poor	0.00%	0.00%	0.00%	100.00%	0.00%
Bad	0.00%	0.00%	0.00%	0.00%	100.00%
2004-2005					
Excellent	70.60%	29.40%	0.00%	0.00%	0.00%
Good	0.00%	70.53%	29.47%	0.00%	0.00%
Fair	0.00%	0.00%	72.72%	27.28%	0.00%
Poor	0.00%	0.00%	0.00%	0.00%	0.00%
Bad	0.00%	0.00%	0.00%	0.00%	100.00%
2005-2006					
Excellent	89.27%	10.73%	0.00%	0.00%	0.00%
Good	0.00%	66.85%	33.15%	0.00%	0.00%
Fair	0.00%	0.00%	72.97%	27.03%	0.00%
Poor	0.00%	0.00%	0.00%	73.93%	26.07%
Bad	0.00%	0.00%	0.00%	0.00%	100.00%

Table 15: Non-Interstate Averaged TPM

District 1					
	Excellent	**Good**	**Fair**	**Poor**	**Bad**
Excellent	62.35%	37.65%	0.00%	0.00%	0.00%
Good	0.00%	62.60%	37.40%	0.00%	0.00%
Fair	0.00%	0.00%	71.63%	28.37%	0.00%
Poor	0.00%	0.00%	0.00%	96.73%	3.27%
Bad	0.00%	0.00%	0.00%	0.00%	100.00%
District 2					
Excellent	75.19%	24.81%	0.00%	0.00%	0.00%
Good	0.00%	65.21%	34.79%	0.00%	0.00%
Fair	0.00%	0.00%	70.22%	29.78%	0.00%

Poor	0.00%	0.00%	0.00%	82.65%	17.35%
Bad	0.00%	0.00%	0.00%	0.00%	100.00%
District 3					
	Excellent	Good	Fair	Poor	Bad
Excellent	77.28%	22.72%	0.00%	0.00%	0.00%
Good	0.00%	68.97%	31.03%	0.00%	0.00%
Fair	0.00%	0.00%	65.76%	34.24%	0.00%
Poor	0.00%	0.00%	0.00%	84.52%	15.48%
Bad	0.00%	0.00%	0.00%	0.00%	100.00%
District 4					
Excellent	77.77%	22.23%	0.00%	0.00%	0.00%
Good	0.00%	61.86%	38.14%	0.00%	0.00%
Fair	0.00%	0.00%	61.12%	38.88%	0.00%
Poor	0.00%	0.00%	0.00%	96.45%	3.55%
Bad	0.00%	0.00%	0.00%	0.00%	100.00%
District 5					
Excellent	72.42%	27.58%	0.00%	0.00%	0.00%
Good	0.00%	70.83%	29.17%	0.00%	0.00%
Fair	0.00%	0.00%	70.82%	29.18%	0.00%
Poor	0.00%	0.00%	0.00%	84.09%	15.91%
Bad	0.00%	0.00%	0.00%	0.00%	100.00%
District 6					
Excellent	61.63%	38.37%	0.00%	0.00%	0.00%
Good	0.00%	67.46%	32.54%	0.00%	0.00%
Fair	0.00%	0.00%	78.12%	21.88%	0.00%
Poor	0.00%	0.00%	0.00%	100.00%	0.00%
Bad	0.00%	0.00%	0.00%	0.00%	100.00%
District 7					
Excellent	67.49%	32.51%	0.00%	0.00%	0.00%

Good	0.00%	61.34%	38.66%	0.00%	0.00%
Fair	0.00%	0.00%	74.88%	25.12%	0.00%
Poor	0.00%	0.00%	0.00%	68.48%	6.52%
Bad	0.00%	0.00%	0.00%	0.00%	100.00%

Due to the data insufficiency of Interstate routes, we processed the interstate data for the TPM computation in a different way: we combined all the working districts together, i.e. no working district categories in the data processing, to obtain the TPM estimation results.

Table 16: Interstate TPM

1999-2000					
	Excellent	**Good**	**Fair**	**Poor**	**Bad**
Excellent	80.27%	19.73%	0.00%	0.00%	0.00%
Good	0.00%	100.00%	0.00%	0.00%	0.00%
Fair	0.00%	0.00%	29.50%	70.50%	0.00%
Poor	0.00%	0.00%	0.00%	100.00%	0.00%
Bad	0.00%	0.00%	0.00%	0.00%	100.00%
2002-2003					
Excellent	90.64%	9.36%	0.00%	0.00%	0.00%
Good	0.00%	86.97%	13.03%	0.00%	0.00%
Fair	0.00%	0.00%	100.00%	0.00%	0.00%
Poor	0.00%	0.00%	0.00%	0.00%	0.00%
Bad	0.00%	0.00%	0.00%	0.00%	100.00%
2003-2004					
Excellent	72.11%	27.89%	0.00%	0.00%	0.00%
Good	0.00%	95.77%	4.23%	0.00%	0.00%
Fair	0.00%	0.00%	100.00%	0.00%	0.00%
Poor	0.00%	0.00%	0.00%	0.00%	0.00%
Bad	0.00%	0.00%	0.00%	0.00%	100.00%
2004-2005					

Excellent	90.62%	9.38%	0.00%	0.00%	0.00%
Good	0.00%	78.91%	21.09%	0.00%	0.00%
Fair	0.00%	0.00%	0.00%	0.00%	0.00%
Poor	0.00%	0.00%	0.00%	0.00%	0.00%
Bad	0.00%	0.00%	0.00%	0.00%	100.00%
2005-2006					
Excellent	53.65%	46.35%	0.00%	0.00%	0.00%
Good	0.00%	80.97%	19.03%	0.00%	0.00%
Fair	0.00%	0.00%	60.97%	39.03%	0.00%
Poor	0.00%	0.00%	0.00%	0.00%	100.00%
Bad	0.00%	0.00%	0.00%	0.00%	100.00%

Table 17: Interstate Averaged TPM

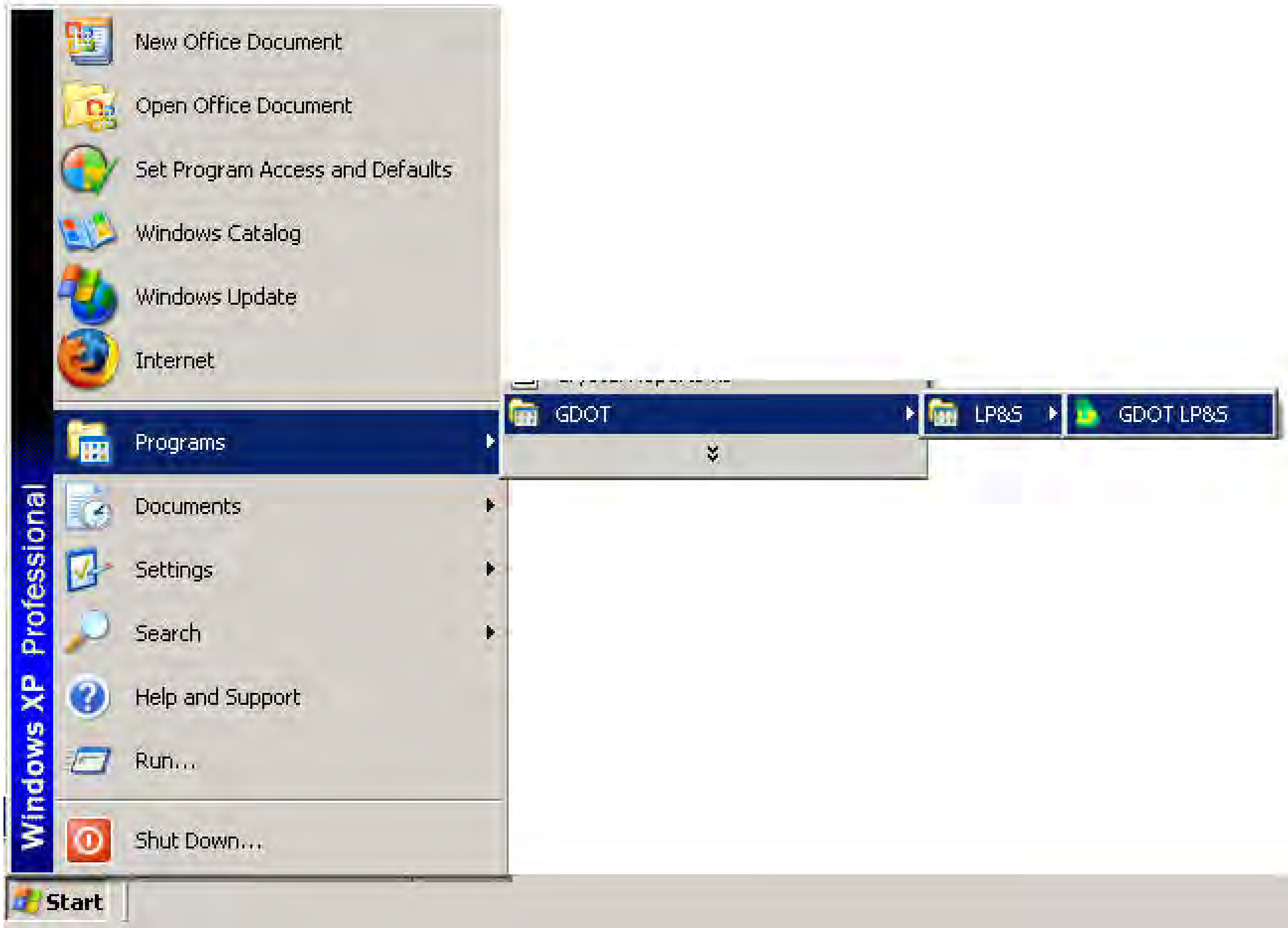
	Excellent	**Good**	**Fair**	**Poor**	**Bad**
Excellent	77.46%	22.54%	0.00%	0.00%	0.00%
Good	0.00%	88.52%	11.48%	0.00%	0.00%
Fair	0.00%	0.00%	72.62%	27.38%	0.00%
Poor	0.00%	0.00%	0.00%	50.00%	50.00%
Bad	0.00%	0.00%	0.00%	0.00%	100.00%

Appendix IV: User's Manual for GDOT LP&S

1 Launch Program

You can launch the GDOT LP&S program by either of the following two methods:

- Click **Start→Programs→GDOT→LP&S→GDOT LP&S**



- Click the **GDOT LP&S** icon on the desktop

2 GDOT LP&S Tutorial

This tutorial shows you how to use the GDOT Asphalt Pavement Network-Level Long-term Performance Forecasting and Simulation (GDOT LP&S) program.

The tutorial is divided into 8 steps.

In this tutorial, you will see how to handle each of the tasks in the GDOT LP&S program, including:

Step 1: Operations on Simulation

Step 2: Operations on Scenario

Step 3: Inputs for a Scenario (1): Initial States

Step 4: Inputs for a Scenario (2): Markov Chains

Step 5: Inputs for a Scenario (3): Budget Allocations

Step 6: Inputs for a Scenario (4): Treatments

Step 7: Inputs for a Scenario (5): Simulation Strategies

Step 8: Running Simulation and Reporting

Step 1: Operations on Simulation

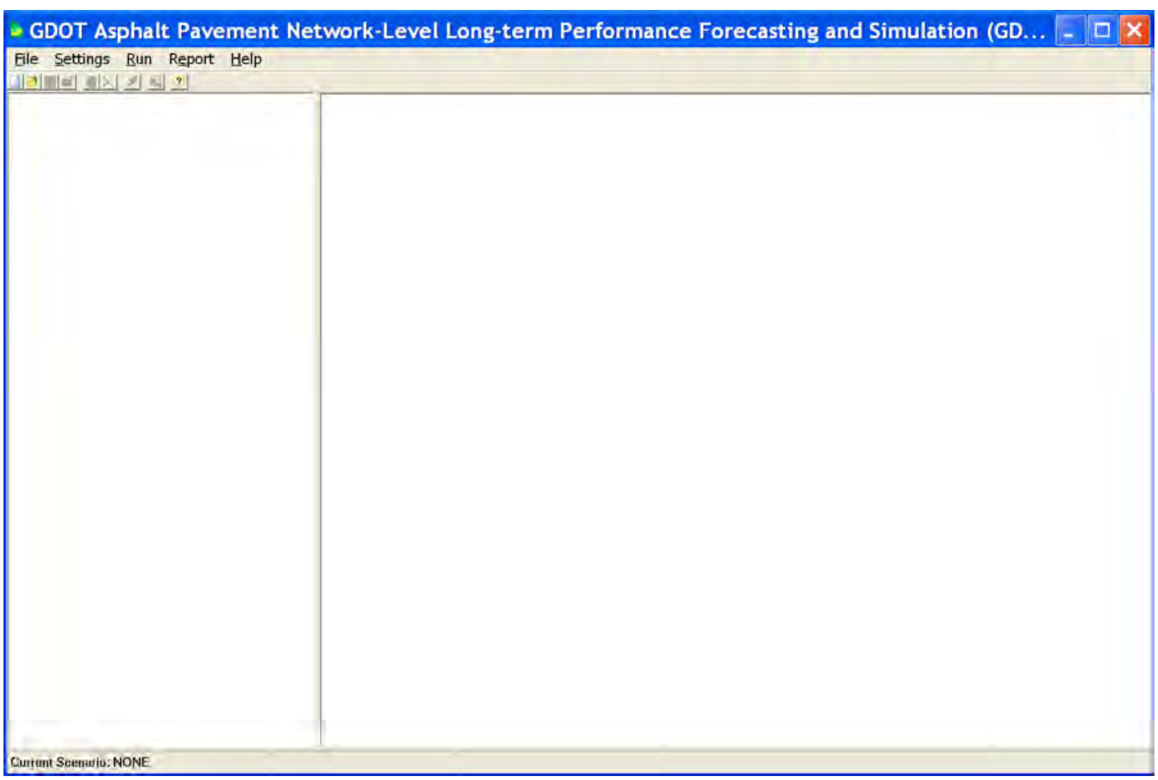
The GDOT LP&S program stores settings (inputs), scenario information, and results in an MS Access database. Each simulation has a corresponding database in which several scenarios can be constructed and analyzed.

The following steps show you how to create a new simulation or open an existing simulation:

- Launch the GDOT LP&S program
- Create a new simulation
- Rename a simulation
- Save a simulation
- Open an existing simulation
- Close the current simulation

Launch the GDOT LP&S program

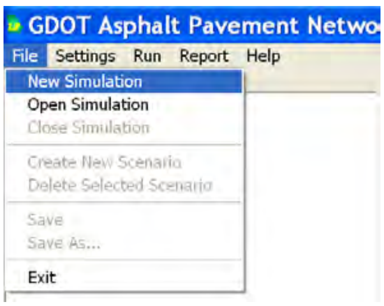
Refer to "Launch Program" to see how to launch the GDOT LP&S program.



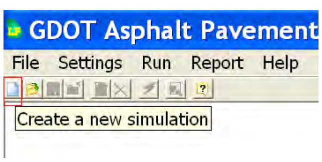
Create a new simulation

To start using the GDOT LP&S program, first create a new simulation. Within this simulation, you can customize all inputs and construct virtually an unlimited number of scenarios to conduct what-if analyses. You can choose either of the following ways by selecting a menu item or clicking a toolbar button to create a new simulation:

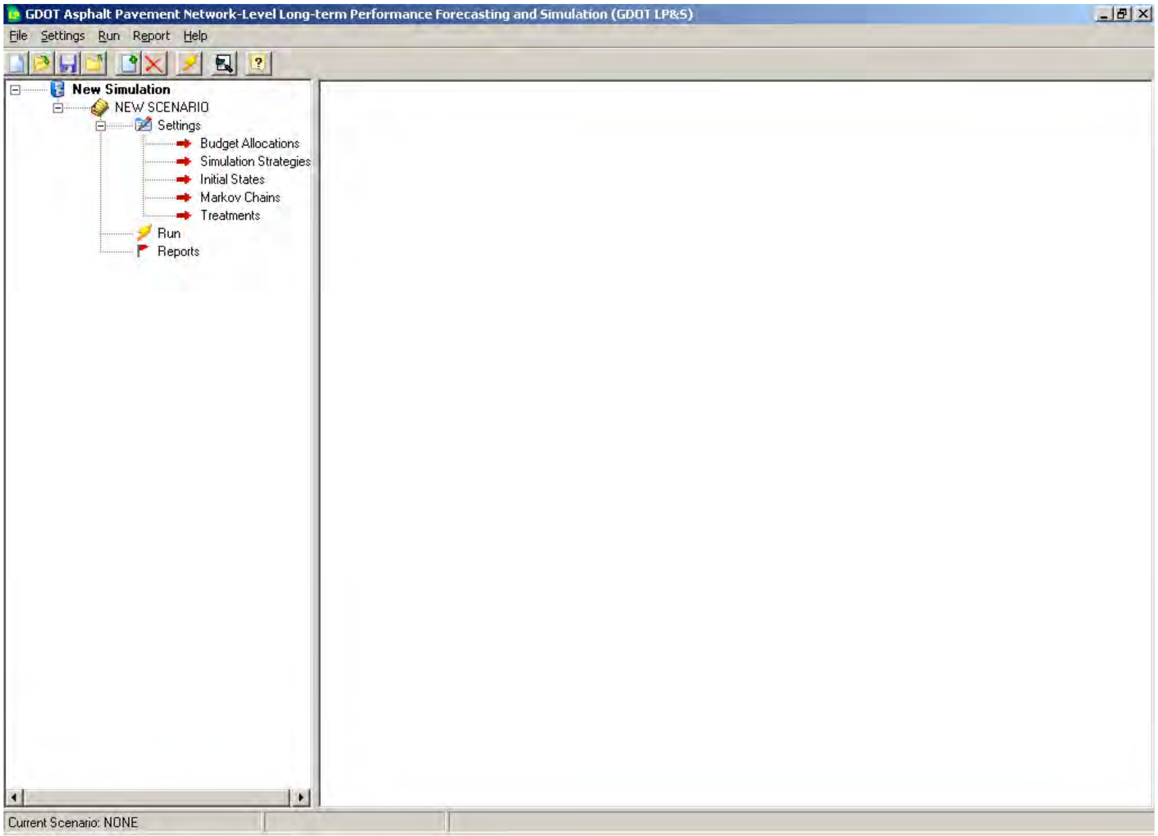
- Select menu item **File→New Simulation**



- Or click the toolbar button



After the new simulation is created, the form changes its appearance as follows:



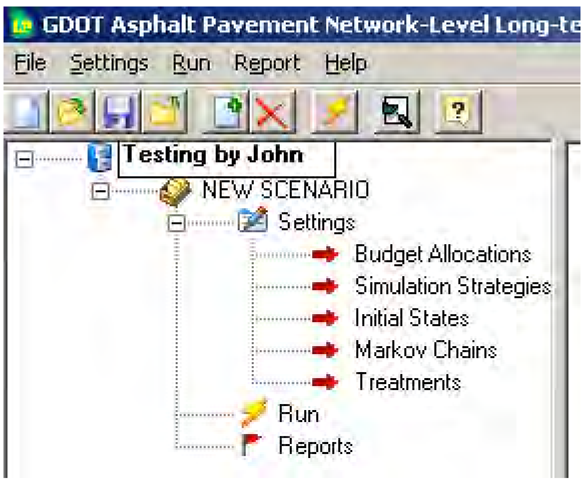
The remainder of the tutorial will introduce the use of all functions. A brief introduction follows:

In the left panel, the hierarchical structure illustrates the organization of the simulation. The **New Simulation** is the only root node (you can change its name to any name desired). The **NEW SCENARIO** is the second-level node (again, you can change its name). In a simulation, several scenarios can be created. Under each scenario node, there are three third-level nodes, **Settings**, **Run,** and **Reports**, which represent the main operation flow in the GDOT LP&S program. Under the **Settings** node, there are 5 items, which are inputs for a scenario. You may want to review or modify each input item before you run the scenario. After you have successfully run a scenario, you can obtain the reports by clicking the **Reports** node.

Rename a simulation

The term **New Simulation** is given by the program as default, which means a new simulation can be saved. You can change it by editing it on the form or saving the simulation as a new name:

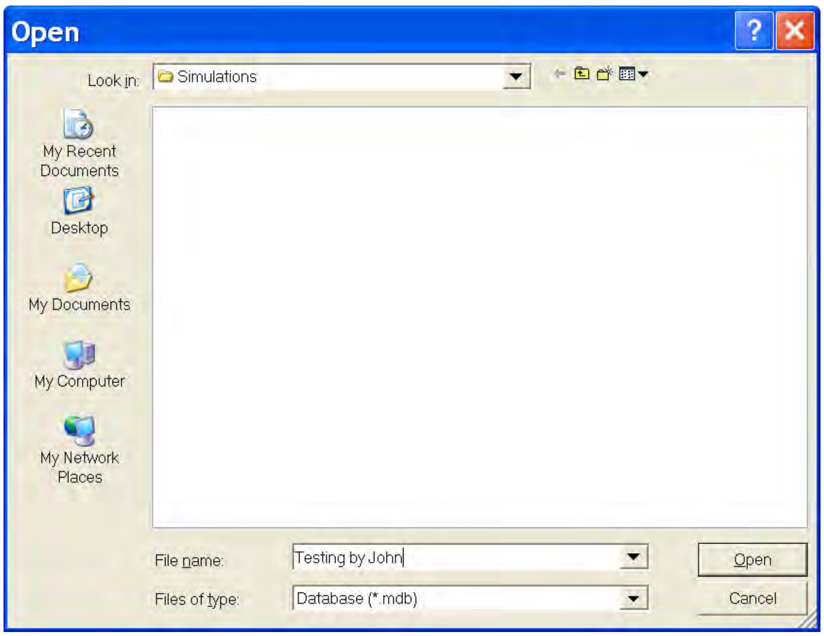
- First, highlight the **New Simulation** node. Then left-click it again. Type in a meaningful name: for example, "Testing by John" .



Tips: The actions of highlighting and left-clicking entails two consecutive mouse clicks in most cases. If you click the left mouse button to highlight the node and the time interval between the first and the second left click is too short, it will perform as a typical double-click, which will unfold the hierarchical structure instead of switching to the editing status. To avoid this, keep the time between two left mouse clicks longer than for a typical double click. An alternative method is to click the right-mouse button for highlighting and use the left-mouse button for switching to the editing status.

or

- Select **File→Save As**. An open file form will pop up. Type the name in the **File name** box and click **Open**.

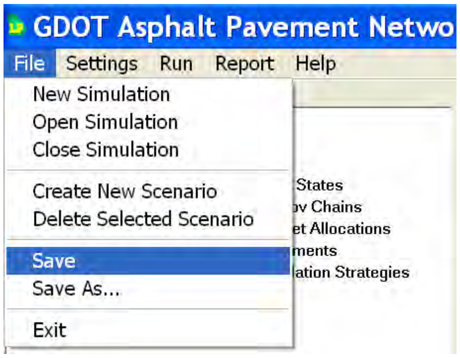


Note: The difference between the above two options is that the first operation doesn't save the simulation until you do it as described in the following section.

Save a simulation

From the above section, you already know how to save the simulation by assigning a name to it. Another method to save a simulation is to do it without explicitly assigning a name. You have two ways to do it:

- First, select **File→Save**



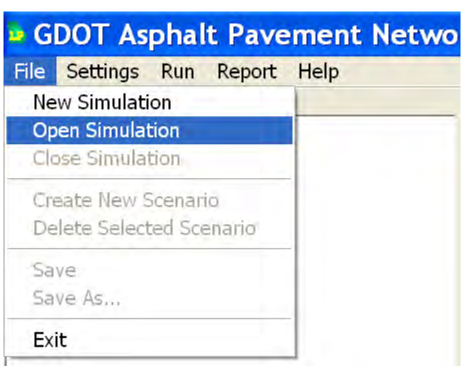
or

- Second, click the toolbar "save" icon (indicated by the red rectangle in the illustration below):

2.1 3.5 Open an existing simulation

To open a simulation you have previously created, choose either of the following two methods:

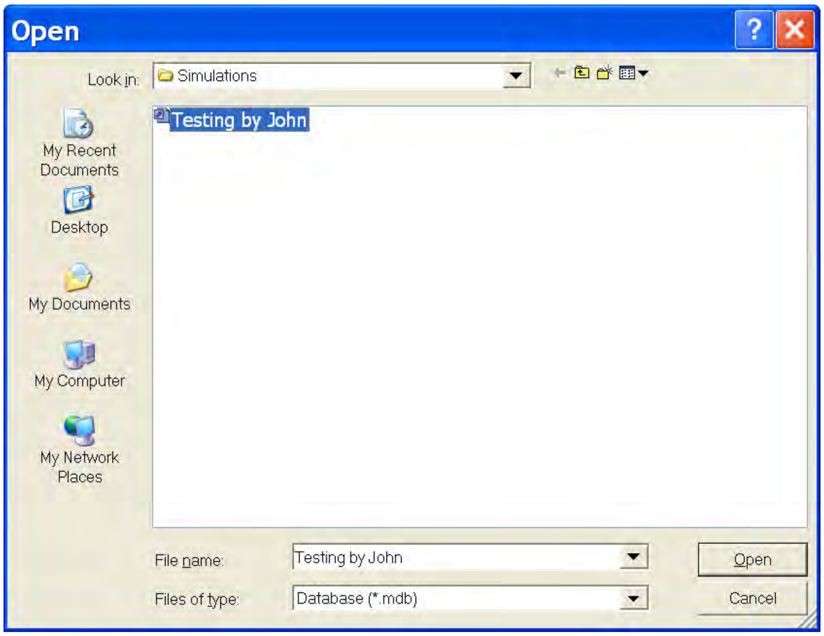
- Select **File→Open Simulation**



or

- Click the toolbar button

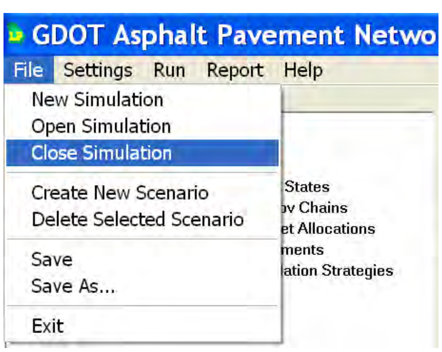
Then the Open file form pops up. Select the simulation database you are going to open and click **Open**.



Close the current simulation

To close the current simulation, you can

- Select **File→Close Simulation**



or

- Click the toolbar button

Step 2: Operations on Scenario

A scenario is one of the combinations of pavement initial conditions, pavement condition transition probabilities, funding allocations, treatment methods, and simulation strategy. By running different scenarios, you can forecast pavement performance, conduct what-if analyses, and perform need analyses under different constraints.

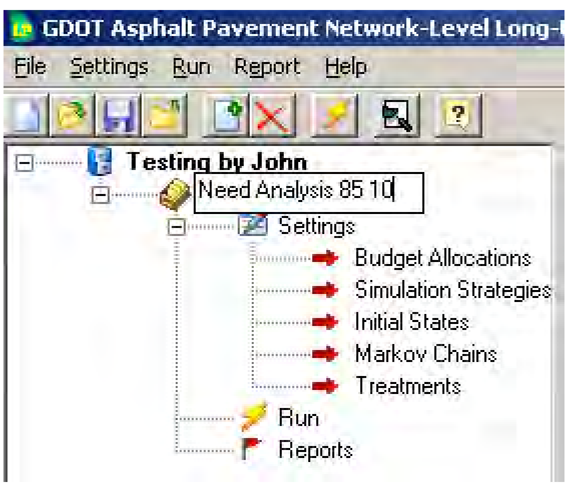
The following steps show how to

- Rename a scenario
- Create a new scenario
- Delete a scenario

Rename a scenario

You may notice that a default scenario named **New Scenario** is always present when a new simulation is created. You can change the default name to a more meaningful one, such as "Need Analysis 85 10", by editing it.

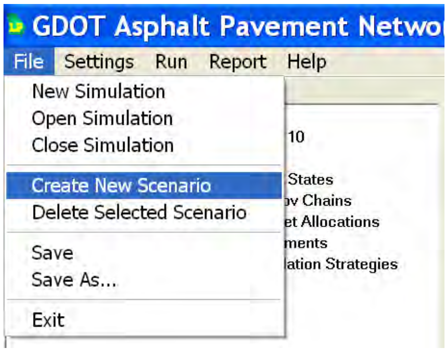
- First, highlight the **New Scenario** node. Then left-click it again. Type in a meaningful name, such as "Need Analysis 85 10".



Create a new scenario

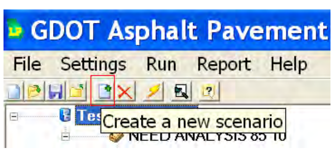
To construct another scenario with a different combination of inputs, you may want to create a new scenario instead of overwriting the existing one by using either of the following two methods:

- Select **File→Create New Scenario**



or

- Click the toolbar button



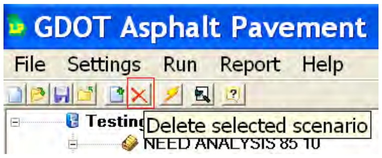
Delete a scenario

To delete a scenario from the current simulation database, highlight the scenario. Then

- Select **File→Delete Selected Scenario**

or

- Click the toolbar button



NOTE: If only one scenario exists in the current simulation database, you cannot delete it.

Step 3: Inputs for a Scenario (1): Initial States

Before you can run a simulation, you need to review or modify 5 settings (inputs).

Each time you create a new scenario, the program will assign each input with default values, which might not fit your needs. Before you run the simulation, review each setting to ensure the values are correct. The red right-direction arrow icon means the corresponding setting has not been reviewed or modified (or simply not touched by the user). Otherwise, it will have been changed to a green OK marker.

The **Initial States** represents the condition distribution of the pavement network at the starting point of an analysis period. In the GDOT LP&S program, Georgia pavements are divided into 14 families (categories) as follows:

No.	Family
1	District 1, Interstate Route
2	District 1, Non-Interstate Route
3	District 2, Interstate Route
4	District 2, Non-Interstate Route
5	District 3, Interstate Route
6	District 3, Non-Interstate Route
7	District 4, Interstate Route
8	District 4, Non-Interstate Route
9	District 5, Interstate Route
10	District 5, Non-Interstate Route
11	District 6, Interstate Route
12	District 6, Non-Interstate Route

13	District 7, Interstate Route
14	District 7, Non-Interstate Route

For each family, the following attributes should be provided as the initial states:

1	Condition distributions (mileage percentages of Excellent, Good, Fair, Poor and Bad)
2	Total mileage (in mile)
3	Composite rating for each state (Excellent, Good, Fair, Poor or Bad)

The definition of a State is as follows.

State	Rating Range
Excellent	91~100
Good	81~90
Fair	71~80
Poor	55~70
Bad	<55

The following steps show how to input initial states for a scenario:

- Open the input form
- Edit the form
- Save the inputs

Open the input form

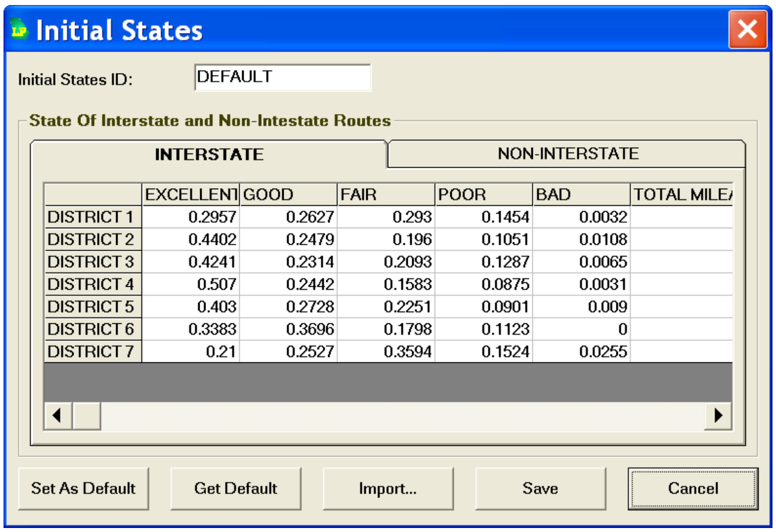
To open the form,

- Click the **Initial States** node under the scenario you are working on.

Or

- Select **Settings→ Initial States**

NOTE: Ensure the proper scenario is selected when you open the form by selecting the appropriate menu item.



The program will show the Initial States ID as **DEFAULT**. You can change it if desired. The 14 families are arranged on two tab grids. To input data for Interstate or Non-interstate, you need to click the appropriate tab to make it visible. The meanings of the 5 buttons are as follows:

- **Set as Default**: Set as default the set of initial conditions shown on the form. Next time, the program will use the current setting as the default value for a new scenario.
- **Get Default**: Load the default initial conditions, and set them set as current.
- **Import**: Load a saved set of initial conditions, and set it as current.
- **Save**: Save the set of initial conditions on the form, and set it as current.
- **Cancel**: Close form without saving.

Edit the form

To modify a value, click on it, and change it. Rules for the data are as follows:

	Rule
1	Each value for Excellent, Good, Fair, Poor or Bad should be less than or equal to 1.0
2	Each value for Excellent, Good, Fair, Poor or Bad should be greater than or equal to 0.0
3	In each family, the sum of Excellent, Good, Fair, Poor and Bad should be equal to 1.0
4	Total mileage for each family should be greater than 0
5	The values for Ave_Rating1, Ave_Rating2, Ave_Rating3, Ave_Rating4 and Ave_Rating5 should fall into the same range with the definition of Excellent, Good, Fair and Poor respectively.

If any of the above rules are violated, an error message will appear when you try to save the current modifications.

Save the inputs

After you finish inputting the initial states, click **Save** to save the setting and exit the form. If you don't want to make any changes, just click **Cancel** to exit the form. If a set of inputs is saved, the program will automatically assign an ID to it according to current time (for example, 100523 represents 10:05:23).

When you quit the form, you will see the red right-direction arrow has changed to a green OK marker:


Settings
Budget Allocations
Simulation Strategies
Initial States
Markov Chains
Treatments

Step 4: Inputs for a Scenario (2): Markov Chains

A Markov chain is an important attribute of a pavement network. It represents the deterioration of a pavement network. In the GDOT LP&S program, 1 year is the basic time unit, which means the Markov chain represents the deterioration probabilities in a one-year period. Generally, a Markov chain has the following attributes:

States	Excellent	Good	Fair	Poor	Bad
Excellent	p_{11}	p_{12}	0	0	0
Good	0	p_{22}	p_{23}	0	0
Fair	0	0	p_{33}	p_{34}	0
Poor	0	0	0	p_{44}	p_{45}
Bad	0	0	0	0	1.0

According to the above table, we can say in a pavement network, p_{11} (percentage) of pavements is Excellent this year and will stay in the same condition next year if no treatment is applied, but p_{12} of pavements will deteriorate to the second state (Good). Similarly, p_{22} of pavements in Good will stay in the same condition next year if no treatment is applied, but p_{23} of pavements will deteriorate to the third state (Fair), etc. For simplicity, we assume that in a one-year period pavement can only deteriorate to the next state. So, only 8 numbers need to be identified for the Markov matrix of a family. Based on the nature of a Markov chain, the following 3 rules will be applied on the matrix items:

	Rule
1	p_{11}, p_{12}, p_{22}, p_{23}, p_{33}, p_{34}, p_{44}, p_{45}, p_{55} should be a number between 0 and 1
2	All other items should be equal to 0
3	$p_{11} + p_{12} = 1$; $p_{22} + p_{23} = 1$; $p_{33} + p_{34} = 1$; $p_{44} + p_{45} = 1$; $p_{55} = 1$;

The following steps show the process to input Markov chains for a scenario:

- Open the Markov chain input form
- Edit on the form
- Save the inputs

Open the Markov chain input form

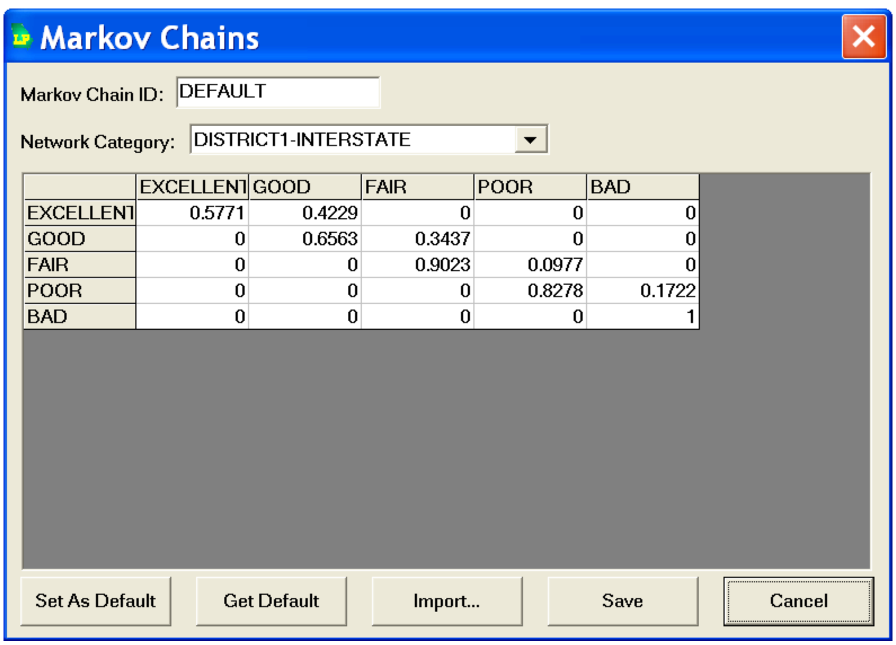
To open the form,

- Click the **Markov Chains** node under the scenario you are working on.

or

- Select **Settings→Markov**

NOTE: Ensure the proper scenario is selected when you open the form by selecting the appropriate menu item.



The program has already assigned Markov Chain ID as **DEFAULT** . You can change it if desired. The 14 families can be selected by clicking the **Network Category** dropdown list. To review or modify a Markov matrix for a family, click the **Network Category** dropdown list and select the corresponding family. The meanings of the 5 buttons are as follows:

- **Set as Default**: Set as default the set of Markov chains shown on the form. Next time, the program will use the current setting as the default value assigned to a new scenario.
- **Get Default**: Load the default Markov chains, and set them set as current.
- **Import**: Load a saved set of Markov chains, and set it as current.
- **Save**: Save the set of Markov chains on the form, and set it as current.
- **Cancel**: Close form without saving.

Edit the form

To modify a value, click it, and change it. The above 3 rules for the data must be followed.

If any of the above rules are violated, an error message will appear when you try to save the current modification.

Save the inputs

After you finish inputting the Markov chains, click **Save** to save the setting and exit the form. If you don't want to make any changes, click **Cancel** to exit the form. If an input is saved, the program will automatically assign an ID to it according to current time (for example, 100523 represents 10:05:23).

When you quit the form, you will see the red right-direction arrow has changed to a green OK marker.

Step 5: Inputs for a Scenario (3): Budget Allocations

Budget is the main issue of a pavement management system. Using total annual budgets, the program can work out a set of optimal budget allocations to achieve the maximum composite rating. You can manually allocate budgets to each family to conduct performance forecasting and simulation. In these two cases, budgets are inputs. The output is its allocations (i.e.., how to spend the money). Another case is that given the annual pavement conditions requirements, the program will find the minimum cost to meet these requirements, in which case the budgets will be the outputs.

The following steps show how to input budgets in a scenario:

- Open the Budget Allocations form
- Edit on the form
- Save the inputs

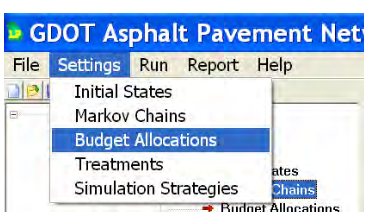
Open the Budget Allocations Form

To open the form

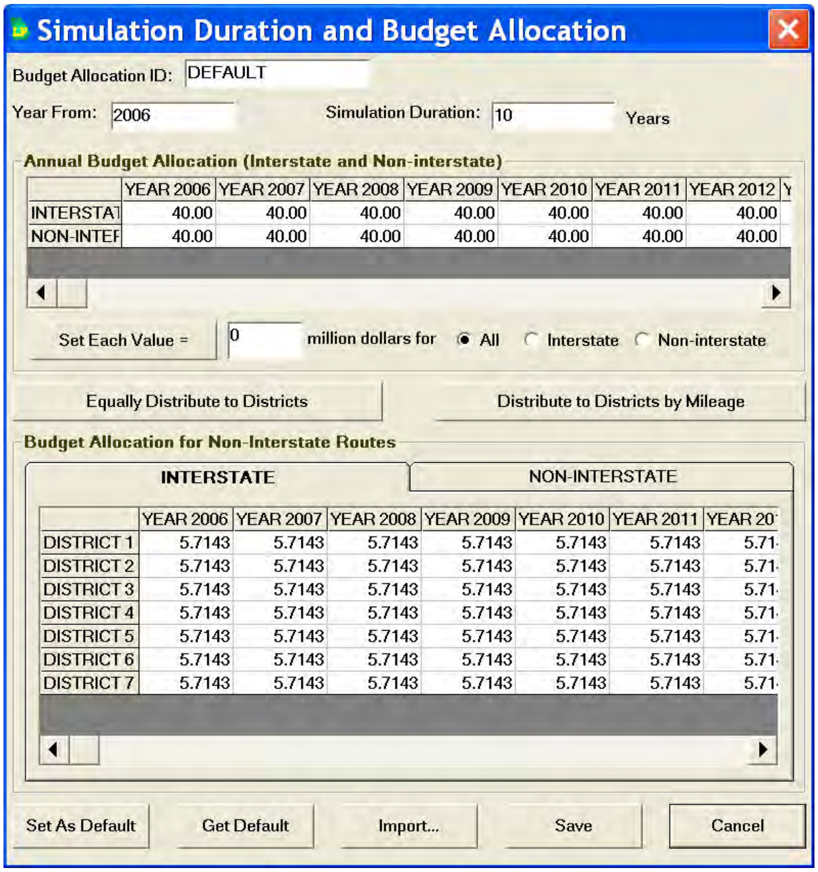
- Click the **Budget Allocations** node under the scenario you are working on.

or

- Select **Settings→Budget Allocations**



NOTE: Ensure the proper scenario is selected when you open the form by selecting the appropriate menu item.



The program has already assigned the Budget Allocation ID as **DEFAULT** . You can change it if desired.

On this form, you will input the simulation starting year and duration. Also, you need to give budget allocations for each family each year.

The meanings of the 5 buttons are as follows:

- **Set as Default**: Set as default the set of budget allocations shown on the form. Next time, the program will use the current setting as the default value assigned to a new scenario.
- **Get Default**: Load the default budget allocations, and set them set as current.
- **Import**: Load a saved set of budget allocations, and set it as current.
- **Save**: Save the set of budget allocations on the form, and set it as current.
- **Cancel**: Close form without saving.

Edit the form

To modify a value, click on it, and change it. In the **Year From** box, type in the year when the simulation starts. In the **Simulation Duration** box, type in how many years the simulation will last. The default is 10 years.

The upper grid lists the annual budgets for interstate and non-interstate routes for the whole state. You can manually click each number to edit it. The program also provides some convenient functions to quickly assign budgets. For example, if you want to assign 30 million dollars to interstate and non-interstate routes for each year, just type 30 in the box to the right of **Set Each Value =** button and make sure the **All** option button is selected; then click **Set Each Value =**. If you just want to assign the number to interstate or non-interstate, type in the number and select the corresponding option button and click **Set Each Value =** to assign the number.

The lower two grids (click the tab to read the grids for interstate and non-interstate) list the detail budget allocations for each family for each year. Because you have already input the total budget for interstate and non-interstate routes, you can distribute the budgets to each family equally or proportionately to the mileage of each family. To do so, click **Equally Distribute to Districts** or **Distribute to Districts by Mileage**. Of course, you can manually modify the budget for each family, and the total budget will be automatically adjusted.

Note that for some simulation strategies (e.g. cases that will be introduced in Step 7), only part of the information on this form is useful. The following table lists the required information on this form for each simulation strategy:

Simulation Strategy	Scope*	Starting Year	Duration	Budget for Interstate	Budget for Non-interstate	Budget for each family
Worst First	Network	Y**	Y	Y	Y	N
	Interstate	Y	Y	Y	N	N
	Non-interstate	Y	Y	N	Y	N

User Customized	Network	Y	Y	Y	Y	N
	Interstate	Y	Y	Y	N	N
	Non-interstate	Y	Y	N	Y	N
Optimization on each family	Network	Y	Y	Y	Y	Y
	Interstate	Y	Y	Y	N	Y
	Non-interstate	Y	Y	N	Y	Y
Optimization on all families	Network	Y	Y	Y	Y	N
	Interstate	Y	Y	Y	N	N
	Non-interstate	Y	Y	N	Y	N
Need analyses	Network	Y	Y	N	N	N
	Interstate	Y	Y	N	N	N
	Non-interstate	Y	Y	N	N	N

* You can specify the scope for each simulation strategy. The network means the whole state, including interstate and non-interstate route systems.

** Y means the attribute is needed for the strategy. N means it is not required. You can input the non-required information, but it won't affect simulation results.

Save the inputs

After you finish inputting budget allocations, click **Save** to save the setting and exit the form. If you don't want to make any changes, click **Cancel** to exit the form. If an input is saved, the program will automatically assign an ID to it according to current time (for example, 100523 represents 10:05:23).

When you quit the form, you will see the red right-direction arrow has changed to a green OK marker:


Settings
Budget Allocations
Simulation Strategies
Initial States
Markov Chains
Treatments

Step 6: Inputs for a Scenario (4): Treatments

Treatments strategies are directly associated with cost. In essence, each simulation strategy finds optimal treatment strategies to maintain the pavement systems to a serviceable condition.

The following steps show how to input treatments for a scenario:

- Open the Treatments form
- Edit on the form
- Save the inputs

Open the Treatments form

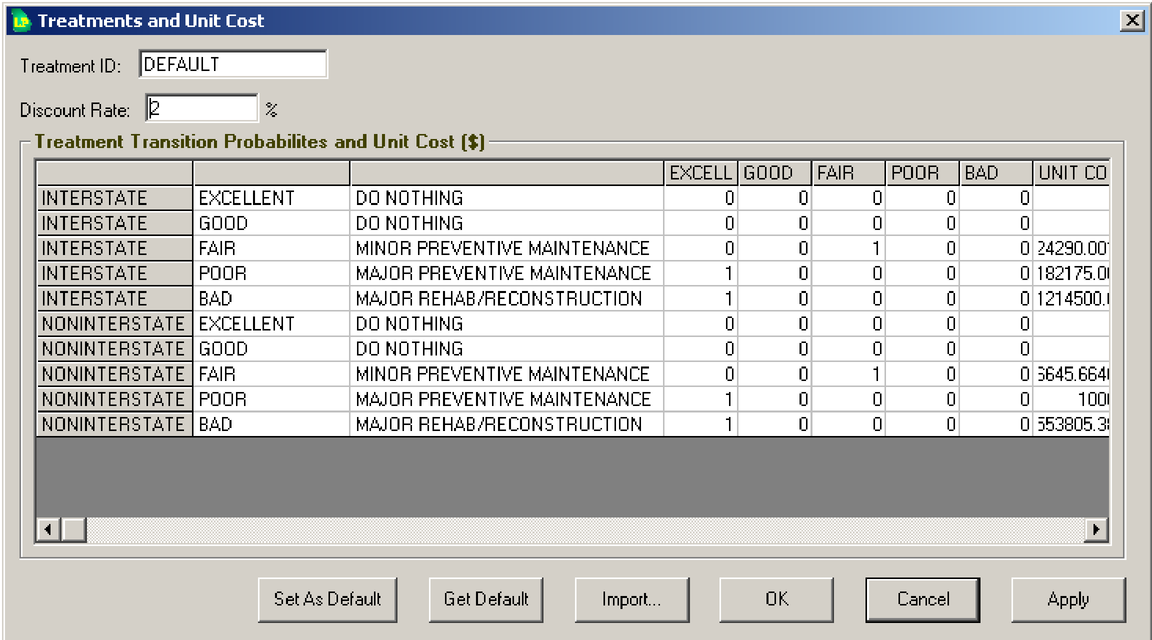
To open the form

- Click the **Treatments** node under the scenario you are working on.

or

- Select **Settings→Treatments**

NOTE: Ensure the proper scenario is selected when you open the form by selecting the appropriate menu item.



			EXCELL	GOOD	FAIR	POOR	BAD	UNIT CO
INTERSTATE	EXCELLENT	DO NOTHING	0	0	0	0	0	
INTERSTATE	GOOD	DO NOTHING	0	0	0	0	0	
INTERSTATE	FAIR	MINOR PREVENTIVE MAINTENANCE	0	0	1	0	0	24290.00
INTERSTATE	POOR	MAJOR PREVENTIVE MAINTENANCE	1	0	0	0	0	182175.0
INTERSTATE	BAD	MAJOR REHAB/RECONSTRUCTION	1	0	0	0	0	1214500.
NONINTERSTATE	EXCELLENT	DO NOTHING	0	0	0	0	0	
NONINTERSTATE	GOOD	DO NOTHING	0	0	0	0	0	
NONINTERSTATE	FAIR	MINOR PREVENTIVE MAINTENANCE	0	0	1	0	0	3645.664
NONINTERSTATE	POOR	MAJOR PREVENTIVE MAINTENANCE	1	0	0	0	0	100
NONINTERSTATE	BAD	MAJOR REHAB/RECONSTRUCTION	1	0	0	0	0	353805.3

The program has already assigned the Treatment ID as **DEFAULT**. You can change it if desired.

On this form, you will input inflation rate. Also, you need to give the transition probabilities and unit costs for all possible treatments for interstate and non-interstate routes respectively.

- **Set as Default**: Set as default the set of treatments shown on the form. Next time, the program will use the current setting as the default value assigned to a new scenario.
- **Get Default**: Load the default Markov chains, and set them set as current.
- **Import**: Load a saved set of Markov chains, and set it as current.
- **Save**: Save the set of budget allocations on the form, and set it as current.
- **Cancel**: Close form without saving.

Edit the form

To modify a value, click on it, and change it.

In the **Discount Rate** box, type in the percentage of discount rate.

In the grid, there are total 10 treatments associated with 5 states for interstate and non-interstate routes. For Excellent and Good, no treatment is needed (i.e. do nothing). Minor preventive maintenance, major preventive maintenance, and major rehab/reconstruction are associated with Fair, Poor, and Bad, respectively. In each row, the values for Excellent, Good, Fair, Poor, and Bad represent the transition probabilities when the treatment is applied.

The unit for unit cost is in millions of dollars.

Save the inputs

After you finish inputting treatments, click **Save** to save the setting and exit the form. If you don't want to make any changes, click **Cancel** to exit the form. If an input is saved, the program will automatically assign an ID to it according to the current time (for example, 100523 represents 10:05:23).

When you quit the form, you will see the red right-direction arrow has changed to a green OK marker:

Step 7: Inputs for a Scenario (5): Simulation Strategies

The GDOT LP&S program provides 5 simulation strategies: Worst first, User specified, Optimization on each family, Optimization on all families, and Need analyses. The following describes each strategy:

- **Worst first**

In this strategy, the program will assign the budget to each treatment based on a worst-first sequence. With the budget you manually assigned in each year, the pavements in Bad condition will be treated first. If budget is left, the pavements in Poor will be treated, followed by pavements in Fair condition.

- **User specified**

In this strategy, the program will assign the budget to each treatment based on user specified distribution. With the budget you manually assigned in each year, the pavements in Bad condition will be treated first, but only with the budget you specified. If budget is left, the pavements in Poor will be treated, also with the budget you specified, followed by pavements in Fair condition.

- **Optimization on each family**

In this strategy, the program will automatically decide the treatments for each family with the budget you manually assigned in each year. The objective is to achieve maximum composite rating for each family.

- **Optimization on all families**

In this strategy, the program will automatically decide the treatments for all families with the total budget you assigned in each year. The objective is to achieve the maximum composite rating for the entire family.

- **Need analyses**

In this strategy, the program will decide the optimal treatments for all families with the minimum total cost needed in each year. You can specify the requirements that should be satisfied. In the GDOT LP&S program, the need analyses can have two requirements: (1) composite rating should be greater than a value, say 85; (2) the total percentage of pavements in Bad and Poor should not exceed a percentage, say 10%.

The following steps show how to input simulation strategy for a scenario.

- Open the Simulation Strategies form
- Edit the form
- Save the inputs

Open the Simulation Strategies form

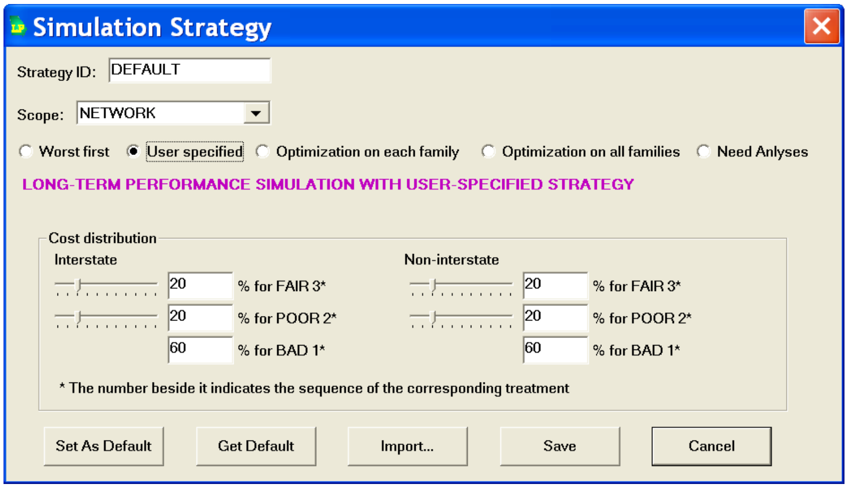
To open the form

- Click the **Simulation Strategies** node under the scenario you are working on.

or

- Select **Settings→Simulation Strategies**

NOTE: Ensure the proper scenario is selected when you open the form by selecting the appropriate menu item.



The program has already assigned the Strategy ID as **DEFAULT**. You can change it if desired.

On this form, you will input simulation scope. Also, you need to specify which strategy you are going to use and the type in the corresponding parameters for the selected strategy.

The meanings of the 5 buttons are as follows:

- **Set as Default**: Set as default the set of simulation strategy shown on the form. Next time, the program will use the current setting as the default value assigned to a new scenario.
- **Get Default**: Load the default simulation strategy, and set it set as current.
- **Import**: Load a saved simulation strategy, and set it as current.
- **Save**: Save the simulation strategy on the form, and set it as current.
- **Cancel**: Close form without saving.

Edit the form

To modify a value, click on it, and change it.

In the **Scope** dropdown list, you can choose **NETWORK**, **INTERSTATE** or **NON-INTERSTATE**. If the item other than **NETWORK** is selected, please note that only the corresponding results in the reports (see Step 8) are meaningful.

Only one of the 5 strategy option buttons can be selected at a time. If **User specified** or **Need analyses** is selected, you need to input some other information for it. For **User specified**, you need to input the budget distribution on treatments for Fair, Poor, and Bad conditions of interstate and non-interstate. For **Need analyses**, you need to input the values for composite rating and total percentage of pavements in Poor and Bad conditions, which are two requirements for need analyses.

Save the inputs

After you finish inputting initial states, click **Save** to save the setting and exit the form. If you don't want to make any changes, click **Cancel** to exit the form. If an input is saved, the program will automatically assign an ID to it according to current time (for example, 100523 represents 10:05:23).

When you quit the form, you will see the red right-direction arrow has changed to a green OK marker:

Step 8: Running Simulation and Reporting

After you have input all required information, it is time to run the simulation and get results:

- Running simulation
- Reporting

Running the simulation

To run the simulation

- Click the **Run** node under the scenario you are working on.

or

- Select **Run→Run Scenario**

NOTE: Ensure the proper scenario is selected when you run the simulation by selecting the appropriate menu item.

- Click the toolbar button

Reporting

If the simulation succeeds, you will get popup information. Click **OK** to confirm it. You will see the red flag beside the **Reports** node has changed to green, which means the reports are ready for review:

To open the reports

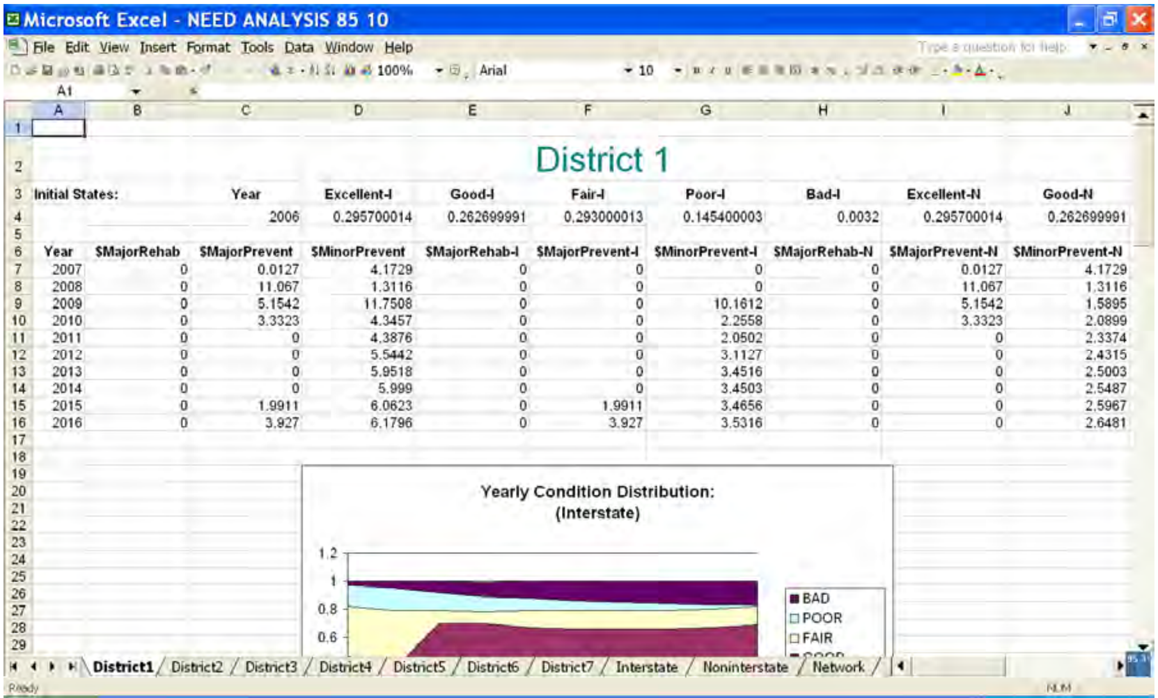
- Click the **Reports** node under the scenario you are working on.

Or

- Select **Run→Run Scenario**

- Click the toolbar button

Please wait for a while; the report in an MS Excel format will be generated as follows:



Initial States:		Year	Excellent-I	Good-I	Fair-I	Poor-I	Bad-I	Excellent-N	Good-N
		2006	0.295700014	0.262699991	0.293000013	0.145400003	0.0032	0.295700014	0.262699991

Year	$MajorRehab	$MajorPrevent	$MinorPrevent	$MajorRehab-I	$MajorPrevent-I	$MinorPrevent-I	$MajorRehab-N	$MajorPrevent-N	$MinorPrevent-N
2007	0	0.0127	4.1729	0	0	0	0	0.0127	4.1729
2008	0	11.067	1.3116	0	0	0	0	11.067	1.3116
2009	0	5.1542	11.7508	0	0	10.1612	0	5.1542	1.5895
2010	0	3.3323	4.3457	0	0	2.2558	0	3.3323	2.0899
2011	0	0	4.3876	0	0	2.0502	0	0	2.3374
2012	0	0	5.5442	0	0	3.1127	0	0	2.4315
2013	0	0	5.9518	0	0	3.4516	0	0	2.5003
2014	0	0	5.999	0	0	3.4503	0	0	2.5487
2015	0	1.9911	6.0623	0	1.9911	3.4656	0	0	2.5967
2016	0	3.927	6.1796	0	3.927	3.5316	0	0	2.6481

There are 10 worksheets in the report, District 1 to 7, interstate, non-interstate, and the whole network. In the worksheet for each district, there are 6 graphs: (1) yearly condition distribution for interstate in this district; (2) yearly condition distribution for non-interstate in this district; (3) yearly condition distribution for the whole district; (4) composite ratings for interstate, non-interstate and the whole district; (5) yearly cost distributions for interstate in this district; and (6) yearly cost distributions for non-interstate in this district. You can find the corresponding tabular data in each worksheet. In the worksheet for interstate, non-interstate, and whole network, there are 3 graphs: (1) yearly condition distributions; (2) yearly composite rating; and (3) yearly cost distributions.

Appendix V: Literature Review on Crack Sealing

The current trend in pavement management is focusing on preventative maintenance treatment in order to preserve pavement life. However, there are several issues with integrating preventive maintenance techniques and decision-making triggers into the existing framework of most pavement management systems (PMS). Other than the fact that studies are not conclusive on the cost benefit, scenario, or proper time to apply several preventive maintenance techniques such as crack sealing, there are further complications such as different offices of a DOT making decisions on preventive maintenance and more complex rehabilitation projects without input from one another (Zimmerman and Peshkin, 2004). Despite these and other challenges, Zimmerman and Peshkin (2004) suggest that they can be overcome by "a concentrated effort on the part of the transportation agency to re-evaluate its data-collection activities, revise its performance-modeling approach, and improve its program-development activities."

The National Cooperative Research Program (NCHRP) Report 523 report by Peshkin et al. (2004) on finding the optimal time to apply preventive maintenance treatments states the following:

> "The literature search performed for this project shows that there is little work being done on the timing of preventive maintenance treatments. However, there is a general consensus on the concepts and definition of preventive maintenance and on the treatments used in preventive maintenance programs. Important attributes of preventive maintenance treatments may be considered for selecting treatments to be included in a preventive maintenance program and for determining when such treatments should be applied."
>
> "There is a need to identify when it is "best" to apply preventive maintenance treatments. Treatment performance is greatly dependent on the condition of the pavement at the time of treatment application, and different types of treatments are likely only to be effective when placed at certain times in a pavement's life. When placed at the right time, a

preventive maintenance treatment becomes a cost-effective means of attaining the desired life and performance of the pavement. Treatments applied too soon add little benefit and treatments applied too late are ineffective; however, there is little guidance available on this topic.

"There are no studies that have successfully determined how to identify the optimal time to apply preventive maintenance treatments; although a number of completed studies have examined this issue and other research continues to study it. These include the studies of maintenance effectiveness under the Specific Pavement Studies (SPS-3 and SPS-4) effort (*17, 18*), and field studies by the DOTs in Iowa (*9*), Arizona (*19*), Texas (*20, 21*), and South Dakota (*22*)."

Preventive Maintenance of Pavements

Zaniewski and Mamlouk (1999) reported that the Federal Highway Administration (FHWA) estimated the cost of maintaining the nation's pavement condition in 1993 would require $50 billion annually and the budget at that time was only $27 billion annually. To eliminate backlog requirements it would take an estimated $220 billion in 1993 dollars. To help alleviate this growing budget crisis, pavement construction and rehabilitation money must be maximized in order to sustain the national pavement infrastructure system, and the Strategic Highway Research Program (SHRP) as well as several other studies have demonstrated that preventive maintenance is cost-effective for roads in the National Highway System (Zaniewski and Mamlouk, 1999). As a result, many agencies are putting more focus on maximizing the benefit of preventive maintenance. Some good examples of this are the focus of this paper and research for Georgia's roads, and the California Department of Transportation (CALTRANS) has created a pavement preservation task group (PPTG) that is an effort between government and industry there to foster coordination and improvements in pavement preservation. More information on California's preservation program can be found at http://www.dot.ca.gov/hq/maint/PavePres/ppindex.htm where one can find information such as the Maintenance Technical Advisory Guide (MTAG) or review findings from the last forum, specifically the crack sealing sub-task group.

In evaluating the life-cycle of flexible pavement preventive maintenance, Labi and Sinha (2005) compared several different treatment scenarios that applied multiple preventive maintenance techniques at various times and then calculated cost-effectiveness on the basis of agency and user costs in years per million dollars. The ratios ranged from 13.09 to 40.48 with various treatment combinations versus the do-nothing-case which has a ratio of 0. In other words, the ratio of pavement life extension to treatment cost was positive for every scenario. However, it is also noted that there is an optimum preventive maintenance cost expenditure meaning the benefit is less for spending too little or too much on maintenance practices (Sinha and Labi, 2005). Sinha and Labi (2005) also caveat that the cost-effectiveness for PM is the most for non-interstate system roads that are still part of the national highway system (NHS) because they generally carry larger volumes of traffic than local roads but may not be designed to high standards such as those for interstates highways (see Figure 2 in Sinha and Labi, 2005 for more details).

As far as the timing and effectiveness of various PM treatments for flexible pavements, Hicks et al. (1999) provides an excellent summary of several factors to consider. Figure V-1, originally from O'Brien (1989), shows the general trend of pavement deterioration and the increased cost to maintain pavement condition once it has reached the steep part of the curve. Therefore, PM treatments such as crack sealing, chip seals, slurry seals, fog seals, microsurfacing, and thin HMA overlays should all be applied while the pavement is still in good condition. Even within the arena of PM, some treatments are more long-term and may be applied later than other methods. Appendix C-4 provides several more graphs and tables from Hicks et al. (1999) for assessing the most appropriate maintenance strategy for different types of distress, typical unit costs and life-expectancy of various PM treatments, guidelines for effective maintenance treatments, a conceptual relationship for timing for various maintenance and rehabilitation treatments, and an example showing equivalent annual costs based on the life of the treatment.

In evaluating the cost-effectiveness of PM treatments, Hicks et al. (1999) suggests using the equivalent annual cost (EAC) method because it is "relatively straightforward." EAC is the ratio of unit cost per expected life of the treatment in years (see Table C4-3 in Appendix C4 for examples). Despite the simplicity of the EAC method, Hicks et al. (1999) advocates using a combination of various factors of performance, constructability, and customer satisfaction for selecting the most appropriate PM treatment since using only EAC will always "skew the decision to the lowest cost product." These factors will be dependent on an agency's practices and will vary on a project specific basis. Finally, separate effectiveness calculations by Eltahan et al. (1999) showed the benefit over control sections (no maintenance performed) by average survival times for thin overlay, slurry seal, and crack seal lasting 3.1, 2.7, and 2.5 years longer respectively. The SPS-3 experiment designed under SHRP contract H-101 by the Texas Transportation Institute was the basis for these calculations.

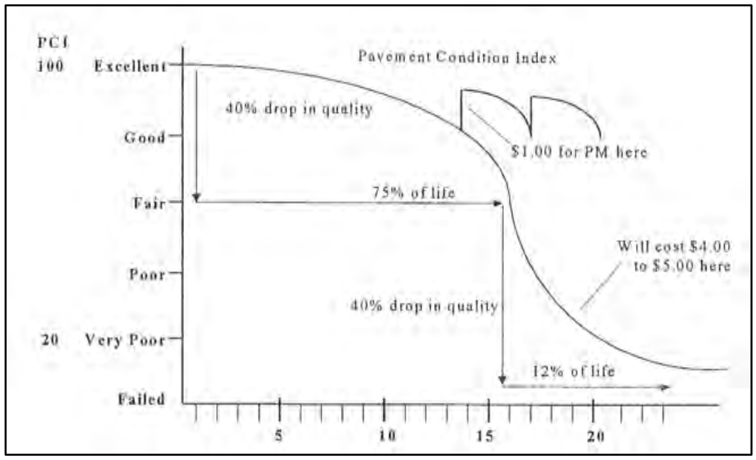


Figure V-1 Typical pavement life-cycle (after O'Brien, 1989; Hicks et al., 1999)

Why Crack Sealing?

Over time and constant cyclic loading from traffic and weather, roads develop distresses such as cracking and other detrimental effects that eventually lead to "failure" of the pavement and the need for new construction. Failure is mentioned in quotes because this is relative based on the expectation of the road due to the amount of use or other limiting expectations set forth by the owner of the pavement. In general though, water intrusion into the pavement structure is the biggest factor that contributes to its deterioration (Christopher, 2006). All of the harmful effects of water on soils (pavement base and subbase structure) are too complex and lengthy to go into here, but it is well known that water is the most destructive element to pavement. A figure from Cedergren (1987) shows that if the underlying structure of a pavement stays saturated 20% of the time (73 days a year) then the expected life reduces to 20% of the useful life; if it is saturated 50% of the time, the useful life drops to 10% of what it was designed for (Christopher, 2006). The American Association of State Highway and Transportation Officials (AASHTO) say that the detrimental effects of water include modulus reduction, loss of tensile strength, and loss of stiffness; modulus is the key property in pavement design (AASHTO, 1993; Christopher, 2006). **Therefore, keeping water out of the pavement structure is the primary goal of the pavement maintenance practices of crack sealing and crack filling.**

One of the most common methods of preventative maintenance is crack sealing because it is relatively easy to perform with an in-house work force, but its effectiveness has been debated. Ioannides et al. (2004) brings up the fact that crack sealing should be done in conjunction with pavements that have good drainage systems and routine inspections of these systems. It is known that crack sealing cannot keep 100% of surface water from getting into the pavement, either due to sealant degradation over time or new cracks forming and sealing not being done instantaneously, and thus a need for drainage of the water that does enter the structure. If drainage is not sufficient, crack sealing may be even more detrimental by trapping the water inside the structure.

Some engineers were also opposed to initial efforts to crack seal because sealant materials and construction practices contributed to poor performance, resulting in a waste of time and money. However, ineffective procedures and materials have been identified, and newer research has shown that filling or sealing pavement cracks properly to prevent water from entering the base and subbase will extend the pavement life by three to five years (Pennsylvania Local Roads Program, 1997). Ponniah and Kennepohl (1996) report at least a 2-year pavement life extension from crack sealing, and Michigan DOT reports that crack sealing can provide up to a 3-year life extension (Bausano et al., 2004). The California Department of Transportation (Caltrans) even reports that crack sealing/filling can provide up to 8-9 years of service life based on research from the US Department of Transportation (FHWA-RD-99-147, 1999).

Variables that Affect Optimal Timing of Treatment

One of the toughest challenges is dealing with the number of variables associated with determining the optimum treatment material, timing, and method. The proposed experiment cited in Appendix C2 will be largely guided by GDOT pavement engineers depending on current practices and availability of materials. One of the first questions to answer is whether to crack seal or crack fill? The next section will present the differences with these methods. The next variable is the type of crack sealant or filler to be used. Caltrans lists several different options such as asphalt emulsion, asphalt cement, fiber-modified asphalt, polymer modified emulsion, various types of asphalt rubber, and silicone (California, 2003). The cost of each material, availability, and time to perform the process will need to be taken into consideration, as well as the performance of each material in order to perform a cost-analysis between them. Zimmerman and Peshkin (2004) talk about the limited number of studies that used control sections in which nothing was done to the pavement; this project would certainly like to include a control section to see how the effects of all the different variables relate to the control section. Different crack sealing products and materials compared by Ioannides et al. (2004) would also like to be varied if money and time permits. Finally, but not all inclusive, the crack reservoir types and differences explored by Johnson et al. (2000) would like to be compared in this study as well.

Several agencies either use decision trees or pavement condition indexes to identify when to perform several preventive maintenance and rehabilitation projects. The Metropolitan Transportation Commission (MTC) in the San Francisco Bay area sets “treatment trigger levels” based on a standard deterioration curve (Zimmerman and Peshkin, 2004). A PCI of 70 is the trigger value between preventive maintenance and light-to-moderate rehabilitation, and heavy rehabilitation occurs at a PCI of 50 (Smith, 2002). Relating this to GDOT pavements, if a PCI of 70 is an unacceptable pavement, then an initial estimate for a trigger value for preventive maintenance may be somewhere around a PCI of 85-90 if cracks are developing at this point. This needs to be further linked to minimum crack widths before taking action. The Minnesota and Kansas DOT's have also taken several steps towards creating complex decision trees in order to incorporate and integrate preventive-maintenance treatments into their optimization analysis within a pavement management system (Zimmerman and Peshkin, 2004). These departments should be contacted to see where they are at in the process and figure out why they make their decisions at the certain trigger values they have selected.

Crack Sealing versus Crack Filling

Caltrans has also put together a comprehensive guide on several aspects of crack filling and crack sealing, and the following is a summary of Chapter 3 of their Maintenance Technical Advisory Guide, which also gains a lot of its material from the Federal Highway Administration's (FHWA) 1999 manual on sealing and filling cracks. The ideas of crack sealing and crack filling are very similar. Both methods prevent water and incompressible materials from getting into cracks by placing generally flexible material either in or over the crack. Materials such as asphalt emulsions, polymer modified emulsions, asphalt rubber, and silicone sealants are used to fill or seal the crack and hopefully retain adhesion to the pavement, as well as flexibility, while also resisting wear from the traffic loads. The primary distinction between crack sealing and filling is **what type of crack it is treating, whether it is working or nonworking and whether it is horizontal or longitudinal.** A working crack means the crack is continuing to propagate relative to some criteria on how much it moves in a year. For example, Caltrans criteria for a working crack is >6mm (1/4 in) of horizontal movement annually (California, 2003). Working cracks can be either horizontal or transverse, but most often are transverse. Crack sealing is used on working cracks, and crack filling is used for nonworking cracks or when cracks are closely spaced.

Table C2-1 in the Caltrans manual referenced in Appendix C2 shows the Federal Highway Administration criteria for whether to crack fill or crack seal. The advantage to crack filling is that it is less expensive because it is less time intensive to perform and generally the materials are cheaper. Crack sealing on the other hand requires thorough crack preparation and more expensive materials, but it is generally considered to be a longer term treatment than crack filling. The material used for the filling or sealing, the placement method, traffic load, and quality of construction are the primary considerations on how effective and how long the preservation will be.

Previous Studies

Although, there is not a study specific to Georgia pavements, some other studies have been performed that are similar to the objective of this study. One of the most well known studies is from Ponniah and Kennepohl (1996) where they aimed to determine the cost-effectiveness of crack sealing through a life-cycle cost analysis. With proper crack preparation (including correct size, equipment, and cleaning) and material, results from 37 test sites in Canada showed that pavement life can be extended by at least 2 years depending on the initial condition, environment, and traffic volume. Crack growth was measured yearly and performance curves were created to compare types of sealants, route size, and the most beneficial time to apply the sealant (e.g., pavements with extensive cracking will not benefit from the treatment). Life-cycle cost analysis showed that crack sealing provides a 48% increase in cost-effectiveness over more elaborate maintenance alternatives. Conclusions from the study include the following: 1) a 40 x 10 mm routing of existing cracks promotes good sealant bonding; 2) not sealing cracks results in increased maintenance cost and decreased service life; 3) crack sealing can retard secondary crack growth; 4) a life-cycle cost analysis indicates that crack sealing is cost effective; and 5) a rout and crack seal program must be applied to suitable pavements, using acceptable materials, and at the correct time.

…Crack Type

Zinke and Mahoney (2006) released a report comparing the two most common types of crack treatment (hot pour {crumb rubber or other additives heated to high temperatures} and cold pour {asphalt emulsions}). Part of their conclusions was that both materials performed better in longitudinal cracks than in transverse cracks. This may be attributed to two reasons: 1) transverse cracks are usually working cracks and continue to propagate thereby reducing the effectiveness of the sealed portion, and 2) longitudinal cracks are generally located between lanes or between a shoulder and a lane and as a result do not take as much direct traffic, whereas wheel loads are constantly passing over at least some point of a transverse crack. For both longitudinal and transverse cracks, the application methods were compared by using the same rating criteria for failed sealants as outlined in the SHRP crack treatment experiment report (see the Federal Highway Administration Report FHWA-RD-99-143). Zinke and Mahoney (2006) concluded that the hot pour treatments outperformed the cold pour methods based on their data from field evaluations despite the fact that the hot-poured joints were two years older.

Yildirim et al. (2006) also compared 3 cold-pour sealants and 4 hot-pour sealants in four Texas DOT districts during a four-year study and came to the following conclusions. First, the cost of the sealants ranged from $0.04 to $0.13 per linear foot with the cold-pour treatments being the most expensive. Their study also found that hot-pour sealants performed better than cold-pour sealants over time and that the initial construction cost of hot-pour materials was also cheaper.

…Type of Sealant Used and Construction Practices

The previous study focused on the general categories of sealants used, but there are other studies that also focused on comparing many different crack sealing materials and brands. In Montana, Johnson et al. (2000) compared nine different materials using both routed and nonrouted methods, as well as varied the size of the rout reservoir (Montana DOT typically uses "square" reservoirs but "shallow" or for-to-one reservoirs were also included due to their reported benefits). The square reservoirs were also filled using flush, recessed, or Band-Aid techniques. Finally, this study comments on the workmanship of the crack sealing performed at some of its test sites. All of these parameters were summarized in the following conclusions: 1) shallow reservoir and flush technique offers better performance than the square reservoir and flush technique; 2) Low Modulus, Polymer Modified and Polymer Modified, Rubberized Asphalt offered the best resistance to adhesion and cohesion failures; 3) Band-Aid and square reservoirs experienced the most failures after three years of service; 4) routing transverse cracks improved performance of sealants; 5) square reservoirs with recessed sealants did not perform well; 6) routing did not appear to be necessary for longitudinal cracks; 7) Band-Aids appear to be less susceptible to snow plow pull-outs; and 8) higher failure rates of the sealants can be expected during the coolest months of the year when cracks are at their widest and the material is the most stiff. Finally, it is noted that the Tarkio site within the study included a control section for comparison to unsealed sections with all other factors the same (Johnson et al. 2000).

A similar joint sealant study was performed by Ioannides et al. (2004) on the Ohio Route 50 test pavement in which they tested 10 different sealant compounds on PCC pavements (4 silicone, 2 hot-applied, and 2 compression seals) and compared them to 4 unsealed sections over a three year period. Though different from flexible pavement cracks, some insight may be gained or reinforced from this study. In general, they found that compression seals outperformed the other sealants, and crew experience in sealant installation is a critical factor. More specifics can be found in the paper, but one thing that is worth noting here is that the brand names were mentioned and compared specifically and not just the sealant type. The various companies represented were Watson Bowman, Delastic, Techstar, Crafco, and Dow.

…Climate and Temperature Effects

The studies reviewed varied widely in temperature, from very cold temperatures in Canada, Michigan and Connecticut, to more mild temperatures in Indiana and Ohio, to hot climates such as Texas. However, none of them specifically mention the performance of the sealants compared to other regions. The study by Johnson et al.

(2000) in Montana did mention that as part of their method of evaluation they characterized the material by using a “coin test” to measure stiffness and resilience changes over time. The test involved pushing a quarter half way into the crack sealant and then measuring how much it recovered in 1 minute; the coin test was only performed when the temperature of the material was above 10ºC (50ºF). In mid-February 2007, the test track at the National Center for Asphalt Technology (NCAT) at Auburn University will be visited to take pictures and receive data on two different types of sealant that were placed there in longitudinal joints of flexible pavements for the Oklahoma DOT. This information will be for a climate that is the most similar to Georgia’s.

Hand et al. (2000) gives a synthesis of the practice of joint and crack sealing which includes a fairly exhaustive literature review on the issue and gives examples of nonsupportive and supportive literature. Hand’s paper will be supplemented by another paper to include the results of an extensive field study started in 2000 and was originally scheduled to only last 3 years. The paper is interesting because it aims at answering some of the same questions that GDOT has about crack sealing, primarily the following:

- Does crack sealing improve the service life or serviceability of pavements?
- If sealing does improve performance, is it cost effective and in what scenarios?

Hand et al. (2000) reviewed over 100 references after searching several databases on the topic and found that only 18 reports specifically addressed cost-effectiveness. This caused the authors to presume that since most of the papers focused on materials and procedures, the general perception in the pavement community is that sealing is cost effective. This was questioned primarily in a paper by Shober (1997) in which the Wisconsin DOT (WDOT) experienced little to no, or in some cases detrimental, effects from joint sealing portland cement concrete (PCC) pavements. WDOT’s study resulted in suspending a previously $6 million crack seal program in 1990. This raises the primary questions posed above, but from mounds of other supporting literature and “some controversial and ambiguous research results” there is no justification for any other state to adopt a no-seal policy similar to WDOT (Hand et al., 2000). Finally, the research from WDOT and Shober's (1997) paper focused only on PCC pavements and does not give any conclusive evidence that sealing is not beneficial for flexible pavements, whereas many other papers such as Chong (1988), Ponniah and Kennepohl (1996), Evart and Bennett (1988), Sharaf and Sinha (1986) and Morian et al. (1997) do support crack sealing in asphalt pavements when performed at the proper time as a preventative maintenance treatment.

Measuring Cracks

Cracks in the pavement can be measured several ways, but many of these methods need improvement and do not currently measure all aspects of the crack that may be useful for treating it properly. Several methods currently being used or developed to measure cracks will be discussed first, and then the proposed idea of the current research team and then the aspects of its conception will be discussed. The latter will include the future plans in which the research team at the Georgia Institute of Technology will pursue in developing a better, more robust crack measurement procedure. This information will then be integrated into the current pavement management system in order to improve the system by optimizing the time at which pavements are selected for crack sealing and other preventive maintenance treatments.

The primary categories in which cracks can be measured include manual, semiautomatic, and fully automatic methods (Offrell et al., 2005). In a test to compare the methods, Offrell et al. (2005) used traditional video based methods, line scan video, distance-measuring laser cameras, and manual windshield survey by different operators to assess the accuracy and repeatability of each. It is noted that automatic systems cannot generally recognize cracks thinner than 1-2 mm. The test was performed on a two-lane road in Sweden where the majority of cracks were longitudinal, which was considered difficult to measure. The laser had an especially difficult time recognizing vertical cracks because they only measure a single point horizontally and may either miss a longitudinal crack entirely or count a meandering longitudinal crack as multiple transverse cracks. Although single point lasers were used in this study, continuous line lasers are more common today and may be able to provide a better map of the cracked area by surveying the entire lane width along the entire driven route. To provide similar lighting situations for the video images, a strobe light bar was used so that ambient light would not affect the images. Other details can be found in Offrell et al. 2005. The ultimate results of the research project were the following: 1) road markings and texture changes affected the video image results; 2) texture changes that were not cracks also affected laser crack detections; 3) the repeatability of both automatic methods used was high; 4) repeatability of distance-measuring laser cameras was very high but a high number of crack registrations were from texture and not cracks; 5) windshield survey is strenuous on the rater and has low repeatability; and 6) automatic video images provide new possibilities for new crack measures.

Another important aspect of measuring cracks is organizing the various types of raw data such as crack width and length into more useful indicators that trigger some sort of action or provide more information about the cracking that is occurring. One of the goals of this research effort will be to determine what and how many parameters can be effectively measured in order to provide a clear picture of the causes, extent, and treatment of pavement cracking. It is desired to standardize the measurement technique and make it as objective as possible by automating the data collection and data analysis portions. Once the parameters to measure and the techniques to measure them are standardized, then the results can be incorporated into a pavement management system. By using previous data on the effective time to seal cracks and any new information discovered in this study, a threshold value can be determined that links the management system's decision recommendation for treatment to the standardized crack measurements.

During the literature review, one concept that is similar to what the current project proposes to include is the development of a crack type index from video images as proposed by Lee and Kim (2005). According to their paper, Lee and Kim (2005) say that the crack type index (CTI) can objectively determine the crack type as longitudinal, transverse or alligator cracking "with a very high level of accuracy." Their CTI method is based on a spatial distribution of image tiles rather than image pixels, which are analyzed vertically and horizontally and results in a single index. The tile grid reduces complex pixel-based computations and also helps to filter out noise. The description of the index calculations, though simple, is again beyond the scope of this paper and one should see Lee and Kim (2005) for more details. The main point is to apply the same type of concept when analyzing video images of pavement cracking. However, rather than just determining the type of cracking, which can easily be done visually by the manual rater, it is proposed by the current research that other meaningful data can be obtained from the crack images.

Two other papers reviewed that deal with different aspects of this study are "An Algorithm to Pavement Cracking Detection Based on Multi-Scale Space" by Liu and Li (2006) and "Experimental Evaluation of a Pavement Imaging System: Florida Department of Transportation's Multipurpose Survey Vehicle" by Mraz et al. (2006). Liu and Li (2006) propose an algorithm to help combat the complexity of image processing, which "made the data processing and data analyzing come to the bottle-neck of the whole system" when gathering pavement data automatically. Liu and Li's conclusions were that the main advantages of the proposed method are accurate tiny crack detection even in noisy images and more efficient and accurate results. This research hopes to further improve algorithm methods of image processing. The other paper by Mraz et al. (2006) looks at testing the accuracy and repeatability of measuring pavement distresses at high speeds (moving in a vehicle) using a line scan camera. The paper notes that "to date there is a lack of standards regarding the accuracy and precision of imaging systems and guidelines for achieving optimum conditions for collecting reliable and accurate data" (Mraz et al., 2006). Conclusions from the paper are that results showed vehicle speed did not significantly affect the amount of noise in pavement images or the ability to recognize cracks accurately and artificial lighting systems may introduce significant noise under conditions in which natural light is sufficient. Mraz et al. (2006) concludes by saying that "the frontier of imaging technology lies in the development of software that can be used to accurately classify and quantify pavement distress on a real-time basis" and that is precisely what part of this research is trying to do.

Next Steps in Crack Detection

Since this study will focus on automatic detection methods using video or still camera images, it is agreed with Offrell et al. (2005) that new possibilities presented by automatic methods could eventually provide more suitable crack measures. Some of the parameters to be measured include but are not limited to the following suggested by Offrell e al., 2005:

- Crack length
- Accumulated crack extent either longitudinally or transverse
- Position of the crack within the image or in the plane of the pavement lane
- Direction
- Shape of cracks
- Percentage of cracked area

Other parameters not listed in the Offrell et al. (2005) paper that may be either critical or insightful to measure also include but are not limited to:

- Crack width
- Number of single-line cracks that connect to other cracks
  (another measure of extent)
- Depth of cracks

Obviously some of these parameters will be more useful than others, and some measurements may not be able to be taken with a high level of accuracy or precision. Therefore, the measurements that will be the most repeatable, provide the best accuracy, and give some information about when to apply crack sealing will be targeted in the data collection. This will have to be determined partly by trial and error and partly by past experience from the field. It is worth mentioning here that the idea is not to make the problem as complex as possible but rather as quick and efficient as possible in order to make the information practical and useful.

From this point, the immediate next steps will be to set up one or more small scale lab experiments to try to accelerate crack propagation in a test pavement. From this lab experience, the objective will be to determine exactly what parameters from above or others that will be useful to measure in the field. Once the parameters are determined the computer science members of the research team will assist in creating algorithms to process digital photo and video images of the cracks to record the data.

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Appendix VI: Analyzing Crack Characteristics and Attempting to Validate the Use of Crack Sealing in Georgia's Pavements

Crack Image Characteristics

In order to determine the validity and accuracy of digital images at identifying various parameters of cracks in pavements, several images will be taken around the Georgia Tech campus. These images will include boundary reference marks that will be drawn on or nailed to the pavement in order to give a reference point when analyzing the images and comparing parameters calculated using the computer to physical measurements of the same area. A set of parameters such as length of cracks, width, depth (cannot capture with image), percentage of cracked area, and direction of cracks will be analyzed and directly compared to achieve some indication of accuracy using the computer to automatically analyze the image.

Based on other literature, it is assumed that the computer vision and physical measurements will not agree 100% because images are based on finite pixel dimensions to calculate various parameters, and images are also susceptible to other errors such as noise. **<u>Noise is the presence of other marks, stains, shadows, etc… on the pavement that can be misinterpreted by the computer algorithm to be a crack due to the contrast in darkness similar to the concept used to detect the presence of a crack.</u>** This noise error can be combated by combining image analysis with laser crack detection, which relies on depth differences to detect a crack, but lasers have their own set of problems when used to detect several crack parameters. Standardized artificial lighting may also be used to apply a more consistent light source directly over the pavement to be analyzed.

As an initial start, at least one area will be permanently marked in the parking lot on the south side of Bldg 145, the Lamar Allen Sustainable Education Building which also is just west of our offices here in Bldg 86, the Bunger-Henry Building. See maps in Figure VI-1 for specific location of the test section.

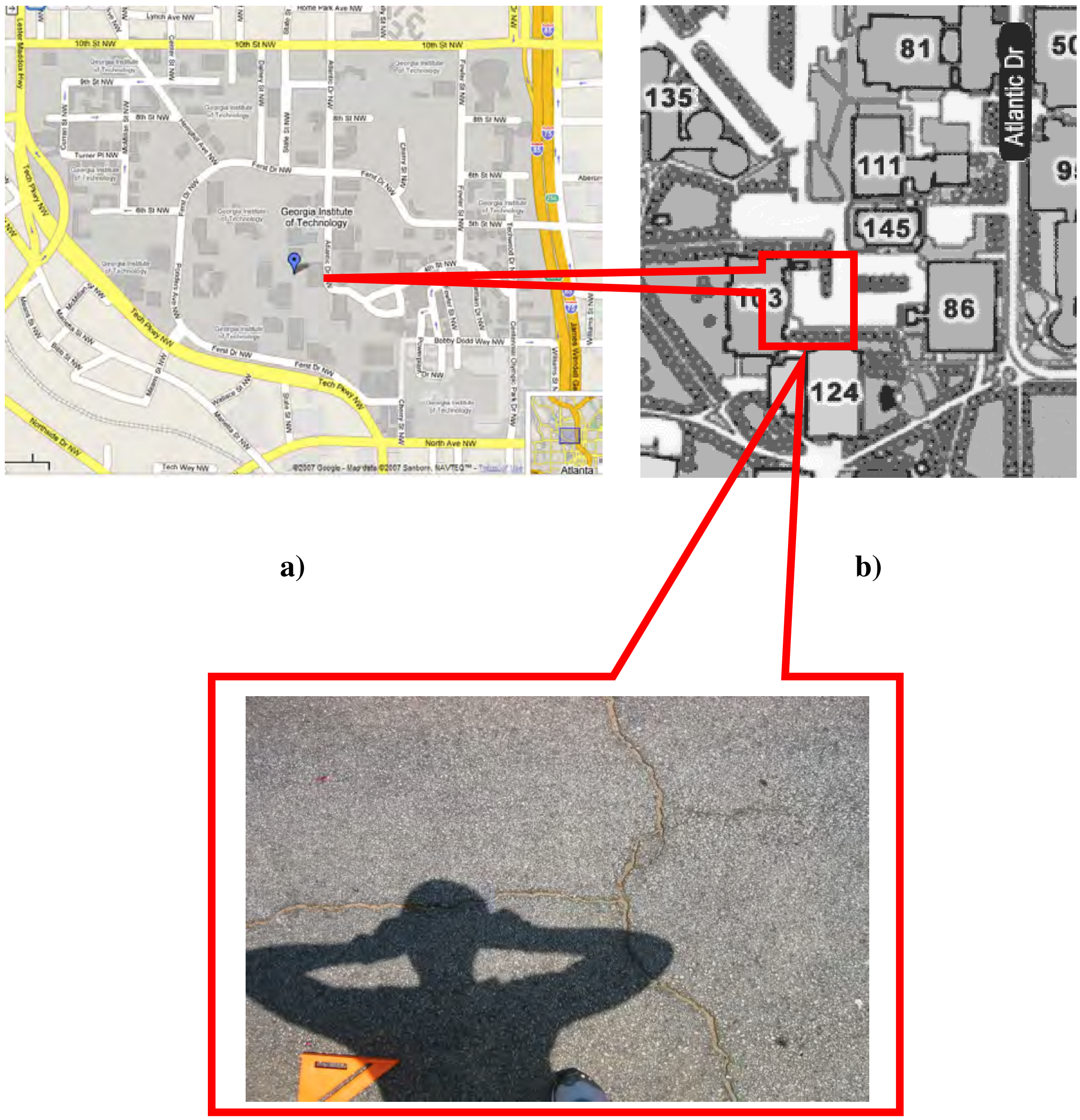


FIGURE VI-1 Location of markers for image study: **a)** Georgia Institute of Technology campus, **b)** parking lot south of SEB (Bldg 145) and west of Bunger-Henry (Bldg 86), and **c)** yellow area is extent of test section within the parking lot described in image b)

The section is approximately 2' x 3'; the longer dimension will define the longitudinal direction and the short dimension will be the transverse direction. This will be important in defining the direction of the cracks. Care should be taken to select a pavement section that is free from other contrasting markings or noise as mentioned above. The initial test section seen in the following pictures has very prominent cracks, but this caused an additional unexpected problem in that the cracks were filled with a lot of sand which caused less contrast between the crack and the surrounding pavement. Several images were taken with varying resolution, at different heights, and with varying camera angles (camera near horizontal versus tilted to one direction).

The total length of the cracks in the section was physically measured by placing a piece of string along side the cracks and measuring them against a straight-edge or measuring tape. The average width of the cracks within the section was also measured by visually estimating the average crack width in the section and then taking several measurements from inside wall to inside wall of the crack using a micrometer in these areas. The average width will then be taken as the average of all of the micrometer readings taken. Even though the depth of the crack cannot be measured using image analysis, these measurements were also taken manually with the micrometer to compare with the correlating width. Lastly, general comments on the type(s) of distresses in the section, direction, and the severity of the distresses will be noted in order to see if the image analysis can define any of these parameters as well.

The image analysis should try to measure the total length of cracks, the average width, and percent of cracks running in the longitudinal and transverse directions (this will be one indicator of the type of cracking). These initial parameters will then be compared to the physical measurements to see how well they match. This process will be repeated for all differences in images mentioned above such as camera height, tilt, and image quality. Finally, the statistics or numerical comparisons will be summarized in a table to compare the methods, accuracy, and sensitivity of the computer vision analysis.

Once this step has been taken, we can select more pavement sections, which introduce other factors that may affect the accuracy of the measurements such as tire markings, oil stains, and differences in pavement color due to its age or materials used in its construction. We will also need to look at the effect of decreasing the size of the cracks from well defined or mature cracks to hairline cracks that are just being initiated as well as varying lighting conditions (sunny, overcast, night-time with artificial lighting). Quantifying the effects of these other factors will give us a sense of how reliable the computer vision analysis will be on any type of roadway surface and condition.

The following images were taken on June 10, 2007 at the location described above. Due to extreme sunlight conditions, the shadow could not be taken out of the image. More images were taken the next day during overcast skies to reflect a differing light condition and eliminate the effect of the shadow. Some of the images were taken with the camera as level as possible while others were taken while purposely tilting the camera approximately 30º.

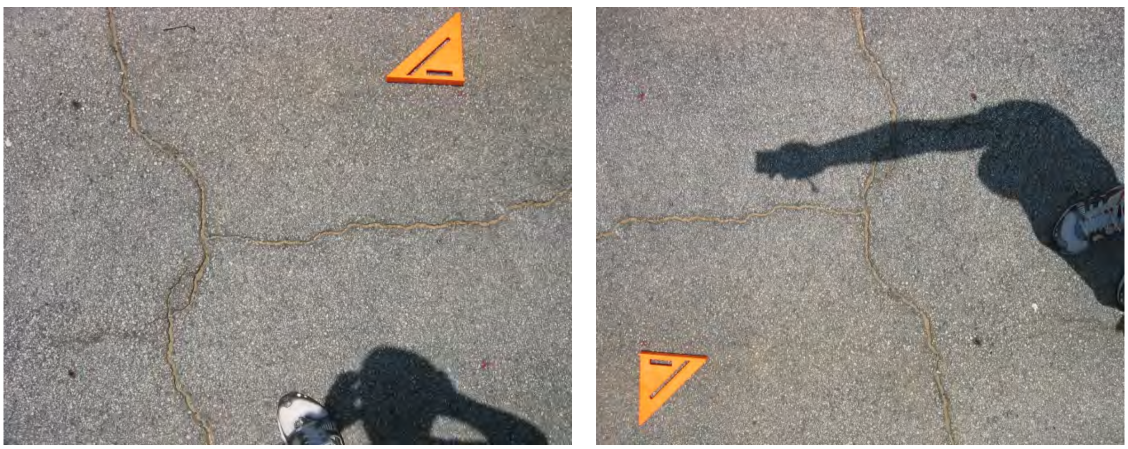


FIGURE VI-2 Overhead images of 3 ft. wide by 2 ft. tall section

a) **b)**

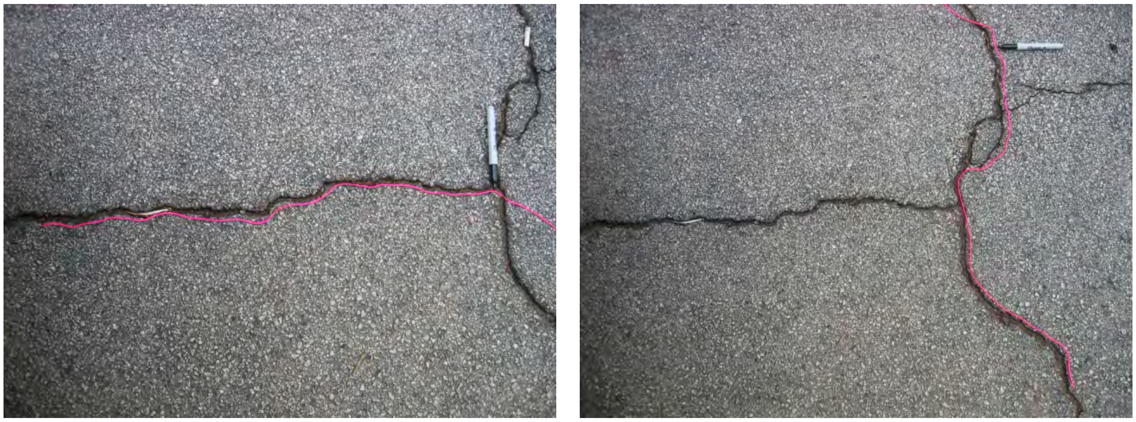
FIGURE VI-3 Images of 3 ft. wide by 2 ft. tall section during "overcast" conditions, **a)** directly overhead and **b)** skewed image by tilting camera

Next, physical measurements were taken with a micrometer to find the average width of the cracks, average depth of the cracks, and various length measurements including longitudinal, transverse and total length of the cracks. See the images in Figure VI-4 for the differences in how these length measurements were taken. The averages and totals of the physical measurements are listed in Table VI-1.

TABLE VI-1 Physical measurements of test section

Width Measurements (in.)	**Depth Measurements (in.)**	**Approximate Length**
1) 0.276	1) 0.335	
2) 0.220	2) 0.344	Longitudinal
3) 0.284	3) 0.378	
4) 0.206	4) 0.380	26.4 in.
5) 0.310	5) 0.361	
6) 0.367	6) 0.268	Transverse
7) 0.146	7) 0.435	
8) 0.588	8) 0.385	36.1 in.
9) 0.423	9) 0.378	
10) 0.518	10) 0.292	
Average = 0.313 in.	**Average = 0.363 in.**	**Total = 62.5 in.**

* Note: Length, width, and depth measurements only include the prominent crack(s) pattern seen in the images and not the much smaller cracks in the southeast corner (upper right in most images) of the section. These smaller cracks measured a total length of approximately 12 in. and would be added to the longitudinal direction.



a) **b)**

FIGURE VI-4 Visual depiction of **a)** longitudinal and **b)** transverse length measurements

From initial processing of the images the following pictures were produced by Vivek Kaul in order to try to separate out the cracks and write an algorithm or other image processing methods to measure the cracks. From initial calculations, the total length of longitudinal and transverse cracks is similar to that from physical measurements in Table VI-1 above. For a complete description of the entire image processing methods used and the full results, see Vivek Kaul's full special problem report.

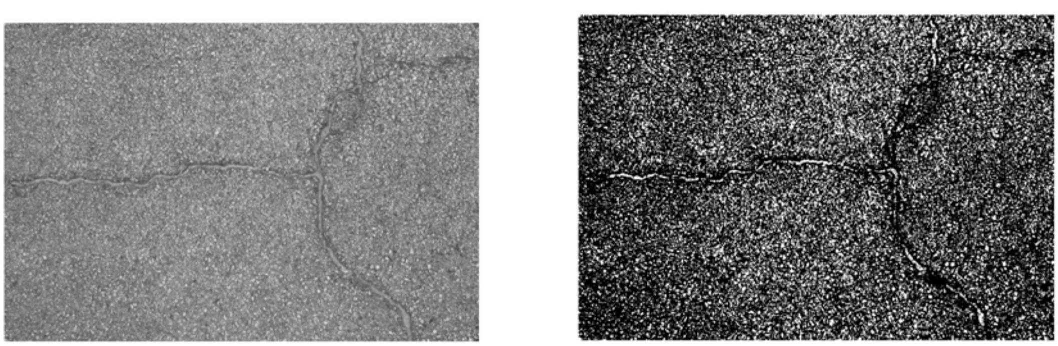


FIGURE VI-5 Initial images produced for image processing

GDOT Crack Sealing Process Performance Assessment

GDOT has been performing crack sealing and crack filling operations for several years now and it is encouraged to keep performing this practice as the majority of the literature suggests that preventive maintenance in the form of crack sealing does increase pavement life and also is cost-effective. This is especially true for asphalt cement concrete (ACC) pavements; there is more debate whether joint sealing for Portland cement concrete (PCC) pavements is cost-effective. The referenced special problem report above talks more about GDOT's current practices, which vary slightly by district, and consist mainly of "hot pour" rubberized asphalt material crack sealing operations and "cold pour" asphalt emulsion crack filling techniques. The literature suggests that hot pour techniques perform better than cold pour, and GDOT also prefers the hot pour technique as well. One advantage the cold pour asphalt emulsion treatment has over the hot pour rubberized material is its ability to seep in and fill much smaller cracks due to its much lower viscosity, and this may be a consideration if the optimum time to apply such treatments is pinpointed to a much smaller crack size than what the hot pour sealant can effectively be placed in.

Analyzing Current Crack Sealing Data

For the past few years GDOT has been recording crack sealing maintenance activities in the Highway Maintenance and Management System (HMMS) database, but this data lacks a lot of distinguishing information that would allow proper assessment of the data. However, one of the next steps that will be taken is to select several projects that have been crack sealed recently and compare the Computerized Pavement Condition Evaluation System (COPACES) pavement condition ratings of these roads to other routes or segments nearby in similar starting condition before crack sealing. The COPACES ratings by project or segment have been plotted for all the selected routes in order to compare the deterioration trends between the sealed and unsealed pavements.

One of the main challenges of this specific task is the lack of historical data. GDOT has only been recording the application of crack sealants for a few years and, which may not have been enough time for the condition ratings to show a definitive trend. Also, the data does not distinguish whether the hot pour or cold pour technique was used, so there is no way to directly compare the two methods. However, this will give a starting point for identifying the initial hypothesis for how effective crack sealing is if the large-scale test project is performed. One critical aspect that will be compared in this initial look at the existing data is the difference in projects in the northern and southern parts of the state. Below the Fall Line (southern Georgia), the soils are typically more sandy in nature as the geology approaches the coastal plain whereas above the Fall Line the soils in Piedmont and Blue Ridge geologic formations tend to contain larger amounts of fines (more silty to clayey soils) due to significant weathering of the parent rock. Figure VI-6 below shows the distinction between these primary geologic regions.

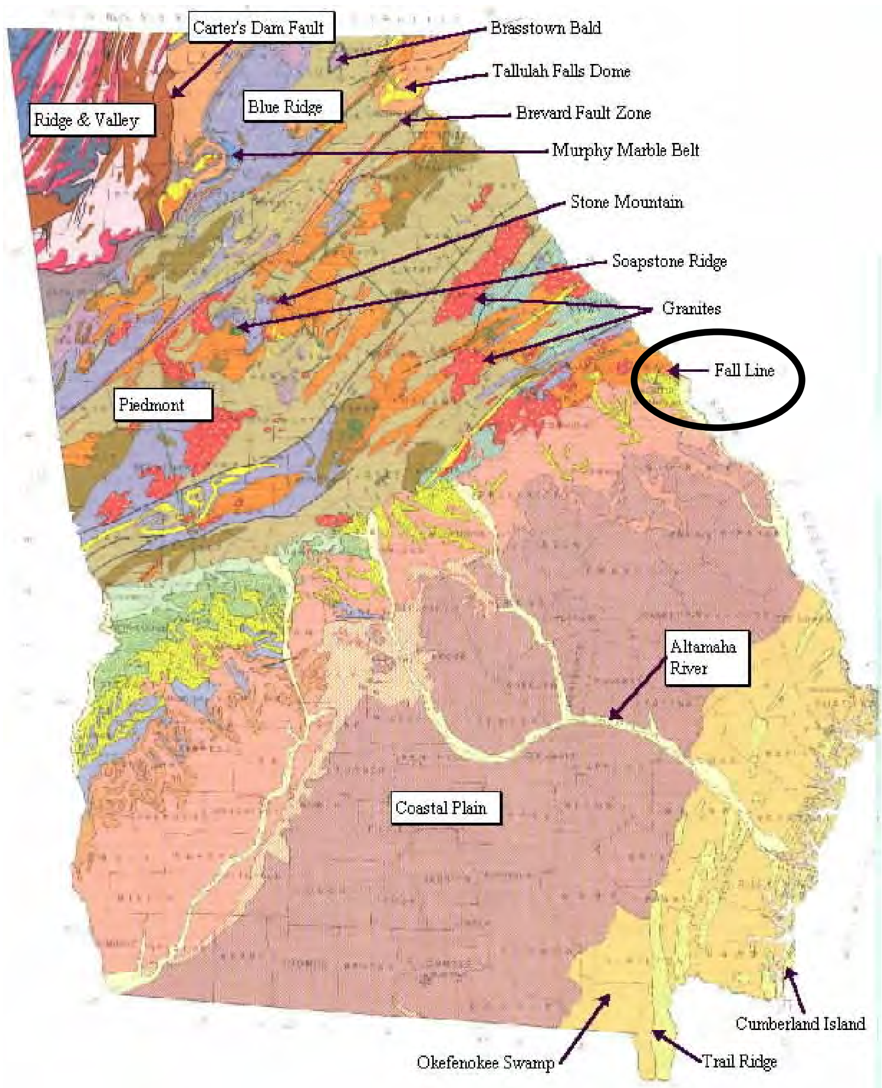


FIGURE VI-6 Georgia Geologic Survey, 1977 (after David Lawton; Chuck and Rachel Cochran—http://home.att.net/~cochrans/geomap01.htm)

It is assumed that an overall trend will be observed in that the pavements that have been crack sealed will have outperformed their counterparts without the crack sealing treatment. However, due to the limited data, low number of years with data, and lack of specifics about the existing crack sealing data, it is presumed that the trend and improvement will be difficult to quantify. After analyzing approximately 200 crack sealing projects from the years 2000 to 2004, samples of the rating trends and comments on the sections are listed below.

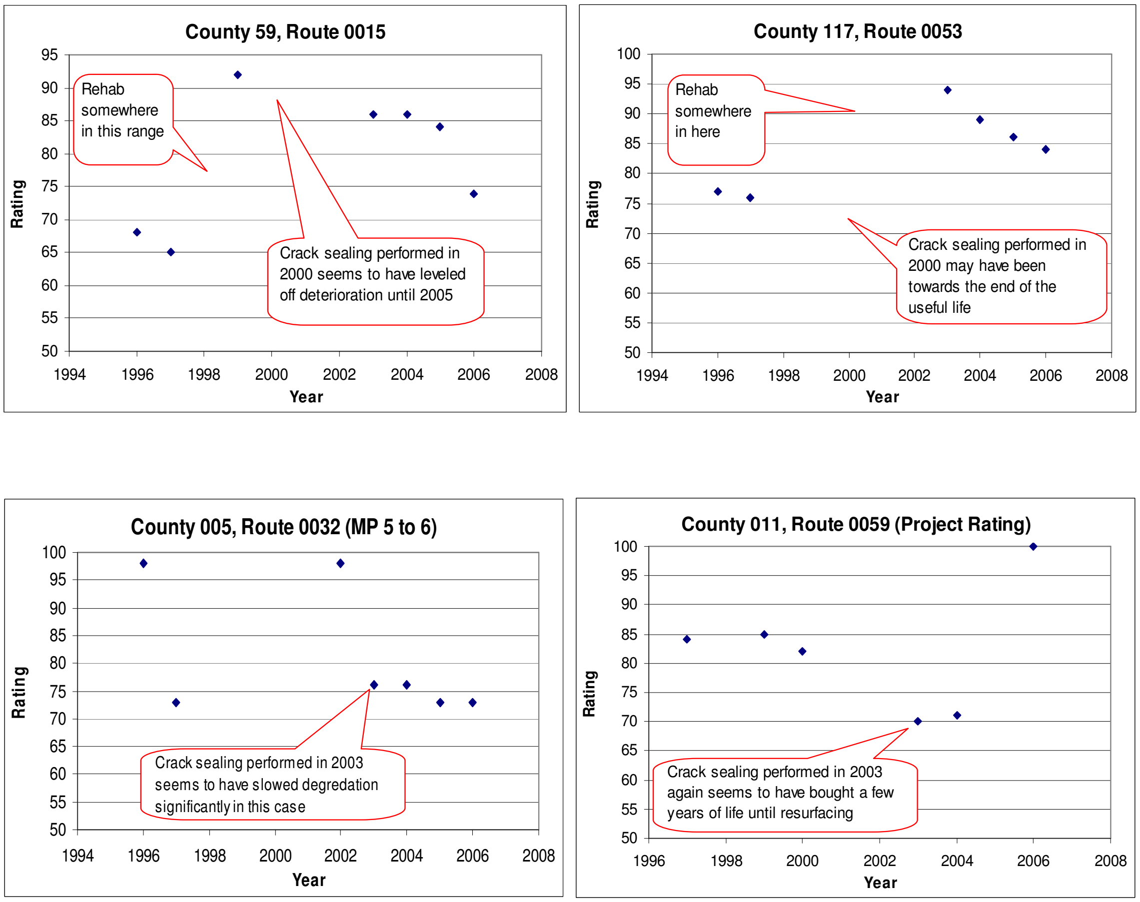


FIGURE VI-7 Examples of condition rating trends plotted from analyzing existing data on projects/segments of roadways that have been crack sealed in recent years

The data is of poor quality for a few reasons: 1) before 2004 no detailed PACES ratings were recorded for projects that were scheduled to be let the next year (the project may not actually have been let for several years due to budget constraints but there is no data for these years that it sat waiting) and 2) there are still micro level inconsistencies in the COPACES ratings (this means that it is possible for a more severe distress condition to actually have a higher project rating due to the way deduct values are applied—see example below). Contributing to the problem is the fact that current data may be skewed since the average project rating may "cover up" localized distresses in various segments of an overall project rating and make it difficult to directly compare the benefits of portions of the road that have been crack sealed. Therefore, these inconsistencies unveil the need for a large-scale test project to be conducted in order to systematically compare various crack sealing parameters under field conditions such as, soil type, climate, sealant materials, various application times, construction practices, and others.

Also, a more accurate measurement technique is needed to objectively quantify all the pavement distresses instead of relying on subjective human opinions that actually rate only 10% of the total length of pavement assessed. This opens the door for new technologies to be applied such as computer vision analysis of pavement distress images. Computer image analysis offers the ability to quickly assess a large amount of data in the form of pavement images (video or still images) in order to quantify the severity and extent of different distress types with improved accuracy.

Example of Inconsistent Calculation within PACES:

Take for example a pavement that only experiences Load Cracking (LC) distresses. In a certain year of the evaluation which we will call Year 1, the severity level (SL) and extent of the distresses are as follows: 20% SL 1, and 60% SL 2. In Year 2 the distress has become more severe and 20% of the SL 2 has now moved to SL 3 leaving 20% SL 1, 40% SL 2, and 20% SL 3. The deduct values are calculated next from the charts or by plugging into the COPACES software.

Year 1 Deducts: SL 1 (20%) = **8** and SL 2 (60%) = **48** by extrapolation (chart only goes up to a deduct of **30** at 45% extent)

Year 2 Deducts: SL 1 (20%) = **8,** SL 2 (40%) = **26**, and SL 3 (20%) = **28**

Per Chapter 4, "Calculating Project Rating", from the PACES manual it says that for load cracking "only the largest load cracking deduct value is used." This means that for Year 1 the value would be 48 (or 30) and for Year 2 it would be 28. Now calculating the project rating by subtracting the deduct values from 100 gives PCI = 52 (or 70) for Year

1 whereas PCI = 72 for Year 2. Regardless of whether a rating of 52 or 70 is used for Year 1, the rating of 72 for Year 2 is higher than both even though the condition in Year 2 is worse. *Therefore, it can be concluded that the PACES condition rating method does not always accurately reflect which pavement is in the worst condition.* This is obviously a flaw when trying to compare various pavement ratings to other pavements in order to make project or funding decisions. The proposed image technology should be capable of always quantifying which pavement is in a worse condition.

Appendix VII: Miscellaneous Guides for Pavement Maintenance, Pavement Distress and Cost

TABLE VII-1 Appropriate maintenance strategies for various distress types (after Hicks et al., 1999)

	Crack Sealing	Fog Seal	Microsurfacing	Slurry Seal	Cape Seal	Chip Seal	Thin Overlay	Mill or Grind[a]
Roughness								
Nonstability Related			X		X		X	X
Stability Related							X	
Rutting			X	X	X		X	
Fatigue Cracking								
Longitudinal and Transverse Cracking	X	X	X	X	X	X	X	
Bleeding			X			X		X
Raveling		X	X	X	X	X		

Key: X = appropriate strategy
[a]This is a corrective maintenance technique.

TABLE VII-2 Typical Unit Costs and Expected Life of Typical Pavement Maintenance Treatments (after Hicks et al., 1999)

Treatment	Cost/m^2	Cost/yd^2	Expected Life
Crack Treatment	3.29[f]	$1.00[f]	2 to 3 years
Fog Seals[a]	0.54	$0.45	3 to 4 years
Slurry Seals[b]	1.08	$0.90	4 to 6 years
Microsurfacing[c]	1.50	$1.25	5 to 7 years
Chip Seals[d]	1.02	$0.85	4 to 6 years
Thin Hot-Mix Overlay[e]	2.09	$1.75	2 to 10 years

Notes:
[a]0.2 1/m^2 (0.05 g/yd^2) of a 1:1 dilution of CSS emulsion and water
[b]7 kg/m^2 of ISSA Type II slurry
[c]14 kg/m^2 of ISSA Type II microsurfacing
[d]15 kg/m^2
[e]30 to 44 mm/m^2
[f]Cost per meter/lineal foot

TABLE VII-3 Guidelines for Effective Maintenance Treatments (after Hicks et al., 1999)

Pavement Conditions		Parameters	Thin Overlay	Slurry Seal	Crack Seal[e]	Rout & Seal[e]	Rout & Fill[e]	Chip Seal (Fine)[c]	Chip Seal Course[c]	Micro Surface	Fog
			Treatments								
Traffic	(ADT/Lane)	[d]<1000	E	E	E	E	E	E	E	E	E
		100<ADT<4000	E	E	E	E	E	E-Q	E-Q	E	E-Q
		>4000	E	E	E	E	E	E-N-Q	E-N-Q	E	E-Q
	Ruts[b]	<3/8 in.	E	E	E	E	E	E	E	E	E
		3/8 in.<R<1 in.	E	M-N	E	E	E	M-N-Q	M-N-Q	E	T
		> 1 in.	E	T	E	E	E	T	T	M-C	T
Cracking	Fatigue	Low	E	E	E	E	E	E	E	E	M
		Moderate	E	M	M	M	M	E	E	M	T
		High	M	T	T	T	T	E	E	T	T
	Longitudinal	Low	E	E	E	E	E	E	E	E	M
		Moderate	E	M	E	E	E	E	E	M	T
		High	M	T	M	E	E	M	M	T	T
	Transverse	Low	E	E	E	E	E	E	E	E	M
		Moderate	E	M	E	E	E	E	E	M	T
		High	M	T	M	E	E	M	M	T	T
Asphalt Surface Condition		Dry	E	E	T	T	T	E	E	E	E
		Flushing	E	E	T	T	T	M-Q	E-Q	E	T
		Bleeding	E	E	T	T	T	N-Q	N-Q	E	T
		Variable	E	E	T	T	T	M-Q	E-Q	E	M[f]
	Raveling	Low	E	E	T	T	T	E	E	E	E
		Moderate	E	E	T	T	T	E	E	E	M
		High	E	M	T	T	T	E-Q	E-Q	E	M
	Potholes	Low	E	E	T	T	T	E	E	E	T
		Moderate	E	M	M	T	T	E	E	M	T
		High	E	M	M	T	T	M	M	M	T

Pavement Conditions	Thin Overlay	Slurry Seal	Crack Seal[e]	Rout & Seal[e]	Rout & Fill[e]	Chip Seal (Fine)[c]	Chip Seal Course[c]	Micro Surface	Fog
	Treatments								
Existing Pavement Texture is Rough	E	E	T	T	T	M-Q	M-Q	E	T
Poor Ride	E	E	T	T	T	T	T	M	T
Rural (minimum turning movements)	E	T	T	T	T	E	E	E	E
Urban (maximum turning movements)	E	E	E	E	E	E-Q	E-Q	E	E
Subsurface Moisture									
High Snow Plow Usage	E	E	E	E	E	E-Q	E-Q	E	E
Low Frictional Resistance	E	E	T	T	T	E	E	E	T

[a]The chart provides general guidance only and engineering judgement and experience should be used to select the proper treatment
[b]Rutting has occurred over an extended period of time
[c]For ADT in excess of 50,000 (total) and/or truck volumes in excess of 20 percent this treatment can be effective, but is not recommended
[d]Higher percentages of trucks have a significant effect on performance
[e]Requires routine retreatment at two year intervals, typically
[f]Spot treatments on dry conditions only

Key:
- E Effective
- M Marginally effective
- N Not recommended
- Q Requires a higher degree of expertise and quality control
- T Not effective

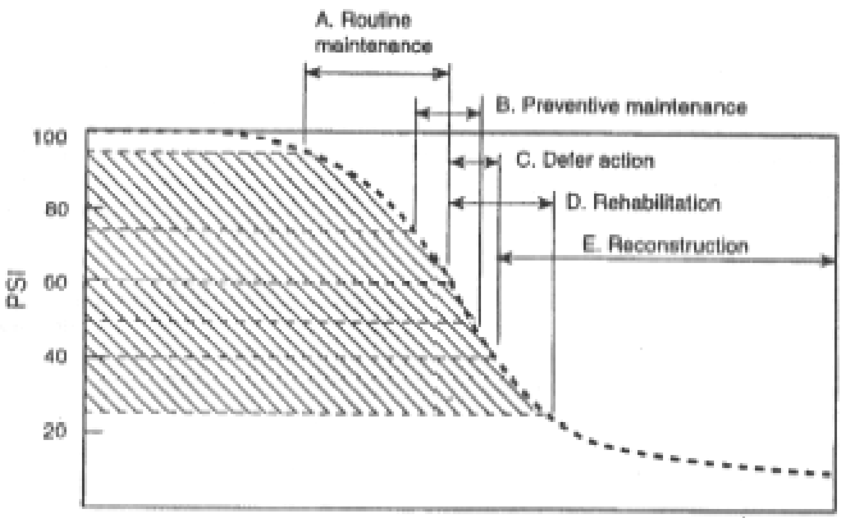


FIGURE VII-1 Conceptual relationship for timing of various maintenance and rehabilitation treatments (after Hicks et al., 1999)

TABLE VII-4 Examples of Cost-Effectiveness of Various Preventive Maintenance Treatments (after Hicks et al., 1999)

Treatment	Life of Treatment[a]	Equivalent Annual Cost
Crack Sealing	2.5	$0.40
Fog Seal	3.5	$0.13
Slurry Seal	5	$0.18
Microsurfacing	6	$0.21
Chip Seals	5	$0.17
Thin Hot-Mix Overlay	7	$0.25

[a]Typical life of maintenance treatment for average conditions

Appendix VIII: GDOT Site Visit of GDOT Crack Sealing Operation

On 13 March 2007 Georgia Tech research team met with Terry Rutledge from the Georgia Department of Transportation (GDOT) to visit two crack sealing operations in north Georgia. The first operation visited was considered by GDOT to be crack filling and consisted of a liquefied asphalt emulsion, and the second site was considered to be crack sealing and consisted of a rubberized material that is melted and then spread over the cracks. Before going to the sites, Terry answered several questions about the operations, and a summary of the answers are provided below.

- Terry first replied to how the crack seal projects are selected. Basically the routes that are considered for crack sealing/filling are flagged by two questions in COPACES when the pavement is rated. First, are cracks greater than 1/4 of an inch? Second, if cracks have been sealed previously, is the sealant in good working condition or degraded severely? If the answer is yes to the first question, then it is a candidate for crack sealing. Terry said that cracks are rarely resealed in later years but indicated that this can and has been done. There is no set PCI or other trigger value to perform sealing other than the crack width. In the field the raters generally use a separate criterion to determine if the crack is wide enough for the rubberized material to seal effectively; if the width of a quarter (coin) can fit into the crack then the rubberized material can be used. Terry mentioned that the liquid emulsion can get into smaller cracks and so this is somewhat subjective as to what pavements with cracks less than the width of a quarter (coin) get sealed.

- When asked if the raters have noticed good outcomes so far for the pavements that have been crack sealed, Terry's response was yes but GDOT wants to know how much benefit it is providing based on their costs. One negative comment that can be mentioned here is that in areas where the liquid emulsion is used complaints from citizens occasionally come saying that it is visually not pleasing to have the dark crack seal lines amplified. Tracking (especially with the liquid emulsion) contributes to "the mess" as well as complaints from the emulsion splattering up onto vehicles. This can be minimized by not over-applying the emulsion, allowing maximum drying time before opening to traffic, and making sure that preventive measures such as applying sawdust over the top get applied sufficiently. In the liquid emulsion site visited, tracking appeared to be a problem and more saw dust could have been applied evenly. However, one section performed the day before appeared to have very little tracking compared to sections on either side of it; this offers some confusion of the exact conditions which produce more severe tracking. In every case though, the entire crack sealed section is opened to traffic in the evening of the same day when the workers go home for the night.

– In response to sealing pavements already in "bad" condition, Terry said this is very seldom done. As a general rule, if the pavement has Severity Level 2 load cracking then crack sealing is not applied because is requires too much sealant (too expensive per lane mile), and the excessive sealant is a safety hazard by lowering the skid resistance too much. Exceptions to this occur and Terry showed a site that had fairly severe block cracking and was scheduled for resurfacing but kept getting bumped. Crack sealing was applied late in the life of this pavement and has helped provide 5-6 years onto the life until the resurfacing can eventually happen very soon. A picture of this site is below, and it should be noted that the cracking is block cracking and therefore there is enough spacing in between the cracks to maintain skid resistance.

Figure VIII-1

- GDOT considers crack sealing to be physically effective but is unsure on the cost-effectiveness. Crack sealing is done by GDOT maintenance crews throughout the winter months when cracks are at their widest, and one of the foremen at the liquid emulsion site commented that they make an effort in their region to crack seal 100% of the roads in their part of the network every year that are considered candidates.

- Drainage characteristics of a site are noted, but a poor drainage condition does not necessarily influence whether or not the pavement gets crack sealed. Other maintenance operations such as ditching are done in conjunction with operations such as crack sealing.

- Next, an explanation of each operation will be explained and the pros and cons will be identified with each method. GDOT almost unanimously agrees that the rubberized material/operation is better and more effective, but there are no hard facts to back up this philosophy.

Site 1: Liquid Asphalt Emulsion

The first site visited was the liquid emulsion operation. Before actually observing the operation, we stopped and looked at some sealant/filler that was applied the previous day. The following photo shows that the procedure seemed to leave several cracks unsealed.

Figure VIII-2

This can be attributed to poor workmanship and/or the emulsion sinking further into the crack and not enough being left to seal the surface. Most of the cracks at this site were not wide enough to fit a quarter into, and therefore one advantage of the liquid is that it can get into tighter spaces and fill smaller cracks. One disadvantage of the less viscous material is that there is little control over where it flows even after placing. If there is a slight slope, the material is susceptible to running and not drying over the crack. The typical crew size for this operation is 8-10 people and consists of a driver pulling an air compressor in the front, two people blowing out or cleaning the cracks with the air compressor, a driver pulling the boiler with the emulsion, two people operating the wands that fill the cracks with the emulsion, a driver/operator for the sawdust spreader, two traffic control people, a foreman, and site superintendent. This operation is more complex in terms of the people and pieces of equipment required. Photos of the emulsion being applied are below and not shown are the air compressor in front and spreader behind. The last photo is the final result after the sawdust is applied to try to help prevent tracking which occurred in the opposite lane after the previous day's operation in the left middle photo.

Figure VIII-3

The operation can fill/seal approximately 2-3 lane miles per day. The emulsion in the boiler must be heated to about 150º F and variation in this temperature can have significant effects on the performance of the sealant. The COPACES report for this site is found in the appendix but it had an overall PCI rating of 77 compared to 80 the previous year mostly due to Severity Level 1 load and block cracking. Even though this is not GDOT's preferred, it is "better than nothing" per Terry and will continue to be used to get the useful life out of the equipment that has already been purchased.

Site 2: Rubberized Asphalt Crack Sealing Material

This operation displayed the procedure that GDOT prefers for crack sealing. The primary machine or boiler costs $1.5k more ($32k versus $30.5k) than then the boiler for the liquid emulsion and the material is also more expensive, but GDOT still believes its performance is worth the extra cost. This operation seemed to be less cumbersome compared to Site 1 on a whole, but one immediate disadvantage is that this machine must heat up to about 450º F which can take 1-2 hours. Also, blocks of rubber equal to 3 gallons of product when melted, must be continually added throughout the operation. If these blocks are added too late, they may not have sufficient time to melt before extruding from the hose. This can cause clogging or insufficient spreading over the crack, therefore creating a raised bump that can be annoying the driver. One other disadvantage if the sealer is applied to thick is the susceptibility to pull-out from vehicles or snowplows. All of the crew is basically focused around the machine and truck which only requires a minimum of three people to operate. The other crew members line up behind the personnel with the wand(s) and an interchange in operator is made every 10 minutes or so. This helps contribute to better quality work because there are frequent breaks and fresh eyes sealing the cracks. This procedure is also less “messy” because the material hardens to a very tacky material only minutes after it is applied and results in virtually no tracking when opened up to traffic. The machine can operate with two wands but the operation on this day only used one wand because the load cracking was primarily isolate to one wheel path. It is difficult to see in the photos, but the wand differs from the other machine in that it has a circular disc at the bottom to help spread the more viscous material and the wand arms in this machine are heated to help prevent the material from hardening in the lines. The maximum output per day is also roughly 2 lane miles per day. Following are some photos of this operation.

Figure VIII-4

Figures VIIIA & VIIIB

This particular site had a PCI rating drop from 95 to 79 in only one year and GDOT is trying to figure out why the site had such a severe drop in quality in such a short period of time. It is also worth noting that this site is a road right off an I-75 Interstate exit. See the COPACES reports in the Appendix for more details.

Final Comments

During the visit Terry mentioned that practices will vary between districts and area offices. He also said that each district gets approximately $1 million annually for equipment purchases such as the boilers used in these operations, but that budget must also buy any other trucks or equipment for every other type of operation so the money does not go far. GDOT has not experimented with any other materials or procedures than the ones presented here and a more detailed description of the practices from the HMMS database can also be found in the appendix. In general, the operations seemed to be running smooth and efficiently, and GDOT believes that their crack sealing operations are contributing to extending pavement life.

HMMS database description and details about crack sealing operations

Revised 7/2006

Activity 120

Activity Name: **Crack Filling**
Crew Size: 7
Person Hours: 56

Inventory Feature: Bit. Lane Miles
Average Daily Production: 1.5
Measure Unit: Lane Miles

Description: This activity includes filling cracks in asphalt pavements with a liquid asphalt to prevent water from entering the pavement and into the base or subgrade.

Note: This work shall be performed using: "Maintenance Work Zone Traffic Control Standards"

Note: Rubberized Asphalt is the preferred application

Note: when converting rubberized asphalt from pounds to gallons use this formula, Total pounds divided by 9.8 = gallons used.

Work Description Category:

Performing Activity

Moving Equipment

Special Performance Conditions: Ideally, cracks should be filled during cold weather (from late fall until early spring), but this activity may be performed at any time as a preventive measure.

Labor:

Number	Labor	Hours
1	Highway Maintenance Foreman	8
1	Assistant Foreman	8
2	Main Equipment Operators	8
2	Equipment Operator 3	8
1	Equipment Operator 2	8

Equipment:

Prefix	Quantity	Description	Hours
007	1	Air Compressor – CFM 51 and over	
019	1	Asphalt Kettles 300 – 650 gallons – truck mounted	
016	1	Asphalt Kettle under 300 gal.	
018	1	Asphalt Kettles 300-600 gal Trailer Mounted	
056	1	Arrow Board (Trailer Mounted)	
058	1	Crash Attenuator	
401	1	Pickup	6

017	1	Rubberized Kettle	6
405	2	Dump Truck 0-7 yards	6

Material:

Description	Unit	Quantity Used
CRS-2H Liquid Asphalt	Gallon	
CRS-3P Liquid Asphalt	Gallon	
Type M Rubberized Asphalt	Gallon	45
Sand	Ton	1
AC 30 Liquid Asphalt Tack	Gallon	*
M10 Stone Screenings	Ton	*
Sawdust	Cubic Yard	
Cold Bituminous Patching Material	Pounds	
Rubberized Asphalt	Gallons	

*Seldom Used Material

Work Distribution by Percentage:

January	17%	July	0%
February	17%	August	0%
March	16%	September	0%
April	16%	October	0%
May	0%	November	17%
June	0%	December	17%

Recommended Procedure:

Place signs and other safety devices.

Airblast any debris or loose material from the cracks using an air compressor.

Heat the asphalt to the specified application temperature and apply to cracks with a filling device.

Sprinkle sand or screenings lightly on the sealed cracks, or use a squeegee to prevent tracking when using CRS2H.

Clean up the work area.

Other Equipment Needed (Non-Prefix):

None

Site 1: COPACES Reports

2005

GEORGIA DEPARTMENT OF TRANSPORTATION
HIGHWAY MAINTENANCE MANAGEMENT SYSTEM

Flexible Pavement Condition Survey Report

Date: **17-NOV-2005** Project Rating: **80** Office: **A1** Rater: **JASON F. MOORE**

Project Location

District: **6** Prefix: **SR** Route: **136** Suffix: **00**

County	Begin MP	End MP
129 - GORDON	8.10	23.61

Project Limits: **MURRAY COUNTY LINE TO M.P. 8.10 @ S.R. 3**
Estimated length of curb and gutter that requires MILLING (mile):

Roadway Information

AADT: **5070** Surface Type: **A** Divided Highway: **NO** Direction:
Typical Pavement Width(ft): **34** Typical Shoulder Width: **8**
STAA: **NO** No. Bridges: **1** Bridge Width(ft): **34**

Remarks

Sample Location							Rut Depth		Load Cracking				Block Cracking		Reflection Cracking			Raveling		Edge Distress		Bleeding /Flushing		Corrug-ation /Pushing		Loss Pavement Section		Cross Slopes			Seg. Rat-ing	Crack Width	Remarks
Coutny	Begin MP	End MP	Sample Location	Lane Direction	Lane No (1,2,3...)	Project Limit	Outside W.P.(1/8inch)	Inside W.P. (1/8 inch)	Severity 1	Severity 2	Severity 3	Severity 4	% Of Sample	Severity (1,2,3)	No. of Cracks	Total Length	Severity (1,2,3)	% of Sample	Severity (1,2,3)	% of Sample	Severity (1,2,3)	% of Sample	Severity (1,2,3)	% of Sample	Severity (1,2,3)	% of Sample	Severity (1,2,3)	Left (1/8 inch)	Right (1/8 inch)	Patches & Potholes	Rating	Greater than 1/4 inch?	
129	9.00	8.10	2	POS.	1	1	1	1	25				25	1																	83	NO	
129	10.00	9.00	1	NEG.	1	0	1	1	40																						85	NO	
129	11.00	10.00	2	NEG.	1	0	1	1	70																						83	NO	
129	12.00	11.00	7	POS.	1	0	1	1	40																						85	NO	
129	13.00	12.00	1	NEG.	1	0			40																						87	NO	
129	14.00	13.00	7	NEG.	1	0	1	1		50																					68	NO	
129	15.00	14.00	7	POS.	1	0		1	100																						83	NO	
129	16.00	15.00	1	POS.	1	0	1	1					75	1																	80	NO	
129	17.00	16.00	1	NEG.	1	0	1	1	100																						83	NO	
129	18.00	17.00	6	NEG.	1	0	1	1	50																						83	NO	
129	19.00	18.00	3	NEG.	1	0	1	1	80																						83	NO	
129	20.00	19.00	3	POS.	1	0	1	1	75																						83	NO	
129	21.00	20.00	5	NEG.	1	0	1	1		85																					68	NO	
129	22.00	21.00	6	NEG.	1	0	1	1	100																						83	NO	
129	23.00	22.00	3	NEG.	1	0	1	1		100																					68	NO	
129	23.61	23.00	2	NEG.	1	1	1	1	20				20	1																	84	YES	

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2006

GEORGIA DEPARTMENT OF TRANSPORTATION
HIGHWAY MAINTENANCE MANAGEMENT SYSTEM

Flexible Pavement Condition Survey Report

Date: **04-DEC-2006** Project Rating: **77** Office: **A1** Rater: **Jason F. Moore**

Project Location

District: **6** Prefix: **SR** Route: **136** Suffix: **00**

County	Begin MP	End MP
129 - GORDON	8.10	24.07

Project Limits: **S.R.. 3 TO MURRAY COUNTY**

Estimated length of curb and gutter that requires MILLING (mile):

Roadway Information

AADT: **5160** Surface Type: **A** Divided Highway: **NO** Direction:

Typical Pavement Width(ft): **34** Typical Shoulder Width: **6**

STAA: **NO** No. Bridges: **3** Bridge Width(ft): **30**

Remarks

Sample Location							Rut Depth		Load Cracking				Block Cracking		Reflection Cracking			Raveling		Edge Distress		Bleeding /Flushing		Corrug-ation /Pushing		Loss Pavement Section		Cross Slopes			Seg. Rat-ing	Crack Width	Remarks
Coutny	Begin MP	End MP	Sample Location	Lane Direction	Lane No (1,2,3...)	Project Limit	Outside W.P.(1/8inch)	Inside W.P. (1/8 inch)	Severity 1	Severity 2	Severity 3	Severity 4	% Of Sample	Severity (1,2,3)	No. of Cracks	Total Length	Severity (1,2,3)	% of Sample	Severity (1,2,3)	% of Sample	Severity (1,2,3)	% of Sample	Severity (1,2,3)	% of Sample	Severity (1,2,3)	% of Sample	Severity (1,2,3)	Left (1/8 inch)	Right (1/8 inch)	Patches & Potholes	Rating	Greater than 1/4 inch?	
129	8.10	9.00	4	NEG.	1	1	1	1	50																						83	NO	
129	9.00	10.00	7	NEG.	1	0	1	1	100																						83	NO	
129	10.00	11.00	4	NEG.	1	0	1	1	50																						83	NO	
129	11.00	12.00	8	POS.	1	0	1	1	100				50	1																	73	NO	
129	12.00	13.00	7	POS.	1	0	1	1	75				60	1																	72	NO	
129	13.00	14.00	8	NEG.	1	0	1	1	100				60	1																	72	NO	
129	14.00	15.00	8	POS.	1	0	1	1	60																						83	NO	
129	15.00	16.00	7	POS.	1	0	1	1	100																						83	NO	
129	16.00	17.00	7	POS.	1	0	1	1	60				30	1																	76	NO	
129	17.00	18.00	8	POS.	1	0	1	1	60				30	1																	76	NO	
129	18.00	19.00	3	NEG.	1	0	1	1	60																						83	NO	
129	19.00	20.00	8	NEG.	1	0	1	1	100				60	1																	72	NO	
129	20.00	21.00	9	POS.	1	0	1	1	80				50	1																	73	NO	
129	21.00	22.00	7	NEG.	1	0	1	1	100				30	1																	76	NO	
129	22.00	23.00	8	NEG.	1	0	1	1	100																						83	NO	
129	23.00	24.00	9	NEG.	1	0	1	1	75																						83	NO	
129	24.00	24.07	1	NEG.	1	1	1	1																							98	NO	

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Site 2: COPACES Reports

2005

GEORGIA DEPARTMENT OF TRANSPORTATION
HIGHWAY MAINTENANCE MANAGEMENT SYSTEM

Flexible Pavement Condition Survey Report

Date: 16-NOV-2005 Project Rating: 95 Office: A1 Rater: JASON F. MOORE

Project Location

District: 6 Prefix: SR Route: 53 Suffix: 00

County	Begin MP	End MP
129 - GORDON	10.80	27.27

Project Limits: M.P. 10.8 TO PICKENS COUNTY LINE
Estimated length of curb and gutter that requires MILLING (mile):

Roadway Information

AADT: 11510 Surface Type: A Divided Highway: NO Direction:
Typical Pavement Width(ft): 50 Typical Shoulder Width: 10
STAA: YES No. Bridges: 2 Bridge Width(ft): 60

Remarks

Sample Location							Rut Depth		Load Cracking				Block Cracking		Reflection Cracking			Raveling		Edge Distress		Bleeding /Flushing		Corrug-ation /Pushing		Loss Pavement Section		Cross Slopes			Seg. Rat-ing	Crack Width	Remarks
Coutny	Begin MP	End MP	Sample Location	Lane Direction	Lane No (1,2,3...)	Project Limit	Outside W.P.(1/8inch)	Inside W.P. (1/8 inch)	Severity 1	Severity 2	Severity 3	Severity 4	% Of Sample	Severity (1,2,3)	No. of Cracks	Total Length	Severity (1,2,3)	% of Sample	Severity (1,2,3)	% of Sample	Severity (1,2,3)	% of Sample	Severity (1,2,3)	% of Sample	Severity (1,2,3)	% of Sample	Severity (1,2,3)	Left (1/8 inch)	Right (1/8 inch)	Patches & Potholes	Rating	Greater than 1/4 inch?	
129	10.80	11.00	9	POS.	1	1							20	1																	94	NO	
129	11.00	12.00	7	POS.	1	0							30	1																	93	NO	
129	12.00	13.00	7	POS.	1	0							35	1																	92	NO	
129	13.00	14.00	6	POS.	1	0							25	1																	94	NO	
129	14.00	15.00	7	POS.	1	0							25	1																	94	NO	
129	15.00	16.00	6	POS.	1	0							10	1																	96	NO	
129	16.00	17.00	9	POS.	1	0							10	1																	96	NO	
129	17.00	18.00	7	POS.	1	0																									100	NO	
129	18.00	19.00	6	POS.	1	0							15	1																	95	NO	
129	19.00	20.00	7	POS.	1	0							20	1																	94	NO	
129	20.00	21.00	5	POS.	1	0																									100	NO	
129	21.00	22.00	6	POS.	1	0							10	1																	96	NO	
129	22.00	23.00	7	POS.	1	0																									100	NO	
129	23.00	24.00	7	POS.	1	0																									100	NO	
129	24.00	25.00	1	POS.	1	0																									100	NO	
129	25.00	26.00	6	POS.	1	0							20	1																	94	NO	
129	26.00	27.00	6	POS.	1	0							10	1																	96	NO	
129	27.00	27.27	1	POS.	1	1							10	1																	96	NO	

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2006

GEORGIA DEPARTMENT OF TRANSPORTATION
HIGHWAY MAINTENANCE MANAGEMENT SYSTEM

Flexible Pavement Condition Survey Report

Date: **04-DEC-2006** Project Rating: **79** Office: **A1** Rater: **Jason F. Moore**

Project Location

District: **6** Prefix: **SR** Route: **53** Suffix: **00**

County	Begin MP	End MP
129 - GORDON	9.70	13.20

Track 6

Project Limits: **MP 9.7 TO 13.2**
Estimated length of curb and gutter that requires MILLING (mile):

Roadway Information

AADT: **34620** Surface Type: **A** Divided Highway: **NO** Direction:
Typical Pavement Width(ft): **50** Typical Shoulder Width: **8**
STAA: **YES** No. Bridges: **1** Bridge Width(ft): **48**

Remarks

Sample Location							Rut Depth		Load Cracking				Block Cracking		Reflection Cracking			Raveling		Edge Distress		Bleeding /Flushing		Corrug-ation /Pushing		Loss Pavement Section		Cross Slopes			Seg. Rat-ing	Crack Width	Remarks
Coutny	Begin MP	End MP	Sample Location	Lane Direction	Lane No (1,2,3...)	Project Limit	Outside W.P. (1/8inch)	Inside W.P. (1/8 inch)	Severity 1	Severity 2	Severity 3	Severity 4	% Of Sample	Severity (1,2,3)	No. of Cracks	Total Length	Severity (1,2,3)	% of Sample	Severity (1,2,3)	% of Sample	Severity (1,2,3)	% of Sample	Severity (1,2,3)	% of Sample	Severity (1,2,3)	% of Sample	Severity (1,2,3)	Left (1/8 inch)	Right (1/8 inch)	Patches & Potholes	Rating	Greater than 1/4 inch?	
129	9.70	10.00	8	NEG.	1	1			60																						85	NO	
129	10.00	11.00	1	NEG.	1	0			60				20	1																	79	NO	
129	11.00	12.00	3	NEG.	1	0			100				40	1																	76	NO	
129	12.00	13.00	3	NEG.	1	0			100				50	1																	75	NO	
129	13.00	13.20	1	NEG.	1	1			75																						85	NO	

12-MAR-07 11:37:28 22 of 24

Appendix IX: Field Verification of GDOT COPACES Rating System

GDOT Pavement Condition Rating Trip

Summary of Pavement Condition Assessment

Route SR 136, District 6, Gordon County, Georgia

(In collaboration with Nathan Rumsey and Chan-Sheng Chung)

In an effort to better manage highway pavements, the Georgia Department of Transportation (GDOT) has adopted a pavement management system (PMS) that includes performing a pavement condition assessment on its entire 18,000-mile road network every year and prioritizing rehabilitation and maintenance projects based on these assessments. As part of this report, a condition assessment was performed on four 1-mile segments of the 8.83 mile project length of the route. The survey started at the zero mile post at the county line and extended to the town of Sugar Valley in the positive (increasing milepost) direction. The following is an in-depth description of the site visit and assessment.

On 23 March 2007 Georgia Tech research team met with Terry Rutledge from GDOT to visit a pavement rout in north Georgia approximately 8 miles in length. The goal of the trip was to perform a pavement condition assessment on the route similar to what GDOT performs annually and obtain a pavement condition index (PCI) as well as other pertinent observations for completing this final project. Before actually traveling the route and performing the assessment, Mr. Rutledge answered several questions about the route and assessment operations, as well as handed us a core of the pavement that was taken from the first mile of the route. A photo of the core is shown below.

Figure IX-1

The core clearly shows approximately 4-5 inches of compacted subbase that actually came from a chert pit that is located along the first mile of the route. The subbase is so stiff that we are curious as to whether it may have been stabilized with lime or cement when it was constructed. Next, one will notice about an inch of asphalt base layer, which can be distinguished from the other asphalt layers by the larger size aggregates. Finally the next 2-3 inches are surface coarse asphalt cement layers with finer aggregate. The design history of this pavement will be requested, but it looks as though at least one overlay has been performed in the past by observing the banding in the core.

We started driving the route from the starting point and traveled in the positive mile direction. For each of the first four miles, we stopped at a representative section in order to record the pavement distresses to calculate the PCI. Mr. Rutledge explained how GDOT personnel perform the surveys and then on the last two sections we compared our ratings to his. The route is currently in the resurfacing program for GDOT; therefore, the ratings obtained should definitely be below 70. In general, the route was characterized by mild to severe load cracking and significant areas of block cracking along most of the route. The following pictures give a good idea of visual condition of the pavement. The dark cracks are cracks that were crack sealed approximately 5 years ago with a liquid emulsion crack sealant.

Figure IX-2A & IX-2B

Other distresses encountered along the route included at least some rutting on every section and isolated cases of raveling and corrugation. Another common distress noticed was a significant longitudinal crack along the centerline or paving joint of the road. Some of the cracks were wide enough that grass and weeds were growing in the crack. The following shows a close-up of the raveling and corrugation encountered. The raveling was isolated at an intersection where it appeared that a recent overlay of the adjoining road did not adhere well to the existing pavement. The corrugation was isolated to an area where a severe curve in the road took place and the recommended speed was reduced from 55 to 35 mph. The reduced speed along with the curve produced this distress over time when large trucks approach this section.

Figure IX-3A & IX-3B

The drainage characteristics of the entire route seemed to be very good. Most of the route consisted of simple ditching along both sides of the road, and the slope in some areas was much greater than in others. Nearly all of the ditches were in good shape and did not seem to be clogged to the point where they would prevent water run-off. Some of the areas did have excess plant growth, and it would be recommended to clean these areas out next winter along with other maintenance operations in the area. Several driveways that come off the route have standard culverts underneath and again, most of these seemed to be in sufficient shape. As we approached the small city of Sugar Valley, the drainage system was a little different with lip culverts along the side of the road that diverted storm water to point drains. Mr. Rutledge said that milling would not need to be performed in this area before an overlay was performed. The left photo on the next page shows the lip drain with a previous overlay already sticking above the concrete lip drain.

Figures IX-4A - D

Due to the severity of the cracks in the pavement, it is assumed that a significant amount of water is infiltrating the sub layers and ultimately shortening the life of the roadway. Although the data for the following statement is for surface cracks in portland cement concrete (PCC), it is assumed that the results will not be different for asphalt cement (AC) concrete pavements. Given the previous statement, Dr. Barry Christopher presented a slide in a seminar last semester at Georgia Tech that said that the percent of runoff entering a 0.9mm (0.035in.) crack is 76% and 97% of surface water enters a crack that is 3.2mm (0.125in.) wide during a 50mm (2in./hr.) rainfall event. AASHTO (1993) says that water in the asphalt surface can lead to moisture damage, modulus reduction (saturation reduces asphalt modulus by as much as 30% or more and unbound aggregate base and subbase by 50% or more), and loss of tensile strength. Figure 1 below is from AASHTO (1993) and it shows that if a pavement system is saturated for only 10% of its life, then the design life expectancy is reduced to about half.

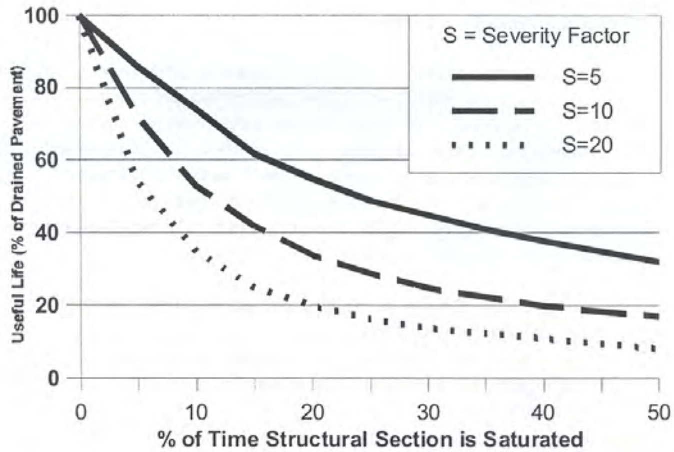


FIGURE IX - 5 Influence of saturation on the design life of a pavement system (after Cedergren, 1987)

As previously mentioned, it is assumed that water can easily infiltrate the analyzed pavement due to the severity of the cracks. In order to estimate the time for the pavement to drain, we took a soil sample from the edge of the road in between it and the drainage ditch. The sample was from the near surface and therefore some topsoil is likely mixed in, but the overall material is similar to that used as the subbase material. The actual subbase from the chert pit mentioned previously likely has a hydraulic conductivity at least a couple orders of magnitude less due to very dense compaction and what seems to be some lime or cement stabilization from how stiff the material is. We classified the soil by running a sieve analysis on the material and the results are outlined in the Appendix. The AASHTO soil classification was A-3 with approximately 7% fines. According to AASHTO (1997), permeability tests showed that 5% fines resulted in a hydraulic conductivity of 0.02 m/day (0.07 ft/day) and 10% fines reduce the permeability to approximately 0.0003 m/day (0.001 ft/day). In order to be conservative, it is assumed that the compacted subbase is at least near the latter value above, which would make the drainage condition for the pavement “Poor” to “Very Poor” or water is removed in a month to never. The core in the first photo does not have any surface cracks so it is unclear if the cracks on the majority of the pavement extend to the subbase level. However, since load cracking initiates at the base of the AC layer it is assumed that the cracks propagate the entire thickness of the AC layer, essentially trapping water in the low-permeability subbase. Photos of the subbase material are shown below.

Figure IX-6A & IX-6B

The overall traffic or the route observed on the day of the assessment was light due to the rural location of the route. Average Annual Daily Traffic (AADT) history from previous COPACES/GDOT data shows only 6,630 vehicles with 15.1% trucks. Another GDOT reference shows 3,800 vehicles with no truck percentage information. More traffic information will need to be gathered in our analysis. Several 18-wheeled vehicles and dump trucks were observed the morning of the observation, and at least several of these are considered to be heavily loaded due to dump trucks that haul material out of the chert pit. The chert pit on the route supplies material to the entire county out of this one location.

The following sections will now go into more detail on how the pavement rating should and was performed. The first section is an excerpt from the PACES manual, and the second section shows the actual recorded distresses as well as the calculated deduct values and overall rating.

Soil classification: Sieve Analysis Results, Plot, and Photos

Coefficient of uniformity $C_u = 20$ Coefficient of curvature $C_c = 0.36$

Water content = 12.65 %

Unified Soil Classification System:

1. 5 – 12 % pass #200
2. Cu >6, Cc<1
3. > 15% gravel

⇨ Poorly graded sand with silt and gravel

ASSHTO soil classification system:

The ASSHTO soil classification ranges from A-1 (best soils) to A-8 (worst soils). The classification is only used for highway subgrade materials.

1. 50 % pass > # 40
2. 10 % pass < #200

⇨ **A-3 Granular materials**

Sieve No.	Diameter (mm)	Retained percent	Cumulative percent retained
3/8 in	9.52	13.48%	86.52%
#6	3.35	14.01%	72.52%
#30	0.6	33.49%	39.03%
#80	0.18	20.26%	18.77%
#100	0.15	3.21%	15.55%
#200	0.075	8.04%	7.51%
Pan		7.51%	0.00%

Figure IX-7

Pictures of the soil sample analyzed to assess the hydraulic conductivity (left) and stack of sieve sizes used to produce the gradation curve

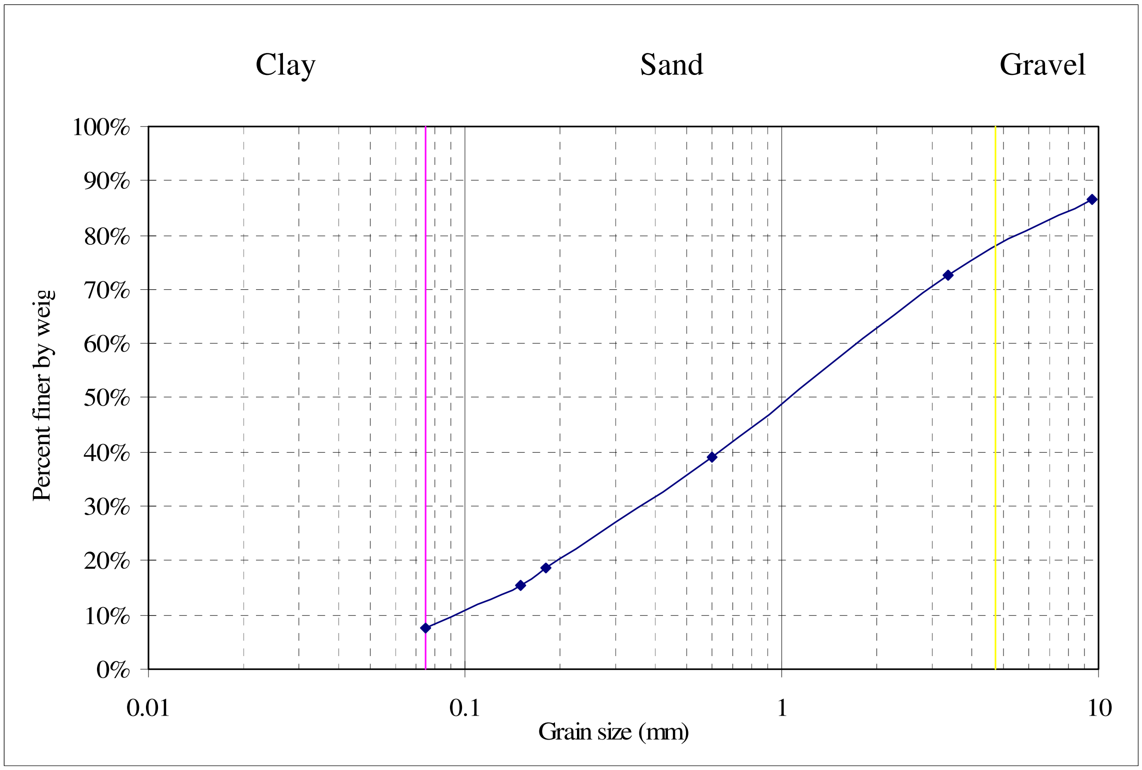


FIGURE IX-8 Plot of sieve analysis by weight

Portion of the route driven the day of the assessment:

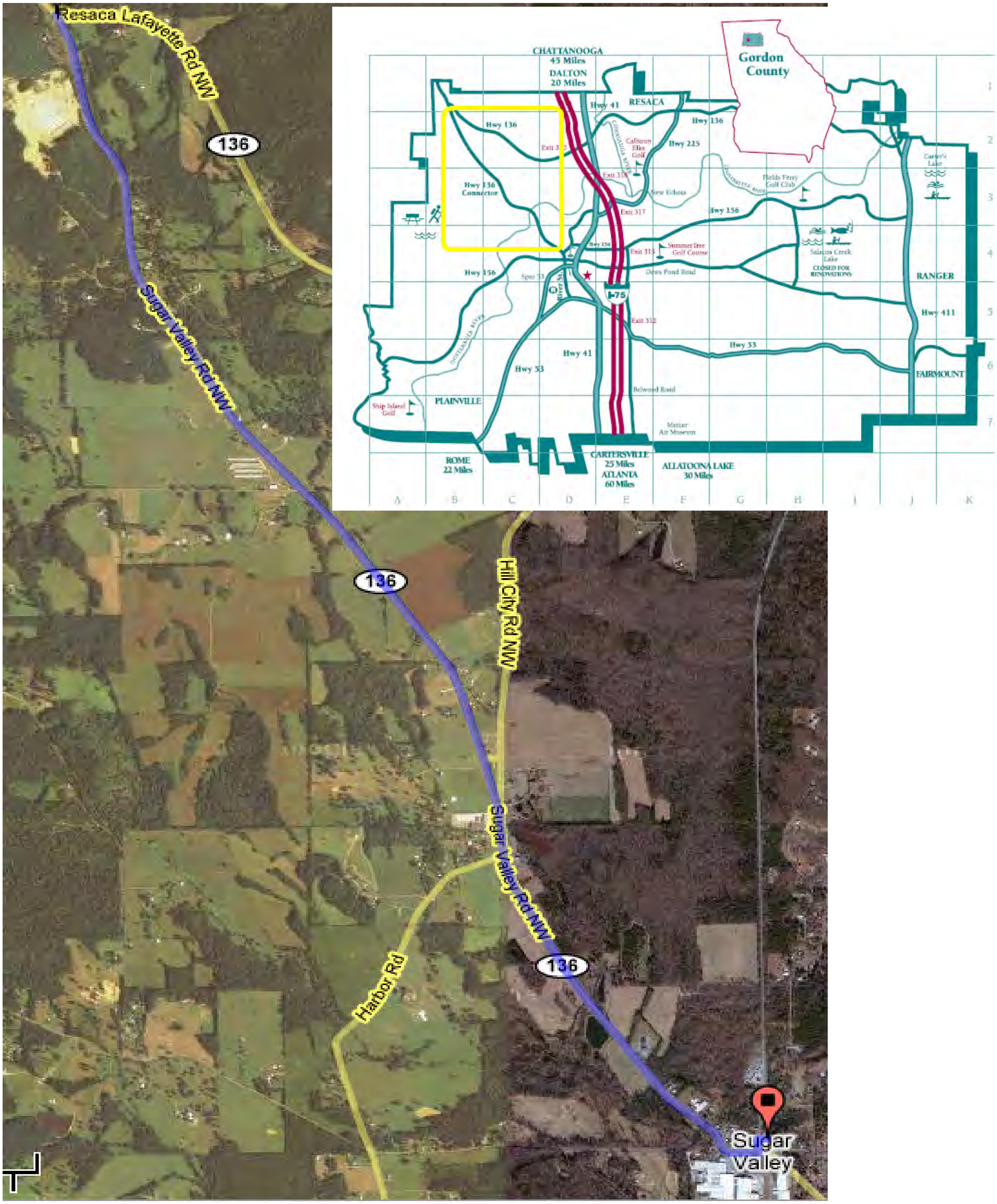


Figure IX-9

Appendix X: User's Manual for Re-Definition of Project Termini

The Change Project Termini module comprises of two parts:

(1) **Spilt Project Termini**: allows users to spilt a particular project into two projects and determine the project rating of these two projects. It also allows the user to submit the new projects to the database, thus making them permanent projects in the system. It also deletes the old project that was split on submitting the changes.

(2) **Merge Project Termini**: allows users to merge two projects into one, determine the project rating of the new project and submit the new project permanently to the system.

To start this function,

(1) Select **Change Project Termini** from **Input** pull down menu, see Figure X-1.

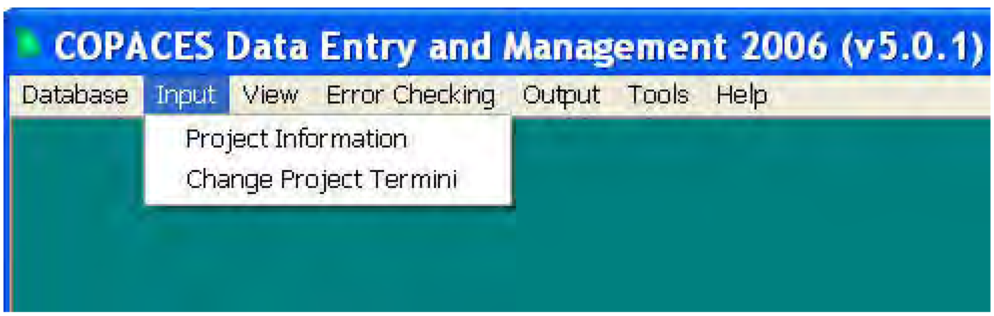


Figure X-1: Change Project Termini From "Input" Pull Down Menu

(2) The **Change Project Termini** form is displayed as shown in Figure X-2 below. The relevant projects can be queried based on the **District**, **Office**, **County Name**, **Route No**,

and **Route Suffix**.

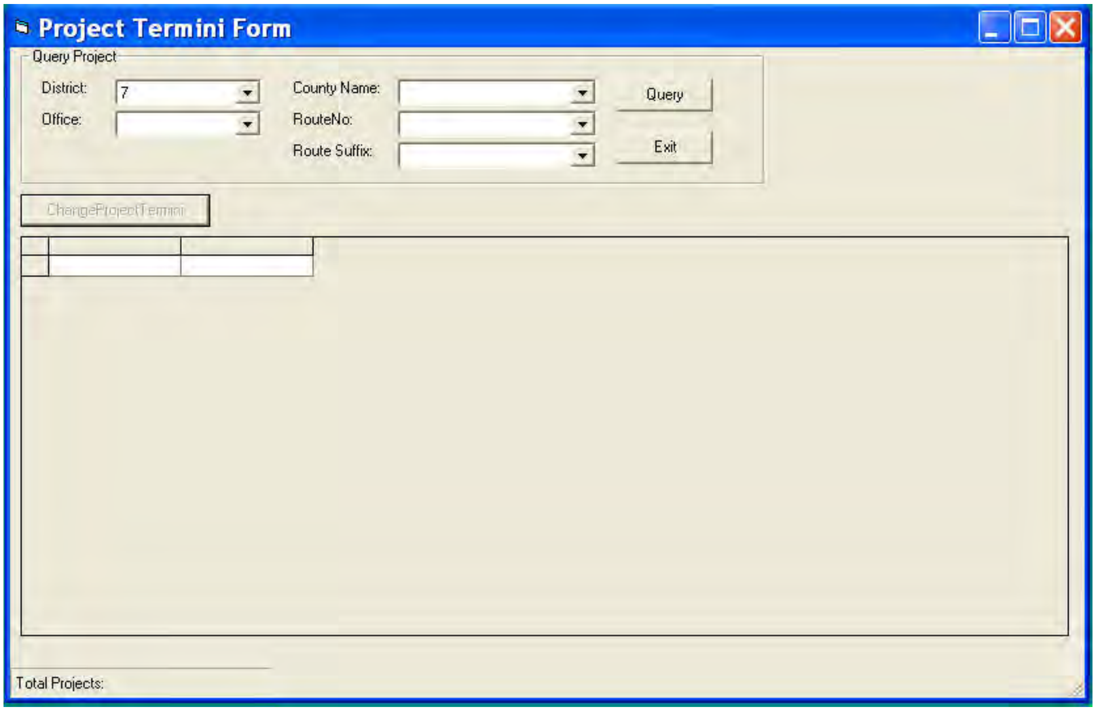
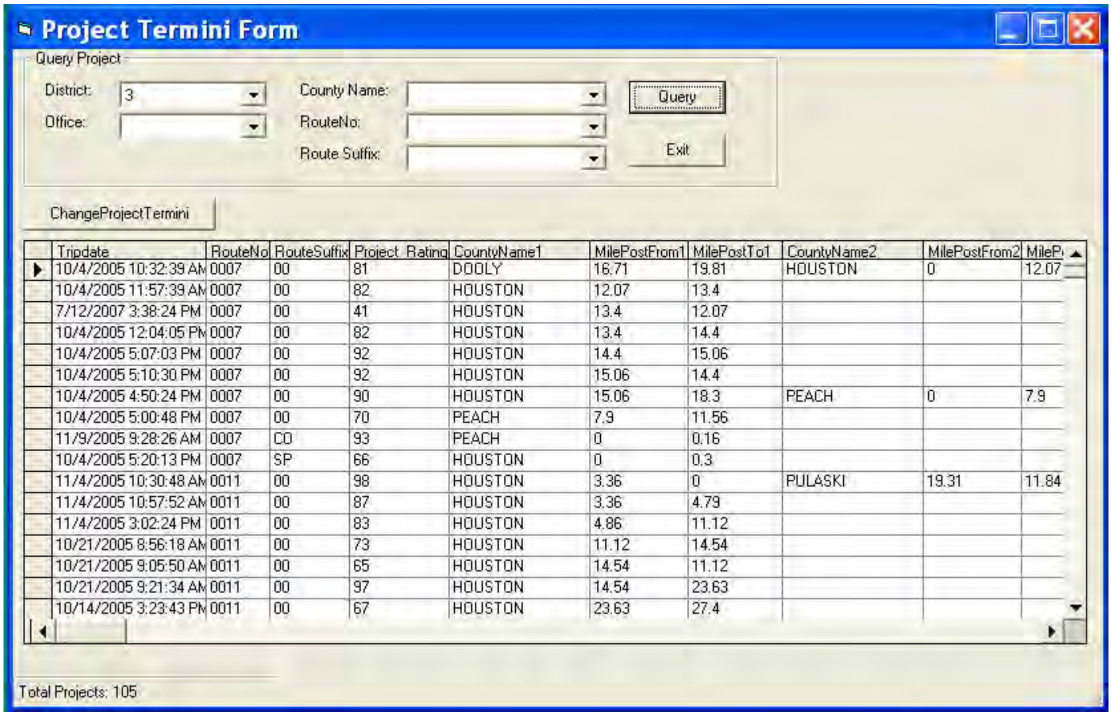


Figure X-2: Change Project Termini Form

(3) Based on the query parameters entered, the corresponding projects will be displayed in the data grid as shown in Figure X-3 below:



Tripdate	RouteNo	RouteSuffix	Project_Rating	CountyName1	MilePostFrom1	MilePostTo1	CountyName2	MilePostFrom2	MileP
10/4/2005 10:32:39 AM	0007	00	81	DOOLY	16.71	19.81	HOUSTON	0	12.07
10/4/2005 11:57:39 AM	0007	00	82	HOUSTON	12.07	13.4			
7/12/2007 3:38:24 PM	0007	00	41	HOUSTON	13.4	12.07			
10/4/2005 12:04:05 PM	0007	00	82	HOUSTON	13.4	14.4			
10/4/2005 5:07:03 PM	0007	00	92	HOUSTON	14.4	15.06			
10/4/2005 5:10:30 PM	0007	00	92	HOUSTON	15.06	14.4			
10/4/2005 4:50:24 PM	0007	00	90	HOUSTON	15.06	18.3	PEACH	0	7.9
10/4/2005 5:00:48 PM	0007	00	70	PEACH	7.9	11.56			
11/9/2005 9:28:26 AM	0007	CO	93	PEACH	0	0.16			
10/4/2005 5:20:13 PM	0007	SP	66	HOUSTON	0	0.3			
11/4/2005 10:30:48 AM	0011	00	98	HOUSTON	3.36	0	PULASKI	19.31	11.84
11/4/2005 10:57:52 AM	0011	00	87	HOUSTON	3.36	4.79			
11/4/2005 3:02:24 PM	0011	00	83	HOUSTON	4.86	11.12			
10/21/2005 8:56:18 AM	0011	00	73	HOUSTON	11.12	14.54			
10/21/2005 9:05:50 AM	0011	00	65	HOUSTON	14.54	11.12			
10/21/2005 9:21:34 AM	0011	00	97	HOUSTON	14.54	23.63			
10/14/2005 3:23:43 PM	0011	00	67	HOUSTON	23.63	27.4			

Figure X-3: Change Project Termini Query Results

(4) On clicking the **Change Project Termini** button, either the **Change Project Termini - Split Project** form or the **Change Project Termini – Merge Project** form will be displayed based on the number of projects selected in the data grid. In case one project is selected in the data grid the **Spilt Project** form will be displayed, and in case two projects are selected then the **Merge Project** form will be displayed.

Change Project Termini - Split Project

To split project:

(1) On selecting a single project in the **Project Termini** form, and clicking the **Change Project Termini** button, the **Change Project Termini – Split Project** form will be displayed as shown in figures below: Figure X-4 shows to split a project located in one county; Figure X-5 shows to split a project located in more than one county.

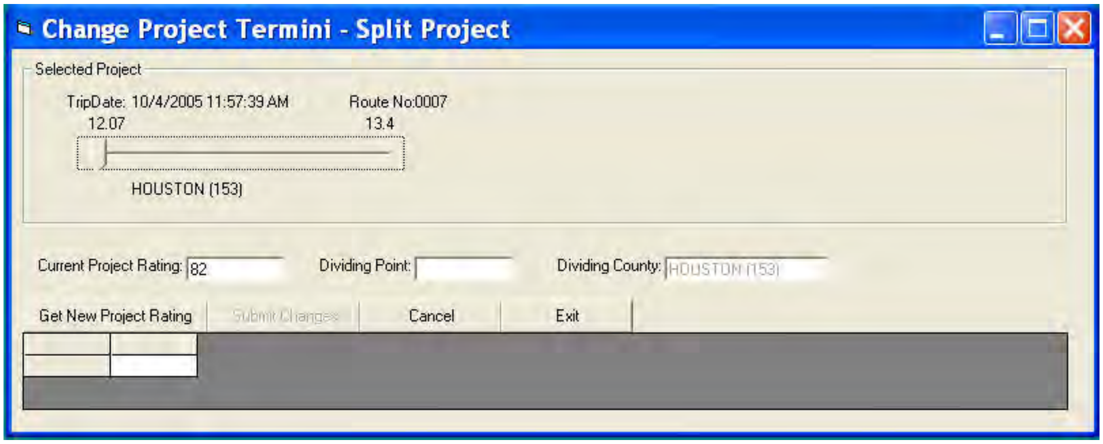


Figure X-4: Change Project Termini - Split a Project Located in One County

Figure X-5: Change Project Termini - Split a Project Located in More Than One County

(2) The project can be split into two projects using the sliding bar and the dividing point value is entered in the Dividing Point text box. The dividing point can be changed manually also. Once the dividing point is determined the Get New Project Rating button displays the new projects in the data grid along with the corresponding rating as shown in Figure below: Figure X-6 shows information of two new projects split from the original project located in one county; Figure X-7 & Figure X-8 & Figure X-9 respectively show information of two new projects via two different splitting ways from the original project located in more than one county.

Note: even a project may include several parts which located in different counties, only one splitting point is allowed to exist when using this function.

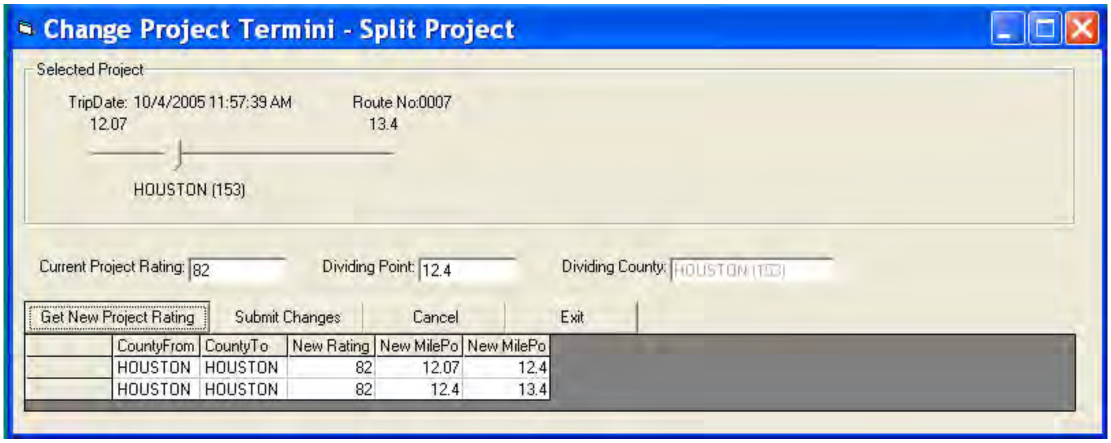


Figure X-6: Change Project Termini - Split a Project Located in One County

Figure X-7: Change Project Termini - Split a Project Located in More Than One County

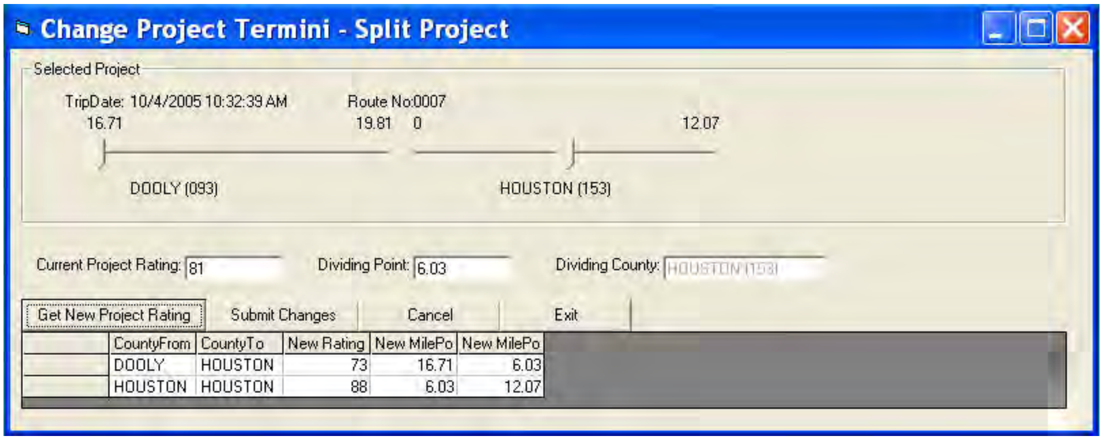


Figure X-8: Change Project Termini - Split a Project Located in More Than One County

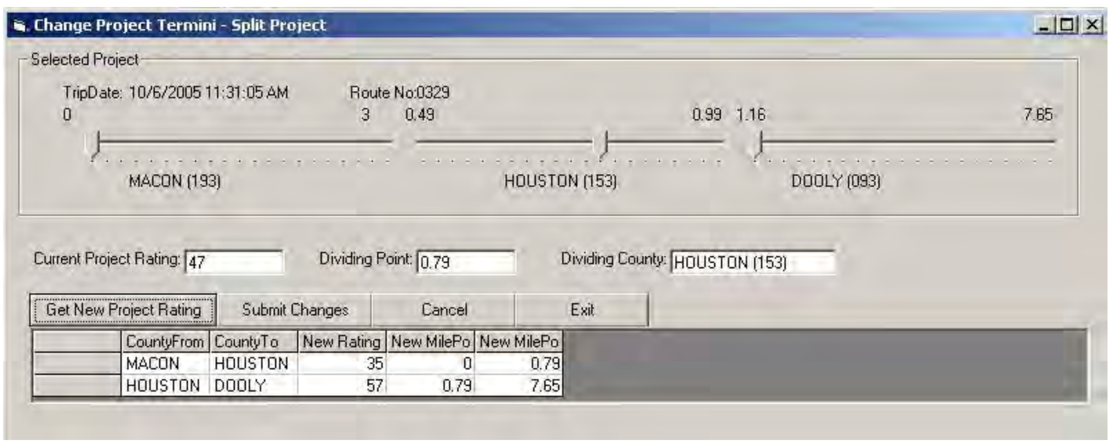


Figure X-9: Change Project Termini - Split a Project Located in More Than One County

(3) On clicking the **Submit Changes** button, the new projects will be submitted to the database, with the current date & time as the trip date of the new projects along with the newly calculated project ratings. The old project will be deleted from the system. On clicking the **Submit Changes** button, the confirmation form as shown in Figure is displayed. Clicking **Yes** submits the changes permanently.

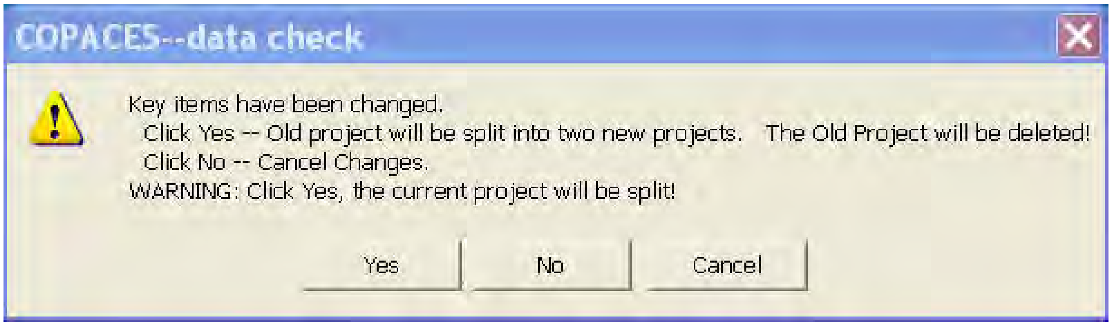


Figure X-10: **Change Project Termini** - Submitting a Split Project Warning Message

Change Project Termini - Merge Projects

To merge projects:

(1) On selecting two projects in the **Project Termini** form and clicking the **Change Project Termini** button, the **Change Project Termini – Merge Projects** form will be displayed as shown in Figure X-11 below:

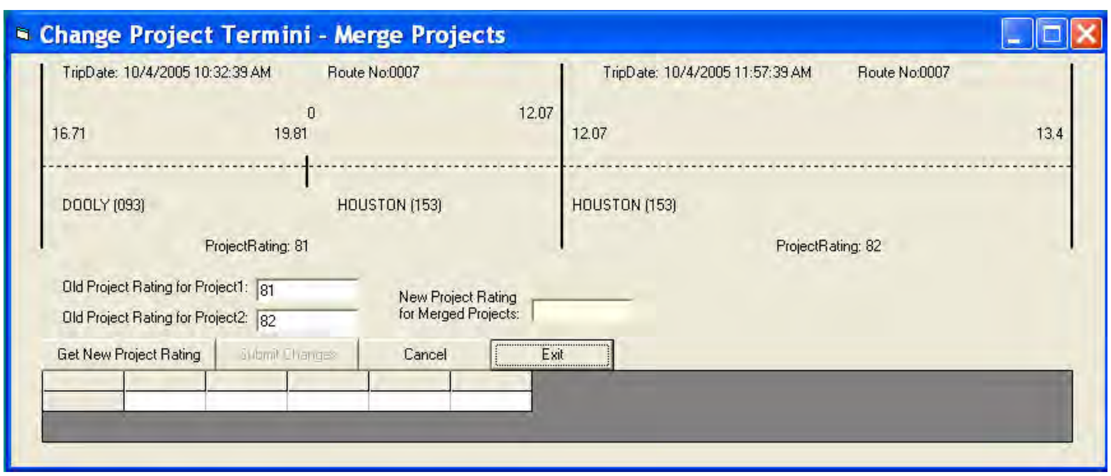


Figure X-11: Change Project Termini - Merge Projects

Note: The following constraints are enforced while merging two projects together:

(i) At a time, only two projects can be merged together.

(ii) The projects being merged should have the same route number, route suffix and status.

(iii) The resultant project cannot comprise of more than three counties. This means that if project 1 has three counties, and project 2 has one county and all the counties are distinct then the projects cannot be merged as the resultant county would need to accommodate four counties.

(2) On clicking the **Get New Project Rating** button the combined project rating of the two projects is displayed as shown in Figure X-12 & Figure X-13 below:

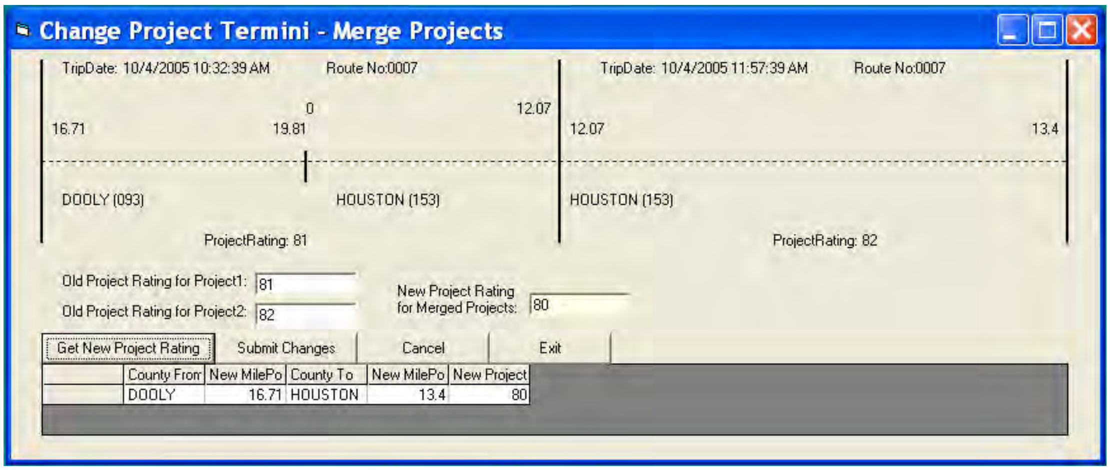


Figure X-12: Change Project Termini - Merge Projects Results

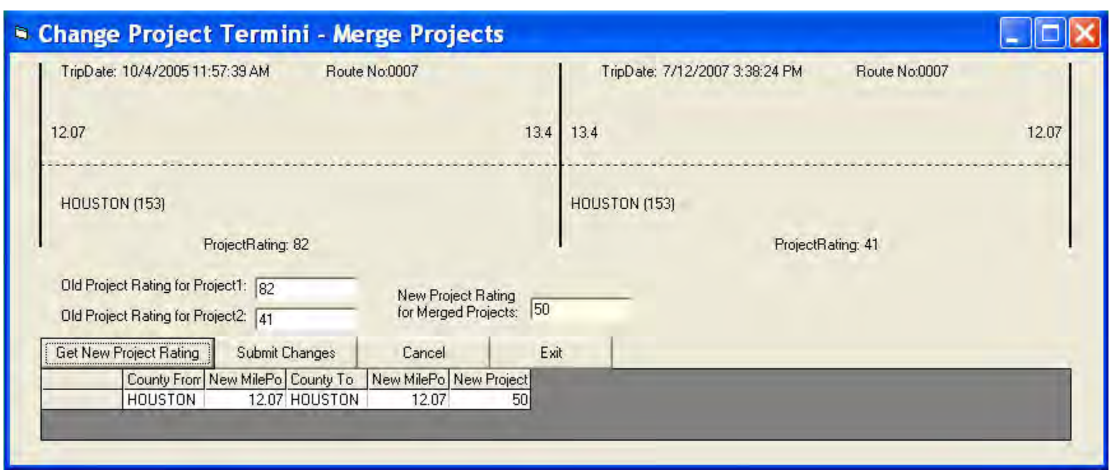


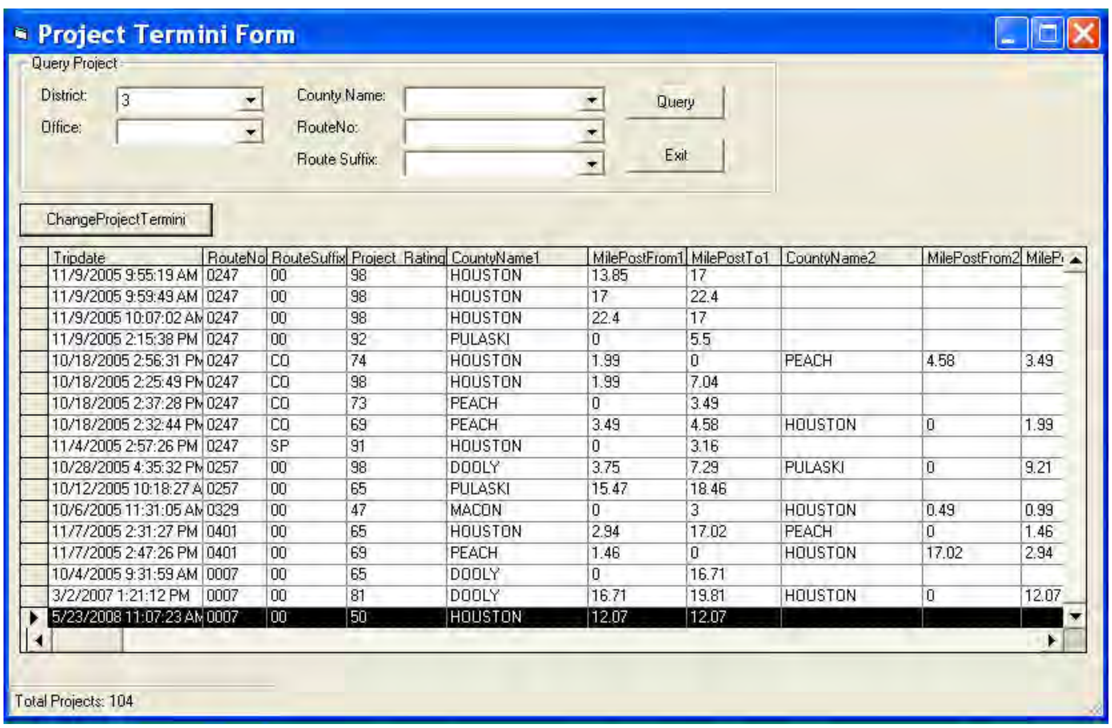
Figure X-13: Change Project Termini - Merge Projects Results

(3) On clicking the **Submit Changes** button, the new project will be submitted to the database, with the current date & time as the trip date along with the newly calculated

project rating. The old projects that were merged will be deleted from the system. On clicking the **Submit Changes** button, the confirmation form as shown in Figure X-14 is displayed. Clicking **Yes** submits the changes permanently.

Figure X-14: Change Project Termini - Submitting Merged Project Warning Message

(4) After clicking **Yes** the new project will be saved in the database as shown in Figure X-15 below.



Tripdate	RouteNo	RouteSuffix	Project_Rating	CountyName1	MilePostFrom1	MilePostTo1	CountyName2	MilePostFrom2	MileP
11/9/2005 9:55:19 AM	0247	00	98	HOUSTON	13.85	17			
11/9/2005 9:59:49 AM	0247	00	98	HOUSTON	17	22.4			
11/9/2005 10:07:02 AM	0247	00	98	HOUSTON	22.4	17			
11/9/2005 2:15:38 PM	0247	00	92	PULASKI	0	5.5			
10/18/2005 2:56:31 PM	0247	CO	74	HOUSTON	1.99	0	PEACH	4.58	3.49
10/18/2005 2:25:49 PM	0247	CO	98	HOUSTON	1.99	7.04			
10/18/2005 2:37:28 PM	0247	CO	73	PEACH	0	3.49			
10/18/2005 2:32:44 PM	0247	CO	69	PEACH	3.49	4.58	HOUSTON	0	1.99
11/4/2005 2:57:26 PM	0247	SP	91	HOUSTON	0	3.16			
10/28/2005 4:35:32 PM	0257	00	98	DOOLY	3.75	7.29	PULASKI	0	9.21
10/12/2005 10:18:27 A	0257	00	65	PULASKI	15.47	18.46			
10/6/2005 11:31:05 AM	0329	00	47	MACON	0	3	HOUSTON	0.49	0.99
11/7/2005 2:31:27 PM	0401	00	65	HOUSTON	2.94	17.02	PEACH	0	1.46
11/7/2005 2:47:26 PM	0401	00	69	PEACH	1.46	0	HOUSTON	17.02	2.94
10/4/2005 9:31:59 AM	0007	00	65	DOOLY	0	16.71			
3/2/2007 1:21:12 PM	0007	00	81	DOOLY	16.71	19.81	HOUSTON	0	12.07
5/23/2008 11:07:23 AM	0007	00	50	HOUSTON	12.07	12.07			

Figure X-15: Change Project Termini - Submitting Merged Project Results

Appendix XI: User's Manual for Determination of Localized Pavement Preservation Need

GDOT is currently using project-level pavement condition data to evaluate the pavement performance and to make final treatment decisions. The objective of this research is to develop procedures, models, and programs that enable GDOT to take advantage of segment-level pavement condition data. Under this major goal, one of the functions identified is to enable the OM to identify individual roadway segments within a pavement project requiring treatment actions based on individual segment ratings and distresses, even though the overall project rating is greater than 70 (the threshold for triggering project treatment) and does not require treatment actions. For example, the function can screen all segments with the segment ratings lower than a specified threshold (e.g. 5 rating points), compare them with the average project rating, and identify any high distresses over the predefined thresholds in the segment level so that appropriate localized treatment, such as patching or edge cracking repair, can be applied. See Figure XI-1 below for the example.

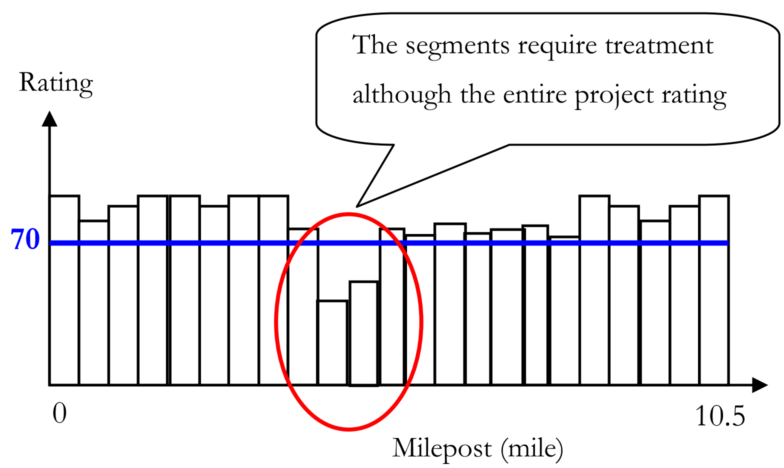


Figure XI-1: Segments require localized treatment

Click **Localized Treatment Report** from **Report** menu (This function is implemented in the program of ProjectSelection).

Figure XI-2: Menu Item - Report

Segment Preservation Need form shows.

On this form (**Figure XI-3**), there are three panes. The upper left pane is used to input project location information; the upper right one is used to add segment selection criteria. The lower left pane is to input project treatment method.

The following items are needed for project location information.

(1) **County**.

(2) **Route Number**.

(3) **Route Suffix**.

The following items are needed for segment selection criteria.

(4) **Project Rating**. User can select one number from the drop-down list as criterion threshold.

(5) **Project Rating - Segment Rating**. User can input one number as criterion threshold.

The following items are needed for project treatment method.

(1) **Treatment**. Give here the treatment method of the project.

After all entries are completed for a query, click **Query Segments**.

The queried segments will appear on the lower grid. If no segments fit those query criteria, a warning message will pop out. User can either change the criteria or quit this function.

Figure XI-4 illustrates a sample project entry.

Click **Export** to export segments queried out into a MS Excel file.

Click **Show Chart**. **Segment Preservation Chart** form appears. **Figure 52** illustrates a sample segment preservation chart.

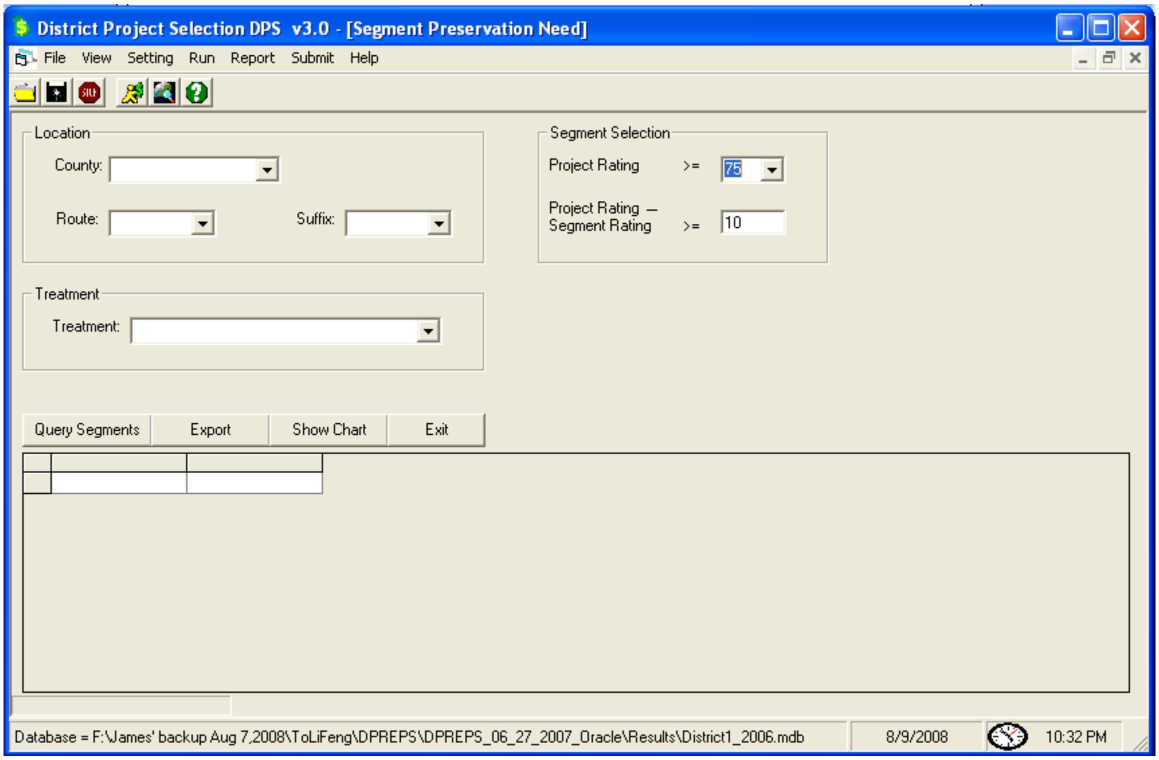


Figure XI-3: Segments require localized treatment

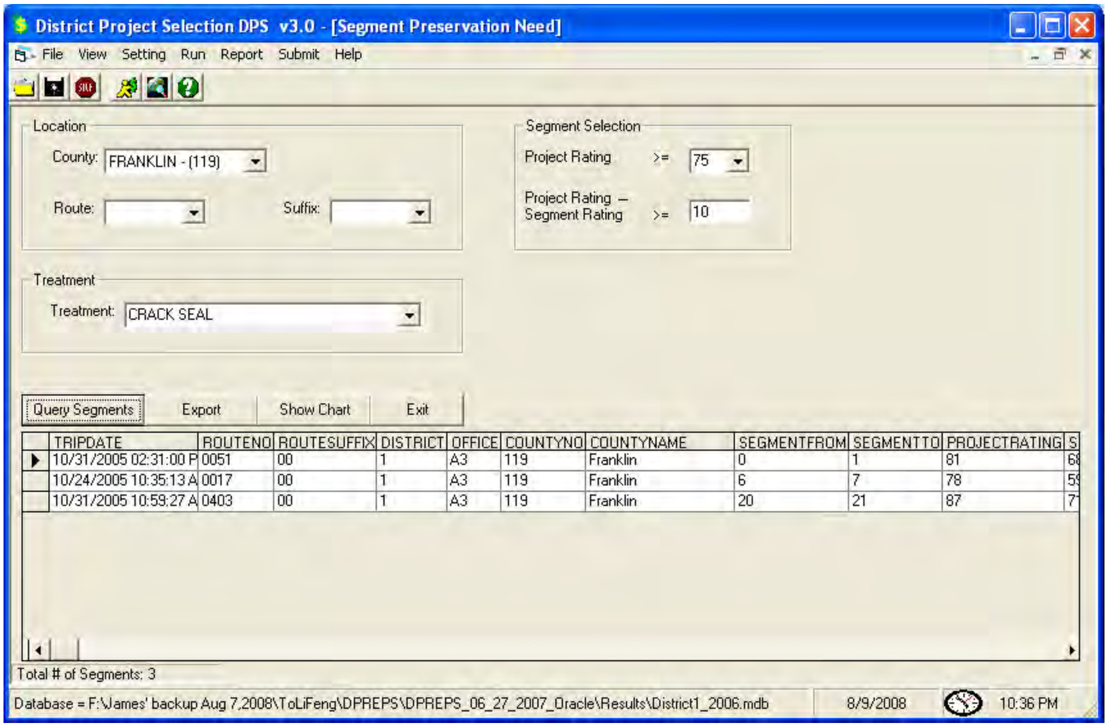


Figure XI-4: Sample of Segments Preservation Need Query

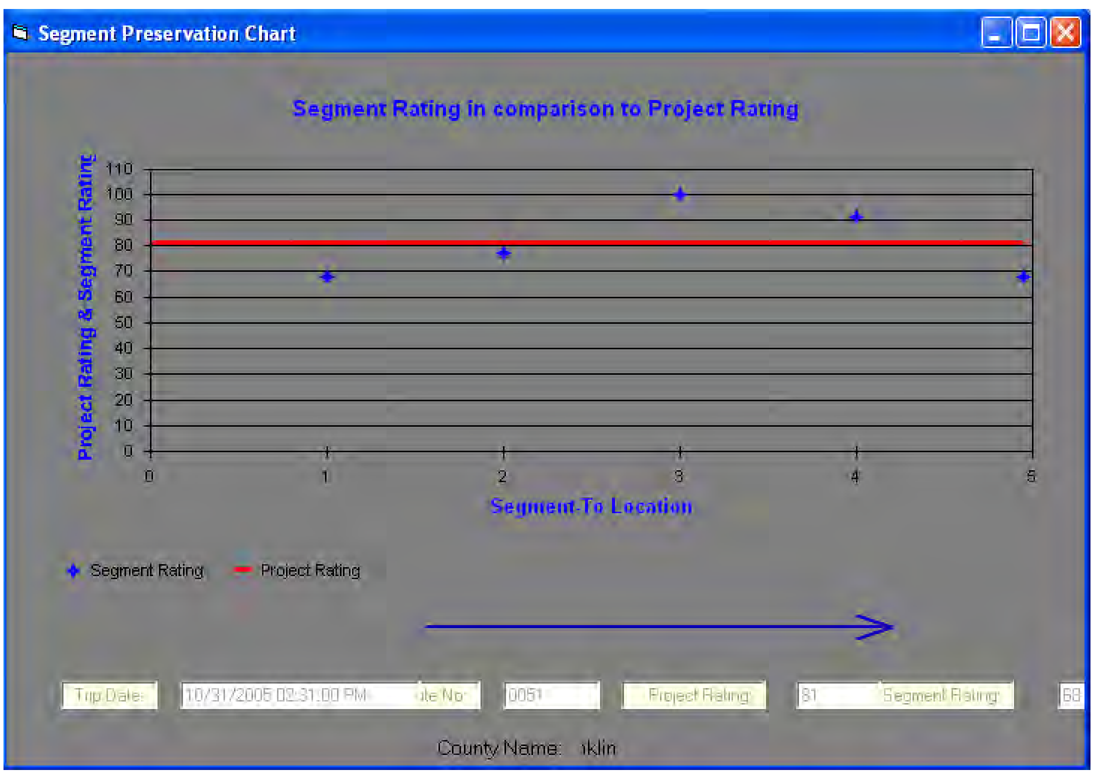


Figure XI-5: Segments Preservation Chart

Appendix XII: User's Manual for Re-construction of Historical Pavement Conditions with Customized Project Termini

This function is part of **Network 2008**. To start this function, launch **Network 2008**. (Figure XII-1) Click **Reconstruct Project Rating History** from **Report** menu. (Figure XII-2).

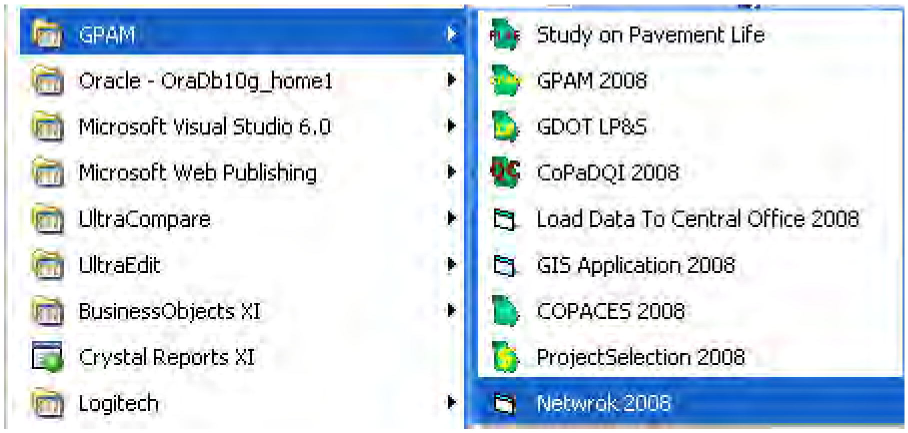


Figure XII-1 Launch Network 2008

Figure XII-2 Menu Item - Reconstruct Project Rating History

Reconstruct Project Rating History form appears. (Figure) This form consists of two major parts. The upper part is input part. It includes following items.

(1) **Fiscal Year From & To**. The default analysis period is from 1986 to 2009.

(2) **District**.

(3) **County No**.

(4) **Route No**.

(5) **Route Suffix**.

(6) **Milepost From & Milepost To**.

In Figure XII-3, choose **District** 7, **County** Fulton, **Route** 0010 and **Route Suffix** 00. The program will suggest a **milepost from** and **milepost to** range according to

COPACES data in central database, and show them in the text boxes, named **From** and **To** respectively. Here, it is suggested from 0 to 2.53. Then click **Add Location**. This location record will show in the following data grid. The user could continue to add other projects. (Figure XII-4) Moreover, the user could change the milepost from and to suggested by the program and specify other project limit. However, the specified project limit should not exceed the suggested milepost from and to.

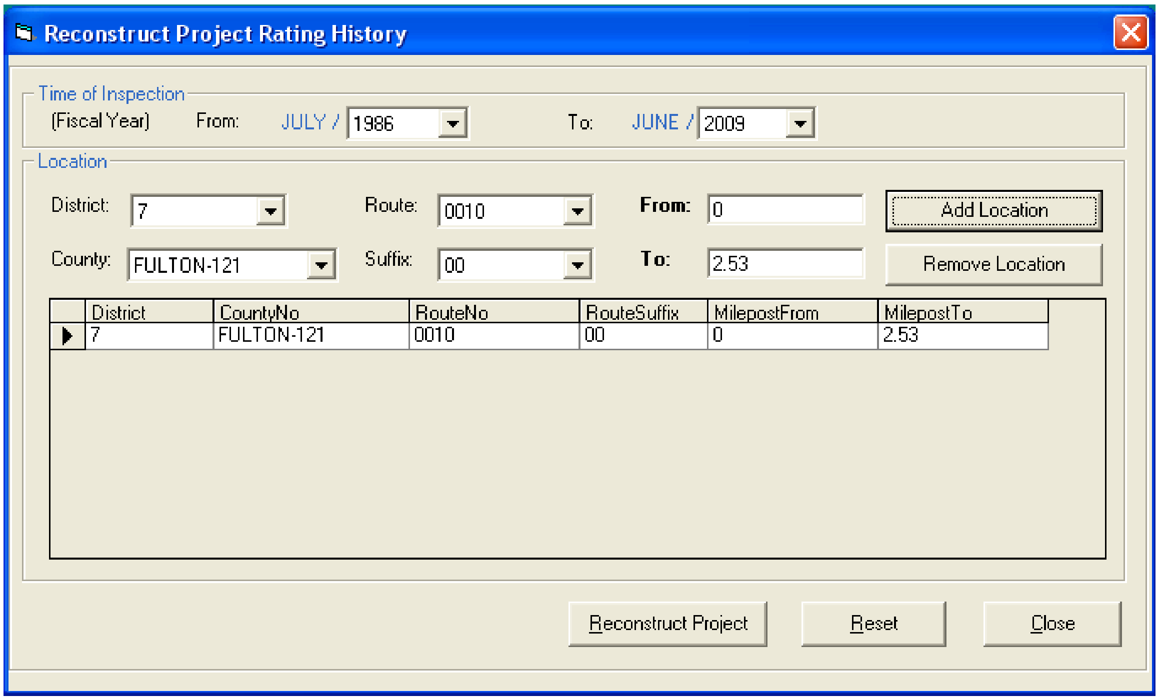


Figure XII-3 Reconstruct Project Rating History Input (1)

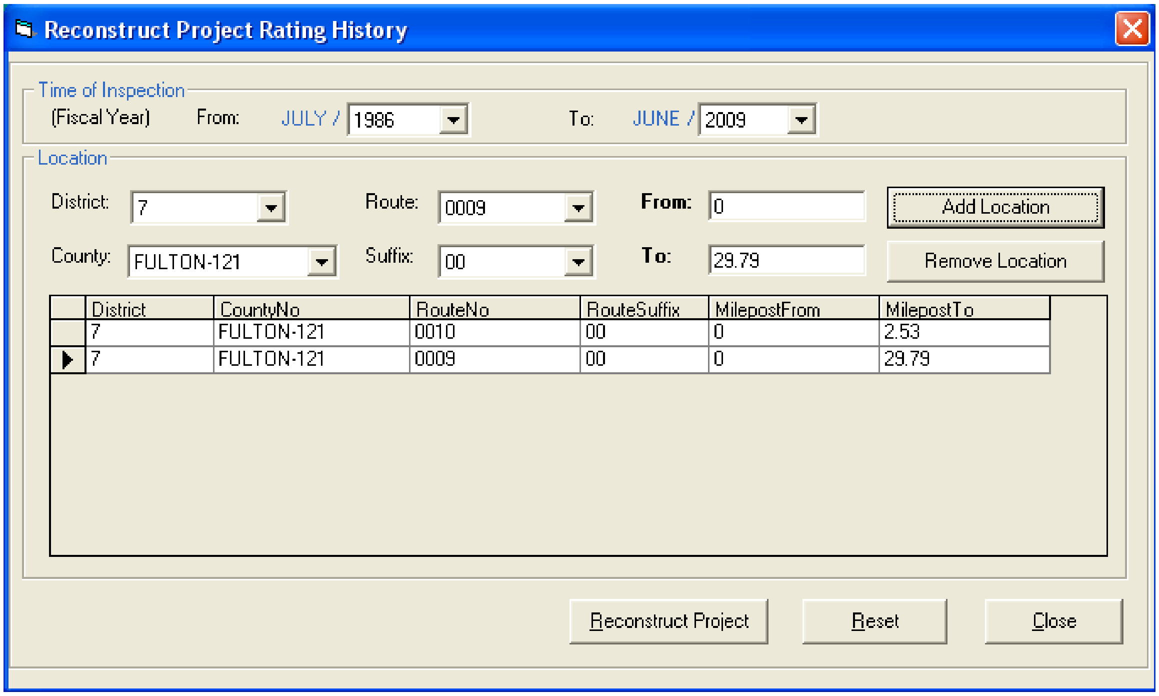


Figure XII-4 Reconstruct Project Rating History Input (2)

After selecting all project sections which comprise the new project, click **Reconstruct Project**. The program begins to calculate new project's rating history. Results are displayed in Figure XII-5. It is a data grid that includes average survey information of the newly constructed project.

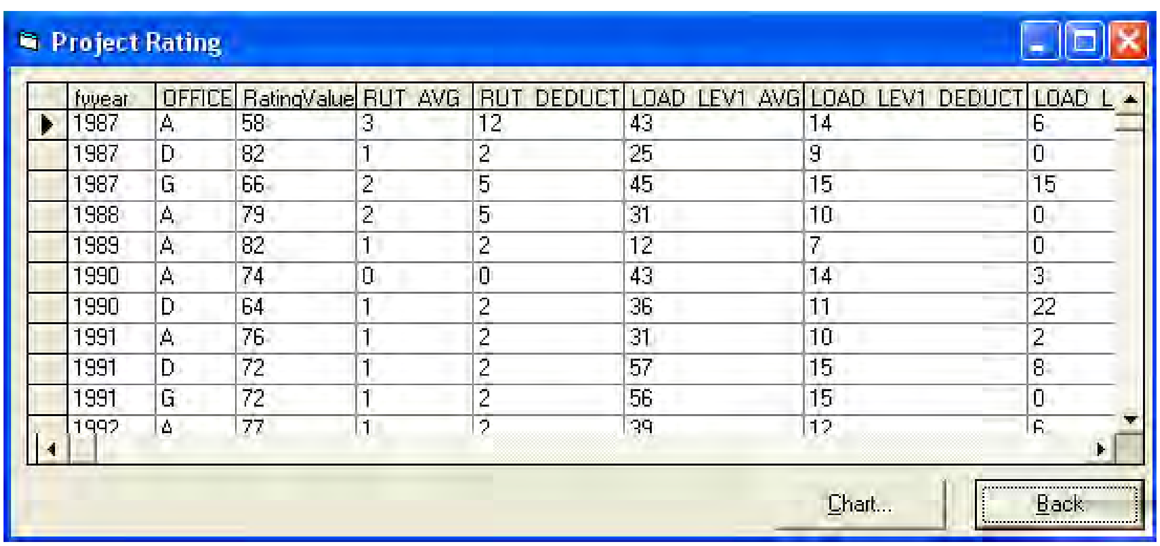


Figure XII-5 Reconstruct Project Rating History Results

Click **Chart**. The user could get **Change Project Termini – Historical Rating Report** form (Figure XII-6) to view new constructed project rating history in chart.

Figure XII-6 is an example of Change Project Termini – Historical Rating Report. This form has following items.

(1) **Project Rating vs. Fiscal Year for Selected Range** Chart. This chart shows reconstructed project rating history, including all survey results from AO, DO and GO. Those red points are survey ratings form Area Office; blue ones belong to District Office; while black ones are surveyed by General Office.

(2) **Check Box with Items (AO, DO, GO, ALL)**. User could either item. By check one of these, the bottom grid will only show segment survey records from that office. For example, if user check **ALL**, each time when he click one rating point in the chart, he will get relative segment survey records from all offices in the bottom grid.

(3) **Grid in the bottom of this form**. This is used to show detailed project information and segment information after user click one of those rating points in the chart.

Figure XII-7 and Figure XII-8 are an example of clicking one of rating points and getting detailed project and segment survey info.

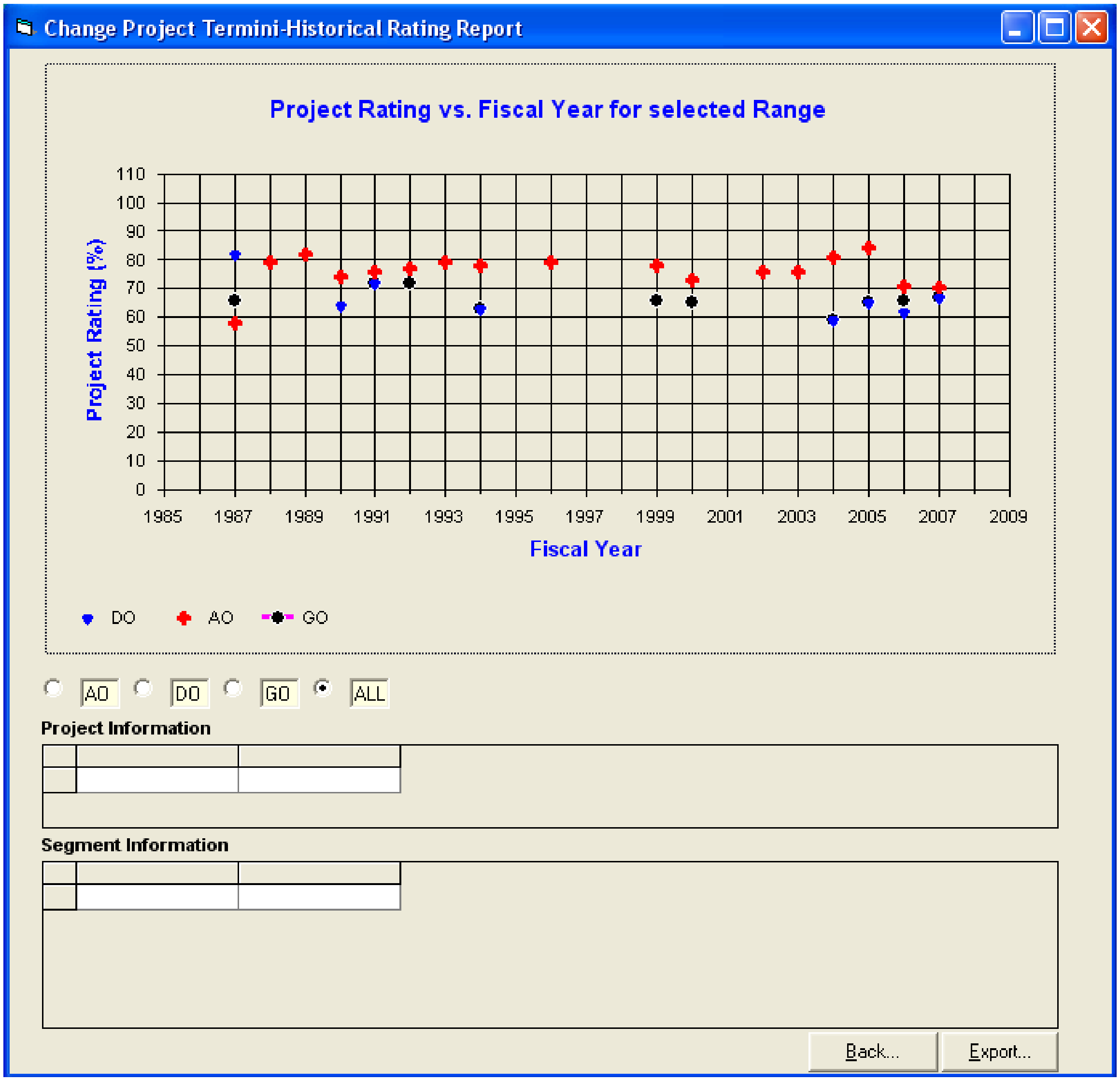


Figure XII-6 Reconstruct Project Rating History Chart (1)

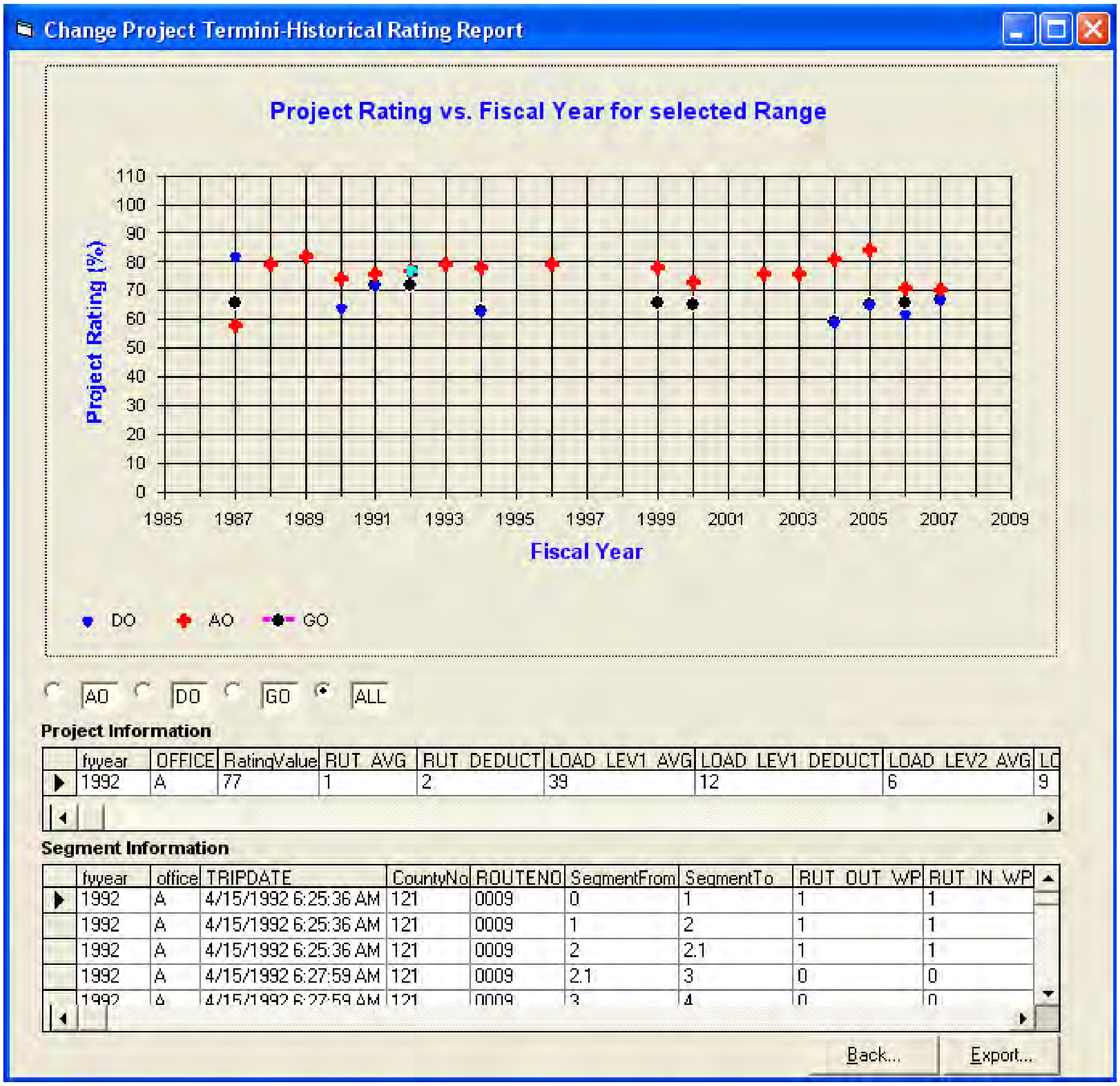


Figure XII-7 Reconstruct Project Rating History Chart (2)

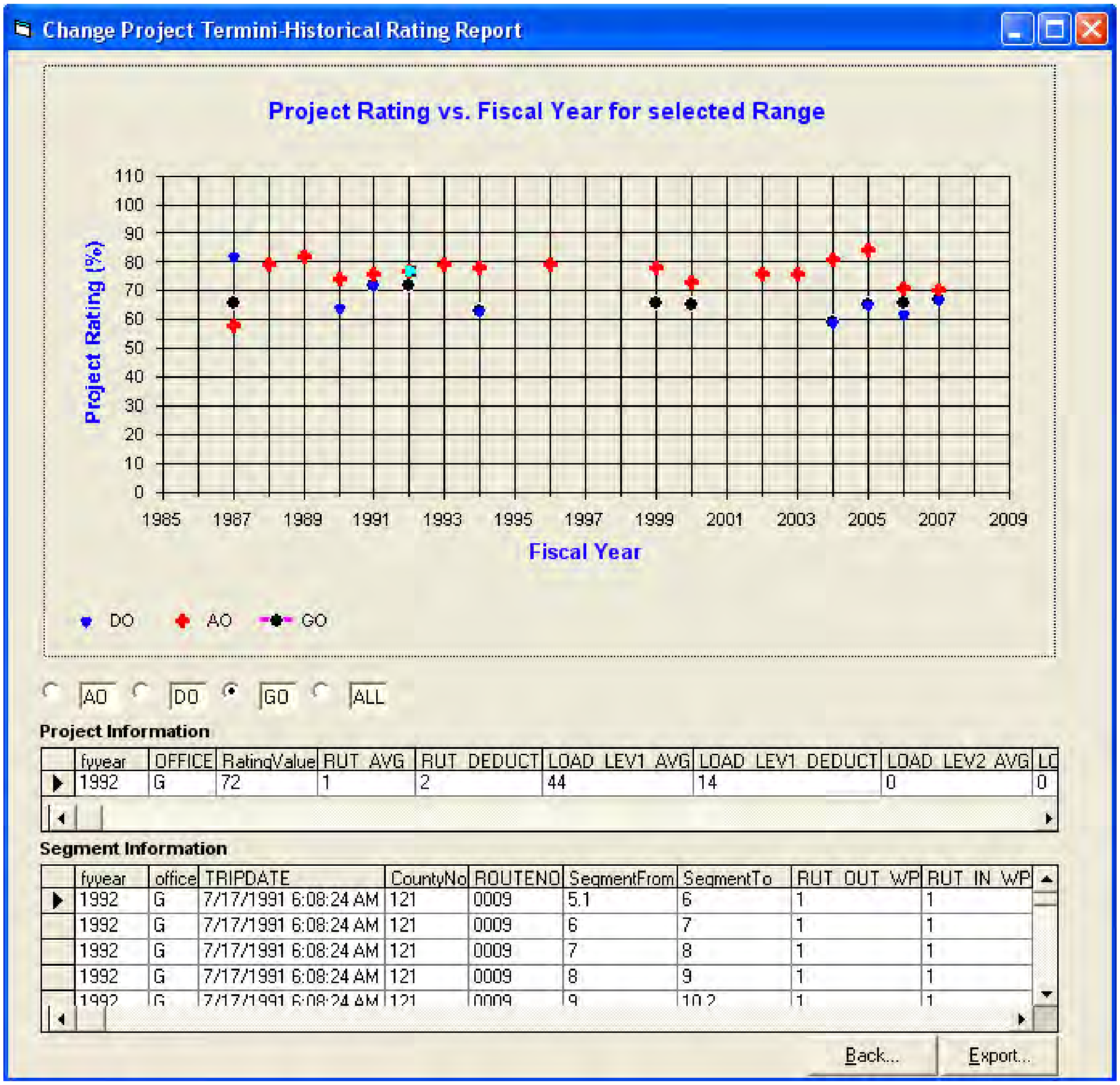


Figure XII-8 Reconstruct Project Rating History Chart (3)

Click **Export**. The reconstructed project rating history could be output to a Microsoft Excel. Figure XII-9, Figure XII-10 and Figure XII-11 are an example of the output file. Figure XII-9 includes information of projects which comprise the new constructed project and detailed rating history of the new project. Figure XII-10 are information of segments that comprise the new constructed project. Figure XII-11 is the chart of reconstructed project rating history.

Microsoft Excel - CustomizedProjReport.xls

E45 56

FLEXIBLE PAVEMENT CONDITION SURVEY

A. PROJECT LOCATION

District: 7 Route Type: 1 Route No: 0010 Route Suffix: 00

County:FULTON Milepost From: 0 To: 2.53

District: 7 Route Type: 1 Route No: 0009 Route Suffix: 00

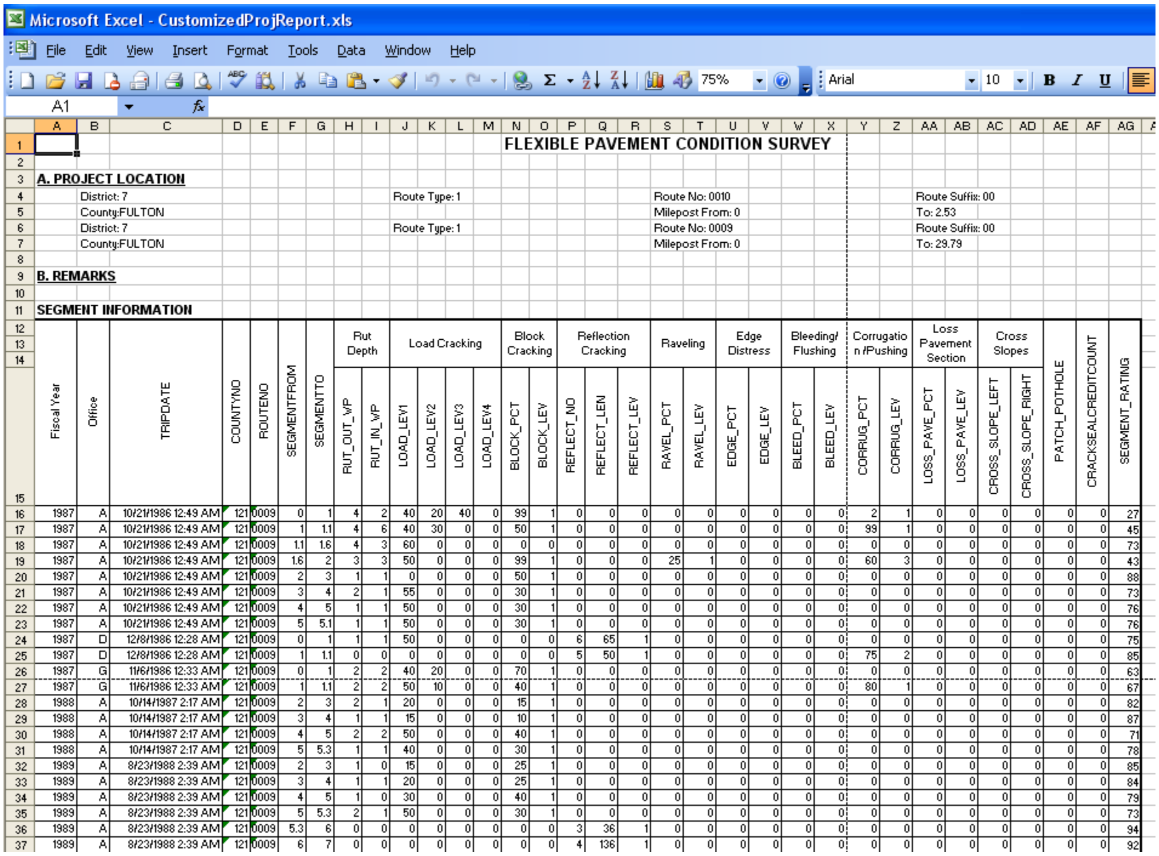
County:FULTON Milepost From: 0 To: 29.79

B. REMARKS

PROJECT INFORMATION

		Rut Depth		Load Cracking								Block Cracking			Reflection Cracking			Raveling			Edge Distress			Bleeding/ Flushing			Corrugation /Pushing			Loss Pavement Section			Cross Slopes		Patches & Potholes		Proj. Rating
Fiscal Year	Office	Avg (1/8 inch)	Deduct (1/8 inch)	Severity 1 Avg	Severity 1 Deduct	Severity 2 Avg	Severity 2 Deduct	Severity 3 Avg	Severity 3 Deduct	Severity 4 Avg	Severity 4 Deduct	Avg % of Sample	Severity (1,2,3)	Deduct	Avg Total Length	Severity (1,2,3)	Deduct	Avg % of Sample	Severity (1,2,3)	Deduct	Avg % of Sample	Severity (1,2,3)	Deduct	Avg % of Sample	Severity (1,2,3)	Deduct	Avg % of Sample	Severity (1,2,3)	Deduct	Avg % of Sample	Severity (1,2,3)	Deduct	Avg (1/8 inch)	Deduct	Avg	Deduct	Rating
1987	A	3	12	43	14	6	9	5	13	0	0	49	1	10	0	0	0	3	1	2	0	0	0	0	0	0	20	2	4	0	0	0	0	0	0	0	58
1987	D	1	2	25	9	0	0	0	0	0	0	0	0	0	58	1	0	0	0	0	0	0	0	0	0	0	38	2	7	0	0	0	0	0	0	0	82
1987	G	2	5	45	15	15	15	0	0	0	0	55	1	10	0	0	0	0	0	0	0	0	0	0	0	0	40	1	4	0	0	0	0	0	0	0	66
1988	A	2	5	31	10	0	0	0	0	0	0	24	1	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	79
1989	A	1	2	12	7	0	0	0	0	0	0	12	1	4	26	1	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	82
1990	A	0	0	43	14	3	5	0	0	0	0	46	1	9	14	1	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	74
1990	D	1	2	36	11	22	17	3	9	0	0	23	2	11	7	2	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	64
1991	A	1	2	31	10	2	4	0	0	0	0	25	1	6	18	1	5	0	1	0	0	0	0	0	0	0	2	1	1	0	0	0	0	0	0	0	76
1991	D	1	2	57	15	8	10	0	0	0	0	49	1	10	0	0	0	0	0	0	0	0	0	0	0	0	2	1	1	0	0	0	0	0	0	0	72
1991	G	1	2	56	15	0	0	0	0	0	0	56	1	10	0	0	0	0	0	0	0	0	0	0	0	0	6	1	1	0	0	0	0	0	0	0	72
1992	A	1	2	39	12	6	9	0	0	0	0	25	1	6	14	1	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	77
1992	G	1	2	44	14	0	0	0	0	0	0	57	1	11	0	0	0	0	0	0	0	0	0	0	0	0	2	1	1	0	0	0	0	0	0	0	72
1993	A	1	2	26	9	2	4	0	0	0	0	29	1	7	6	1	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	79
1994	A	1	2	26	9	0	0	0	0	0	0	33	1	8	3	1	0	0	0	0	0	0	0	0	0	0	3	3	3	0	0	0	0	0	0	0	78
1994	D	1	2	50	15	0	0	0	0	0	0	87	1	18	0	0	0	0	0	0	0	0	0	0	0	0	20	1	2	0	0	0	0	0	0	0	63
1994	G	1	2	50	15	0	0	0	0	0	0	87	1	18	0	0	0	0	0	0	0	0	0	0	0	0	20	1	2	0	0	0	0	0	0	0	63
1995																																					
1996	A	1	2	15	7	0	0	0	0	0	0	25	1	6	7	1	3	0	0	0	0	0	0	0	0	0	1	3	3	0	0	0	1	0	0	0	79
1997																																					
1998																																					
1999	A	1	2	31	10	1	3	0	0	0	0	34	1	8	2	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	2	78
1999	G	2	5	73	15	3	5	0	0	0	0	63	1	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	66
2000	A	1	2	34	11	0	0	0	0	0	0	43	1	9	0	0	0	0	0	0	2	1	0	1	1	2	1	1	1	0	0	0	0	0	1	2	73
2000	G	2	5	99	15	0	0	0	0	0	0	55	1	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	5	65
2001																																					
2002	A	1	2	33	10	0	0	0	0	0	0	39	1	8	0	0	0	1	1	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	76

Figure XII-9 Reconstruct Project Rating History Output (1)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FLEXIBLE PAVEMENT CONDITION SURVEY

A. PROJECT LOCATION

District: 7	Route Type: 1	Route No: 0010	Route Suffix: 00
County:FULTON		Milepost From: 0	To: 2.53
District: 7	Route Type: 1	Route No: 0009	Route Suffix: 00
County:FULTON		Milepost From: 0	To: 29.79

B. REMARKS

SEGMENT INFORMATION

Row								Rut Depth		Load Cracking				Block Cracking		Reflection Cracking
	Fiscal Year	Office	TRIPDATE	COUNTYNO	ROUTENO	SEGMENTFROM	SEGMENTTO	RUT_OUT_WP	RUT_IN_WP	LOAD_LEV1	LOAD_LEV2	LOAD_LEV3	LOAD_LEV4	BLOCK_PCT	BLOCK_LEV	REFLECT_NO
16	1987	A	10/21/1986 12:49 AM	121	0009	0	1	4	2	40	20	40	0	99	1	0
17	1987	A	10/21/1986 12:49 AM	121	0009	1	1.1	4	6	40	30	0	0	50	1	0
18	1987	A	10/21/1986 12:49 AM	121	0009	1.1	1.6	4	3	60	0	0	0	0	0	0
19	1987	A	10/21/1986 12:49 AM	121	0009	1.6	2	3	3	50	0	0	0	99	1	0
20	1987	A	10/21/1986 12:49 AM	121	0009	2	3	1	1	0	0	0	0	50	1	0
21	1987	A	10/21/1986 12:49 AM	121	0009	3	4	2	1	55	0	0	0	30	1	0
22	1987	A	10/21/1986 12:49 AM	121	0009	4	5	1	1	50	0	0	0	30	1	0
23	1987	A	10/21/1986 12:49 AM	121	0009	5	5.1	1	1	50	0	0	0	30	1	0
24	1987	D	12/8/1986 12:28 AM	121	0009	0	1	1	1	50	0	0	0	0	0	6
25	1987	D	12/8/1986 12:28 AM	121	0009	1	1.1	0	0	0	0	0	0	0	0	5
26	1987	G	11/6/1986 12:33 AM	121	0009	0	1	2	2	40	20	0	0	70	1	0
27	1987	G	11/6/1986 12:33 AM	121	0009	1	1.1	2	2	50	10	0	0	40	1	0
28	1988	A	10/14/1987 2:17 AM	121	0009	2	3	2	1	20	0	0	0	15	1	0
29	1988	A	10/14/1987 2:17 AM	121	0009	3	4	1	1	15	0	0	0	10	1	0
30	1988	A	10/14/1987 2:17 AM	121	0009	4	5	2	2	50	0	0	0	40	1	0
31	1988	A	10/14/1987 2:17 AM	121	0009	5	5.3	1	1	40	0	0	0	30	1	0
32	1989	A	8/23/1988 2:39 AM	121	0009	2	3	1	0	15	0	0	0	25	1	0
33	1989	A	8/23/1988 2:39 AM	121	0009	3	4	1	1	20	0	0	0	25	1	0
34	1989	A	8/23/1988 2:39 AM	121	0009	4	5	1	0	30	0	0	0	40	1	0
35	1989	A	8/23/1988 2:39 AM	121	0009	5	5.3	2	1	50	0	0	0	30	1	0
36	1989	A	8/23/1988 2:39 AM	121	0009	5.3	6	0	0	0	0	0	0	0	0	3
37	1989	A	8/23/1988 2:39 AM	121	0009	6	7	0	0	0	0	0	0	0	0	4

Row	Reflection Cracking		Raveling		Edge Distress		Bleeding/ Flushing		Corrugation /Pushing		Loss Pavement Section		Cross Slopes				
	REFLECT_LEN	REFLECT_LEV	RAVEL_PCT	RAVEL_LEV	EDGE_PCT	EDGE_LEV	BLEED_PCT	BLEED_LEV	CORRUG_PCT	CORRUG_LEV	LOSS_PAVE_PCT	LOSS_PAVE_LEV	CROSS_SLOPE_LEFT	CROSS_SLOPE_RIGHT	PATCH_POTHOLE	CRACKSEALCREDITCOUNT	SEGMENT_RATING
16	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	27
17	0	0	0	0	0	0	0	0	99	1	0	0	0	0	0	0	45
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	73
19	0	0	25	1	0	0	0	0	60	3	0	0	0	0	0	0	43
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	88
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	73
22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	76
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	76
24	65	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	75
25	50	1	0	0	0	0	0	0	75	2	0	0	0	0	0	0	85
26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	63
27	0	0	0	0	0	0	0	0	80	1	0	0	0	0	0	0	67
28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	82
29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	87
30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	71
31	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	78
32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	85
33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	84
34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	79
35	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	73
36	36	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	94
37	136	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	92

Figure XII-10 Reconstruct Project Rating History Output (2)

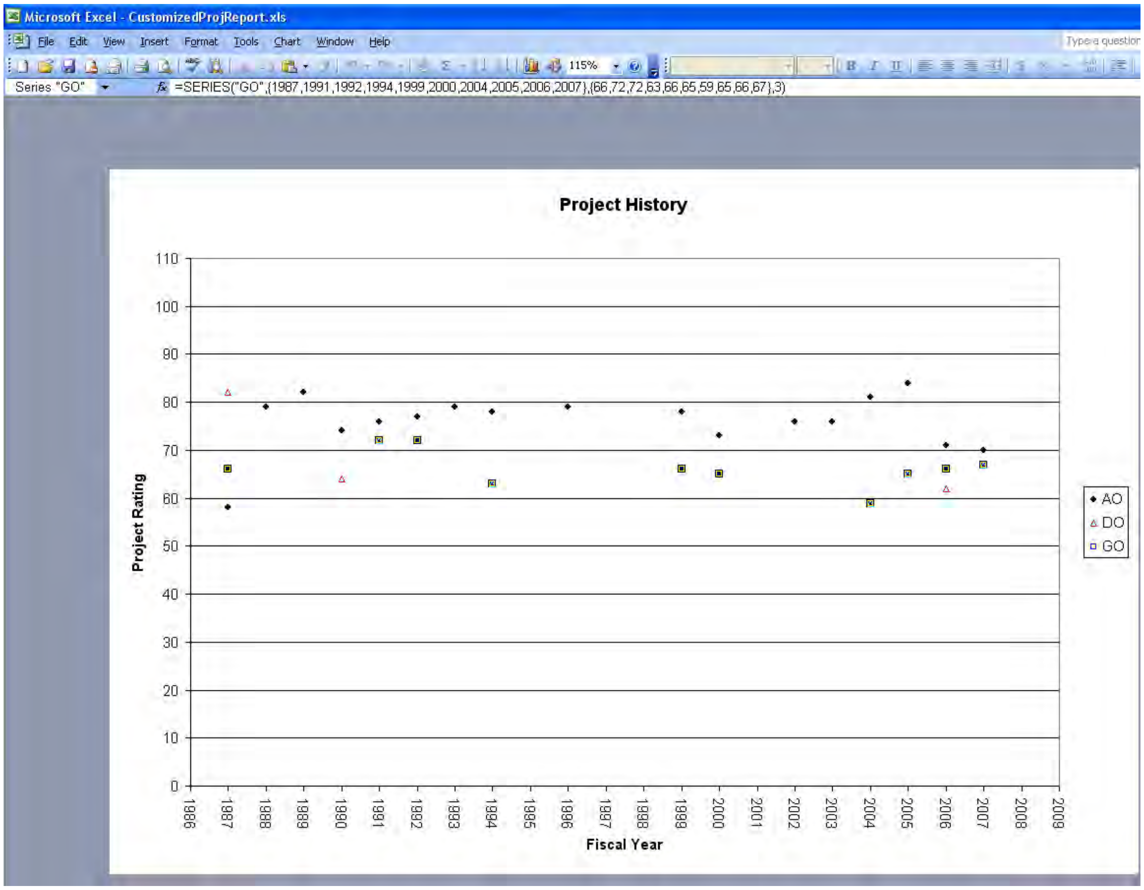


Figure XII-11 Reconstruct Project Rating History Output (3)

Appendix XIII: User's Manual for Visualization of Sequential Segment Ratings on Selected Route Section

This function is part of **Network Module**. To start this function, launch **Network Module**. Click **Seg Rating along Route Seq** from **Query** menu. (**Figure XIII-1**)

Segment Rating along Route Sequences form appears. (**Figure XIII-2**) This form consists of two major parts separated by four buttons. The upper part is input part. It includes following items.

(1) **Route No**. The user can set the route no by selecting from the drop-down list.

(2) **Route Suffix**. The user can select one from the drop-down list.

(3) **Fiscal Year From and To**. User can input these two together or just let them to be empty. If they are empty, it is default set to be from 1986 to current year, like 2009.

The lower grid is to show county sequences along the route.
The blank part in the bottom of this form is used to show segment rating along route sequences in chart.

Three buttons are:

(1) **OK**. After finish inputs, click **OK** to get county sequences of this route shown in the following grid and segment rating along route sequences shown in the bottom chart. (**Figure XIII-3**)

(2) **Report**. This button currently is deactivated. It will be activated after click **OK** and get segment rating along route sequences. By clicking **Report**, the user could get an excel file (**Figure XIII-7**) listing all route and segment information.

(3) **Reset**. Click **Reset** to clear all info on this form, including inputs, data shown in the grid and the chart. (**Figure XIII-2**)

(4) **Exit**. Click **Exit** to exit this function.

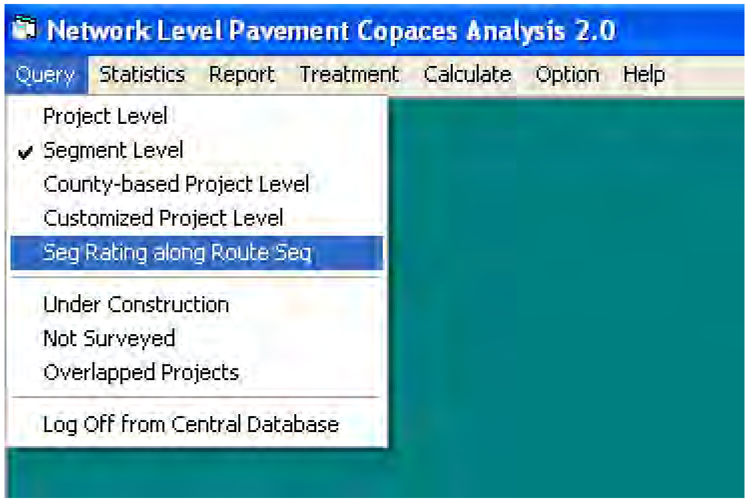


Figure XIII-1: Menu Item – Seg Rating along Route Seq

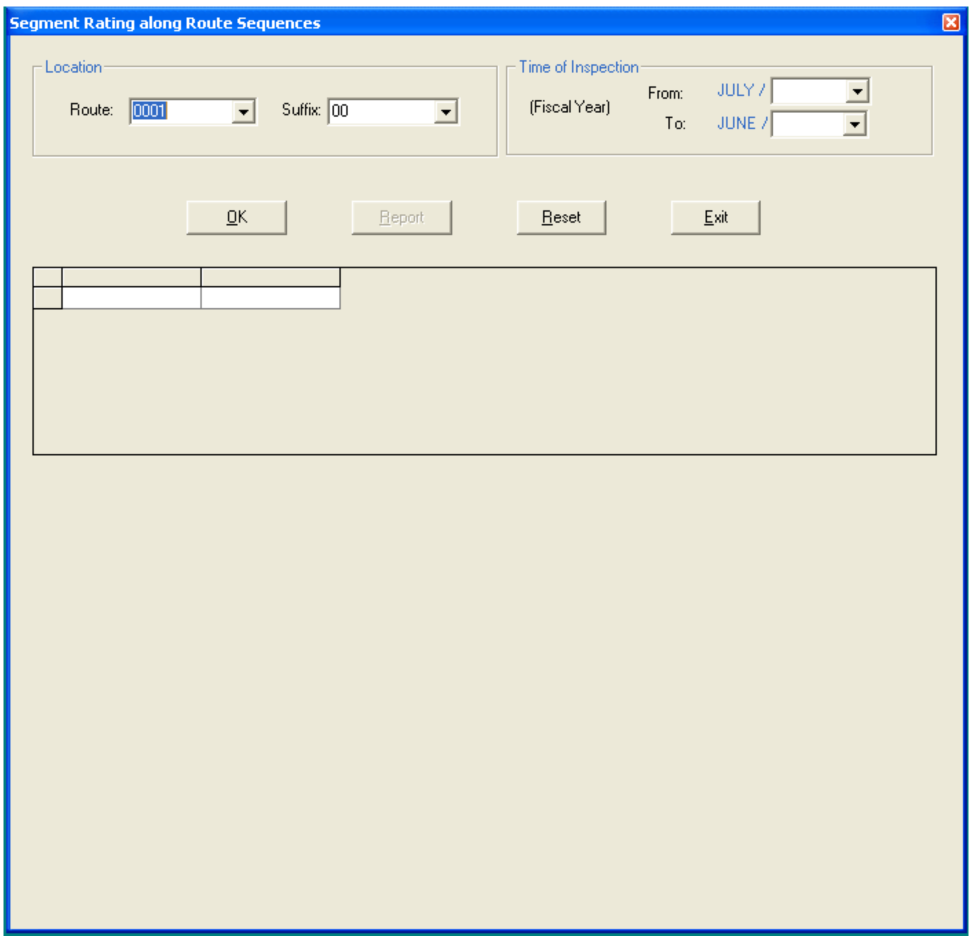


Figure XIII-2: Segment Rating along Route Sequences

Figure XIII-3 illustrates an example of getting **Segment Rating along Route Sequences**.

Figure XIII-4 is an example result after running this function.

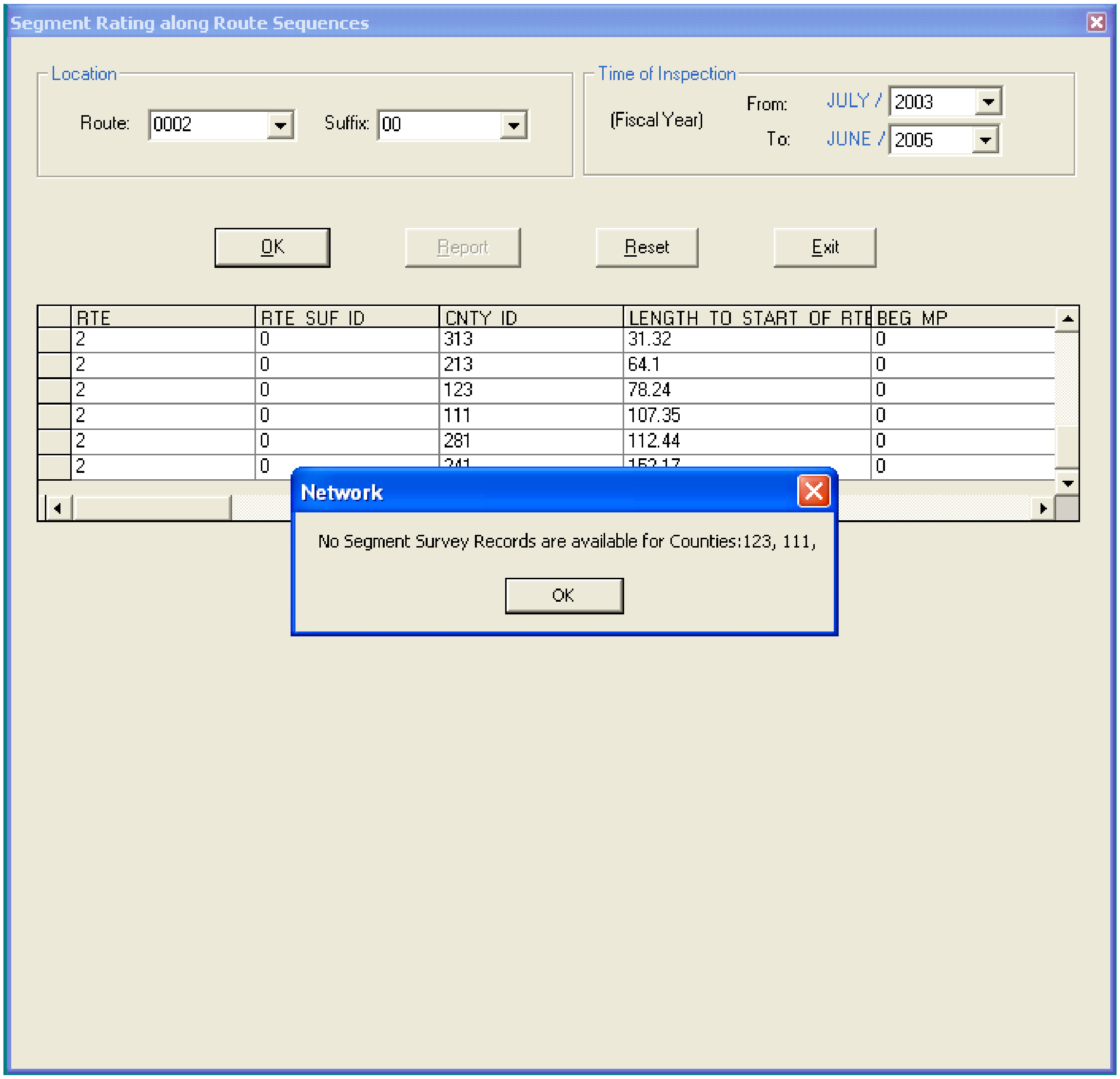


Figure XIII-3: Segment Rating along Route Sequences Example

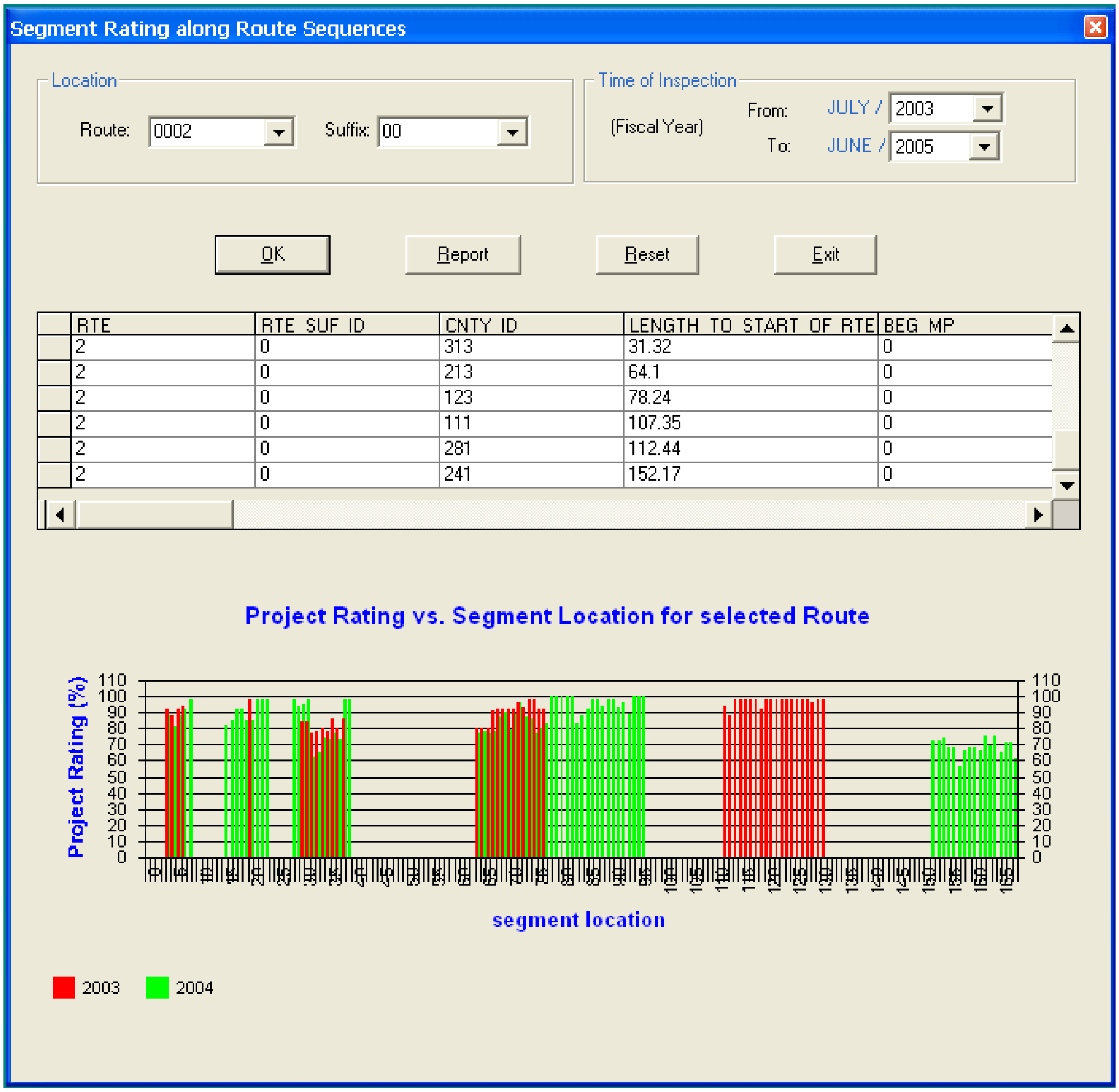


Figure XIII-4: Segment Rating along Route Sequences Example (2)

Figure XIII-5 is what the form would be like after click **Reset**.

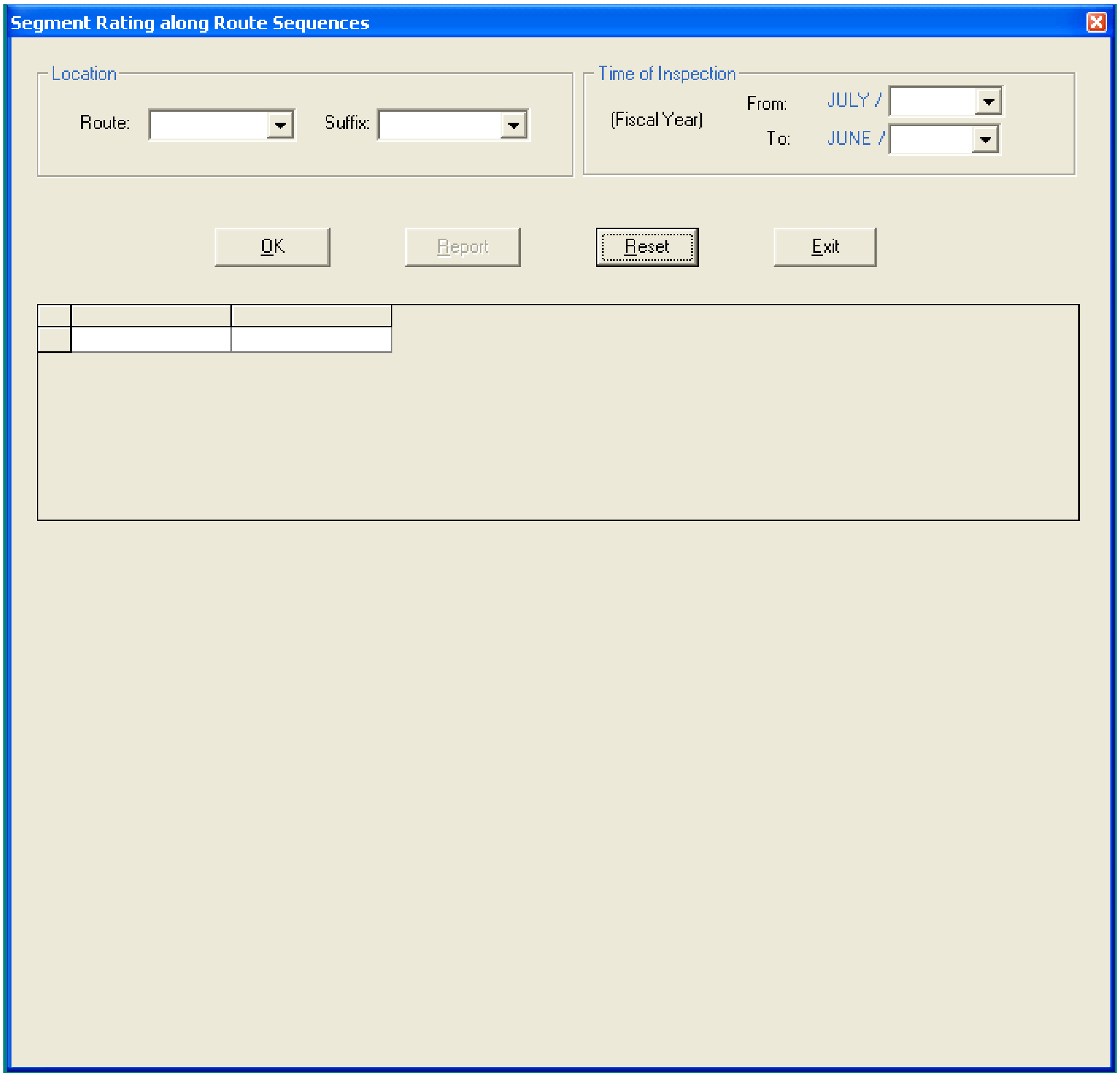


Figure XIII-5: Segment Rating along Route Sequences – **Reset** Example

Figure XIII-7 is an example of output excel file, which consists of three types of sheets.

(1) **Sequence info**. This sheet lists county info along this route. (**Figure XIII-7**)

(2) **Seqchart**. This sheet shows segment ratings along this route in different fiscal years.

(3) **Seg info***. These sheets including detailed segment information along this route in certain fiscal year. Here, * represents the fiscal year. It could be 2003 or 2004 like in **Figure XIII-9** and **Figure XIII-10**. If the analysis period is longer than two years, more sheets with similar name will be further added.

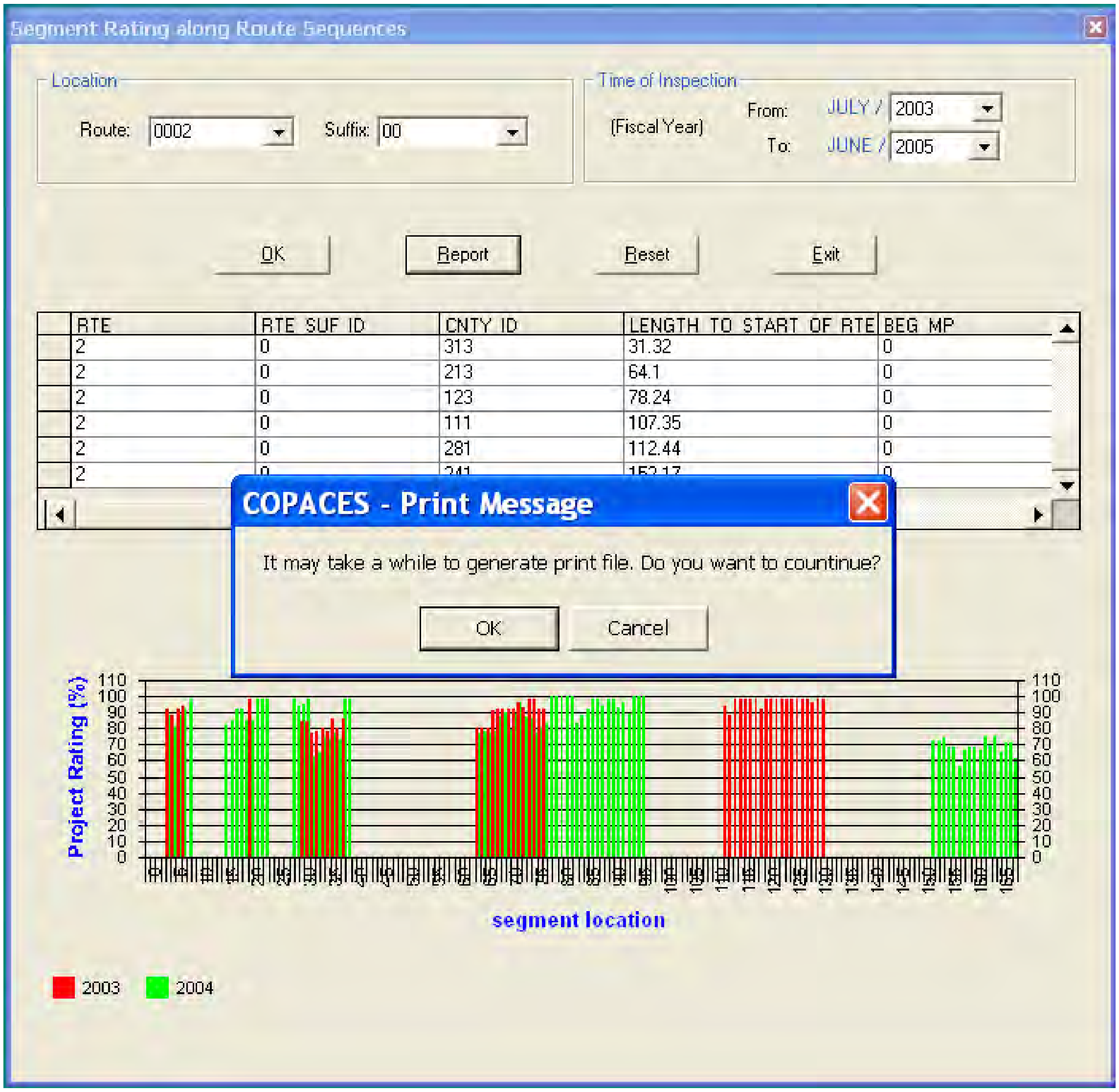
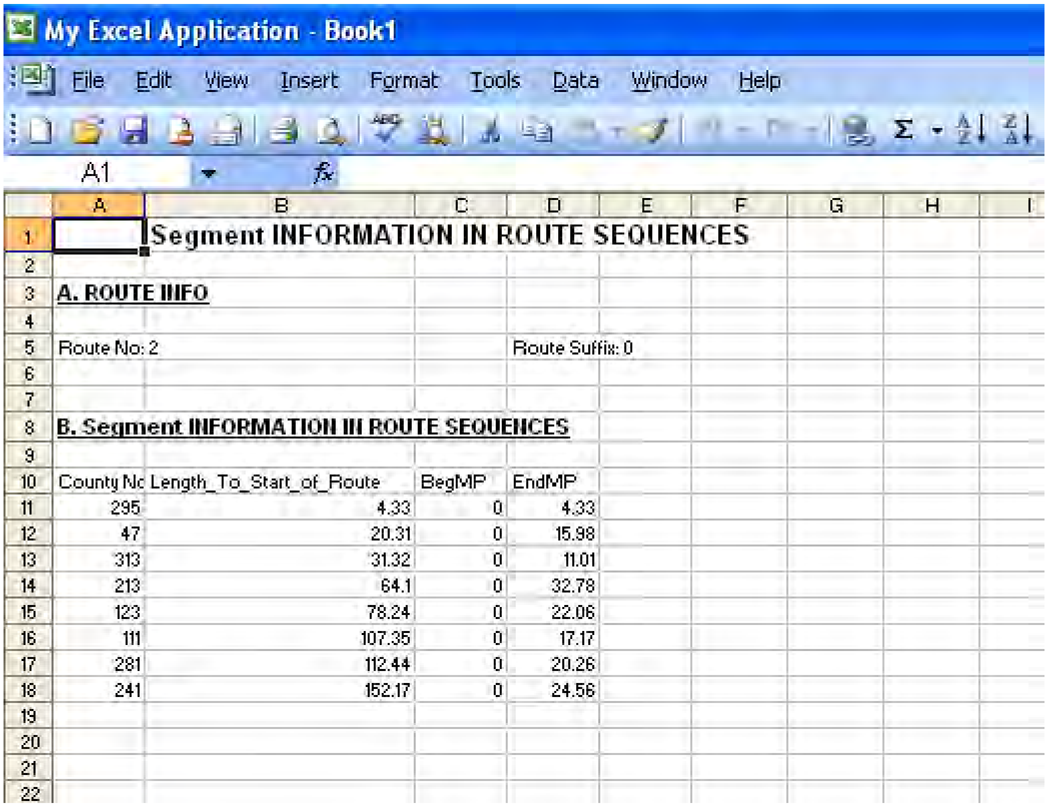


Figure XIII-6: Segment Rating along Route Sequences - **Report** Example



My Excel Application - Book1

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Segment INFORMATION IN ROUTE SEQUENCES

A. ROUTE INFO

Route No: 2 Route Suffix: 0

B. Segment INFORMATION IN ROUTE SEQUENCES

County Nc	Length_To_Start_of_Route	BegMP	EndMP
295	4.33	0	4.33
47	20.31	0	15.98
313	31.32	0	11.01
213	64.1	0	32.78
123	78.24	0	22.06
111	107.35	0	17.17
281	112.44	0	20.26
241	152.17	0	24.56

Figure XIII-7: Segment Rating along Route Sequences - **Excel** Example

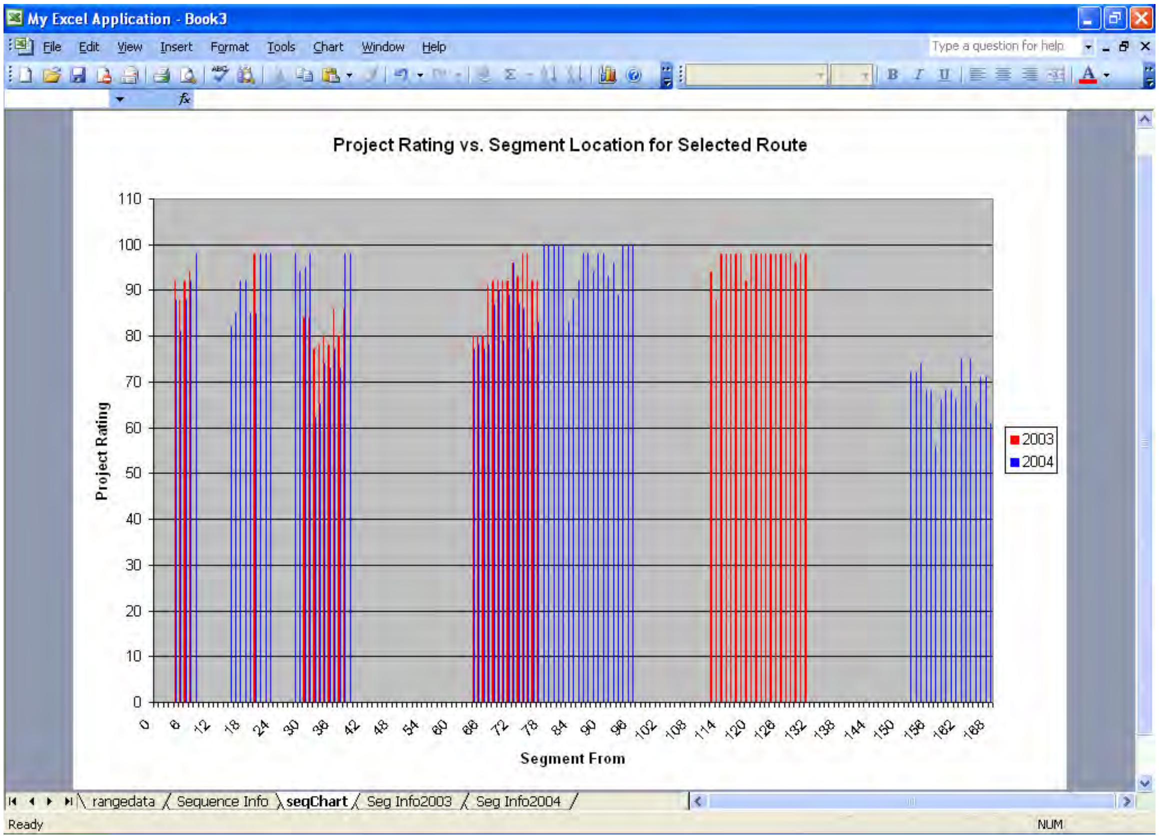
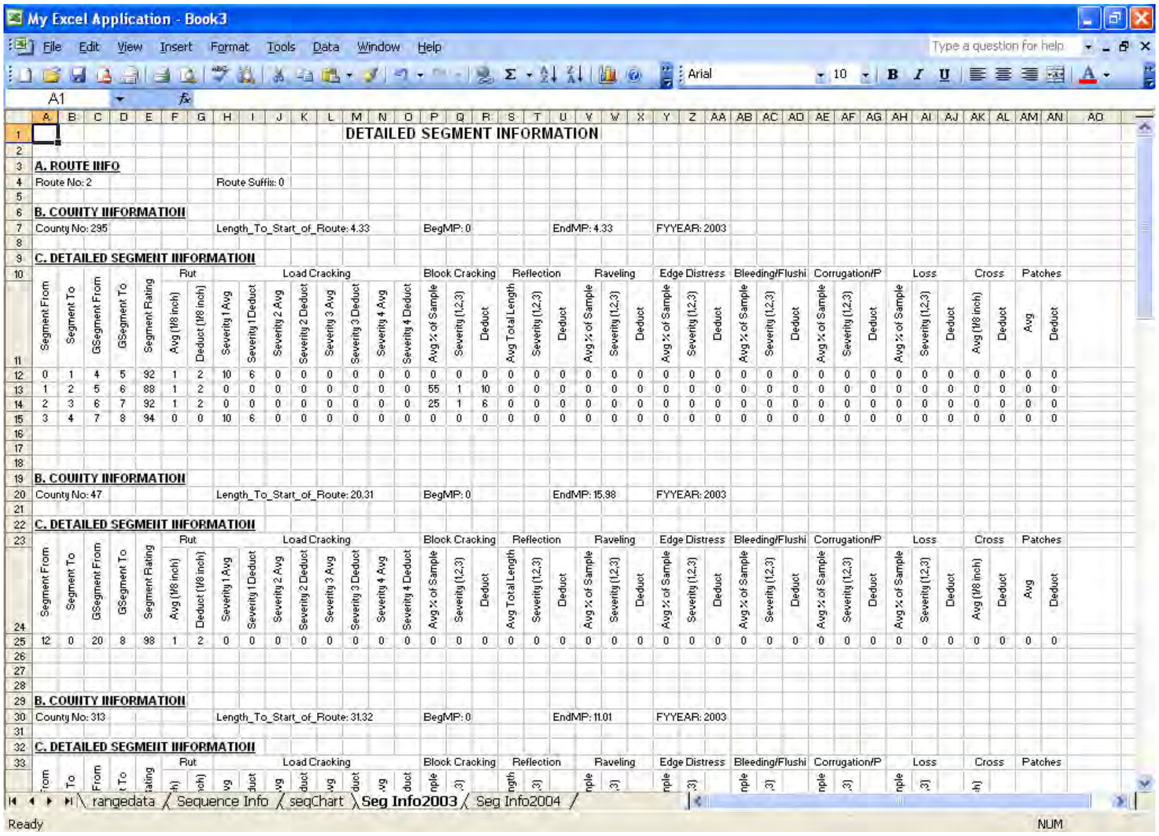


Figure XIII-8: Segment Rating along Route Sequences - **Excel** Example (2)



DETAILED SEGMENT INFORMATION

A. ROUTE INFO

Route No: 2 Route Suffix: 0

B. COUNTY INFORMATION

County No: 295 Length_To_Start_of_Route: 4.33 BegMP: 0 EndMP: 4.33 FYYEAR: 2003

C. DETAILED SEGMENT INFORMATION

					Rut		Load Cracking								Block Cracking			Reflection			Raveling			Edge Distress			Bleeding/Flushi			Corrugation/P			Loss			Cross		Patches	
Segment From	Segment To	GSegment From	GSegment To	Segment Rating	Avg (1/8 inch)	Deduct (1/8 inch)	Severity 1 Avg	Severity 1 Deduct	Severity 2 Avg	Severity 2 Deduct	Severity 3 Avg	Severity 3 Deduct	Severity 4 Avg	Severity 4 Deduct	Avg % of Sample	Severity (1,2,3)	Deduct	Avg Total Length	Severity (1,2,3)	Deduct	Avg % of Sample	Severity (1,2,3)	Deduct	Avg % of Sample	Severity (1,2,3)	Deduct	Avg % of Sample	Severity (1,2,3)	Deduct	Avg % of Sample	Severity (1,2,3)	Deduct	Avg % of Sample	Severity (1,2,3)	Deduct	Avg (1/8 inch)	Deduct	Avg	Deduct
0	1	4	5	92	1	2	10	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	2	5	6	88	1	2	0	0	0	0	0	0	0	0	55	1	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	3	6	7	92	1	2	0	0	0	0	0	0	0	0	25	1	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	4	7	8	94	0	0	10	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

B. COUNTY INFORMATION

County No: 47 Length_To_Start_of_Route: 20.31 BegMP: 0 EndMP: 15.98 FYYEAR: 2003

C. DETAILED SEGMENT INFORMATION

					Rut		Load Cracking								Block Cracking			Reflection			Raveling			Edge Distress			Bleeding/Flushi			Corrugation/P			Loss			Cross		Patches	
Segment From	Segment To	GSegment From	GSegment To	Segment Rating	Avg (1/8 inch)	Deduct (1/8 inch)	Severity 1 Avg	Severity 1 Deduct	Severity 2 Avg	Severity 2 Deduct	Severity 3 Avg	Severity 3 Deduct	Severity 4 Avg	Severity 4 Deduct	Avg % of Sample	Severity (1,2,3)	Deduct	Avg Total Length	Severity (1,2,3)	Deduct	Avg % of Sample	Severity (1,2,3)	Deduct	Avg % of Sample	Severity (1,2,3)	Deduct	Avg % of Sample	Severity (1,2,3)	Deduct	Avg % of Sample	Severity (1,2,3)	Deduct	Avg % of Sample	Severity (1,2,3)	Deduct	Avg (1/8 inch)	Deduct	Avg	Deduct
12	0	20	8	98	1	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

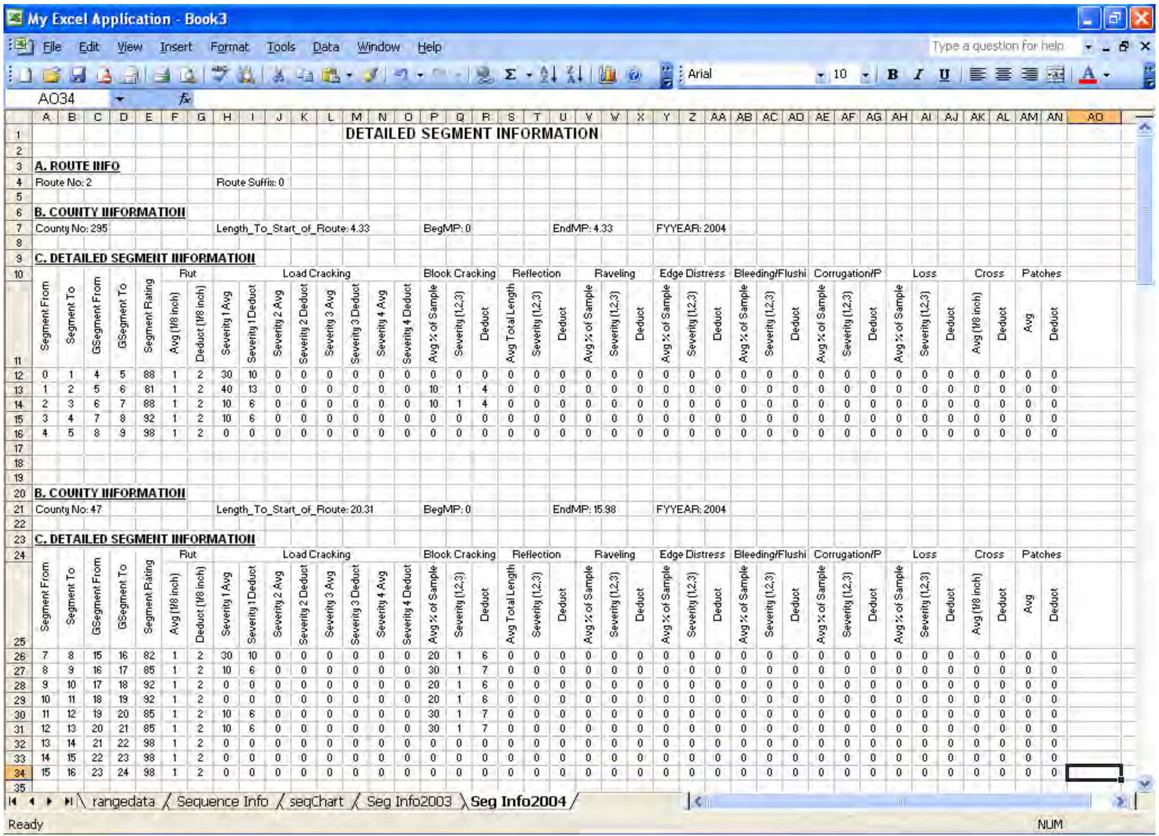
B. COUNTY INFORMATION

County No: 313 Length_To_Start_of_Route: 31.32 BegMP: 0 EndMP: 11.01 FYYEAR: 2003

C. DETAILED SEGMENT INFORMATION

Rut Load Cracking Block Cracking Reflection Raveling Edge Distress Bleeding/Flushi Corrugation/P Loss Cross Patches

Figure XIII-9: Segment Rating along Route Sequences - **Excel** Example (3)



DETAILED SEGMENT INFORMATION

A. ROUTE INFO

Route No: 2 Route Suffix: 0

B. COUNTY INFORMATION

County No: 295 Length_To_Start_of_Route: 4.33 BegMP: 0 EndMP: 4.33 FYYEAR: 2004

C. DETAILED SEGMENT INFORMATION

					Rut		Load Cracking								Block Cracking			Reflection			Raveling			Edge Distress			Bleeding/Flushi			Corrugation/P			Loss			Cross		Patches	
Segment From	Segment To	GSegment From	GSegment To	Segment Rating	Avg (1/8 inch)	Deduct (1/8 inch)	Severity 1 Avg	Severity 1 Deduct	Severity 2 Avg	Severity 2 Deduct	Severity 3 Avg	Severity 3 Deduct	Severity 4 Avg	Severity 4 Deduct	Avg % of Sample	Severity (1,2,3)	Deduct	Avg Total Length	Severity (1,2,3)	Deduct	Avg % of Sample	Severity (1,2,3)	Deduct	Avg % of Sample	Severity (1,2,3)	Deduct	Avg % of Sample	Severity (1,2,3)	Deduct	Avg % of Sample	Severity (1,2,3)	Deduct	Avg % of Sample	Severity (1,2,3)	Deduct	Avg (1/8 inch)	Deduct	Avg	Deduct
0	1	4	5	88	1	2	30	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	2	5	6	81	1	2	40	13	0	0	0	0	0	0	10	1	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	3	6	7	88	1	2	10	6	0	0	0	0	0	0	10	1	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	4	7	8	92	1	2	10	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	5	8	9	98	1	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

B. COUNTY INFORMATION

County No: 47 Length_To_Start_of_Route: 20.31 BegMP: 0 EndMP: 15.98 FYYEAR: 2004

C. DETAILED SEGMENT INFORMATION

					Rut		Load Cracking								Block Cracking			Reflection			Raveling			Edge Distress			Bleeding/Flushi			Corrugation/P			Loss			Cross		Patches	
Segment From	Segment To	GSegment From	GSegment To	Segment Rating	Avg (1/8 inch)	Deduct (1/8 inch)	Severity 1 Avg	Severity 1 Deduct	Severity 2 Avg	Severity 2 Deduct	Severity 3 Avg	Severity 3 Deduct	Severity 4 Avg	Severity 4 Deduct	Avg % of Sample	Severity (1,2,3)	Deduct	Avg Total Length	Severity (1,2,3)	Deduct	Avg % of Sample	Severity (1,2,3)	Deduct	Avg % of Sample	Severity (1,2,3)	Deduct	Avg % of Sample	Severity (1,2,3)	Deduct	Avg % of Sample	Severity (1,2,3)	Deduct	Avg % of Sample	Severity (1,2,3)	Deduct	Avg (1/8 inch)	Deduct	Avg	Deduct
7	8	15	16	82	1	2	30	10	0	0	0	0	0	0	20	1	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	9	16	17	85	1	2	10	6	0	0	0	0	0	0	30	1	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	10	17	18	92	1	2	0	0	0	0	0	0	0	0	20	1	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	11	18	19	92	1	2	0	0	0	0	0	0	0	0	20	1	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	12	19	20	85	1	2	10	6	0	0	0	0	0	0	30	1	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	13	20	21	85	1	2	10	6	0	0	0	0	0	0	30	1	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	14	21	22	98	1	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	15	22	23	98	1	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	16	23	24	98	1	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure XIII-10: Segment Rating along Route Sequences - **Excel** Example (4)

Appendix XIV: User's Manual for Generation of Historical Pavement Performance Curves

This function is part of **Network Module**.

(1) Click **Performance Curve** from **Report** menu. Or click **Performance and Traffic Curves** from **Report** menu. **Report** form (Figure XIV-2) appears.

Figure XIV-1 Menu Item – Report Performance Curve

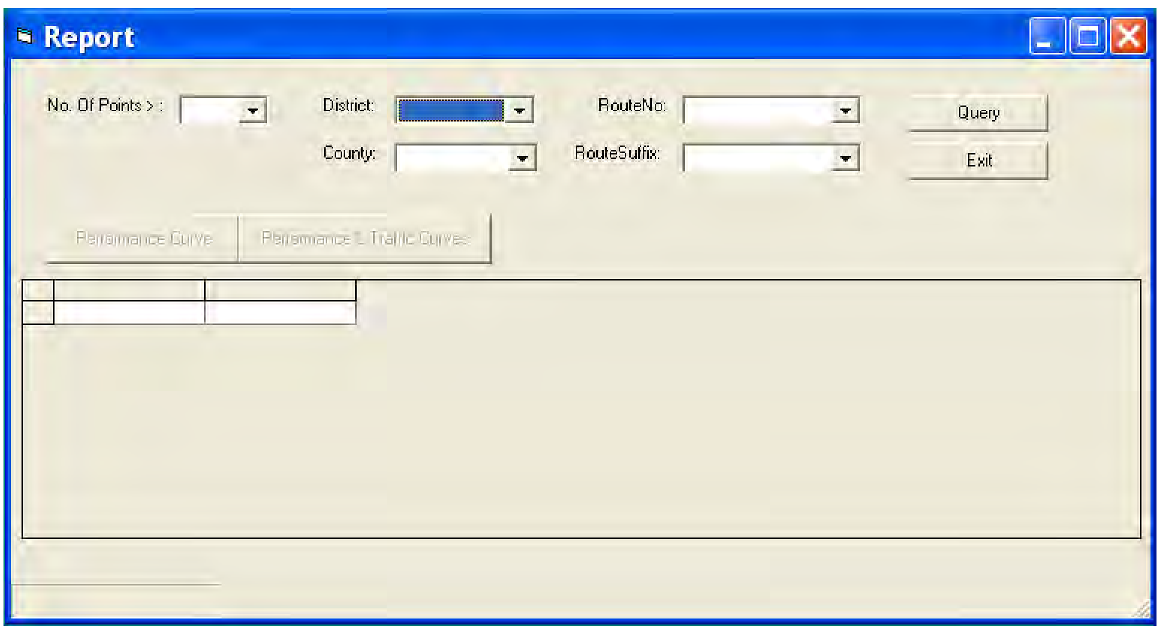
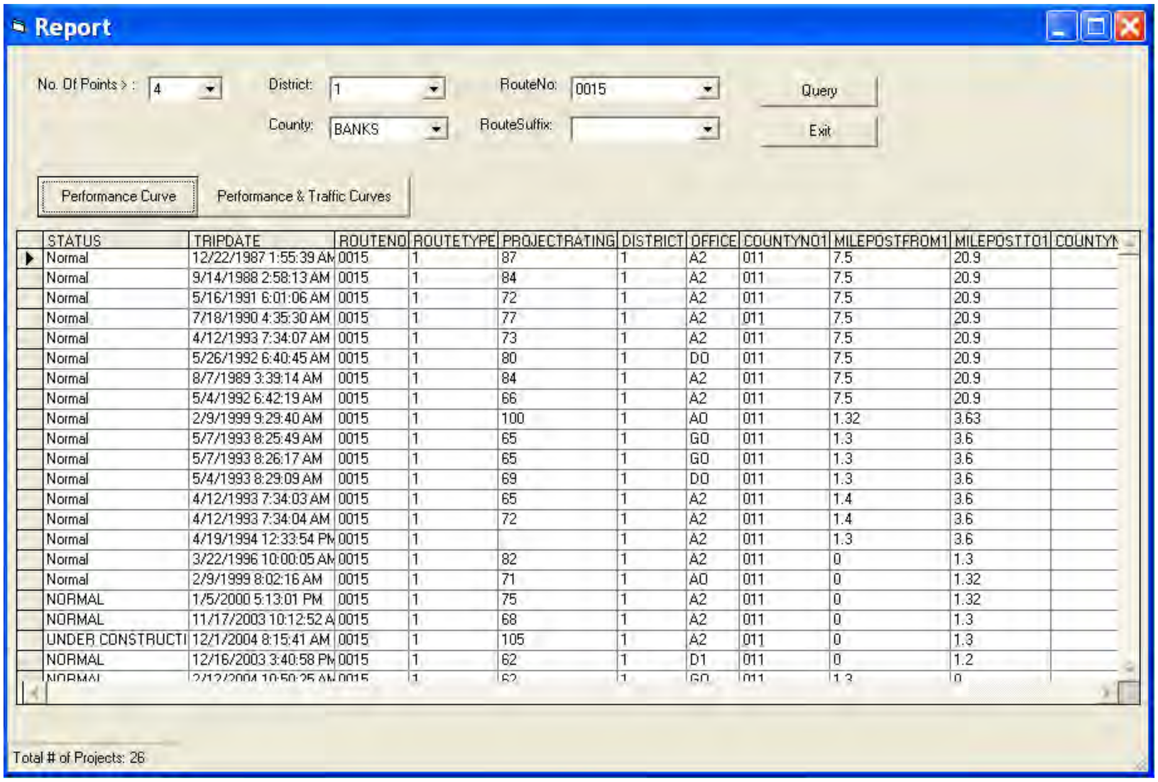


Figure XIV-2 Report Form

(2) Input query criteria may but not necessary including **No. of Points**, **District**, **County**, **Route No**, **Route Suffix**, and click **Query**.



STATUS	TRIPDATE	ROUTENO	ROUTETYPE	PROJECTRATING	DISTRICT	OFFICE	COUNTYNO1	MILEPOSTFROM1	MILEPOSTTO1	COUNTYN
Normal	12/22/1987 1:55:39 AM	0015	1	87	1	A2	011	7.5	20.9	
Normal	9/14/1988 2:58:13 AM	0015	1	84	1	A2	011	7.5	20.9	
Normal	5/16/1991 6:01:06 AM	0015	1	72	1	A2	011	7.5	20.9	
Normal	7/18/1990 4:35:30 AM	0015	1	77	1	A2	011	7.5	20.9	
Normal	4/12/1993 7:34:07 AM	0015	1	73	1	A2	011	7.5	20.9	
Normal	5/26/1992 6:40:45 AM	0015	1	80	1	DO	011	7.5	20.9	
Normal	8/7/1989 3:39:14 AM	0015	1	84	1	A2	011	7.5	20.9	
Normal	5/4/1992 6:42:19 AM	0015	1	66	1	A2	011	7.5	20.9	
Normal	2/9/1999 9:29:40 AM	0015	1	100	1	AO	011	1.32	3.63	
Normal	5/7/1993 8:25:49 AM	0015	1	65	1	GO	011	1.3	3.6	
Normal	5/7/1993 8:26:17 AM	0015	1	65	1	GO	011	1.3	3.6	
Normal	5/4/1993 8:29:09 AM	0015	1	69	1	DO	011	1.3	3.6	
Normal	4/12/1993 7:34:03 AM	0015	1	65	1	A2	011	1.4	3.6	
Normal	4/12/1993 7:34:04 AM	0015	1	72	1	A2	011	1.4	3.6	
Normal	4/19/1994 12:33:54 PM	0015	1		1	A2	011	1.3	3.6	
Normal	3/22/1996 10:00:05 AM	0015	1	82	1	A2	011	0	1.3	
Normal	2/9/1999 8:02:16 AM	0015	1	71	1	AO	011	0	1.32	
NORMAL	1/5/2000 5:13:01 PM	0015	1	75	1	A2	011	0	1.32	
NORMAL	11/17/2003 10:12:52 A	0015	1	68	1	A2	011	0	1.3	
UNDER CONSTRUCTI	12/1/2004 8:15:41 AM	0015	1	105	1	A2	011	0	1.3	
NORMAL	12/16/2003 3:40:58 PM	0015	1	62	1	D1	011	0	1.2	
NORMAL	2/12/2004 10:50:25 AM	0015	1	62	1	GO	011	1.3	0	

Figure XIV-3 Query Results

(3) Click **Performance Curve**.

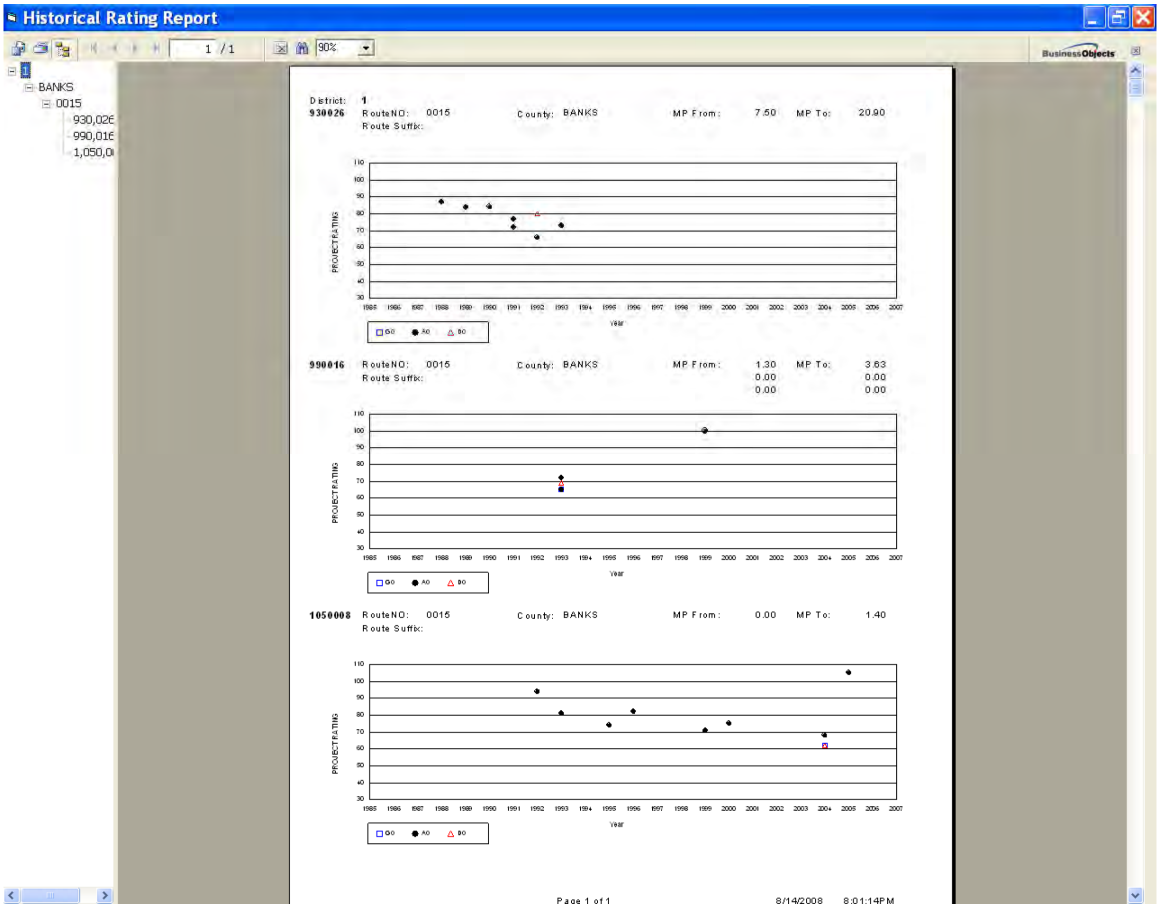
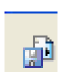
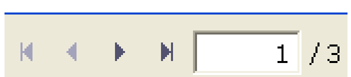


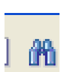
Figure XIV-4 Performance Curve

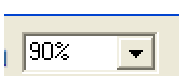
● Click the left column to select project performance curve by district, county, route no, and project no.

● Click  button on the menu to export the report to pdf. document.

● Click 

on the menu to change to other pages of report.

● Click  button to search text in the report.

● Click 

button to change the scale of layout of report.

(4) Click **Performance & Traffic Curves**.

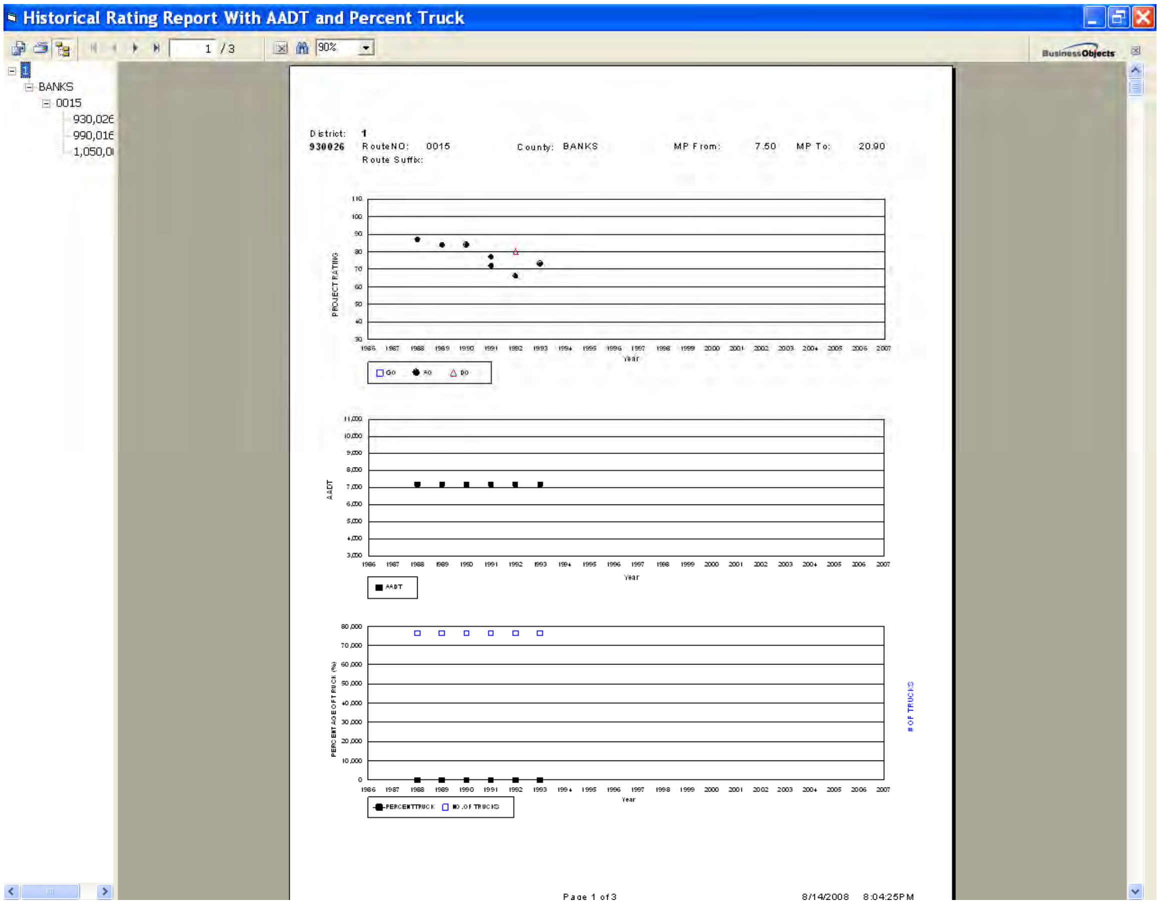
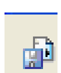
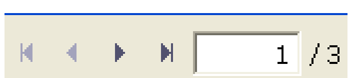
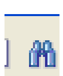


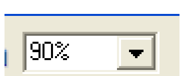
Figure XIV-5 Performance & Traffic Data Curve

● Click the left column to select project performance curve by district, county, route no, and project no.

● Click  button on the menu to export the report to pdf. document.

● Click  on the menu to change to other pages of report.

● Click  button to search text in the report.

● Click  button to change the scale of layout of report.

Appendix XV: User's Manual for Study on Pavement Life

This program of Pavement Life Query consists of following three functions:

(1)**Projects Query**: Query projects with criteria designated by user in order to proceed to view the life of selected project.

(2)**Historical Data** Output and Scatter Figure Plot: Output pavement life and location information for the project selected by user. Plot a scatter figure of pavement historical rating data in each fiscal year.

(3)**Result Export**: Export all of pavement life information and location information, and historical performance scatter plot to MS excel file.

Start Program

To start the program, open the GPAM 2008 program interface and click **PaveLife**, as shown in Figure XV-1. The main interface of the program is as shown in Figure XV-2.

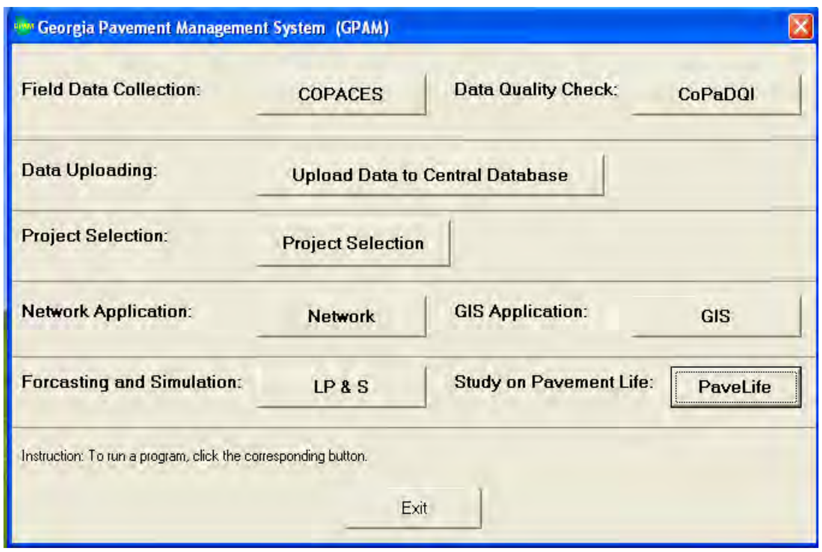


Figure XV-1 Start the Program from GPAM 2008 Interface

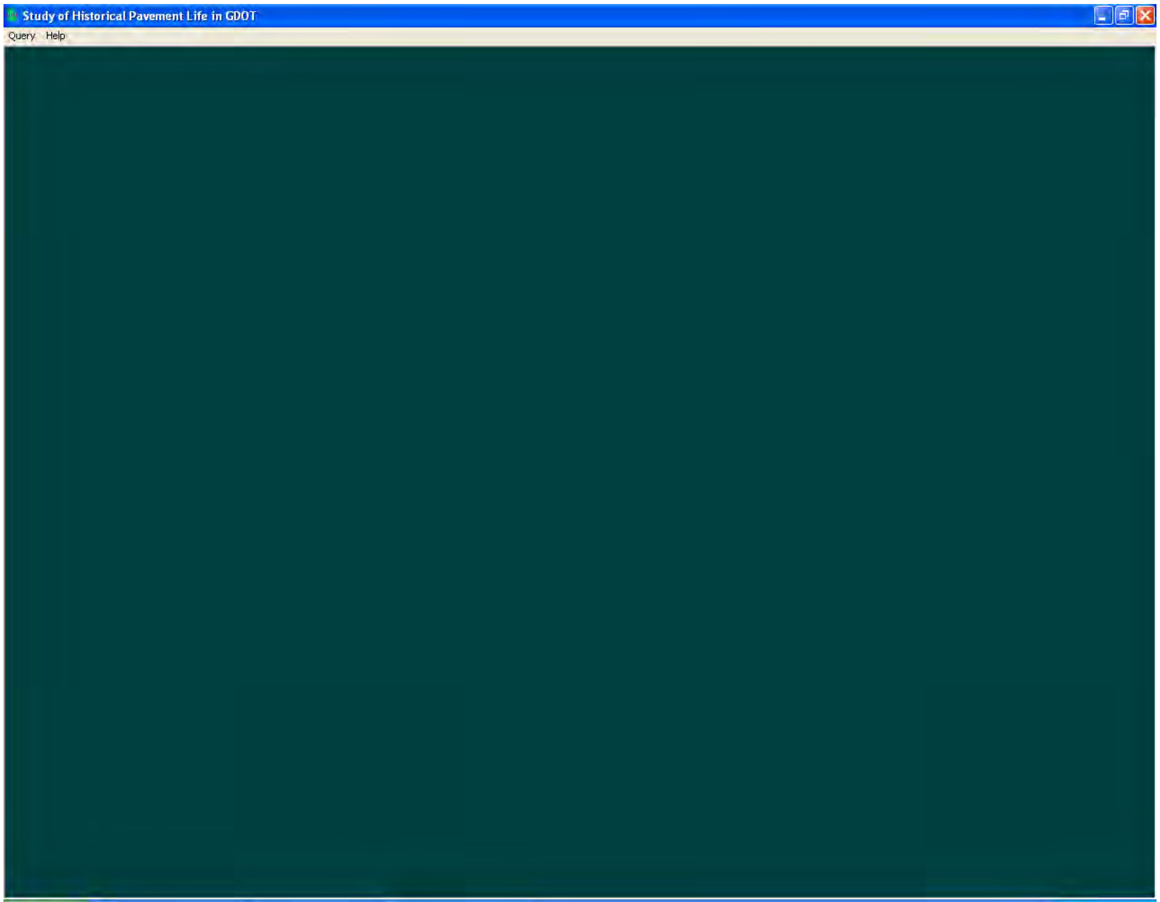


Figure XV-2 Main Interface of the Program

User can click **Query** >> **Project Query** to proceed to Project Query form, or click **Exit** to close the current form and quit the program as shown in Figure XV-3.

Figure XV-3 Query Menu on the Main Interface

If need help or information about the program, user can click **Help >> Online Help** and **About** button as shown in Figure XV-4.

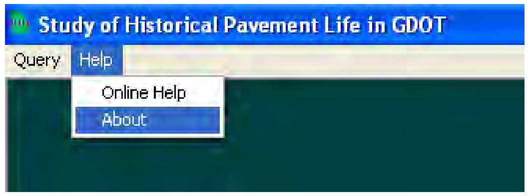


Figure XV-4 Help Menu on the Main Interface

Projects Query

User can query projects from the pavement life database with designated query criteria. The projects query interface is also program main interface as shown by Figure XV-5. Since there is still no project queried and listed in the following data grid, the button of **Export** and **Graph** are gray. User can input **District**, **County**, **RouteNo**, **RouteSuffix, Start Year, End Year** information to query projects. **RouteSuffix** criteria can not be selected until **RouteNo** has been selected as shown in Figure XV-5. However, user can input any of them (except **RouteSuffix**) or even no information to query.

If click **Query** without criteria input, all projects in the database will be listed in the query result data grid, as shown in Figure XV-7.

User can also select **Confidence Level** to be any one, or two, or all of **High, Medium, or Low** level. Please be cautious that if no confidence level is checked, it is the same effect as all confidence level been selected. User should also select one and only one pavement life range.

User can select **Resurfacing Life** or **70_Life** and input **Min** and **Max** value to set the lower bound and upper bound of selected life type. If user do not want this query criteria, just leave **Min** and **Max** blank.

Following explains the meaning of each pavement life information item.
Start year -- The start of pavement life.
70_year -- The year pavement rating deteriorates to 70.
End year -- The end of pavement life (the year pavement being resurfaced).
Resurf life -- The length of pavement life from start year to end year.

70_life -- The length of pavement life from start year to 70_year.

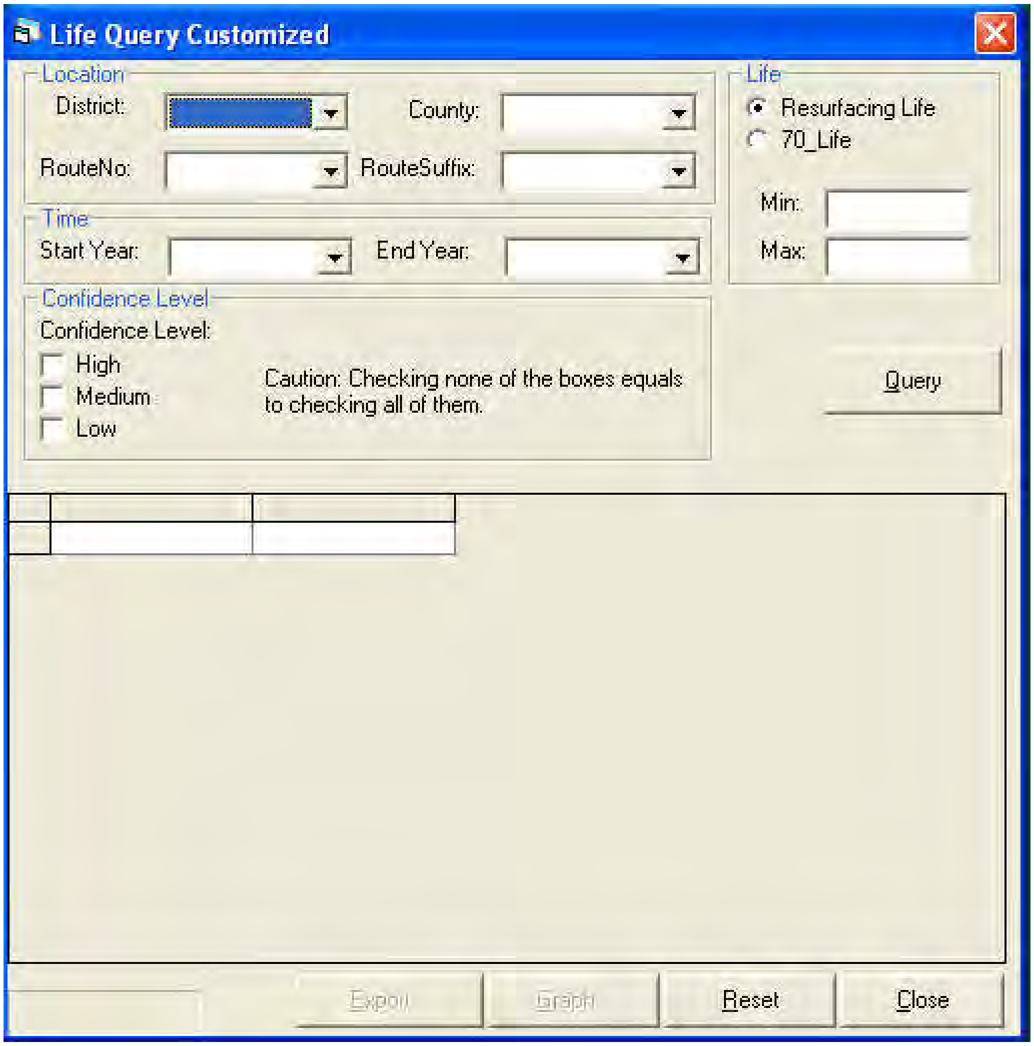


Figure XV-5 Main Interface of the Program

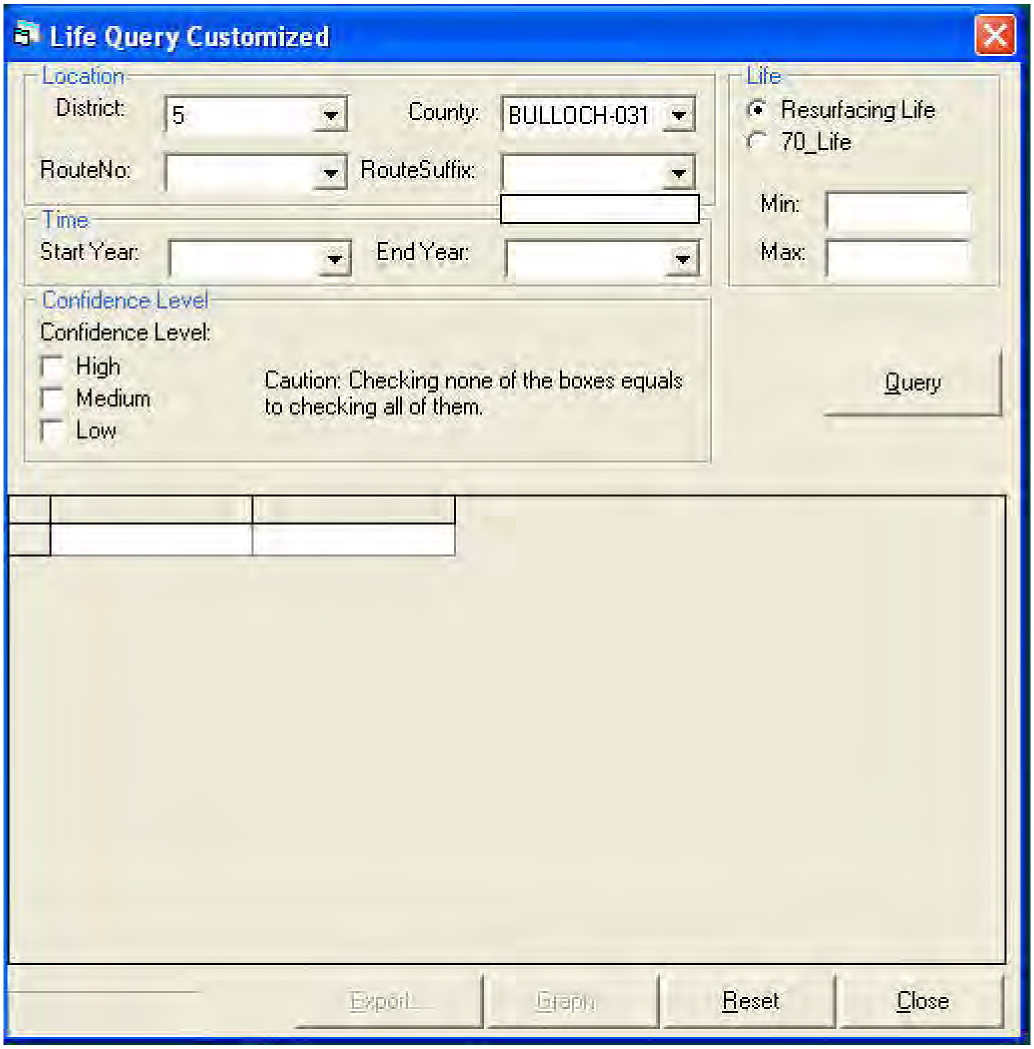


Figure XV-6 RouteSuffix Information Unavailable without RouteNo

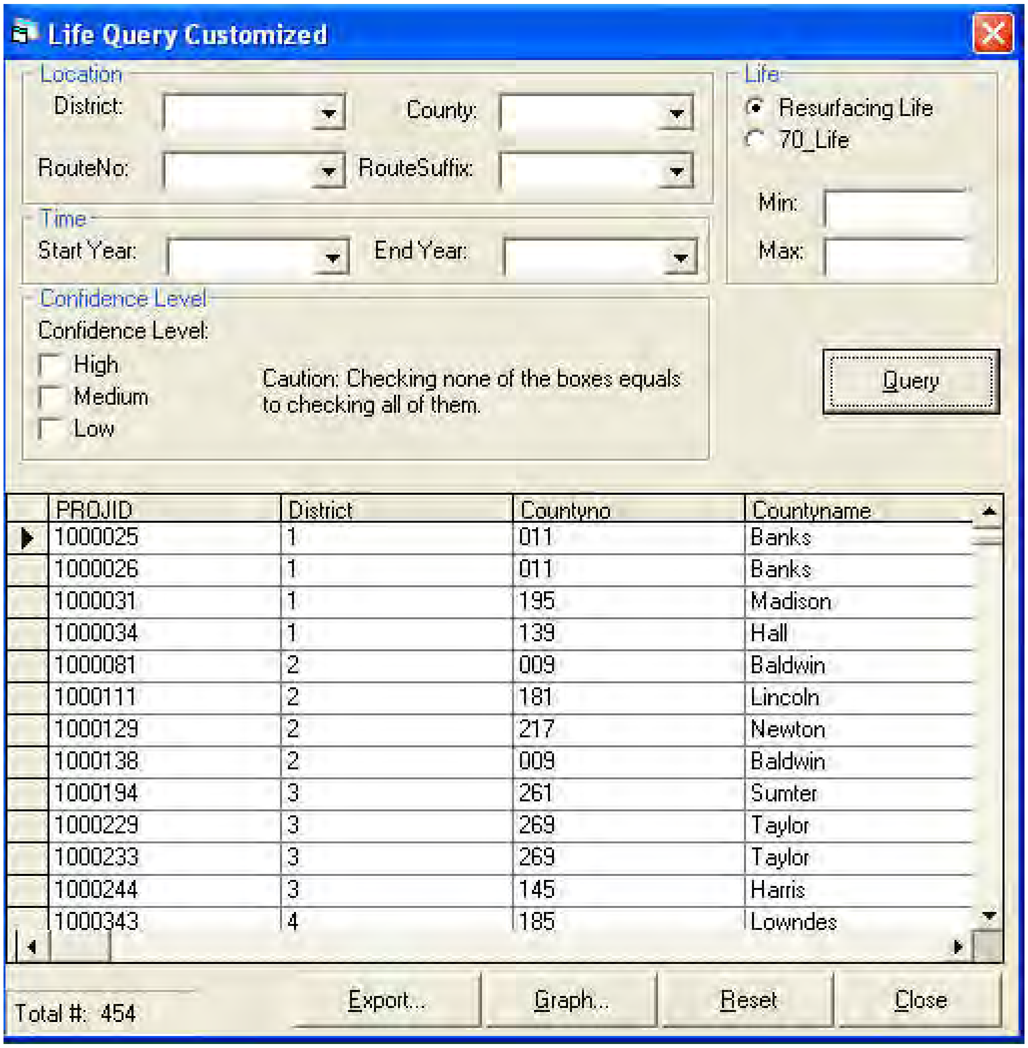


Figure XV-7 Query without Input Criteria

After complete the input of query criteria, user can click **Query** to list all projects satisfying query requirements in the below data grid. Then, the button of **Export** and **Graph** will be activated. Project information include **District, Countyno, Countyname, Routeno, Routesuffix, MilepostFrom, MilepostTo, STRYR (Start Year), ENDYR (End Year), RES_LIFE (Resurfacing Life), LIFE70 (70_Life), RES_CONF (Confidence Level), avgAADT (Average AADT), and avgAADTT (Average Annual Daily Truck Traffic)** will be displayed as shown in Figure XV-8.

User can also bookmark any project in the data grid and click **Graph** to proceed to **Output Project Location Information and Historical Performance Data**. However, only one project should be bookmarked each time in order to proceed to output further information. Otherwise, warning message will pop up as shown in Figure XV-9. If no project is bookmarked to proceed to output further information, another warning message will also pop up as shown in Figure XV-10.

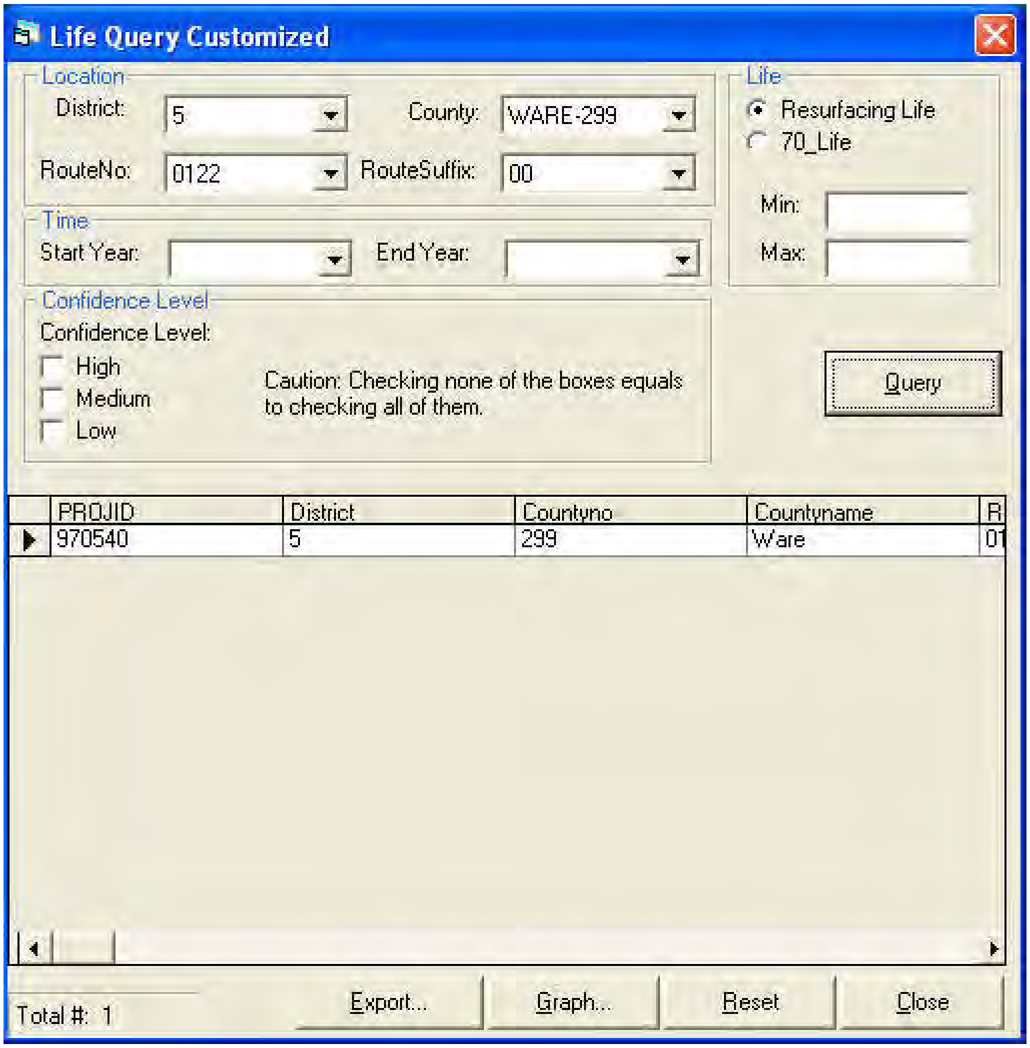


Figure XV-8 Query Result Listed in the Data Grid

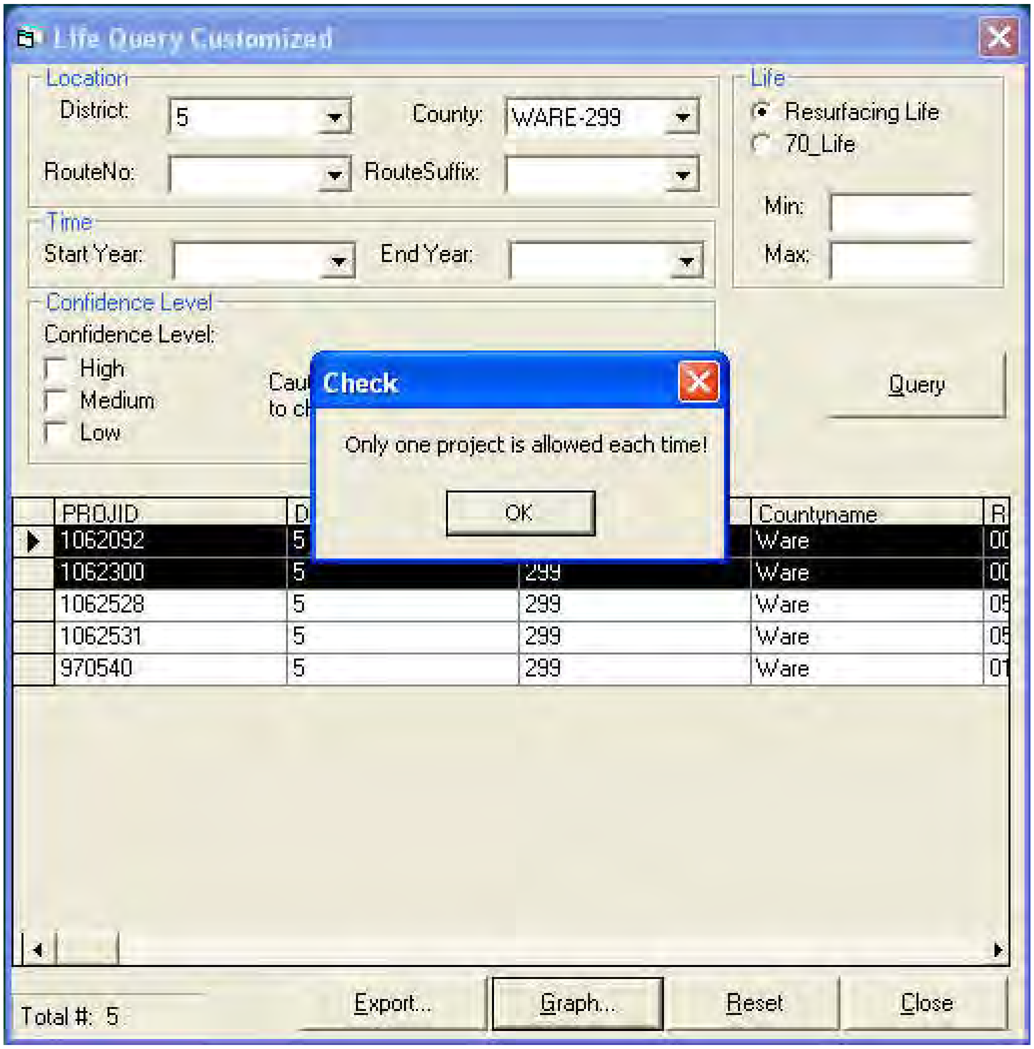


Figure XV-9 Warning for More Than One Projects Been Processed

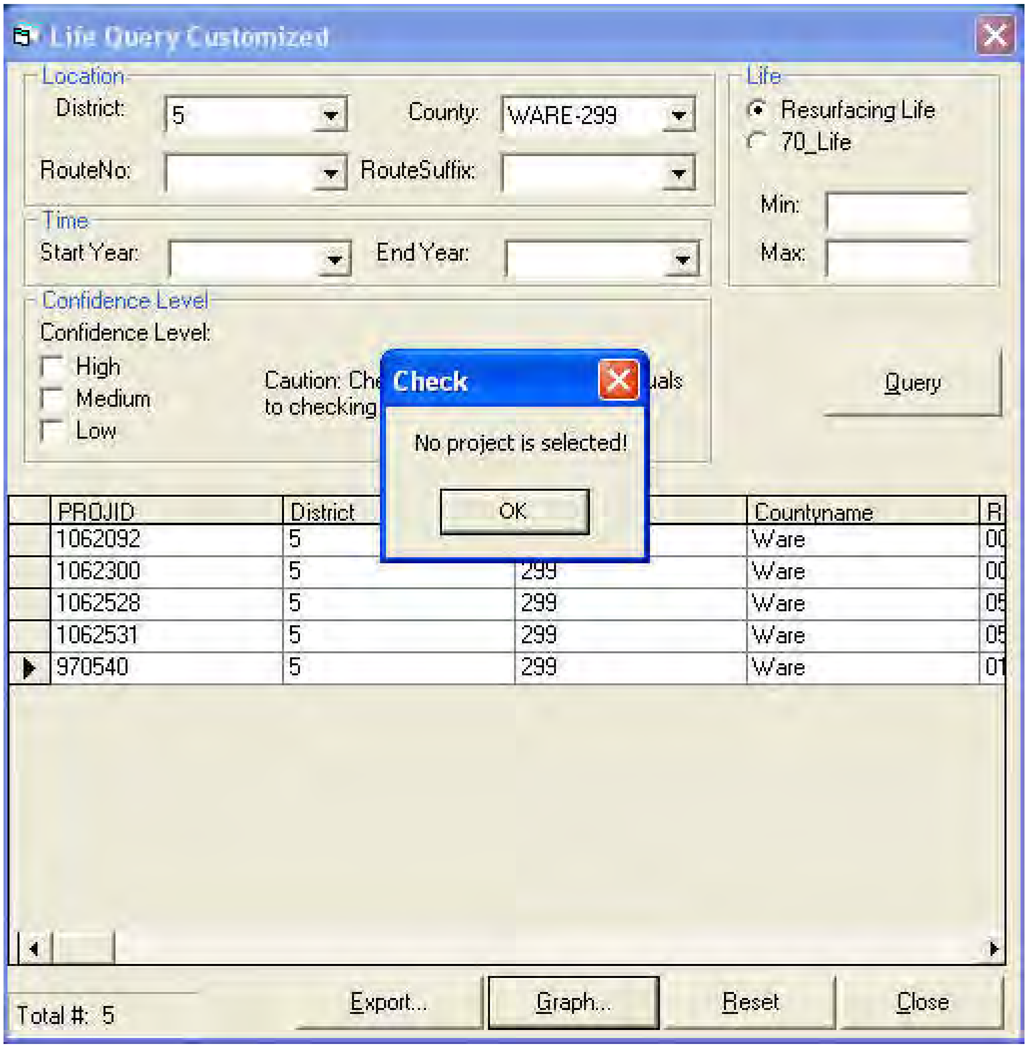


Figure XV-10 Warning Message for No Project Selected

User can also click **Reset** to clear all query result and query criteria information. Then, the button of **Export** and **Graph** will be changed to be inactive. User can click **Close** to close the query form.

If user want to output query project result to MS excel file, just click **Export** button. Before exporting, a warning message will pop up to warn that the exporting process may take a while as shown in Figure XV-11. User can click **YES** to continue export or click **NO** to quit the export.

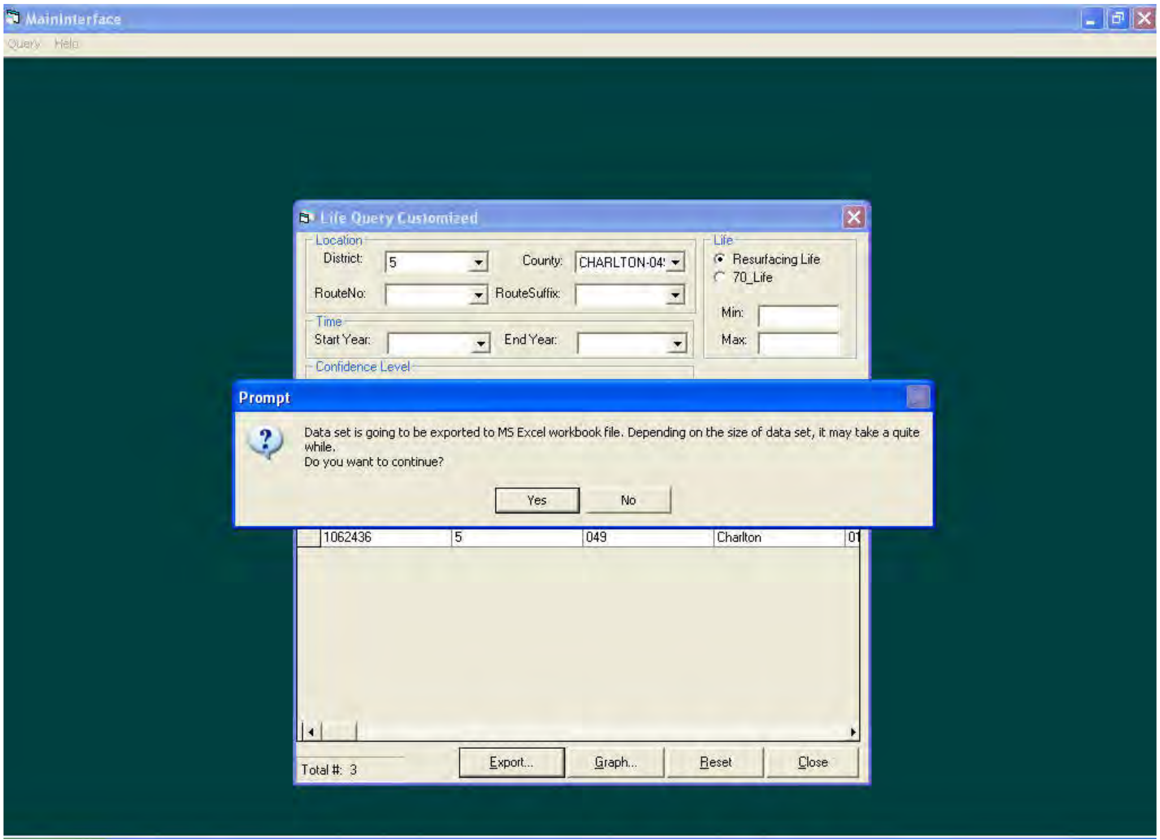
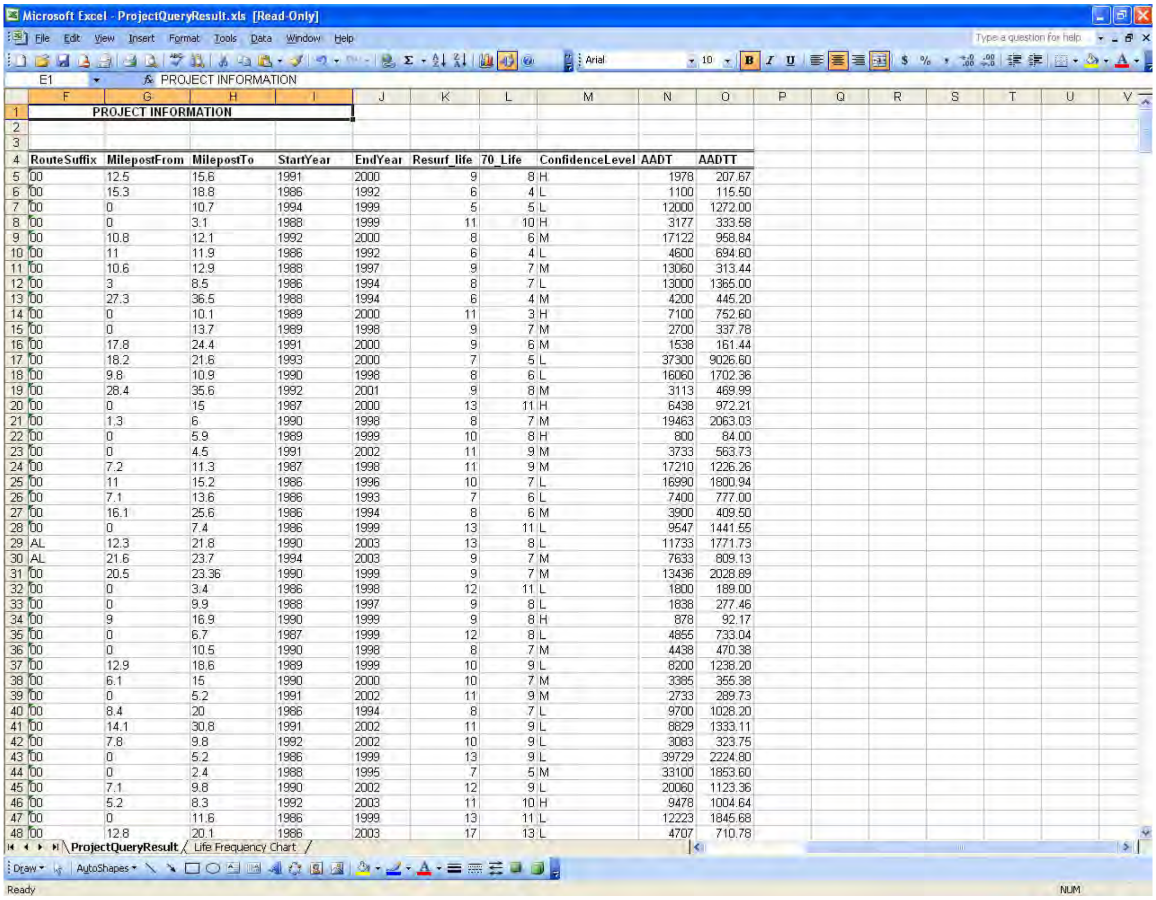


Figure XV-11 Warning Message for Exporting

If click **YES**, export MS excel will be opened as shown in Figure XV-12. Project location, and life information will be shown.

If click **YES**, export MS excel will be opened as shown in Figure XV-12. Project location, and life information will be shown in the sheet of **Project Query Result**. The pavement life statistics result (max life, min life, average life, and standard deviation), and pavement life frequency chart for those projects been queried in previous form will be shown in the sheet of **Life Frequency Chart**, as shown in Figure XV-13.



RouteSuffix	MilepostFrom	MilepostTo	StartYear	EndYear	Resurf_life	70_Life	ConfidenceLevel	AADT	AADTT
00	12.5	15.6	1991	2000	9	8	H	1978	207.67
00	15.3	18.8	1986	1992	6	4	L	1100	115.50
00	0	10.7	1994	1999	5	5	L	12000	1272.00
00	0	3.1	1988	1999	11	10	H	3177	333.58
00	10.8	12.1	1992	2000	8	6	M	17122	958.84
00	11	11.9	1986	1992	6	4	L	4600	694.60
00	10.6	12.9	1988	1997	9	7	M	13060	313.44
00	3	8.5	1986	1994	8	7	L	13000	1365.00
00	27.3	36.5	1988	1994	6	4	M	4200	445.20
00	0	10.1	1989	2000	11	3	H	7100	752.60
00	0	13.7	1989	1998	9	7	M	2700	337.78
00	17.8	24.4	1991	2000	9	6	M	1538	161.44
00	18.2	21.6	1993	2000	7	5	L	37300	9026.60
00	9.8	10.9	1990	1998	8	6	L	16060	1702.36
00	28.4	35.6	1992	2001	9	8	M	3113	469.99
00	0	15	1987	2000	13	11	H	6438	972.21
00	1.3	6	1990	1998	8	7	M	19463	2063.03
00	0	5.9	1989	1999	10	8	H	800	84.00
00	0	4.5	1991	2002	11	9	M	3733	563.73
00	7.2	11.3	1987	1998	11	9	M	17210	1226.26
00	11	15.2	1986	1996	10	7	L	16990	1800.94
00	7.1	13.6	1986	1993	7	6	L	7400	777.00
00	16.1	25.6	1986	1994	8	6	M	3900	409.50
00	0	7.4	1986	1999	13	11	L	9547	1441.55
AL	12.3	21.8	1990	2003	13	8	L	11733	1771.73
AL	21.6	23.7	1994	2003	9	7	M	7633	809.13
00	20.5	23.36	1990	1999	9	7	M	13436	2028.89
00	0	3.4	1986	1998	12	11	L	1800	189.00
00	0	9.9	1988	1997	9	8	L	1838	277.46
00	9	16.9	1990	1999	9	8	H	878	92.17
00	0	6.7	1987	1999	12	8	L	4855	733.04
00	0	10.5	1990	1998	8	7	M	4438	470.38
00	12.9	18.6	1989	1999	10	9	L	8200	1238.20
00	6.1	15	1990	2000	10	7	M	3385	355.38
00	0	5.2	1991	2002	11	9	M	2733	289.73
00	8.4	20	1986	1994	8	7	L	9700	1028.20
00	14.1	30.8	1991	2002	11	9	L	8829	1333.11
00	7.8	9.8	1992	2002	10	9	L	3083	323.75
00	0	5.2	1986	1999	13	9	L	39729	2224.80
00	0	2.4	1988	1995	7	5	M	33100	1853.60
00	7.1	9.8	1990	2002	12	9	L	20060	1123.36
00	5.2	8.3	1992	2003	11	10	H	9478	1004.64
00	0	11.6	1986	1999	13	11	L	12223	1845.68
00	12.8	20.1	1986	2003	17	13	L	4707	710.78

Figure XV-12 Project Information Export to MS Excel File

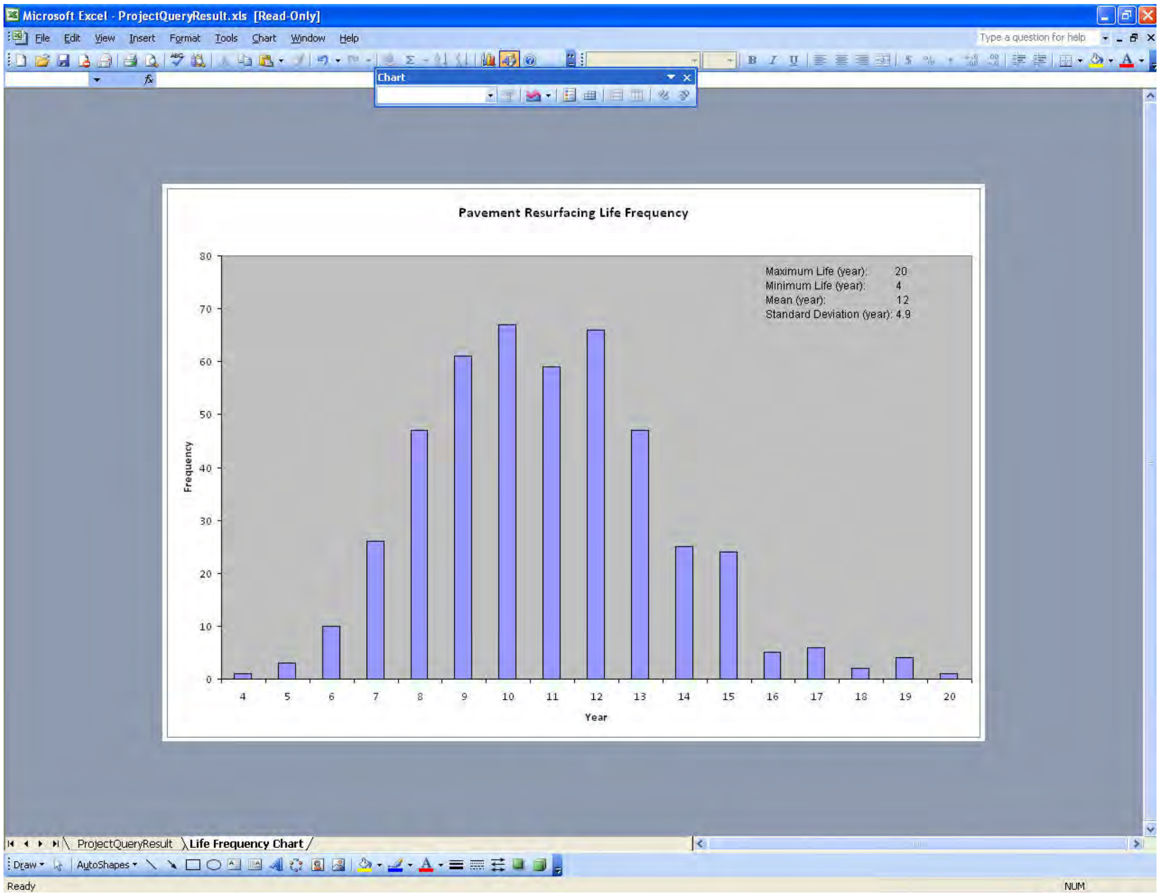


Figure XV-13 Projects Life Frequency Chart Exported to MS Excel

The excel file is read only as shown at the left right corner in Figure XV-13. If user clicks button at the top right corner to close the file, a warning message will pop up for user to choose save the file or not, as shown in Figure XV-14.

Figure XV-14 Warning Message for User to Save the File

User can choose to click **Yes** to close the file and save it, or **No** to close the file and not save the file, or **Cancel** to not close the file. If user clicks Yes, then a common dialog for user to choose the directory for save the file will pop up, as shown in Figure XV-15. If user click  button or click **File** >> **Save**, the same dialog in Figure XV-15 will also pop up. User can choose the file name and file directory, and then click **Save** to save it, or click **Cancel** to quit.

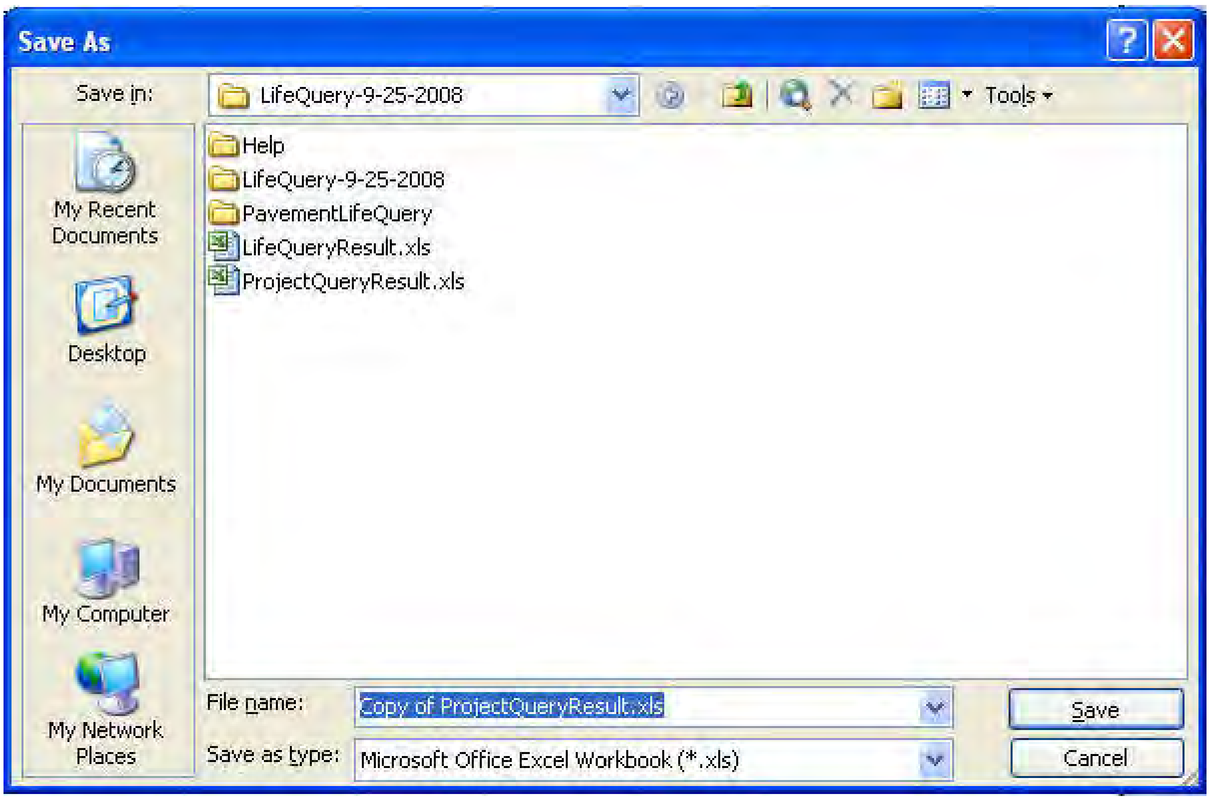


Figure XV-15 Choose Directory to Save the MS Excel File

Historical Data Output and Scatter Figure Plot

By bookmark project and click **Graph** in previous form, user will proceed to output all project historical performance and location information in the form as shown in Figure XV-16.

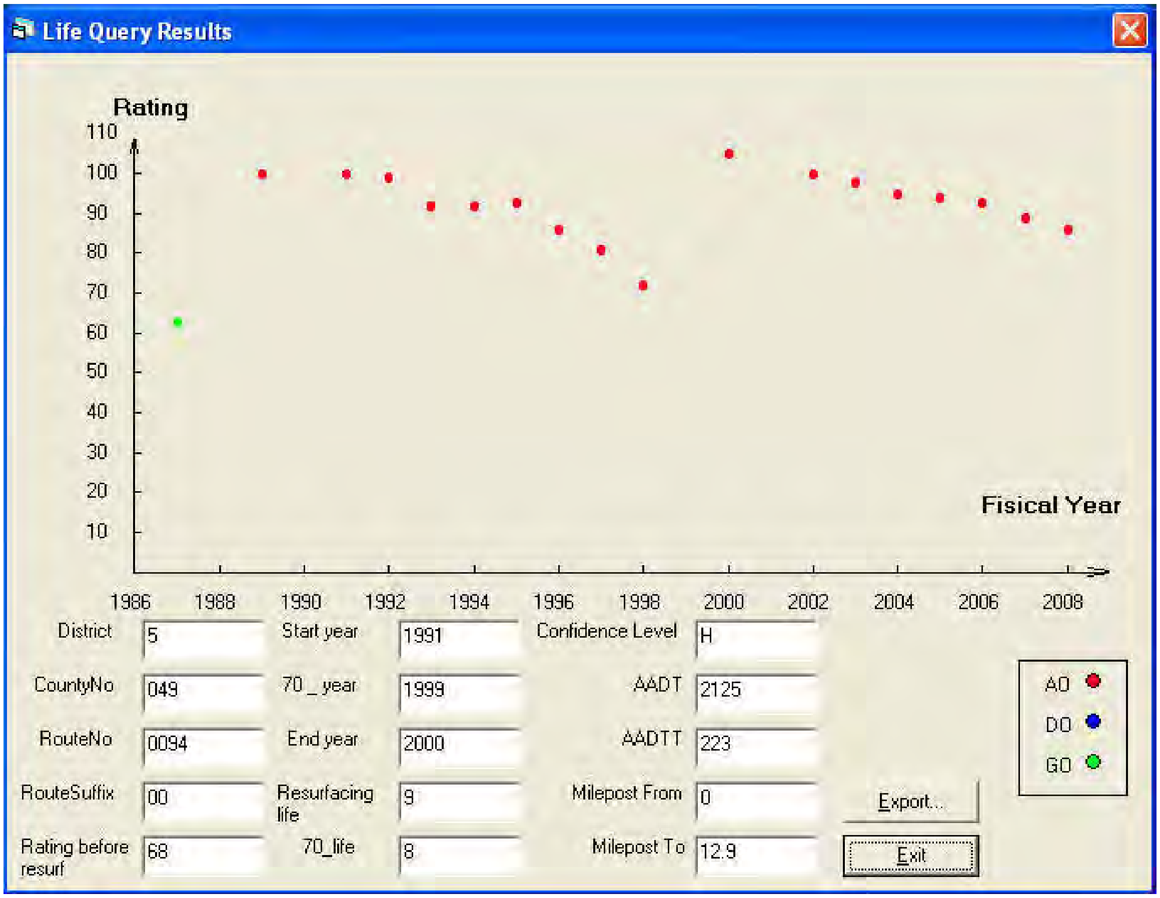


Figure XV-16 Project Location and Historical Performance Information Output

In this form, all project location information include **District, CountyNo, RouteNo, RouteSuffix, Milepost From, Milepost To** and pavement life information include **Start year, 70_year, End year, Resurfacing Life, 70_life, and Rating before resurf,** and other information include **AADT, AADTT, and Confidence Level** will be displayed. Pavement historical rating information is also displayed as a scatter plot in this form. The horizontal axle displays **Fiscal Year**, and vertical axle displays pavement **Rating** in corresponding fiscal year. Red circle points represent pavement rating information collected by area office; blue and green ones represent district office and general office correspondingly, as shown in Figure XV-16.

User can click **Exit** to close the form. By click **Export,** all these project information will be exported to MS excel file and displayed.

Result Export

User can click **Export** in previous form to export all information to MS excel file. Before exporting, a warning message will pop up to warn that the exporting process may take a while as shown in Figure XV-17. User can click **YES** to continue export or click **NO** to quit the export.

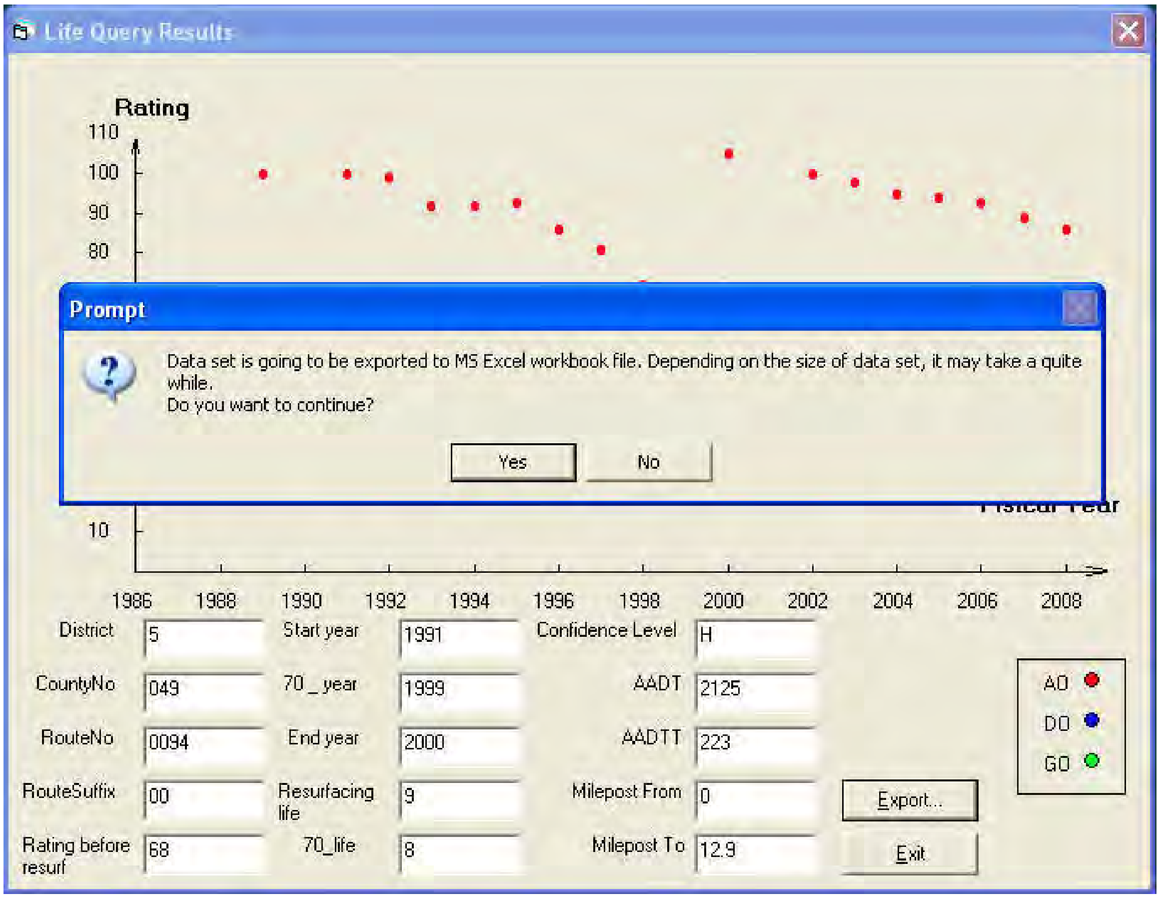
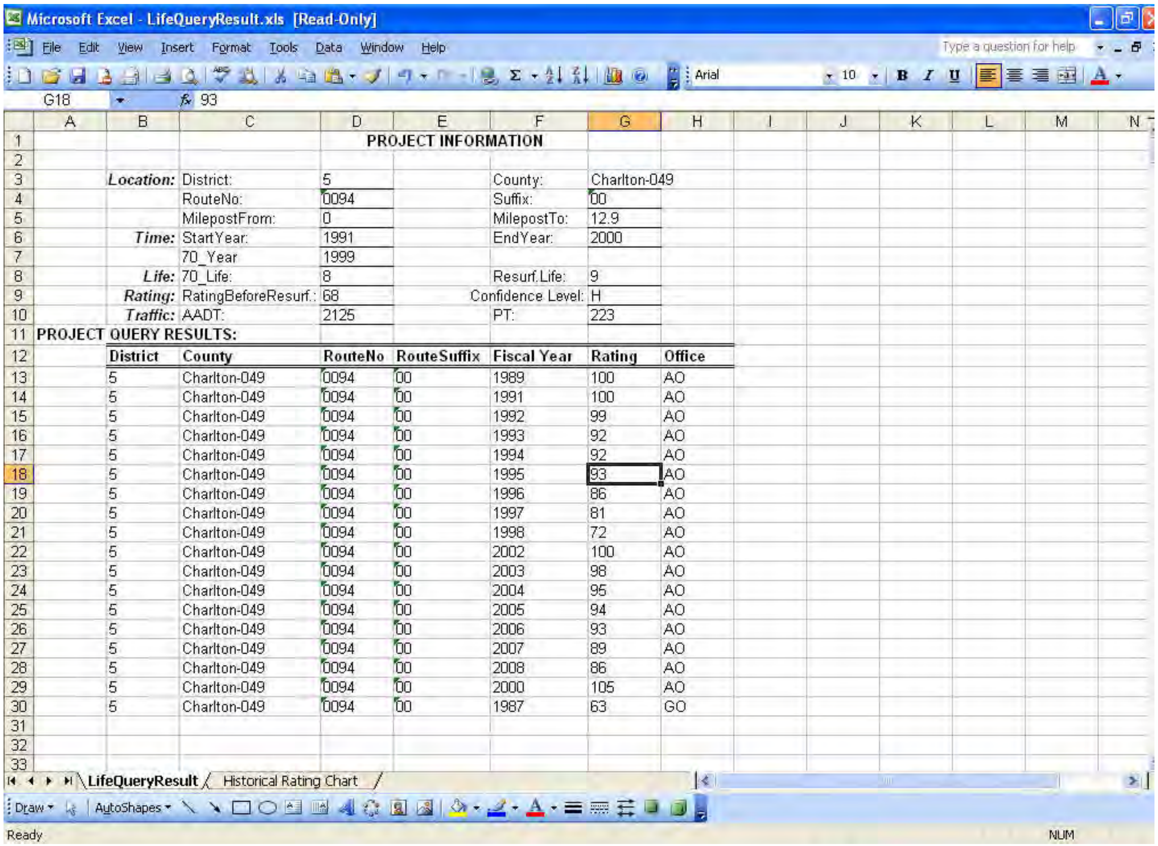


Figure XV-17 Warning Message for Exporting

If click **YES**, export MS excel will be opened as shown in Figure XV-18. Excel worksheet displayed first is **LifeQueryResult**, in which project location, life, and historical rating information will be shown. User can click **Historical Rating Chart** to view the same scatter chart in Figure XV-17, as shown in Figure XV-19.



PROJECT INFORMATION

Location:	District:	5	County:	Charlton-049
	RouteNo:	0094	Suffix:	00
	MilepostFrom:	0	MilepostTo:	12.9
Time:	StartYear:	1991	EndYear:	2000
	70_Year	1999		
Life:	70_Life:	8	Resurf.Life:	9
Rating:	RatingBeforeResurf.:	68	Confidence Level:	H
Traffic:	AADT:	2125	PT:	223

PROJECT QUERY RESULTS:

District	County	RouteNo	RouteSuffix	Fiscal Year	Rating	Office
5	Charlton-049	0094	00	1989	100	AO
5	Charlton-049	0094	00	1991	100	AO
5	Charlton-049	0094	00	1992	99	AO
5	Charlton-049	0094	00	1993	92	AO
5	Charlton-049	0094	00	1994	92	AO
5	Charlton-049	0094	00	1995	93	AO
5	Charlton-049	0094	00	1996	86	AO
5	Charlton-049	0094	00	1997	81	AO
5	Charlton-049	0094	00	1998	72	AO
5	Charlton-049	0094	00	2002	100	AO
5	Charlton-049	0094	00	2003	98	AO
5	Charlton-049	0094	00	2004	95	AO
5	Charlton-049	0094	00	2005	94	AO
5	Charlton-049	0094	00	2006	93	AO
5	Charlton-049	0094	00	2007	89	AO
5	Charlton-049	0094	00	2008	86	AO
5	Charlton-049	0094	00	2000	105	AO
5	Charlton-049	0094	00	1987	63	GO

Figure XV-18 Project Information Export to MS Excel File

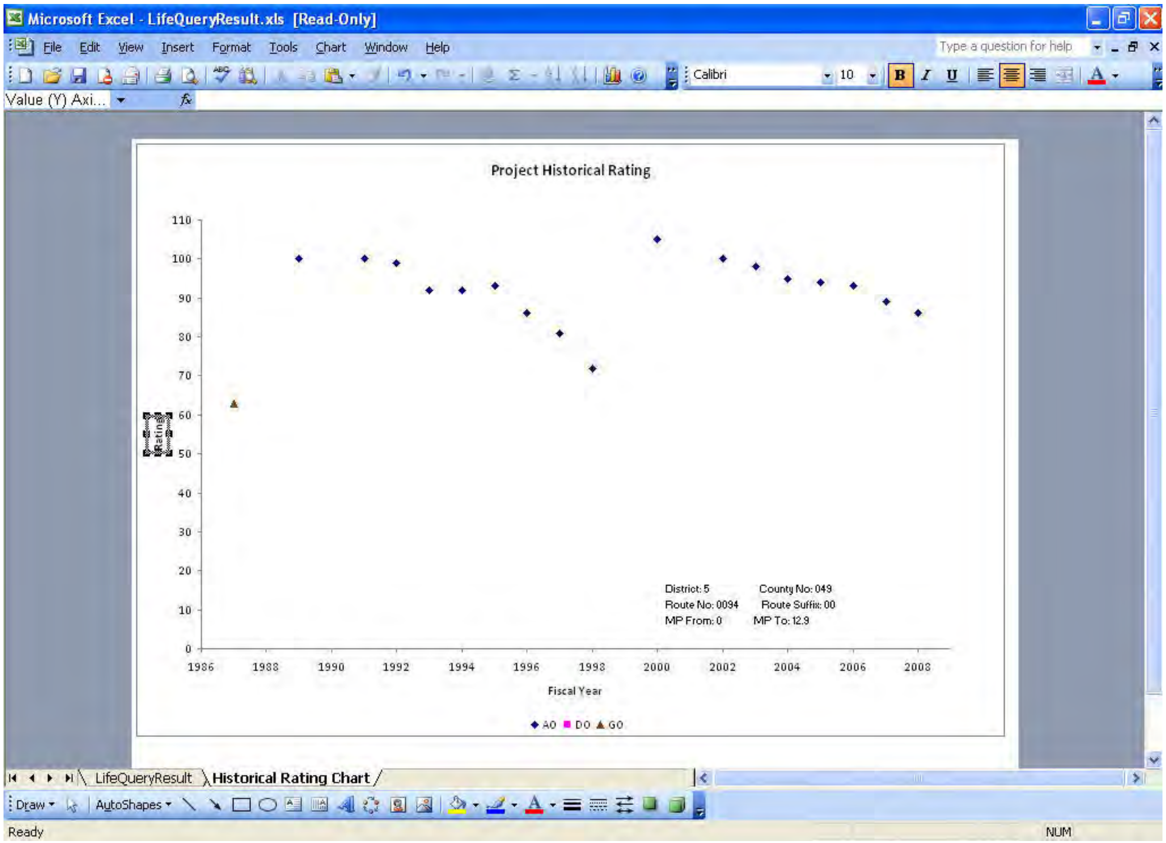


Figure XV-19 Historical Rating Chart in MS Excel

The excel file is read only as shown at the left right corner in Figure XV-18 or Figure XV-19. If user clicks button at the top right corner to close the file, a warning message will pop up for user to choose save the file or not, as shown in Figure XV-20.

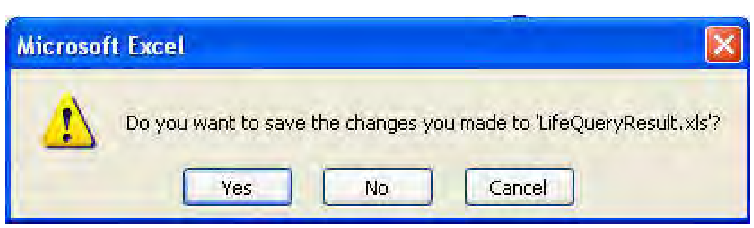


Figure XV-20 Warning Message for User to Save the File

User can choose to click **Yes** to close the file and save it, or **No** to close the file and not save the file, or **Cancel** to not close the file. If user click Yes, then a common dialog for user to choose the directory for save the file will pop up, as shown in Figure XV-21. If user click button or click **File** >> **Save**, the same dialog in Figure XV-21will also pop up. User can choose the file name and file directory, and then click **Save** to save it, or click **Cancel** to quit.

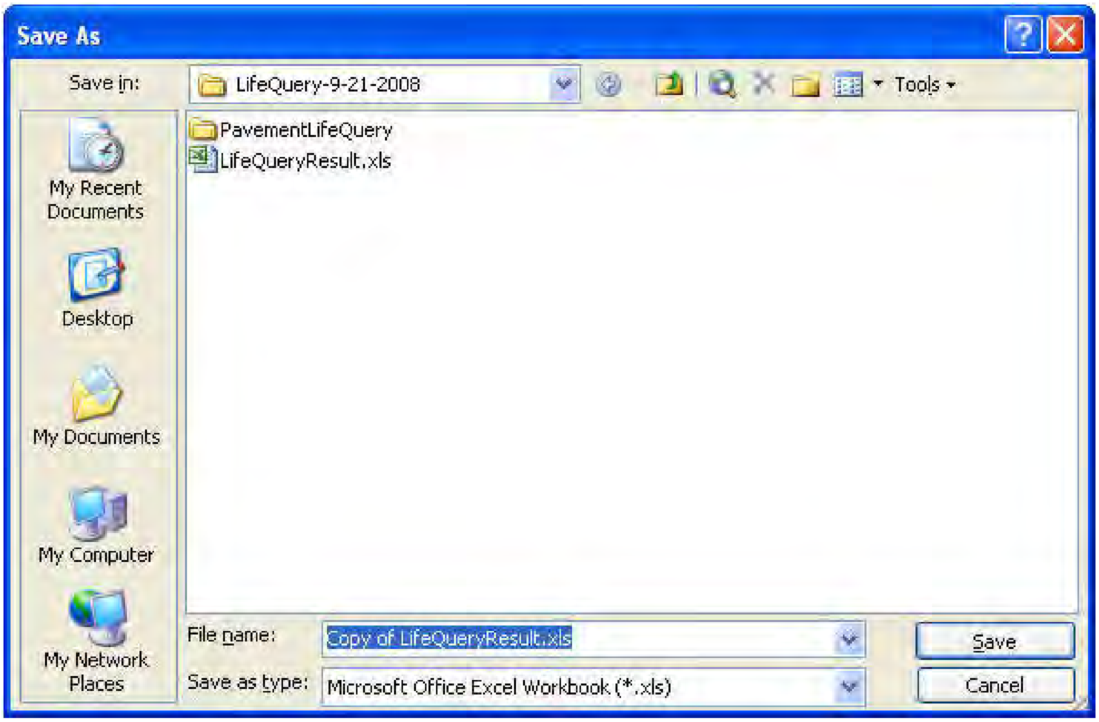


Figure XV-21 Choose Directory to Save the MS Excel File