Development of Pavement Design and Investigation Strategies for Non-Interstate Routes

Final Report

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16. Abstract

This project investigated the state-of-the-practice on conducting field investigation for rehabilitation of non-interstate routes and whether field investigation is cost effective for the SCDOT. An online survey was conducted to determine the state-of-the-practice on pavement rehabilitation for non-interstate routes. A total of 29 responses were received from 21 state DOTs and eight state agencies. All of the respondents (100%) indicated that they perform field investigation before rehabilitation design. Some state DOTs perform a preliminary survey of the pavement condition and then perform field investigation, if needed. Other state DOTs use the same field investigation procedure for rehabilitation as new construction and some perform the field investigation regardless of the pavement functional condition. The top three methods being used to perform field investigation are: coring (93.1%), falling-weight deflectometer measurements (89.7%), and mobile scanning (55.2%). When cores are taken, the majority of the respondents (85.2%) indicated that they use them to measure both pavement thickness and distress. Lastly, the majority of the respondents (93.1%) indicated that they also investigate pavement distresses during rehabilitation design.

To determine whether field investigation is cost-effective, the life-cycle costs and equivalent uniform annual costs of two different designs, one with field investigation and one without field investigation, were compared. The design with field investigation represents the design the SCDOT would use in the future if the SCDOT required field investigation to guide rehabilitation design for non-interstate routes. The design without field investigation represents the current design being used by SCDOT district engineers. The life-cycle cost analysis indicated that when the design *with* investigation is used instead of the design *without* investigation, the cost difference to maintain one lane-mile of pavement in good functional condition is -$27,030, in fair functional condition is -$12,220, and in poor functional condition is -$37,348 over the 50-year analysis period; the negative cost difference indicates that it is a savings to the SCDOT. These findings indicate that field investigation is generally cost-effective. Therefore, it is recommended that the SCDOT consider performing field investigation on pavements that are in fair and poor conditions. The investigation procedure for good pavements will likely be modified by on-going efforts from the traffic-speed deflectometer (TSD) pooled fund study and SPR 748.

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EXECUTIVE SUMMARY

The objectives of this project are to research the state-of-the-practice on conducting field investigation for rehabilitation of non-interstate routes and determine whether field investigation is cost effective for the SCDOT.

State-of-the Practice on Conducting Field Investigation for Rehabilitation
An online survey was conducted to understand the state-of-practice on conducting field investigation for rehabilitation of non-interstate routes. A total of 29 responses were received from 21 state DOTs and eight state agencies. The majority of the respondents (69%) indicated they have a guide or method for the rehabilitation design of flexible pavements. When asked about the importance of field investigation to rehabilitation design on primary routes on a scale of 1 to 5 where 5 is very important, 72.4% rated it as a 5, 24.1% rated it as 4, and 3.5% rated it as a 3. For secondary routes, fewer respondents rated it as a 5; specifically, 51.7% rated it as a 5, 38% rated it as a 4, and 10.3% rated it as a 3. All of the respondents (100%) indicated that they perform field investigation before developing the rehabilitation design. Some state DOTs first perform a preliminary survey of the pavement condition and then perform field investigation, if needed. Other state DOTs use the same field investigation procedure for rehabilitation as new construction and some perform the field investigation regardless of the pavement functional condition. A number of different methods are used to perform field investigation: mobile scanning (e.g., ground penetrating radar), falling weight deflectometer (FWD), vibratory deflection, static deflection, dynamic cone penetration and coring. The top three methods are: coring (93.1%), FWD (89.7%), and mobile scanning (55.2%). When cores are taken, the majority of the respondents (85.2%) indicated that they use them to measure both pavement thickness and distress. Lastly, the majority of the respondents (93.1%) indicated that they also investigate pavement distresses during rehabilitation design.

Cost-effectiveness of Performing Field Investigation for SCDOT
The cost-effectiveness of performing field investigation was determined by comparing life-cycle costs and equivalent uniform annual costs (EUAC) of the two different rehabilitation design options, one *with* field investigation and one *without* field investigation. Comparison of 10-year design SNs *with* investigation and *without* investigation indicated that the design *with* field investigation is more consistent in providing a pavement structure that has the required SN than the one *without* (inter-quartile range of 15.54% versus 35.40%). Comparison of the number of maintenance treatments needed in a 50-year period between the 10-year designs *with* and *without* field investigation using SN method indicated a correlation between the design SN and number of maintenance treatments needed. Specifically, the higher the design SN the fewer the number of maintenance treatments is required, and vice-versa. In other words, a properly designed pavement will require fewer maintenance treatments. Since designs *with* field investigation are more consistent in providing the required pavement structure, they prolong the time when the first maintenance treatment is needed. Comparison of deterministic life-cycle cost (in thousands) per lane for a 50-year analysis period between the designs *with* and *without* field investigation indicated that the total life-cycle cost (in thousands) per lane with field investigation is cost-effective for good, fair, and poor pavements (good: $41,316.03 vs. $45,459.19; fair: $40,287.80 vs. $42,160.88; poor: $68,262.37 vs. $73,987.05). Lastly, comparison of EUAC for fair pavements in a 15-year period between the 10-year designs *with* and *without* field investigation indicated that

the 10-year design *with* field investigation is cost-effective for fair pavements (*with* investigation: $1,706.88 vs. *without* investigation: $2,009.74).

Based on this project's findings, it is recommended that the SCDOT consider the following:

- Have the District Contract Managers (DCMs) conduct field investigation for primary routes that are in fair or poor condition.
- Have the State Pavement Engineer hold annual or bi-annual workshops to review and discuss the procedure for identifying which project requires field investigation with all DCMs.
- Develop a pavement design decision support system (DSS) that integrates all of the SCDOT pavement design tools and roadway maintenance history to eliminate guesswork regarding existing pavement condition and facilitate the development of an appropriate reconstruction/rehabilitation/preservation treatment.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1: INTRODUCTION

The South Carolina Department of Transportation (SCDOT) has the fourth largest state-maintained highway system in the nation, consisting of approximately 41,377 centerline miles of roadway and 90,598 lane miles; this represents 54% of the state's roads compared to the national average of 19% (SPR, 2016) maintained by other state DOTs. Due to the limited funds and significant transportation system responsibility, SCDOT has the lowest amount of maintenance support on its highway system in the nation ($39,000 per mile vs national average of $162,000 per mile) (Bland, 2015). As a result, maintenance has been deferred for the majority of non-interstate roadways, especially the secondary system. Further compounding the challenges of managing such a large transportation system for the SCDOT is the increasing rate of deterioration, which is accelerated by rapid population growth in the state. The 2015 growth and population data estimates from the US Census Bureau indicated that only eight other states have a larger percentage of population growth since 2010. The population growth brought an increase in vehicle miles traveled (VMT) and an increase in truck traffic. The combination of increased traffic and aging pavement system accelerated deterioration of the state's pavement system. Deteriorated pavements present a hazard to the traveling public and can present a liability for SCDOT if these roads are not maintained at an acceptable level (SPR, 2016).

The SCDOT, like other state transportation agencies, is faced with making pavement rehabilitation decisions for roadways annually. Rehabilitation is defined as work to improve a pavement's structural and/or functional serviceability characteristics. The current rehabilitation design procedure for non-interstates at SCDOT is focused primarily on efficiency of contract preparation and does not typically include a detailed field investigation. However, the SCDOT recognizes that the design choices may affect the future performance and maintenance cost of a pavement if the existing distresses are not adequately addressed. This research project aimed to assist the SCDOT in understanding the cost-effectiveness of performing field investigation at the design stage of pavement rehabilitation projects.

Field investigation is labor intensive and costly, and it requires traffic control which has safety implications for both the traveling public and SCDOT personnel. On the other hand, the rehabilitation design guided by field investigation results could make the pavement last longer, and therefore, save money for the SCDOT in the long run. To determine whether field investigation is cost-effective, the life-cycle costs and equivalent uniform annual costs of two different designs, one *with* field investigation and one *without* field investigation, were compared. The design *with* field investigation represents the design the SCDOT would use in the future if the SCDOT required field investigation to guide rehabilitation design for *non-interstate* routes. The design *without* field investigation represents the current design being used by SCDOT district engineers.

Two different methods were used to estimate the service life of a pavement given a certain rehabilitation design. The first method is based on the structural number (SN) method which uses coefficient depreciation values based on visual inspection and age of pavement. The accuracy of the SN method, based on the 1972 AASHTO design guidelines, is limited to the material properties and climate conditions for which the empirical relationship was developed (*NCHRP 1-37A).* The second method is based on the Mechanistic-Empirical (M-E) design which considers project-specific material properties, climate conditions, and traffic loadings, as well as pavement distress accumulation and ride quality deterioration. To apply the M-E method, AASHTOWARE Pavement ME Design software (*AASHTOWARE, 2020*) was used.

The service life was determined considering when to perform the pavement maintenance treatment. The terminal present serviceability index (PSI) was used as the criterion for determining when pavement maintenance treatment should be applied. The chosen threshold values for terminal PSI was 3.0, 2.0 and 1.0. If a terminal PSI of 3 is used as the threshold, then the pavements on primary routes would always end up having a PSI of 3.0 or higher. Pavements with PSI ≥ 3.0 are referred to as "good" pavements. Similarly, if a terminal PSI of 2.0 is used as the threshold, then the pavements on primary routes would always end up having a PSI of 2.0 or higher. Pavements with PSI ≥ 2.0 are referred to as "fair" pavements. "Poor" pavements are those with PSI ≥ 1.0.

Figure 1.1 provides an overview of the cost analysis performed. For each of the 31 primary routes, the cost of the design *with* field investigation is compared against the cost of the design *without* field investigation. The cost used for comparison depends on whether the SN method or M-E method was used to determine the service life. With the SN method, the cost used was the life-cycle cost over a 50-year period. The life cycle costs were determined using the FHWA's life-cycle cost analysis (LCCA) software, RealCost version 2.5 (FHWA, 2002). With the M-E method, the cost used was the Equivalent Uniform Annual Cost (EUAC) over a 15-year period. The M-E method was performed for only the fair pavements.

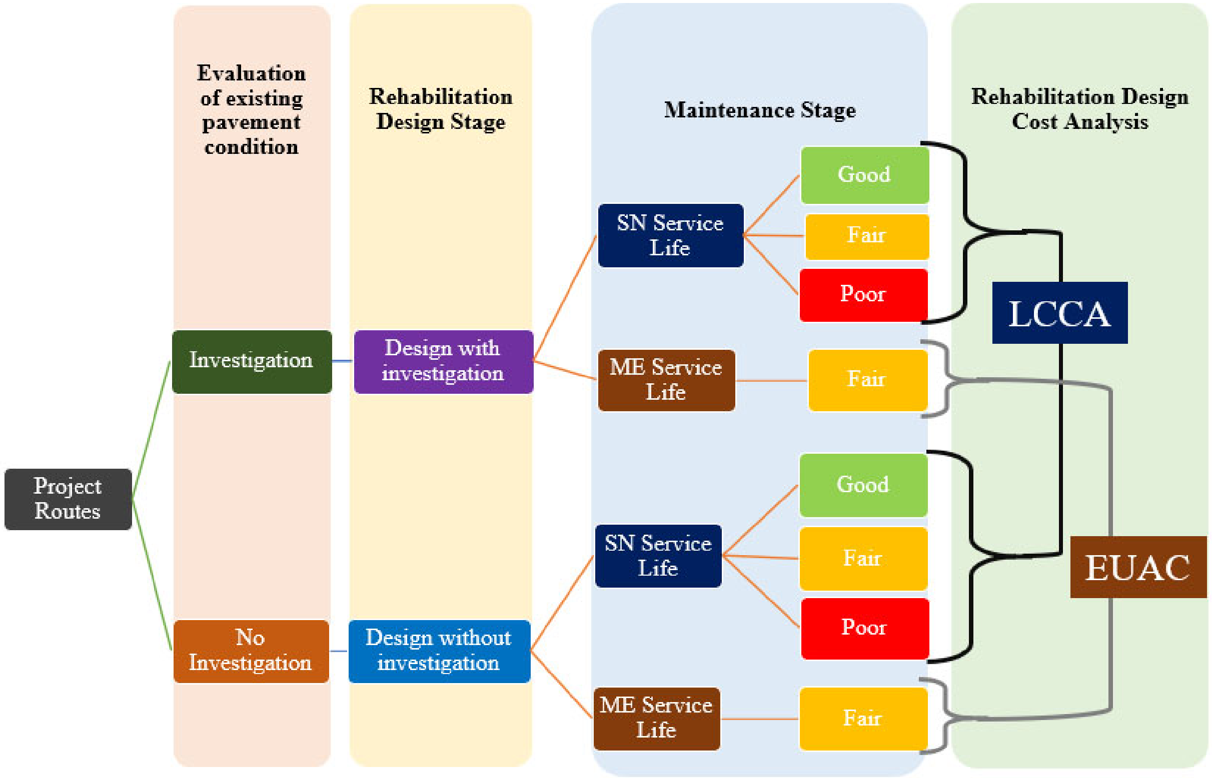


Figure 1.1 Overview of design cost analysis

The next chapter (Chapter 2) presents a literature review of related work and state-of-the-practice on pavement rehabilitation based on survey responses from state DOTs. Chapter 3 first lists the primary routes considered in this study, and then describes the methodology used to perform field investigation, determine the rehabilitation design, *with* and *without* field investigation, evaluate life-cycle and EUAC costs, and conduct hypothesis testing. Chapter 4 presents the findings of the cost analysis. Lastly, Chapter 5 provides a summary of this study's conclusions and a set of recommendations based on this study's findings.

CHAPTER 2: LITERATURE REVIEW

2.1 Pavement Condition Evaluation Techniques

Evaluation of existing pavement condition is essential for appropriate rehabilitation design. Most state transportation agencies use the visual inspection method and its pavement condition rating (PCI). The PCI is a combined score, typically range between 0 and 100, that considers the different pavement distresses (e.g., rutting, longitudinal cracking, roughness, etc.) (Lytton, 1987). The higher the PCI score, the better the condition of the pavement. One major drawback of using the PCI is that it is not always reliable for rehabilitation design decision making. While PCI can be an effective measure for ride quality and surface distresses, it may not be indicative of the pavement structural condition. In their Federal Highway Administration (FHWA) study, Rada et al. (2012) found a lack of correlation between ride quality and structural capacity, indicating that good ride quality does not mean good structural adequacy. That is, when a road surface is rough, the underlying pavement may be weak and when the road surface is smooth the underlying pavement may be strong. However, the inverse can also be true. Therefore, a pavement's surface does not always accurately portray the underlying conditions related to the remaining service life or the potential for future deterioration. Application of non-destructive testing such as falling-weight deflectometer (FWD), ground penetrating radar (GPR), dynamic cone penetrometers (DCP), and a few others is regarded as effective tools to evaluate the structural capacity of the pavement. Some studies have examined the benefits of using non-destructive tests (e.g., FWD, GPR) to perform field investigation (Appea and Al Qadi, 2000; Chen and Scullion, 2007; Mehta and Roque, 2003; Rahim and George, 2003; Noureldin, Zhu, and Harris, 2003; Maser, 1996; Saarenketo, and Scullion, 2000). In these studies, the objective of using non-destructive tests was to 1) characterize layer properties and structural condition, 2) use the test results to select the optimal rehabilitation strategy, or 3) use the test results to evaluate pavement condition at the network level.

2.2 Cost-effectiveness of Rehabilitation Design

Life-cycle cost is an important metric and some state transportation agencies such as Caltrans have modified it to suit their needs (Changmo et al., 2015). It has been used to evaluate economic feasibility of new pavements and cost of different rehabilitation design alternatives (Chan, Keoleian, and Gabler 2008; Guo and Sultan, 2016). Alternative rehabilitation designs were examined to find a cost saving design for low volume roads in Nevada by Maurer, Bemanian, and Polish (2007) and for interstate I-710 in California by Lee, Kim and Harvey (2011). Zaghloul and Kerr (1999) compared the rehabilitation designs using FWD and pavement management system (PMS) data for national highway system (NHS) routes in New Jersey. The authors found that rehabilitation designs that used FWD data resulted in higher cost savings. Zaghloul and Elfino (2000) compared cost of rehabilitation design using FWD data and cost of design using visual inspection for an interstate section (I-85) in Virginia. The life-cycle cost results suggested that rehabilitation designs that used FWD data reduces the agency cost for overdesigned sections. Nobakht et al. (2018) developed a framework to identify cost-effective rehabilitation alternatives for NHS routes in Oklahoma using mechanistic-empirical methodology. In this study, the authors evaluated the life-cycle cost of three rehabilitation design alternatives: light, medium, and heavy. Their analysis indicated that the heavy rehabilitation strategy is cost-effective.

2.3 Use of Mechanistic-Empirical Design Concept in Rehabilitation Design

Mechanistic-Empirical (M-E) design is a relatively new pavement design technique being used in the United States (Li et. al., 2011). This technique was developed for new and rehabilitated pavement structures. A few studies have explored the use of M-E technique for pavement rehabilitation. Mandapaka et. al. (2012) used CalME and life-cycle cost to evaluate and select optimal maintenance and rehabilitation strategy for designed flexible pavement. CalME is AASHTOWare Pavement ME Design that uses Caltrans calibrated parameters. In addition to developing time-based rehabilitation strategies, Nobakht et. al. (2018) used M-E to determine the structural life of different rehabilitation design alternatives for national highways in Oklahoma.

2.4 State-of-the-Practice on Pavement Rehabilitation Method

As part of this study, an online survey was conducted to understand the state-of-practice on pavement rehabilitation for non-interstate routes. The survey was distributed to other state DOTs on September 19, 2017. The survey focused on gathering information about the use of a guide for rehabilitation design, importance of field investigation in rehabilitation design, methods used in field investigation, information obtained from field investigation, and lastly the current and future use of ME for rehabilitation design. A total of 29 responses were received from 21 state DOTs and 8 state agencies.

The following summary will first list the question in *italic* followed by a summary of responses.

1. *Do you have a guide or method for the rehabilitation design of flexible pavements?*

Table 2.1 State DOTs/agencies availability of guide for flexible pavement rehabilitation design

Responses	No. of Responses	Percent of Responses
Yes	20	69%
No	9	31%
Total	**29**	**100%**

As shown in Table 2.1, the majority of the respondents (69%) indicated they have a guide or method for the rehabilitation design of flexible pavements.

2. *How important are field investigations to rehabilitation design on primary routes?*

Table 2.2 Importance of field investigation to rehabilitation design on primary routes

Responses	No. of Responses	Percent of Responses
1	0	0%
2	0	0%
3	1	3.5%
4	7	24.1%
5	21	72.4%
Total	**29**	**100%**

When asked about the importance of field investigation to rehabilitation design on *primary routes* on a scale of 1 to 5 where 5 is very important, Table 2.2 indicates that 72.4% rated it as a 5, 24.1% rated it as 4, and 3.5% rated it as a 3.

3. *How important are field investigations to rehabilitation design on secondary routes?*

Table 2.3 Importance of field investigation design on secondary routes

Responses	No. of Responses	Percent of Responses
1	0	0%
2	0	0%
3	3	10.3%
4	11	38%
5	15	51.7%
Total	**29**	**100%**

As shown in Table 2.3, for *secondary routes*, fewer respondents rated it as a 5; specifically, 51.7% rated it as a 5, 38% rated it as a 4, and 10.3% rated it as a 3.

4. *Is field investigation performed before rehabilitation design?*

Table 2.4 Time of performing field investigation design for rehabilitation design

Responses	No. of Responses	Percent of Responses
Yes	29	100%
No	0	0%
Total	**29**	**100%**

As shown in Table 2.4, all of the respondents (100%) indicated that they perform field investigation before rehabilitation design.

5. *Which of the following are used to gather data during a field investigation?*

Table 2.5 Methods used to perform field investigation

	No. of Responses	Percent of Responses
Mobile Scanning (such as GPR)	16	55.2%
Falling Weight Deflectometer	26	89.7%
Vibratory Deflection Device	1	3.4%
Static Deflection Device	1	3.4%
Dynamic Cone Penetrometer	10	34.5%
Coring	27	93.1%

A number of different methods are used to perform field investigation: mobile scanning such as ground penetrating radar (GPR), falling weight deflectometer (FWD), vibratory deflection device, static deflection device, dynamic cone penetrometer and coring. As shown in Table 2.5, The top three methods are: coring (93.1%), FWD (89.7%), and mobile scanning (55.2%).

6. *If cores are used, which of the following information is obtained from the cores? Check all that apply.*

Table 2.6 Information obtained from coring of pavement

Responses	No. of Responses	Percent of Responses
Pavement Thickness	4	14.8%
Pavement Distress	0	0%
Both Pavement Thickness and Distress	23	85.2%
Total	**27**	**100%**

As shown in Table 2.6, the majority of the respondents (85.2%) indicated that they use cores to measure both pavement thickness and distress.

7. *Are pavement distresses investigated during the rehabilitation design?*

Table 2.7 Investigation of pavement distresses during rehabilitation design

Responses	No. of Responses	Percent of Responses
Yes	27	93.1%
No	2	6.9%
Total	**29**	**100%**

As shown in Table 2.7, the majority of the respondents (93.1%) indicated that they investigate pavement distresses during rehabilitation design.

8. *Are pavement material properties (e.g. CBR, Resilient Modulus) investigated during the rehabilitation design?*

Table 2.8 Investigation of pavement material properties during rehabilitation design

Responses	No. of Responses	Percent of Responses
Yes	21	72.4%
No	8	27.6%
Total	**29**	**100%**

As shown in Table 2.8, approximates three-fourth (72.4%) of the respondents indicated that they investigate pavement material properties during rehabilitation design.

9. *Do you use a separate method or guide for field investigation during the selection of preservation candidates?*

Table 2.9 Guide selection for preservation pavement candidates

Responses	No. of Responses	Percent of Responses
Yes	10	34.5%
No	19	65.5%
Total	**29**	**100%**

As shown in Table 2.9, nearly two-thirds (65.5%) of the respondents do not use a separate method or guide for field investigation during the selection of preservation pavement candidates.

10. Are you using Mechanistic Empirical Pavement Design Guide (MEPDG) for rehabilitation design?

Table 2.10 Use of MEPDG for rehabilitation design

Responses	No. of Responses	Percent of Responses
Yes	10	34.5%
No	19	65.5%
Total	**29**	**100%**

As shown in Table 2.10, nearly two-thirds (65.5%) respondents do not use MEPDG for rehabilitation design.

11. Do you plan on using MEPDG in the future?

Table 2.11 Use of MEPDG for rehabilitation design in the future

Responses	No. of Responses	Percent of Responses
Yes	11	57.9%
No	8	42.1%
Total	**19**	**100%**

As shown in Table 2.11, a little over half (57.9%) of the respondents indicated that they have plan to use MEPDG as a guide in future rehabilitation design.

12. Do you investigate life cycle cost as part of the rehabilitation of flexible pavements?

Table 2.12 Use of life-cycle cost for rehabilitation design of flexible pavement

Responses	No. of Responses	Percent of Responses
Yes	11	37.9%
No	18	62.1%
Total	**29**	**100%**

As shown in Table 2.12, close to two-thirds (62.1%) of the respondents do not investigate life-cycle cost as a part of the rehabilitation of flexible pavements.

CHAPTER 3: METHODOLOGY

3.1 Route Selection and Description

Annually, a number of roadways in South Carolina are selected for rehabilitation. These include interstate and non-interstate routes. The SCDOT currently conducts detailed field investigations on the interstate system. However, this is not typically done on non-interstate roadways. This study is focused on *primary* routes (i.e., roadways with more than 10,000 vehicle/day); the reason for selecting these types of routes is because there must be a minimum volume of truck traffic to exacerbate existing and future pavement distresses relative to a proposed rehabilitation design. Also, it has a higher potential payoff given the emphasis to improve condition of primary routes as stipulated in the SCDOT Transportation Asset Management Plan (SCDOT, 2018). As part of this project, the SCDOT performed field investigations on 31 roadways in South Carolina prior to their rehabilitation. The routes chosen for field investigation were based on average annual daily traffic (AADT), truck traffic, pavement quality index (PQI), international roughness index (IRI), and functional class to provide a representative sample of primary routes in South Carolina. The field investigation performed included a visual assessment of pavement surface condition, taking core samples, and performing FWD testing. The selected routes and their characteristics are provided in Table 3.1. It should be noted that these routes are located in various districts throughout the state. In Table 3.1, AADTT refers to Annual Average Daily Truck Traffic. To simplify the task of dealing with mixed traffic for Equivalent Single Axle Load (ESAL) calculation, the 2008 SCDOT Pavement Design Guide (SCDOT, 2008) identifies a set of Road Groups based on the typical mix of traffic on different types of roads. These Road Groups are shown in Table 3.2.

Table 3.1 Characteristics of primary routes considered in this project

Route ID	Lane-miles	Functional classification	AADT	AADTT	Truck (%)	Road Group
1	3.00	RPA	18,500	2,035	11.0	J
2	0.05	UMC	42,800	7,276	17.0	I
3	0.91	UPA	31,200	5,616	18.0	I
4	0.98	UMC	3,100	1,686	54.4	K
5	0.05	UMA	18,700	1,590	8.5	H
6	7.43	RPA	11,700	702	6.0	J
7	10.43	RPA	14,900	745	5.0	J
8	2.40	RPA	8,600	2,064	24.0	J
9	4.59	RMA	6,700	536	8.0	J
10	7.38	RMA	3,800	304	8.0	J
11	14.20	RMA	6,900	552	8.0	?
12	0.29	RPA	2,200	933	42.4	J
13	0.22	UPA	21,100	3,927	18.6	I
14	0.21	UMA	6,300	504	8.0	H
15	0.62	UMA	3,500	228	6.5	I
16	0.37	UPA	28,700	1,280	4.5	I
17	0.83	RMA	4,500	360	8.0	J

Route ID	Lane-miles	Functional classification	AADT	AADTT	Truck (%)	Road Group
18	0.46	UMA	7,500	638	8.5	H
19	7.24	RPA	12,200	2,440	20.0	J
20	4.27	UPA	36,700	4,771	13.0	I
21	10.21	RMA	8,300	664	8.0	J
22	10.00	RMA	8,900	739	8.3	J
23	20.00	RPA	11,300	1,582	14.0	J
24	2.78	RMA	16,500	1,700	10.3	J
25	1.40	RMA	3,000	618	20.6	J
26	9.87	RMA	7,100	632	8.9	J
27	2.00	RPA	12,300	3,321	27.0	I
28	2.00	RPA	12,300	3,321	27.0	I
29	10.00	RMA	5,100	408	8.0	J
30	9.11	RMA	9,000	720	8.0	J
31	10.00	RPA	3,700	1,369	37.0	J

* RPA = Rural Principal Arterial; UMC = Urban Minor Collector; UPA = Urban Principal Arterial; UMA = Urban Minor Arterial.

Table 3.2 Truck type distribution for various Road Groups (SCDOT, 2008))

Road Group	Distribution of Trucks by type (%)					ESALs per truck (Flexible)	ESALs per truck (Rigid)
	Class 5	Class 6	Class 8	Class 9	All others		
A	94	-	-	-	6	0.1864	0.1821
B	90	5	-	4	1	0.2419	0.2637
C	81	5	5	7	2	0.2841	0.3189
D	73	6	6	10	5	0.3023	0.3533
E	68	6	8	12	6	0.3443	0.4172
F	64	6	7	15	8	0.3774	0.4766
G	59	8	5	19	10	0.4178	0.5345
H	54	6	7	25	9	0.4721	0.6185
I	48	7	5	31	8	0.5269	0.6981
J	44	8	5	36	7	0.5822	0.7929
K	40	7	6	41	7	0.6398	0.8838
L	33	7	6	49	6	0.7052	0.9948
M	27	7	6	55	5	0.7713	1.0971
N	24	3	6	60	7	0.8346	1.2086
O	21	0	6	66	8	0.9027	1.3214
P	12	3	4	72	9	0.9891	1.5227

3.2 Rehabilitation Design without Field Investigation

To determine the rehabilitation design (*without* field investigation) for the 31 routes shown in Table 3.1, the SCDOT district engineers used an in-house program called Pavement Estimator that is based on the 1972 edition of the American Association of State Highway and Transportation

Officials (AASHTO, 1972) guidelines for pavement design. The rehabilitation design used by the district engineers for the 31 primary routes are shown in Table 3.4. It should be noted that these designs were developed without any knowledge of the field investigation results.

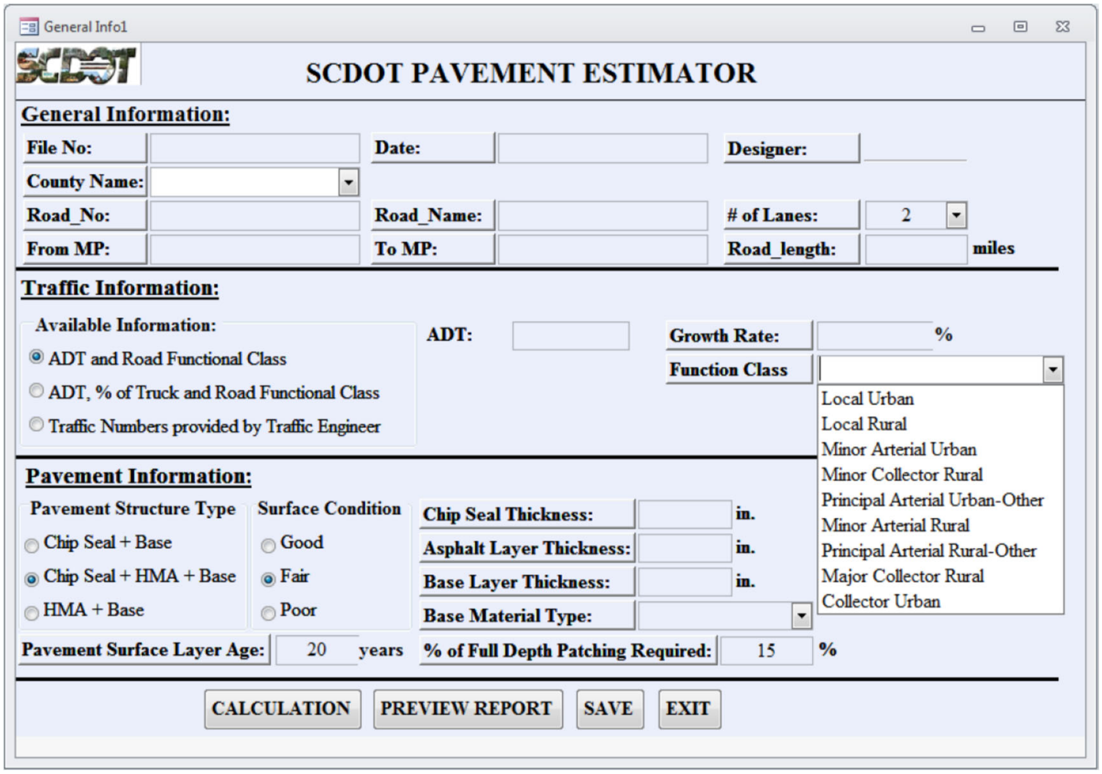
The first section of the Pavement Estimator as shown in Figure 3.1 requires basic information such as county name, road number, road name, number of lanes, from and to mile marker, and road length. When a county name is selected, the program selects a corresponding soil support value (SSV).

The second section requires information about traffic, particularly the average daily traffic (ADT), expressed in vehicles per day. The design engineer has three options to specify traffic data. The first option is the "ADT and Road Functional Class." With this option, the engineer only has to input the ADT, growth rate, and functional class of the roadway. These data are used by the Pavement Estimator to estimate the equivalent number of 18-kip equivalent single axle loads (ESAL). The second option is the "ADT, % of Truck and Road Functional Class." With this option, the engineer has to input the percentage of trucks on the roadway. This information allows the Pavement Estimator to select a more appropriate Road Group as discussed previously. The third option is the "Traffic Numbers provided by Traffic Engineer." With this option, the engineer uses traffic data provided by a traffic engineer. The difference between this option and the second option is that the designer is inputting the ADT for year 5, 10, 15, and 20 instead of a growth rate. Hence, this option can capture the non-linear increase in traffic loads (ESAL) over the pavement design life.

The third section requires information about the pavement condition, specifically the pavement structure type, surface condition, and thickness of various pavement layers, as well as base material type. This information is used to calculate the structural number (SN) of the existing pavement. Other information required in the third section includes pavement surface layer age and the percentage of full-depth patching required. This information is used to determine if full depth reclamation (FDR) should be used to rehabilitate the pavement instead of overlay or mill and fill. Figure 3.2 shows an example report generated by the Pavement Estimator. It can be seen in the "Results" section the estimated 10-year ESALs, existing pavement's SN, and the SN needed to carry the 10-year design traffic. The existing SN is calculated from the user provided input. Specifically, it uses information about the asphalt layer thickness, base layer thickness and base material type. Information about layer thickness and material type were obtained from the SCDOT's archived construction plans. From this information, SN is computed using Equation 1.

$$SN = \sum_{i=1}^{n} a_i \cdot h_i \tag{1}$$

where a_i = coefficient of relative strength for the ith layer and h_i = thickness of the ith layer. The coefficients of relative strength for South Carolina paving materials are provided in the SCDOT's Pavement Design Guidelines (SCDOT, 2008). The difference between the two SN values determines the appropriate overlay thickness. In this example, since the percent of full-depth patching required is 15 percent, the Pavement Estimator strongly recommends Full Depth Reclamation (FDR). *It should be noted that in practice, the district engineer has the discretion to deviate from the Pavement Estimator recommended rehabilitation design.*



SCDOT PAVEMENT ESTIMATOR

General Information:

File No:
Date:
Designer:
County Name:
Road_No:
Road_Name:
# of Lanes: 2
From MP:
To MP:
Road_length: miles

Traffic Information:

Available Information:
● ADT and Road Functional Class
○ ADT, % of Truck and Road Functional Class
○ Traffic Numbers provided by Traffic Engineer

ADT:
Growth Rate: %
Function Class

- Local Urban
- Local Rural
- Minor Arterial Urban
- Minor Collector Rural
- Principal Arterial Urban-Other
- Minor Arterial Rural
- Principal Arterial Rural-Other
- Major Collector Rural
- Collector Urban

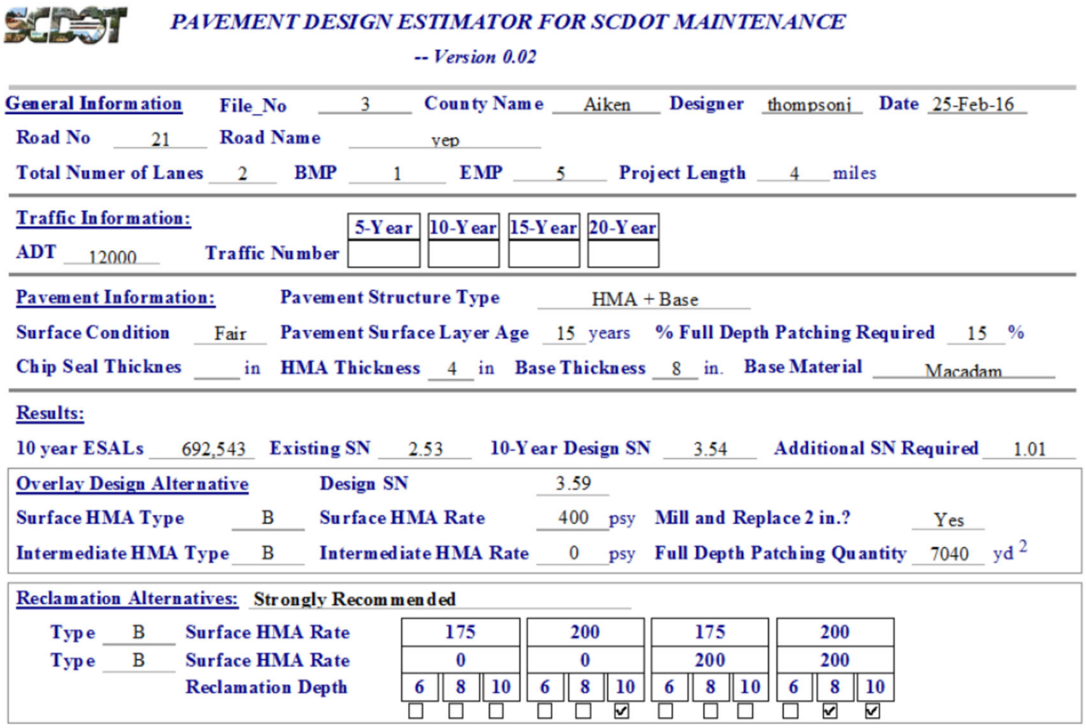
Pavement Information:

Pavement Structure Type
○ Chip Seal + Base
● Chip Seal + HMA + Base
○ HMA + Base

Surface Condition
○ Good
● Fair
○ Poor

Chip Seal Thickness: in.
Asphalt Layer Thickness: in.
Base Layer Thickness: in.
Base Material Type:
Pavement Surface Layer Age: 20 years
% of Full Depth Patching Required: 15 %

Figure 3.1 Input screen of the SCDOT Pavement Estimator



PAVEMENT DESIGN ESTIMATOR FOR SCDOT MAINTENANCE

-- Version 0.02

General Information
File_No 3
County Name Aiken
Designer thompsonj
Date 25-Feb-16
Road No 21
Road Name vep
Total Numer of Lanes 2
BMP 1
EMP 5
Project Length 4 miles

Traffic Information:
ADT 12000
Traffic Number

5-Year	10-Year	15-Year	20-Year

Pavement Information:
Pavement Structure Type HMA + Base
Surface Condition Fair
Pavement Surface Layer Age 15 years
% Full Depth Patching Required 15 %
Chip Seal Thicknes in
HMA Thickness 4 in
Base Thickness 8 in.
Base Material Macadam

Results:
10 year ESALs 692,543
Existing SN 2.53
10-Year Design SN 3.54
Additional SN Required 1.01

Overlay Design Alternative
Design SN 3.59
Surface HMA Type B
Surface HMA Rate 400 psy
Mill and Replace 2 in.? Yes
Intermediate HMA Type B
Intermediate HMA Rate 0 psy
Full Depth Patching Quantity 7040 yd ^{2}

Reclamation Alternatives: Strongly Recommended

Type	B	Surface HMA Rate	175			200			175			200		
Type	B	Surface HMA Rate	0			0			200			200		
		Reclamation Depth	6	8	10	6	8	10	6	8	10	6	8	10
			☐	☐	☐	☐	☐	☑	☐	☐	☐	☐	☑	☑

Figure 3.2 Output screen of the SCDOT Pavement Estimator

3.3 SCDOT Rehabilitation design with field investigation

Developing a rehabilitation design generally requires a detailed investigation to assess the current condition of the existing pavement structure. Table 3.3 shows a list of tests and observations performed by the SCDOT as part of this project.

Table 3.3 Data obtained from field investigation

Activity	Derived Data
Construction History	Base course type and depth
Visual inspection	Distress evaluation, percentage of cracking, rutting, drainage
Cores	Crack depth, crack type (top-down/full-depth), pavement depth
FWD	Existing SN, subgrade modulus

Core samples were taken from the outside lane, right-wheel path representative of the condition of the pavement at each 0.5-mile interval. These samples were then used to identify crack depth, crack type and pavement depth to determine the most appropriate rehabilitation design.

FWD testing was performed using a Dynatest 8000 machine, which consists of 7 sensors located at 7 different offsets from the loading plate: 0.0 in., 7.9 in., 11.8 in., 17.7 in., 23.6 in., 35.4 in., and 47.2 in. The testing was performed by applying a load of 4 different magnitudes (6.1 kip, 14.5 kip, 10.9 kip, and 8.6 kip) and collecting deflection data for those loads as measured by the 7 sensors. Deflection data were then used to back-calculate the layer moduli. This information was then used to determine the existing SN via SCDOT's in-house back-calculation software.

To determine the most appropriate rehabilitation design (using the derived data from field investigation), first, the required SN was obtained using a modified version of the 1972 edition of AASHTO guidelines for pavement design as provided in the 2008 SCDOT Pavement Design Guide. Then, the rehabilitation design was developed to provide sufficient structure (i.e., SN) by adding any required asphalt overlay and remove existing distresses (e.g., reflective and bottom-up cracking). Note that this design will often result in a higher SN than the design *without* field investigation because it calculates the existing SN using FWD data and it develops a design that meets or exceeds the required SN. The design *without* field investigation comes from the Pavement Estimator which relies on the district engineers' input for asphalt layer thickness, base layer thickness and base material type thickness; oftentimes, the district engineers have to make an educated guess about this information. For example, if multiple cores from a section show 4 inches or more of crack depth, milling 2 inches would not fully remove the existing distress. In this case, either full-depth patching or FDR may be recommended depending on the surface cracking percentage. Starting in 1994, the SCDOT recommends FDR if the percentage of full-depth patching exceeds 15%; this particular trigger value should be revisited to determine if additional cost savings could be obtained by lowering it.

Table 3.4 shows the difference between the rehabilitation designs with and without field investigation for 31 primary routes. The existing SN for each route was determined using the deflection data obtained from the FWD test. The soil support values were determined based on project location and were provided by the SCDOT to the research team. The SCDOT has developed a number of different hot mix asphalt types, for surface, intermediate, and base to be used for different conditions; these asphalt types and their recommended use are shown in Table 3.5. As shown in Table 3.5, Surface and Intermediate Type B are used on primary routes and high-volume secondary routes (more than 10,000 veh/day), whereas Surface and Intermediate Type C are used for low-volume primary routes and high-volume secondary routes (less than 5,000 veh/day). The reason is because Type B has greater strength than Type C.

Table 3.4 10-Year rehabilitation designs field investigation vs. 10-Year and 20-Year designs with field investigation

Route ID	**Existing AC (inch)**	**Existing SN**	**SSV**	**Rehabilitation Designs**		
				Design with investigation (10-year Design)	**Design without investigation (10-year Design)**	**Design with investigation (20-year Design)**
1	7.0	3.28	2.9	Mill 2” 8" FDP 15% 200 psy Surf B 200 psy Int B	8" FDP 11% 150 psy Surf C 200 psy Surf C	Mill 2” 8" FDP 15% 350 psy Surf B 200 psy Int B
2	12.3	4.75	3.8	Mill 2" 200 psy Surf B	Mill 2" 200 psy Surf B	Mill 2” 200 psy Surf B
3	8.8	2.93	3.0	8" FDP 15% Mill 2” 200 psy Surf B 400 psy Int B	Mill 2" 200 psy Surf B 200 psy Int B	8" FDP 15% Mill 2” 400 psy Surf B 400 psy Int B
4	5.1	2.16	3.8	12" CMRB 175 psy Surf C	200 psy Surf B 200 psy Int Surf B	12" CMRB 150 psy Surf C 200 psy Int Surf C
5	7.1	2.74	2.5	10" CMRB 175 psy Surf B 200 psy Int B	10" CMRB 175 psy Surf C	12" CMRB 175 psy Surf B 200 psy Int B
6	X	3.72	1.0	8" FDP 10% 200 psy Surf B	Mill 2" 175 psy Surf C 200 psy Int surf C	8" FDP 10% 400 psy Surf B
7	5.3	3.62	1.7	Mill 2" 200 psy Surf B	Mill 2" 600 psy Surf B	Mill 2" 400 psy Surf B
8	9.1	4.71	1.7	Mill 2" 200 psy Sur B	Mill 2" 600 psy Surf B	Mill 2" 300 psy Surf B
9	X	2.73	1.5	12" CMRB 200 psy int Surf B 175 psy Surf B	12" CMRB 200 psy int Surf B	12" CMRB 200 psy int Surf B 200 psy Surf B
10	5.8	2.47	1.8	10" CMRB 200 Int Surf B 175 psy Surf C	Mil 2" 8" FDP 10% 440 psy Surf B	12" CMRB 300 psy Surf C
11	14.0	4.51	1.5	12" CMRB 300 psy Surf B	8" FDP 10% 220 psy Surf B	12" CMRB 200 psy Int B 175 psy Surf B
12	13.1	3.84	1.4	Mill 4" 8" FDP 10% 200 psy Surf C 240 psy Int C	8" FDP 10% 150 psy Surf B 200 psy Int Surf C	Mill 4" 8" FDP 10% 300 psy Surf C 300 psy Int C
13	10.4	3.95	1.2	Mill 2" 8" FDP 10% 350 psy Surf B 200 psy Int B	8" FDP 10% 200 psy Surf B	Mill 2" 8" FDP 10% 300 psy Surf B 400 psy Int B

Route ID	Existing AC (inch)	Existing SN	SSV	Rehabilitation Designs		
				Design with investigation (10-year Design)	Design without investigation (10-year Design)	Design with investigation (20-year Design)
14	9.4	3.21	1.0	12" CMRB 150 psy Surf B 150 psy Surf B	200 psy Surf B	12" CMRB 200 psy Surf B 200 psy Int Surf B
15	5.8	2.12	1.0	12" CMRB 200 psy Surf C	Mill 1.5" 8" FDP 10% 175 psy Surf C	12" CMRB 150 psy Surf C 200 psy Int Surf B
16	13.6	5.4	1.4	Mill 2" 200 psy Surf B	Mill 1.75" 200 psy Surf B	Mill 2" 200 psy Surf B
17	7.9	2.07	1.0	12" CMRB 150 psy Surf C 200 psy Int Surf C	Mill 2 " 12" CMRB 175 psy Surf B 175 psy Surf B	12" CMRB 200 psy Surf C 200 psy Int C
18	11.1	4.57	1.5	Mill 4" 8" FDP 10% 200 psy Surf B 200 psy surf B	Mill 1.75" 200 psy Surf B	Mill 4" 8" FDP 10% 200 psy Surf B 200 psy Int B
19	26.0	8.17	1.8	Mill 2" 6" FDP 10% 200 psy Surf B	200 psy Surf B	Mill 2" 6" FDP 10% 200 psy Surf B
20	4.0	5.63	2.5	Mill 2" 8" FDP 10% 200 psy Surf B	Mill 4" 8" FDP 10% 200 psy Surf B 200 psy Surf B	Mill 2" 10" FDP 10% 200 psy Surf B
21	17.2	7.43	2.0	175 psy Surf B	200 psy Surf B	175 Surf B
22	9.8	2.81	2.0	6" FDP 10% 200 Int Surf B 200 psy Surf B	Microsurfacing	6" FDP 10% 200 psy surf B 300 psy int C
23	7.0	2.86	4.1	Mill 2" 150 psy surf B 150 psy surf B	Mill 1.75" 200 psy Surf B	Mill 2" 400 psy Surf B
24	9.9	4.7	3.0	Do nothing	Mill 2" 200 psy Surf B	Do nothing
25	4.9	2.67	3.0	8" CMRB 175 psy Surf C 200 int Surf C	Microsurfacing	10" CMRB 175 psy Surf C 200 int Surf C
26	7.8	2.98	2.2	10" CMRB 175 Surf B 200 Int Surf B	Mill 1.75" 200 psy Surf B	12" CMRB 175 Surf B 200 Int Surf B
27	19.5	7.4	3.0	12" CMRB 200 psy Int Surf B 175 psy Surf B	Mill 2" 8" FDP 10% 200 psy Surf B	4" mill 200 psy Surf B 200 psy Surf B 12" CMRB
28	10.4	5.63	3.0	4" Mill 200 psy Surf B	Mill 2" 8" FDP 10% 200 psy Surf B	4" mill 200 psy Surf B 200 psy Surf B
29	7.3	3.1	2.0	150 Surf C	6" FDP 10% 200 psy Surf B	300 psy Surf C
30	12.6	5.47	2.2	Do nothing	6" FDP 10% 200 psy Surf B	Do nothing

Route ID	Existing AC (inch)	Existing SN	SSV	Rehabilitation Designs		
				Design with investigation (10-year Design)	**Design without investigation (10-year Design)**	**Design with investigation (20-year Design)**
31	14.8	4.97	3.0	Mill 2" 8" FDP 10% 200 psy Surf B	Mill 2" 8" FDP 10% 200 psy Surf B 200 psy Surf B	Mill 2" 8" FDP 10% 200 psy Surf B

psy: pound per square yard; FDP = Full Depth Patching; CMRB = Cement Modified Recycled Base; AAB = Asphalt Aggregate Base; X: No information available

Table 3.5 SCDOT guidelines for selection of Hot Mix Asphalt type (SCDOT, 2008)

		Type Facility				
		Interstate, Intersections, and Problem Areas	**NHS, Primary, and High Volume Secondary (more than 10,000 vpd)**	**Primary and High Volume Secondary (10,000 vpd or less)**	**Low Volume Primary and High Volume Secondary (5,000 vpd or less)**	**Low Volume Secondary (1500 vpd or less)**
Asphalt Type	Surface	Type A	Type B	Type CM	Type C	Type D
	Intermediate	Type B or Type A (problem areas only)	Type B (min. rate 200 psy)	Type C (minimum rate 200 psy)		
	HMA Base	Type A or C		Type B, C, or D		
	Leveling and Build-up	Surface Types B, CM, C, or E Intermediate Type B HMA Base Type A or C		Surface Types C, D, or E Intermediate Type C HMA Base Type B or D		

3.4 Determination of Service Life using SN method

For the SN method, the service life was calculated using Equation 2 for each design.

$$\text{service life} = \frac{design\ ESALs}{projected\ ESALs} \tag{2}$$

The projected ESALs was calculated using Equation 3 and the design ESALs was calculated using the 1972 AASHTO pavement equation (AASHTO, 1972) as shown in Equation 4:

$$W_{18} = AADT * 365 * TP * RdF * DF * LF * \frac{(1+GF)^{DL} - 1}{GF} \tag{3}$$

Where,

W_{18} = 18-kip equivalent single-axle loads
TP = Percentage of truck
RdF = Road group Factor
DF = Directional Factor
LF = Lane Factor
GF = Growth Factor
DL = Design Life

$$\log_{10} W_{18} = 9.36\log_{10}(SN_B + 1) - 0.20 + \frac{\log_{10}[\frac{4.2 - PSI}{4.2 - 1.5}]}{0.40 + [\frac{1094}{(SN_B + 1)^{5.19}}]} + \log_{10}(\frac{1}{R}) + 0.372(SSV - 3.0) \tag{4}$$

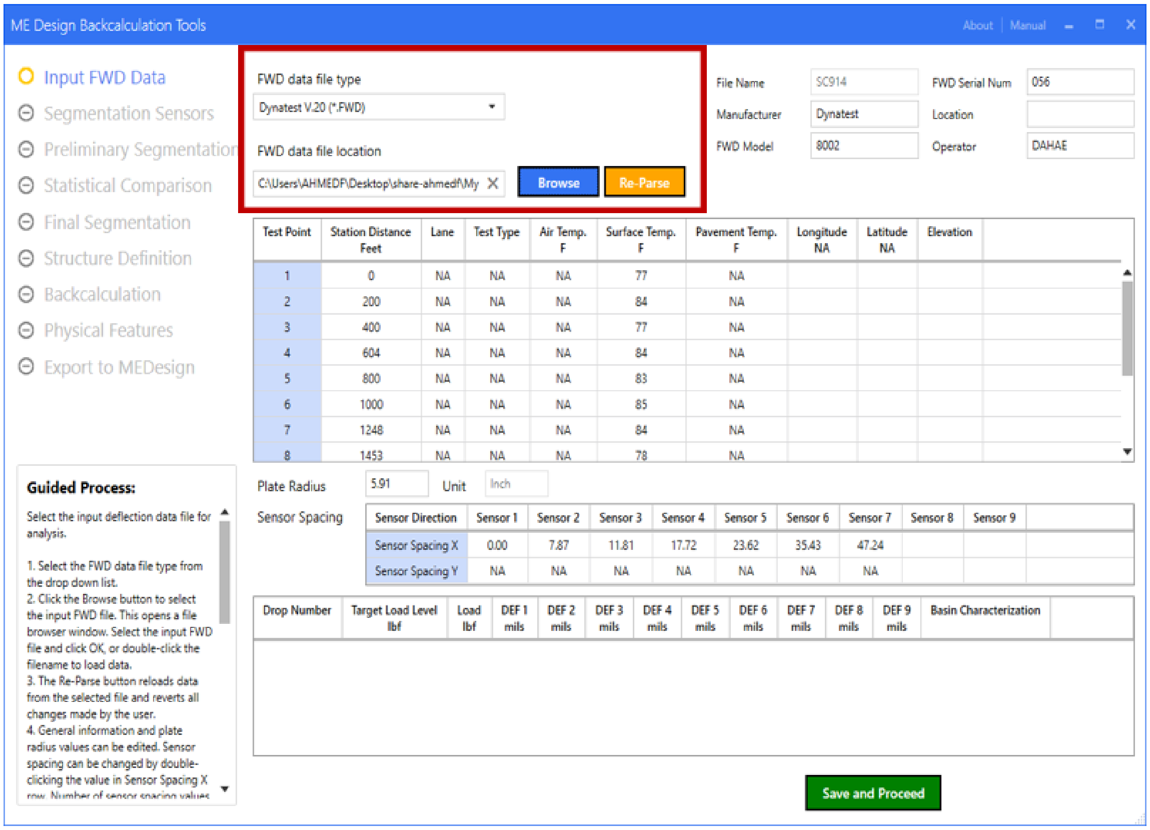
Where,
PSI = Present Serviceability Index (PSI)
R = Regional factor
SSV = Soil Support Value
SN_B = Structural Number of the pavement at the beginning of the service life

The SN of pavement at the end of service life (SN_E) for each design is calculated using the Coefficient Depreciation Method (SCDOT, 2008). As noted in chapter 1, three different pavement types are considered in this project: good, fair, and poor. In the case of good, the pavement was assumed to depreciate to 80 percent of its original structural value (i.e., depreciation coefficient for good pavement is 0.80). For fair and poor pavements, the depreciation coefficients are 0.70 and 0.60, respectively. To determine SN_E for each design, the depreciated SN is subtracted from SN_B. The depreciated SN is calculated from by taking the product of the existing layer thickness, the depreciation coefficient, and the structural coefficient. The structural coefficient for AC surface layer is 0.44 (SCDOT, 2008). To determine SN_B for the next maintenance cycle, the SN corresponding to the maintenance treatment is added to SN_E of the previous maintenance cycle. SN_B is used in Equation 4 to find the service life (via Equation 2) of the maintenance treatment. This procedure is repeated until the cumulative service life of pavement reaches the economic life of 50 years.

3.5 Determination of Service Life using M-E Method

The AASHTOWare Pavement ME software requires the overall condition (i.e., pavement structure definition, layer properties, and rehabilitation strategy) of the existing pavement for evaluation of rehabilitation designs. AASHTOWare Pavement ME Deflection Data Analysis and Backcalculation Tool (referred to as Backcalculation tool hereafter) was used to generate backcalculation inputs to the Pavement ME Design software. The analysis in Backcalculation tool consists of three phases: pre-processing of the FWD deflection data, backcalculation, and post-processing of the results. Screenshots of these processes are shown in Figure 3.6, Figure 3.7, and Figure 3.8, respectively.

In the pre-processing phase, the Backcalculation tool requires an input file for the deflection data. The FWD data obtained from field investigation for each route was used. Using the provided FWD data, the Backcalculation tool generates segments along the route length based on cumulative area difference method as described in the 1993 AASHTO Design Guide. Segmentation is required to address the variability of the deflection values along the length of the pavement. This variability results from differences in the layer structure (change in pavement layer types, materials or properties), layer thickness or subgrade properties. The user manual of the Backcalculation tool provides details regarding the Segmentation Sensor module (AASHTOWare Pavement ME Design, 2017). The user can choose to use the automatically generated segments or define their own segments. In this project, the automatically generated segments were used for all routes.



FWD data file type: Dynatest V.20 (*.FWD)

FWD data file location: C:\Users\AHMEDF\Desktop\share-ahmedf\My

File Name	SC914	FWD Serial Num	056
Manufacturer	Dynatest	Location	
FWD Model	8002	Operator	DAHAE

Test Point	Station Distance Feet	Lane	Test Type	Air Temp. F	Surface Temp. F	Pavement Temp. F	Longitude NA	Latitude NA	Elevation
1	0	NA	NA	NA	77	NA			
2	200	NA	NA	NA	84	NA			
3	400	NA	NA	NA	77	NA			
4	604	NA	NA	NA	84	NA			
5	800	NA	NA	NA	83	NA			
6	1000	NA	NA	NA	85	NA			
7	1248	NA	NA	NA	84	NA			
8	1453	NA	NA	NA	78	NA			

Plate Radius 5.91 Unit Inch

Sensor Spacing

Sensor Direction	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 5	Sensor 6	Sensor 7	Sensor 8	Sensor 9
Sensor Spacing X	0.00	7.87	11.81	17.72	23.62	35.43	47.24		
Sensor Spacing Y	NA	NA	NA	NA	NA	NA	NA		

Drop Number	Target Load Level lbf	Load lbf	DEF 1 mils	DEF 2 mils	DEF 3 mils	DEF 4 mils	DEF 5 mils	DEF 6 mils	DEF 7 mils	DEF 8 mils	DEF 9 mils	Basin Characterization

Guided Process:

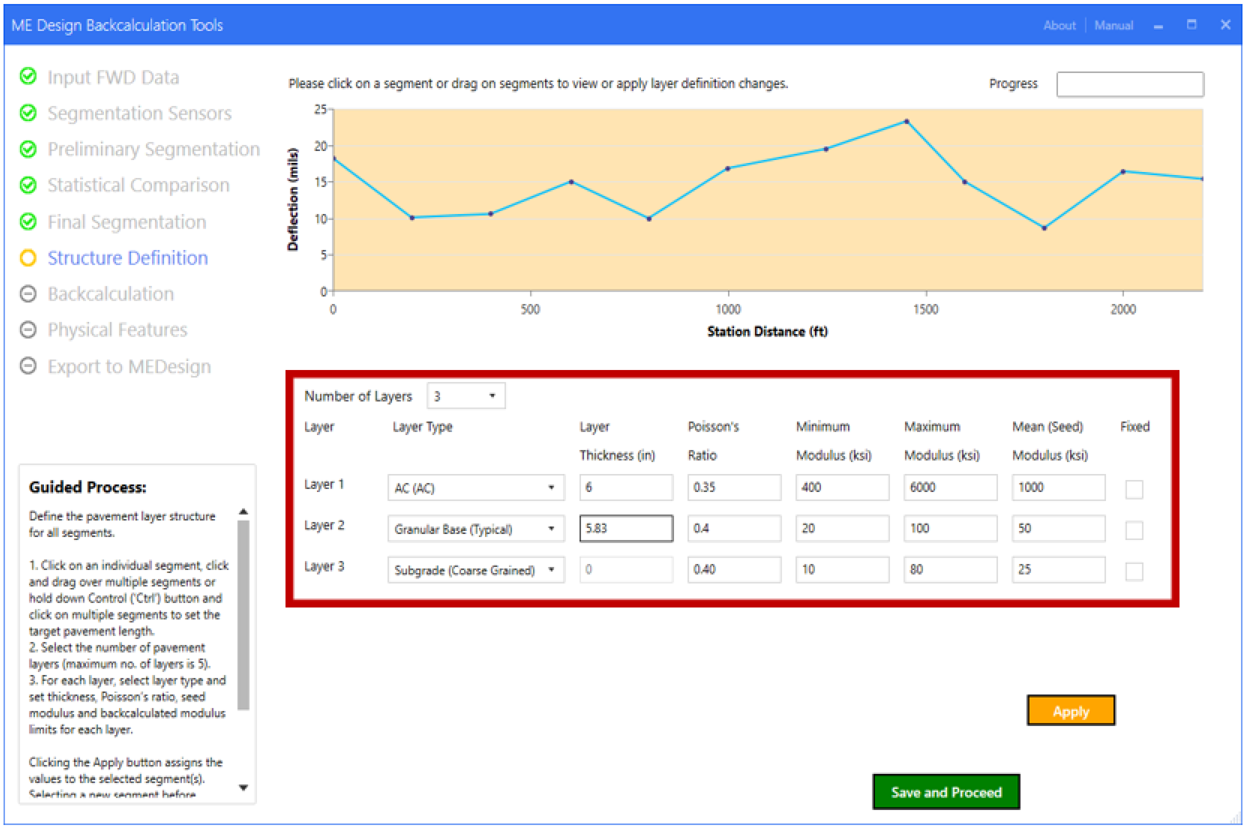
Select the input deflection data file for analysis.

1. Select the FWD data file type from the drop down list.
2. Click the Browse button to select the input FWD file. This opens a file browser window. Select the input FWD file and click OK, or double-click the filename to load data.
3. The Re-Parse button reloads data from the selected file and reverts all changes made by the user.
4. General information and plate radius values can be edited. Sensor spacing can be changed by double-clicking the value in Sensor Spacing X row. Number of sensor spacing values

Figure 3.3 Input screen of pre-processing phase

In the backcalculation phase, the user inputs the properties of pavement layer structure. As shown in Figure 3.7, the Backcalculation tool requires inputs for number of layers, type of layer and layer thickness. This information was obtained from the core samples taken for each route as a part of the field investigation. When the user specifies the layer type, the Backcalculation tool automatically loads the values for Poisson's ratio, seed modulus (i.e., initial guess), minimum modulus, and maximum modulus for backcalculation of average layer modulus of a pavement segment. Figure 3.7 shows an example input for a route with three different pavement layers. The first layer of this pavement is a 6-inch asphalt concrete (AC(AC)). The second layer is a 5.83-inch base (Granular Base (Typical)), and the third layer is a semi-infinite subgrade (Subgrade (Coarse

Grained)). The Backcalculation tool uses these inputs to backcalculate the moduli values for each pavement layer.



Please click on a segment or drag on segments to view or apply layer definition changes.

Guided Process:

Define the pavement layer structure for all segments.

1. Click on an individual segment, click and drag over multiple segments or hold down Control ('Ctrl') button and click on multiple segments to set the target pavement length.
2. Select the number of pavement layers (maximum no. of layers is 5).
3. For each layer, select layer type and set thickness, Poisson's ratio, seed modulus and backcalculated modulus limits for each layer.

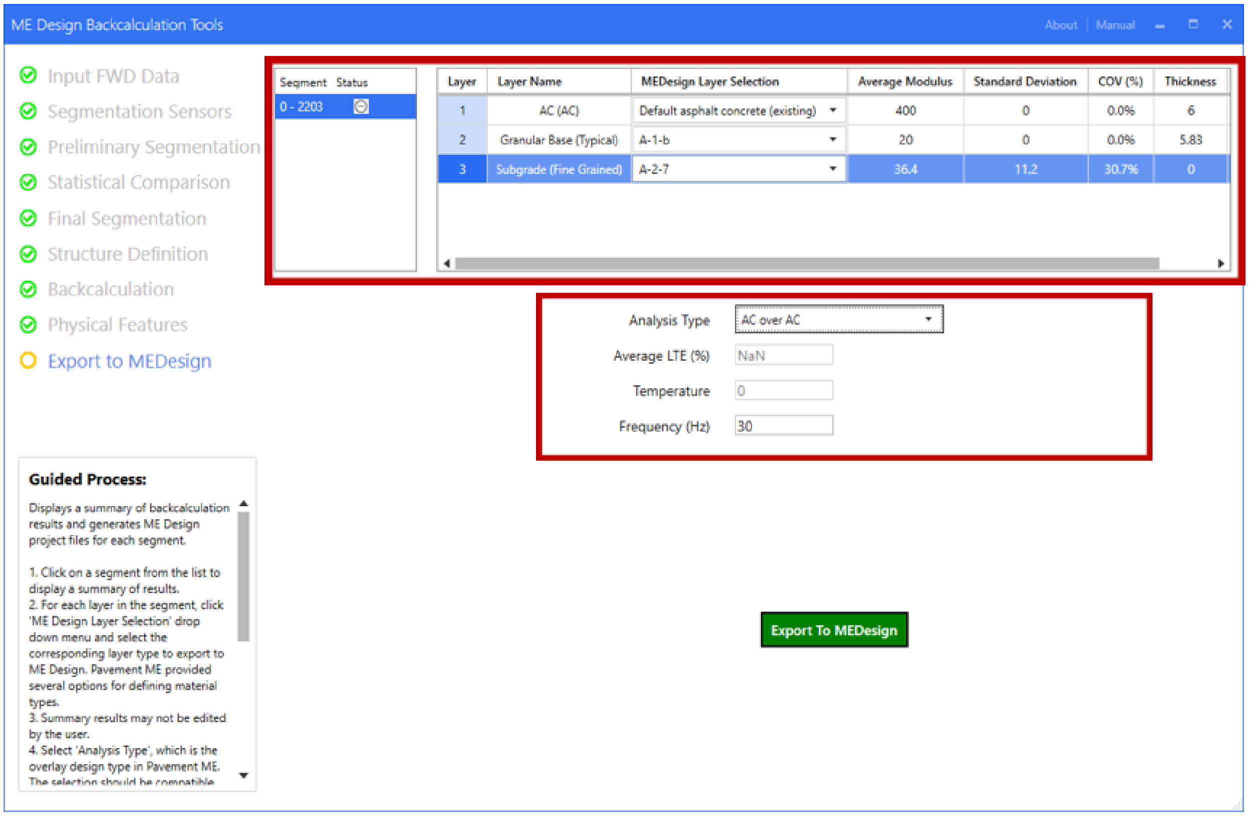
Clicking the Apply button assigns the values to the selected segment(s). Selecting a new segment before

Number of Layers: 3

Layer	Layer Type	Layer Thickness (in)	Poisson's Ratio	Minimum Modulus (ksi)	Maximum Modulus (ksi)	Mean (Seed) Modulus (ksi)	Fixed
Layer 1	AC (AC)	6	0.35	400	6000	1000	☐
Layer 2	Granular Base (Typical)	5.83	0.4	20	100	50	☐
Layer 3	Subgrade (Coarse Grained)	0	0.40	10	80	25	☐

Figure 3.4 Input screen of backcalculation phase

In the post-processing phase, the Backcalculation tool shows the estimated values of layer properties of pavement segments. For the example route discussed earlier, the average modulus for the asphalt, base, and subgrade layers are 400 ksi, 20 ksi, and 36.4 ksi, respectively. In this phase, the Backcalculation tool requires the user to specify the materials for each layer type ("MEDesign Layer Selection") and the type of rehabilitation strategy ("Analysis Type") for the existing flexible pavement. In the example shown in Figure 3.8, the material for AC layer is "Default Asphalt Concrete". Similarly, the material for base and subgrade layer are soil type "A-1-b" and "A-2-7", respectively. For all the routes investigated in this project, the material type for AC layer was selected as "Asphalt Concrete" since they all have flexible pavements. The type of material (i.e., soil type) for base and subgrade to be inputted for each route depends on its location and this information was provided by the SCDOT to the research team. The Backcalculation tool provides several options (e.g., AC over AC, AC over AC with seal coat, AC over Semi-Rigid, etc.) to choose from for the rehabilitation strategy of the existing flexible pavement. As shown in Figure 3.8, the rehabilitation strategy selected for the example route is AC over AC and this rehabilitation strategy was selected for all the routes in fair pavement condition. Lastly, the Backcalculation tool outputs a Pavement ME Design file with pavement layer definition, layer properties, and information regarding rehabilitation strategy.



Segment	Status
0 - 2203	⊖

Layer	Layer Name	MEDesign Layer Selection	Average Modulus	Standard Deviation	COV (%)	Thickness
1	AC (AC)	Default asphalt concrete (existing)	400	0	0.0%	6
2	Granular Base (Typical)	A-1-b	20	0	0.0%	5.83
3	Subgrade (Fine Grained)	A-2-7	36.4	11.2	30.7%	0

Analysis Type: AC over AC
Average LTE (%): NaN
Temperature: 0
Frequency (Hz): 30

Guided Process:

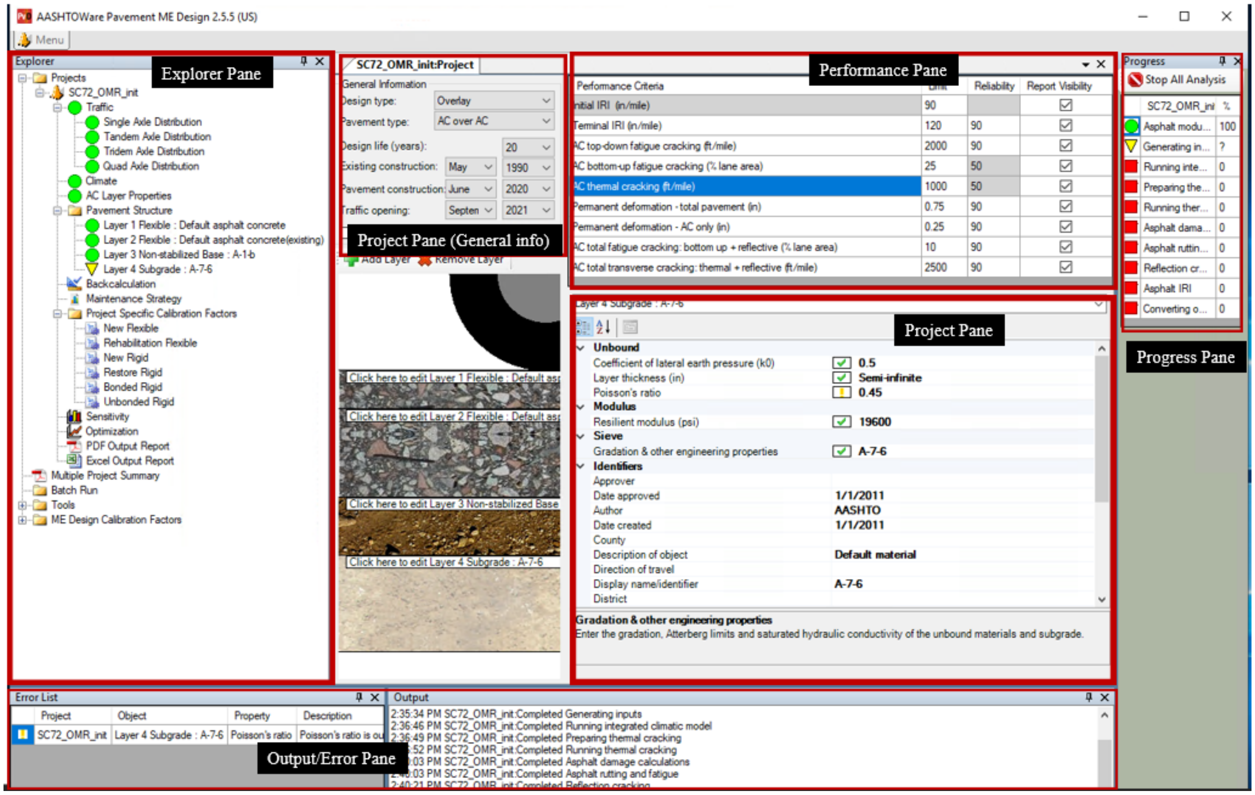
Displays a summary of backcalculation results and generates ME Design project files for each segment.

1. Click on a segment from the list to display a summary of results.
2. For each layer in the segment, click 'ME Design Layer Selection' drop down menu and select the corresponding layer type to export to ME Design. Pavement ME provided several options for defining material types.
3. Summary results may not be edited by the user.
4. Select 'Analysis Type', which is the overlay design type in Pavement ME. The selection should be compatible

Figure 3.5 Output screen of post processing phase

Given the Pavement ME Design file generated by the Backcalculation tool, the AASHTOWare Pavement ME software can then be used to determine the service life of the pavement given a certain rehabilitation design. Figure 3.9 shows a screenshot of pavement ME Design software. Its user interface has five panes: the explorer pane, project tab, project tab: general information, performance criteria, output/error list pane, and progress pane. Users first provide general design information in the general information page under the project tab. Next, users specify the performance target values in the performance criteria pane. Subsequently, users use the explorer pane to provide required input values for traffic, climate, and layer properties.

The explorer pane of Pavement ME Design software is where all the relevant information associated with a route need to be specified, such as traffic, climate, and pavement structure. In addition, explorer pane shows status of user inputs using three different notations. The green circle indicates that all inputs are within the expected range and the design is ready for processing, the yellow inverted triangle indicates the analysis will run, but there may be a warning or value out of the recommended range, and a red square indicates missing information and the analysis will not run.



General Information
Design type: Overlay
Pavement type: AC over AC
Design life (years): 20
Existing construction: May 1990
Pavement construction: June 2020
Traffic opening: Septen 2021

Performance Criteria	Limit	Reliability	Report Visibility
nitial IRI (in/mile)	90		☑
Terminal IRI (in/mile)	120	90	☑
AC top-down fatigue cracking (ft/mile)	2000	90	☑
AC bottom-up fatigue cracking (% lane area)	25	50	☑
AC thermal cracking (ft/mile)	1000	50	☑
Permanent deformation - total pavement (in)	0.75	90	☑
Permanent deformation - AC only (in)	0.25	90	☑
AC total fatigue cracking: bottom up + reflective (% lane area)	10	90	☑
AC total transverse cracking: thermal + reflective (ft/mile)	2500	90	☑

Layer 4 Subgrade : A-7-6

Unbound	
Coefficient of lateral earth pressure (k0)	☑ 0.5
Layer thickness (in)	☑ Semi-infinite
Poisson's ratio	0.45
Modulus	
Resilient modulus (psi)	☑ 19600
Sieve	
Gradation & other engineering properties	☑ A-7-6
Identifiers	
Approver	
Date approved	1/1/2011
Author	AASHTO
Date created	1/1/2011
County	
Description of object	Default material
Direction of travel	
Display name/identifier	A-7-6
District	

Gradation & other engineering properties
Enter the gradation, Atterberg limits and saturated hydraulic conductivity of the unbound materials and subgrade.

	SC72_OMR_ini	%
🟢	Asphalt modu...	100
▽	Generating in...	?
🟥	Running inte...	0
🟥	Preparing the...	0
🟥	Running ther...	0
🟥	Asphalt dama...	0
🟥	Asphalt ruttin...	0
🟥	Reflection cr...	0
🟥	Asphalt IRI	0
🟥	Converting o...	0

Error List

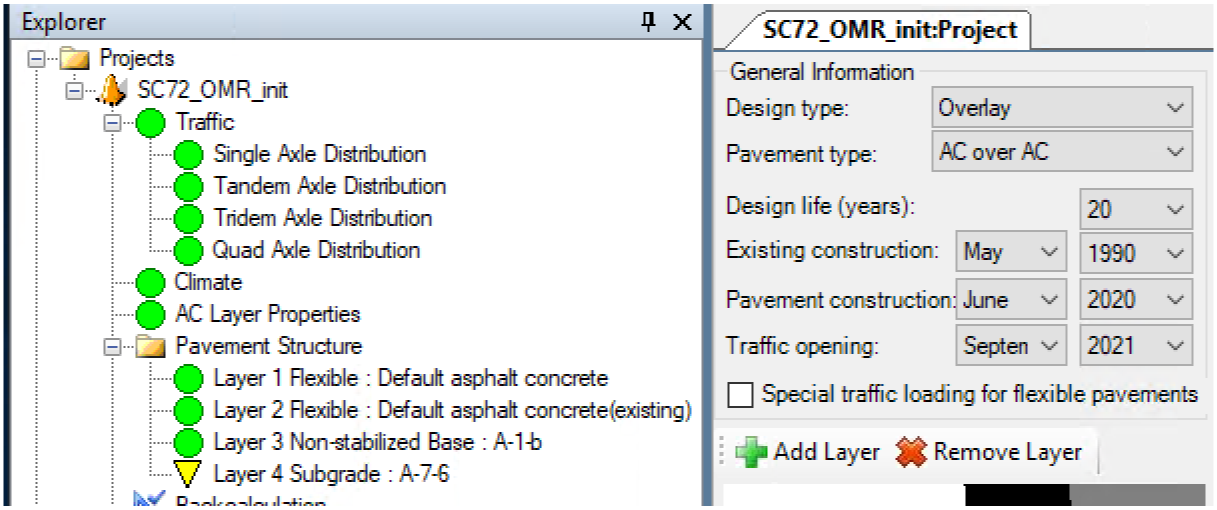
	Project	Object	Property	Description
!	SC72_OMR_init	Layer 4 Subgrade : A-7-6	Poisson's ratio	Poisson's ratio is ou

Output

```
2:35:34 PM SC72_OMR_init:Completed Generating inputs
2:36:46 PM SC72_OMR_init:Completed Running integrated climatic model
2:36:49 PM SC72_OMR_init:Completed Preparing thermal cracking
52 PM SC72_OMR_init:Completed Running thermal cracking
:03 PM SC72_OMR_init:Completed Asphalt damage calculations
:03 PM SC72_OMR_init:Completed Asphalt rutting and fatigue
2:40:21 PM SC72_OMR_init:Completed Reflection cracking
```

Figure 3.6 User interface of Pavement ME Design software

In the general information page under the project tab, as shown in Figure 3.10, values for general information of each route such as design type, pavement type, and design life are specified. For all the routes, the design type, and pavement type were selected as "Overlay", and "AC over AC", respectively. Note that this information is loaded as rehabilitation strategy from the ME design output file from Backcalculation tool. In this project, a 20-year design life was used. This page also requires the timeline for base construction and pavement construction. It was assumed that rehabilitation is performed in current year of analysis (i.e., year 2020) and the base construction is 30-years old (i.e., year 1990). As shown in Figure 3.10, the default values for month were used for both pavement and base construction timeline.



- Projects
  - SC72_OMR_init
    - Traffic
      - Single Axle Distribution
      - Tandem Axle Distribution
      - Tridem Axle Distribution
      - Quad Axle Distribution
    - Climate
    - AC Layer Properties
    - Pavement Structure
      - Layer 1 Flexible : Default asphalt concrete
      - Layer 2 Flexible : Default asphalt concrete(existing)
      - Layer 3 Non-stabilized Base : A-1-b
      - Layer 4 Subgrade : A-7-6

SC72_OMR_init:Project

General Information

Design type: Overlay

Pavement type: AC over AC

Design life (years): 20

Existing construction: May 1990

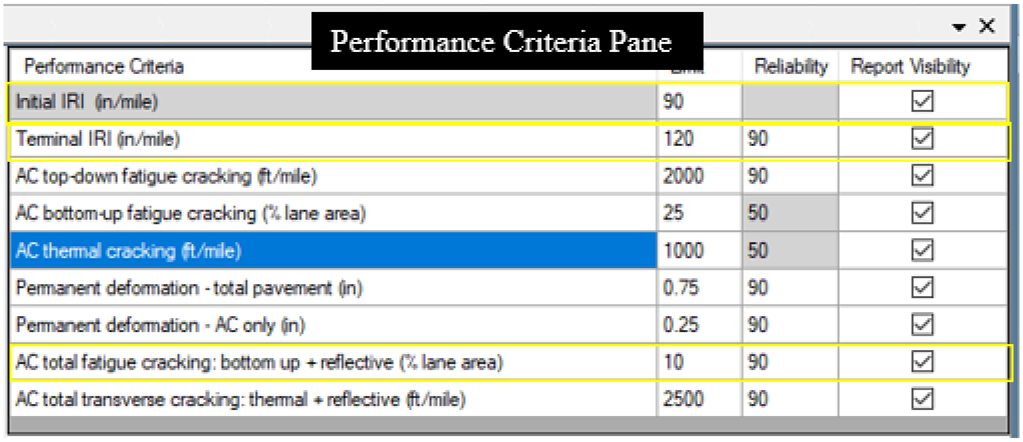
Pavement construction: June 2020

Traffic opening: Septen 2021

☐ Special traffic loading for flexible pavements

Figure 3.7 User interface of project general information tab

In the Performance Criteria pane, as shown in Figure 3.11, users can set threshold values for pavement smoothness and predicted distresses. In this project, terminal International Roughness Index (IRI) and AC total fatigue cracking (i.e., AC bottom up and reflecting cracking) were used as performance criteria to determine the service life of pavements. The IRI represents the rideability condition whereas the fatigue cracking represents the distress condition in the pavements. The service life of the pavement was determined when one of the threshold values for the performance criteria is reached. For fair pavements, the chosen threshold values for terminal IRI was 120 inch per mile and AC total fatigue cracking was 10%. Both of these performance criteria were evaluated with 50% reliability. The initial IRI value was assumed to be 90 inch per mile for all the routes. It should be noted that FHWA's MAP 21 defines a pavement as good if IRI < 95 inch per mile and fatigue cracking < 5% and as poor if IRI > 170 inch per mile and fatigue cracking > 20% (*FHWA MAP-21*).

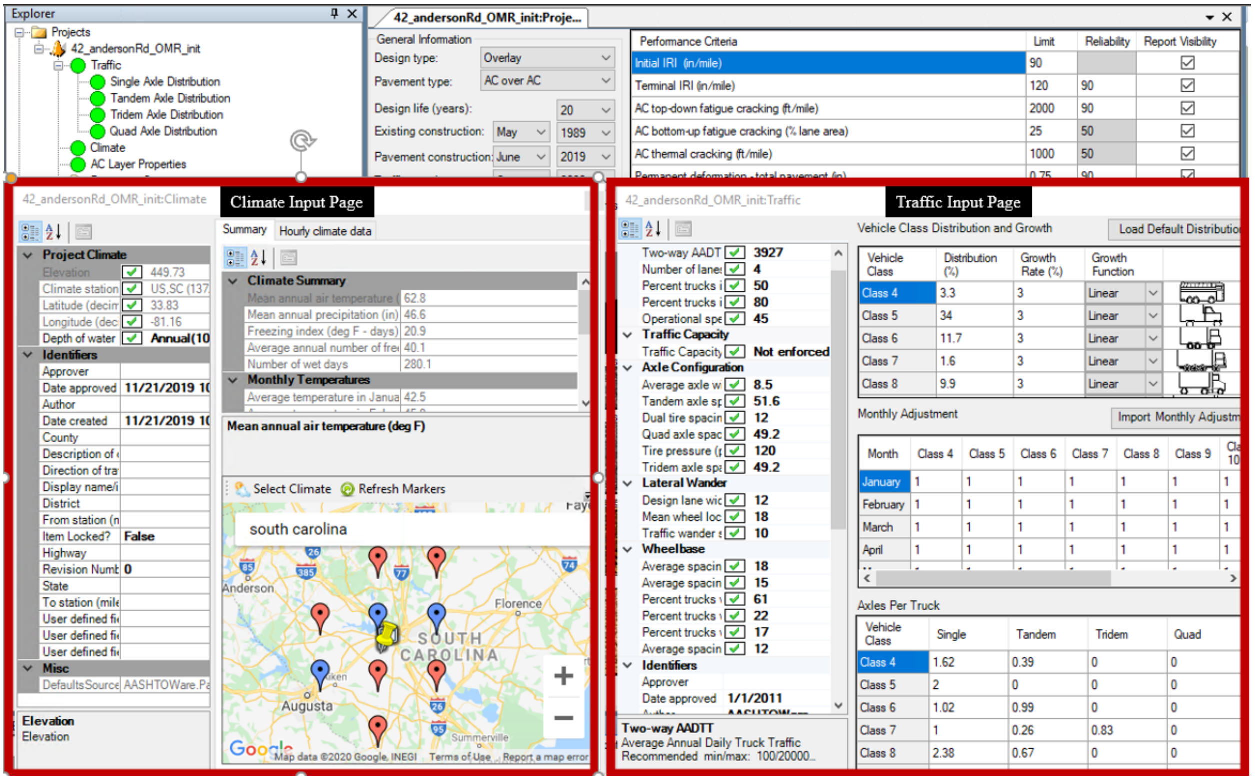


Performance Criteria		Reliability	Report Visibility
Initial IRI (in/mile)	90		☑
Terminal IRI (in/mile)	120	90	☑
AC top-down fatigue cracking (ft/mile)	2000	90	☑
AC bottom-up fatigue cracking (% lane area)	25	50	☑
AC thermal cracking (ft/mile)	1000	50	☑
Permanent deformation - total pavement (in)	0.75	90	☑
Permanent deformation - AC only (in)	0.25	90	☑
AC total fatigue cracking: bottom up + reflective (% lane area)	10	90	☑
AC total transverse cracking: thermal + reflective (ft/mile)	2500	90	☑

Figure 3.8 User interface of project performance criteria pane

As shown in Figure 3.12, the traffic input page is selected from the explorer pane to provide traffic information in the Pavement ME Design software. Required information are two-way Average Annual Daily Truck Traffic (AADTT), number of lanes, percentage of trucks in design direction (i.e., Directional Distribution Factor), percentage of trucks in design lane (i.e., Lane Distribution

Factor), and operational speed. The values for AADTT were presented in Table 3.1. For primary routes, it was assumed that 50% of the trucks are in the design direction. The percentage of trucks in design lane is dependent on the number of lanes on the route. For 2, 3, and 4 or more lanes in each direction, the percentage of trucks in the design lane is 80%, 65%, and 60%, respectively (SCDOT, 2008). It was assumed that the operational speed for all the routes is 45 miles per hour. This constant value for operational speed was used to avoid influence of speed in the determination of service life. Default values were used for all other inputs in the Traffic Input page.



General Information
Design type: Overlay
Pavement type: AC over AC
Design life (years): 20
Existing construction: May 1989
Pavement construction: June 2019

Performance Criteria	Limit	Reliability	Report Visibility
Initial IRI (in/mile)	90		☑
Terminal IRI (in/mile)	120	90	☑
AC top-down fatigue cracking (ft/mile)	2000	90	☑
AC bottom-up fatigue cracking (% lane area)	25	50	☑
AC thermal cracking (ft/mile)	1000	50	☑
Permanent deformation - total pavement (in)	0.75	90	☑

Project Climate
Elevation ☑ 449.73
Climate station ☑ US,SC (137
Latitude (decim ☑ 33.83
Longitude (dec ☑ -81.16
Depth of water ☑ **Annual(10**

Identifiers
Approver
Date approved **11/21/2019 10**
Author
Date created **11/21/2019 10**
County
Description of
Direction of tra
Display name/i
District
From station (n
Item Locked? **False**
Highway
Revision Numb **0**
State
To station (mile
User defined fi
User defined fi
User defined fi

Misc
DefaultsSource AASHTOWare.Pa

Elevation
Elevation

Climate Summary
Mean annual air temperature (62.8
Mean annual precipitation (in) 46.6
Freezing index (deg F - days) 20.9
Average annual number of fre 40.1
Number of wet days 280.1

Monthly Temperatures
Average temperature in Janua 42.5

Mean annual air temperature (deg F)

south carolina

Two-way AADT ☑ **3927**
Number of lane: ☑ **4**
Percent trucks i ☑ **50**
Percent trucks i ☑ **80**
Operational spe ☑ **45**

Traffic Capacity
Traffic Capacity ☑ **Not enforced**

Axle Configuration
Average axle w ☑ **8.5**
Tandem axle sp ☑ **51.6**
Dual tire spacin ☑ **12**
Quad axle spac ☑ **49.2**
Tire pressure (p ☑ **120**
Tridem axle spa ☑ **49.2**

Lateral Wander
Design lane wic ☑ **12**
Mean wheel loc ☑ **18**
Traffic wander ☑ **10**

Wheelbase
Average spacin ☑ **18**
Average spacin ☑ **15**
Percent trucks ☑ **61**
Percent trucks ☑ **22**
Percent trucks ☑ **17**
Average spacin ☑ **12**

Identifiers
Approver
Date approved **1/1/2011**

Two-way AADTT
Average Annual Daily Truck Traffic
Recommended min/max: 100/20000...

Vehicle Class Distribution and Growth

Vehicle Class	Distribution (%)	Growth Rate (%)	Growth Function
Class 4	3.3	3	Linear
Class 5	34	3	Linear
Class 6	11.7	3	Linear
Class 7	1.6	3	Linear
Class 8	9.9	3	Linear

Monthly Adjustment

Month	Class 4	Class 5	Class 6	Class 7	Class 8	Class 9	Cla 10
January	1	1	1	1	1	1	1
February	1	1	1	1	1	1	1
March	1	1	1	1	1	1	1
April	1	1	1	1	1	1	1

Axles Per Truck

Vehicle Class	Single	Tandem	Tridem	Quad
Class 4	1.62	0.39	0	0
Class 5	2	0	0	0
Class 6	1.02	0.99	0	0
Class 7	1	0.26	0.83	0
Class 8	2.38	0.67	0	0

Figure 3.9 User interface of traffic and climate data input page

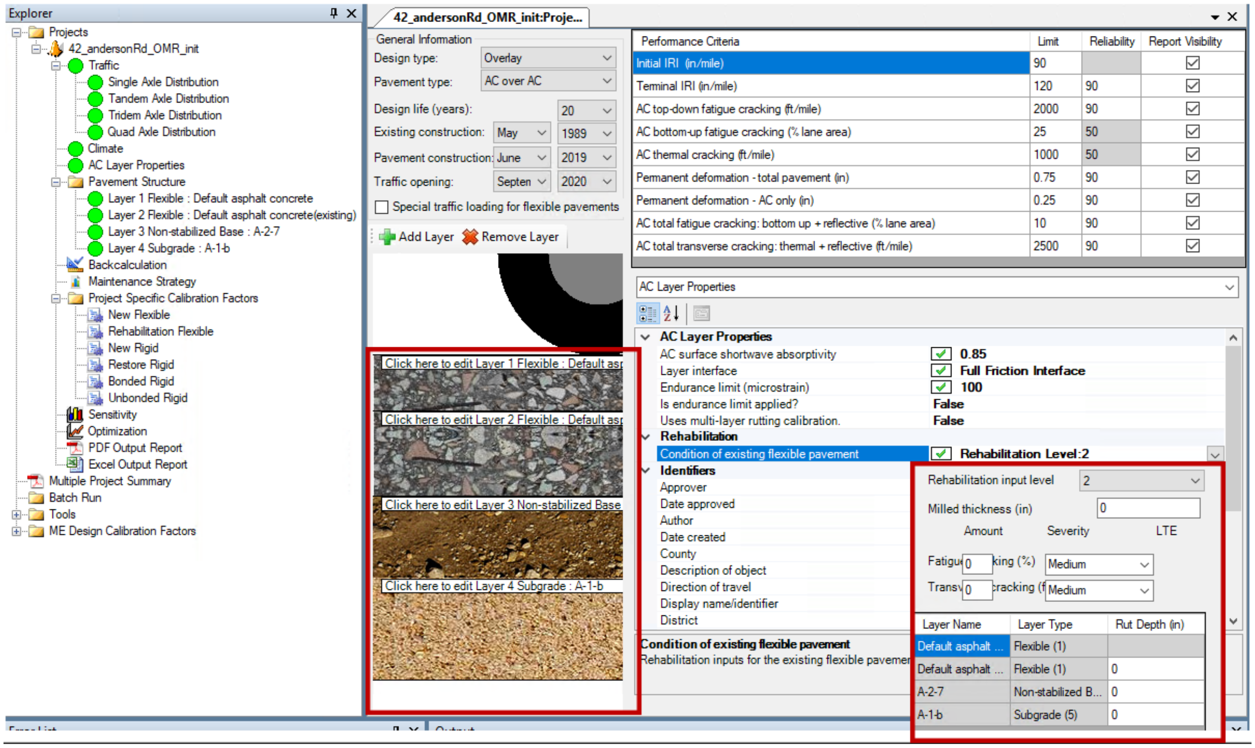
From the explorer pane, as shown in Figure 3.12, users are able to select the Climate page to provide the climate information in the proximity of the route. Pavement ME Design requires inputs on hourly temperature, precipitation, wind speed, relative humidity, and percentage of sunshine/cloud coverage data. All of this information is contained in the climate files which were downloaded from LTTP InfoPave (https://infopave.fhwa.dot.gov/) and loaded into the Pavement ME. There are nine climate stations in South Carolina. For each route, the closest climate station was selected as the input station for analysis.

As shown in Figure 3.13, users are able to select the AC Layer Properties page from the explorer pane. This page shows M-E rehabilitation analysis input levels and its properties. In this project, input level 2 was used for designs *with* and *without* field investigation. With input level 2, the Pavement ME Design uses estimated regional values for the analysis. The following assumptions on the percentage of fatigue cracking (i.e., percentage of fatigue cracking reflected in the surface after rehabilitation) and transverse cracking were used for analysis:

- For rehabilitation designs *with* field investigation, fatigue cracking is zero percent (0%) and transverse cracking is zero (0) inch per mile. These values imply that rehabilitation design with investigation addresses all the fatigue cracking in the pavement layers.
- For rehabilitation designs *without* field investigation
    - Fatigue cracking is zero (0%) if designs include the same amount of milling as designs with investigation. This value implies that the rehabilitation design addresses all the existing fatigue cracking.
    - Fatigue cracking is 20% if designs did not include any milling of existing surface layer. This value implies that rehabilitation design did not address the existing fatigue cracking at all.
    - Fatigue cracking is 10% if designs include half the amount of milling of existing layer compared to designs with investigation. This value implies that rehabilitation designs partially addressed the existing fatigue cracking.
    - Transverse cracking is zero (0 ft/mi) if designs include any amount of milling of the existing surface layer.
    - Transverse cracking is 100 ft/mi if designs did not include milling of existing layer.
- If the rehabilitation design *with* investigation used CMRB, then:
    - Fatigue cracking is 0% for the design *with* investigation
    - Fatigue cracking is 35% for the design *without* field investigation if it did not require milling
    - Fatigue cracking is 20% for the design *without* field investigation if it required milling.
- The severity level of both fatigue cracking and transverse cracking were set to "Medium".
- After the end of service life of the rehabilitated pavement, the percentage of fatigue cracking present in the pavement was carried over to the next maintenance cycle for both rehabilitation designs, *with* and *without* field investigation.

The aforementioned assumptions are drawn from observations of the cracking in the cores, the visual inspection of pavement surface condition, and engineering judgment from field investigation. In future research, route specific measurements of fatigue cracking and transverse cracking can be applied to obtain more accurate results.

On the Pavement Structure page in the explorer pane, as shown in Figure 3.13, all of the required inputs are prefilled from the ME Design output file except for Asphalt Binder. The SuperPave: 64-22 was selected as the asphalt binder for all Asphalt Concrete layers (i.e., existing surface and overlay layer).



General Information
Design type: Overlay
Pavement type: AC over AC
Design life (years): 20
Existing construction: May 1989
Pavement construction: June 2019
Traffic opening: Septen 2020
☐ Special traffic loading for flexible pavements

Performance Criteria	Limit	Reliability	Report Visibility
Initial IRI (in/mile)	90		☑
Terminal IRI (in/mile)	120	90	☑
AC top-down fatigue cracking (ft/mile)	2000	90	☑
AC bottom-up fatigue cracking (% lane area)	25	50	☑
AC thermal cracking (ft/mile)	1000	50	☑
Permanent deformation - total pavement (in)	0.75	90	☑
Permanent deformation - AC only (in)	0.25	90	☑
AC total fatigue cracking: bottom up + reflective (% lane area)	10	90	☑
AC total transverse cracking: thermal + reflective (ft/mile)	2500	90	☑

AC Layer Properties

AC Layer Properties
AC surface shortwave absorptivity ☑ **0.85**
Layer interface ☑ **Full Friction Interface**
Endurance limit (microstrain) ☑ **100**
Is endurance limit applied? **False**
Uses multi-layer rutting calibration. **False**

Rehabilitation
Condition of existing flexible pavement ☑ **Rehabilitation Level:2**

Identifiers
Approver
Date approved
Author
Date created
County
Description of object
Direction of travel
Display name/identifier
District

Condition of existing flexible pavement
Rehabilitation inputs for the existing flexible paveme

Rehabilitation input level 2
Milled thickness (in) 0
Amount Severity LTE
Fatigu 0 king (%) Medium
Transv 0 racking (f Medium

Layer Name	Layer Type	Rut Depth (in)
Default asphalt ...	Flexible (1)	
Default asphalt ...	Flexible (1)	0
A-2-7	Non-stabilized B...	0
A-1-b	Subgrade (5)	0

Figure 3.10 User interface of AC Layer properties input page

To find the service life of the pavement, the rehabilitation pavement ME Design file for the route was saved and run. The Pavement ME Design software tracks the progress of analysis and displays it in the Progress Pane as shown in Figure 3.9. After the analysis is complete, it generates an output of the results in PDF and spreadsheet format. The output shows the predicted pavement condition relative to performance targets. Figures 3.15 shows an example output for IRI. In this figure, the black dotted line represents the predicted IRI value of the pavement over time and the solid red line denotes the performance target value. The point when black line intersects with the red line represents the service life of the pavement. In this example, the IRI service life is 14 years. Similarly, fatigue cracking was examined to determine the service life of the pavement as shown in Figure 3.16. In this example, the fatigue cracking remained well below the performance target. The service life of the pavement using the ME method was determined using the time when the IRI and fatigue cracking reached their performance targets and selecting the lower value between the two. In this example, the service life of the pavement is 14 years.

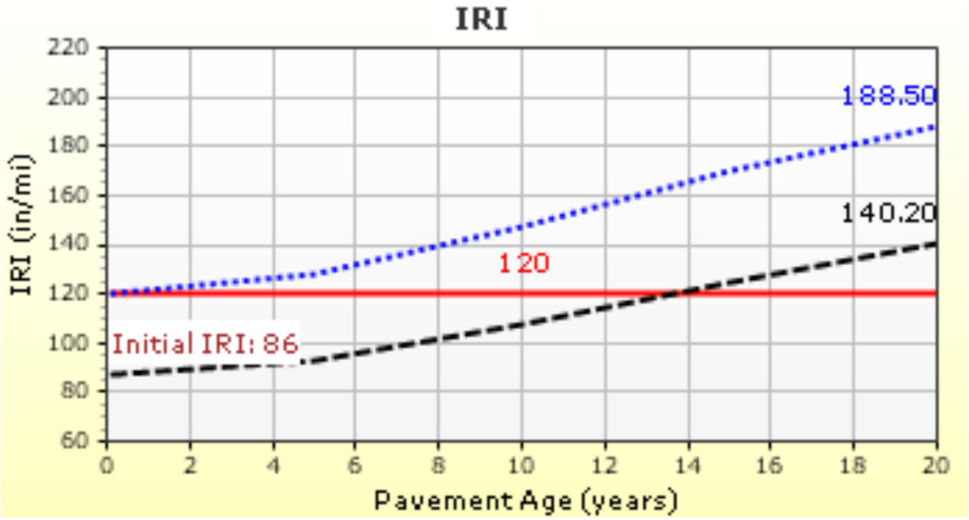


Figure 3.11 IRI performance from Pavement ME distress output

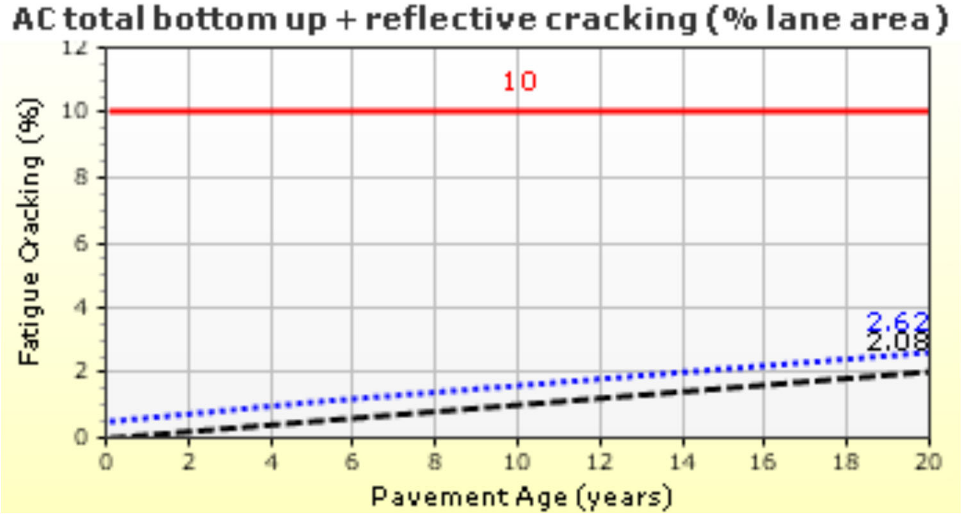


Figure 3.12 AC bottom up and reflective cracking performance curve from Pavement ME distress output

3.6 Life-Cycle Cost Analysis

The FHWA's life-cycle cost analysis tool, RealCost version 2.5, was used to compare the deterministic life-cycle cost of rehabilitation designs *with* and *without* field investigation. RealCost is an engineering economic analysis tool designed for comparing life-cycle costs of design alternatives. The comparison is based on the net present value concept. As shown in Figure 3.3, RealCost provides a graphical user interface to facilitate the data entry. Details about RealCost can be found in the user manual (FHWA, 2002). The following provides and explains some of the key input parameters used in this project.

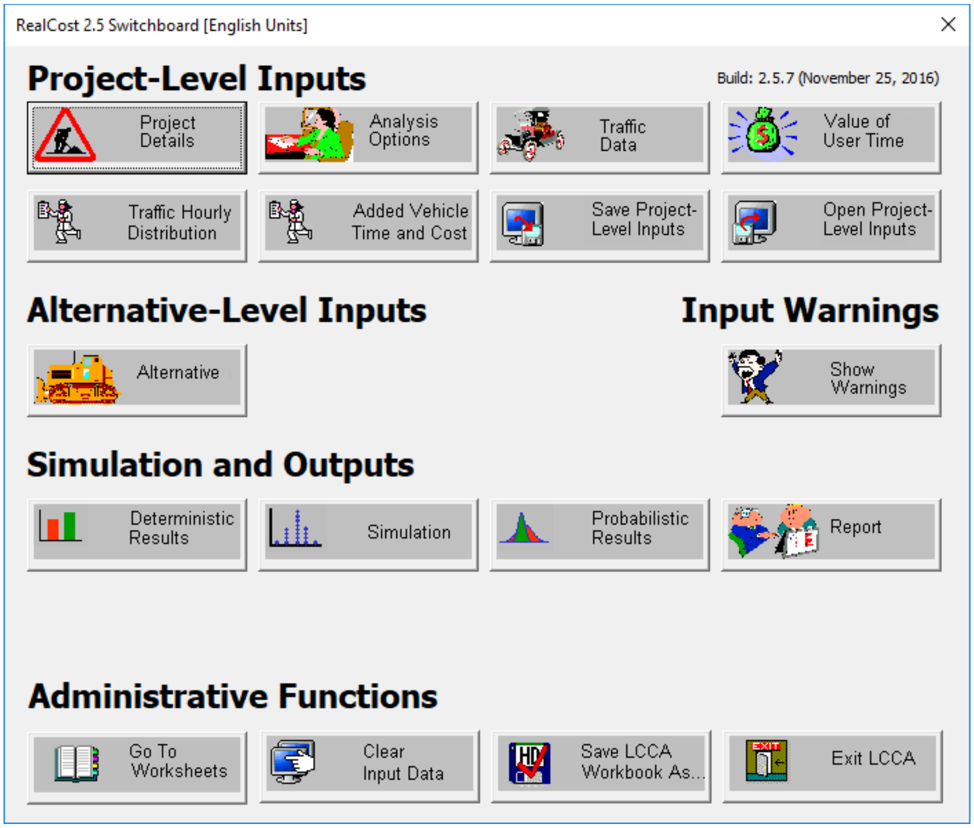
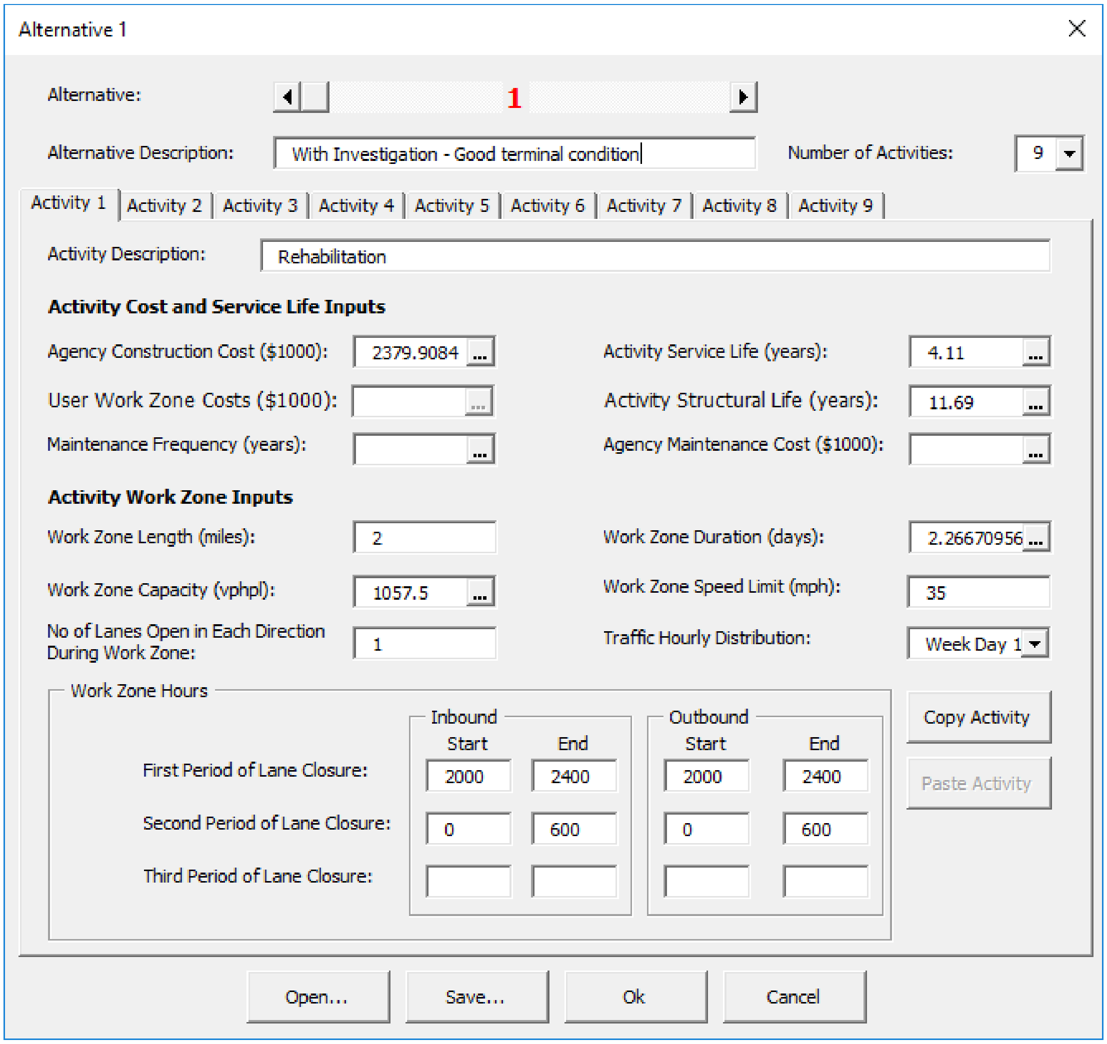


Figure 3.13 Main input screen of RealCost

In Project Details, the user specifies information about the project; these data are not used in the analysis. In Analysis Options, the user specifies the agency's policy regarding analysis period, discount rate, beginning year, inclusion of residual service life, and the treatment of user costs in the LCCA. In this project, an analysis period of 50 years was chosen, and the discount rate was assumed to be 1.6%. In Traffic Data, the user specifies the traffic data such as AADT, percent of single-unit trucks, annual growth rate, and speed limit. In Traffic Hourly Distribution, the default values are used to convert AADT to an hourly distribution. User cost was not considered in this study; thus, default input values were used in for both Value of User Time and Added Vehicle Time and Cost.

Once all of the project-level inputs are provided, the user then inputs information about each alternative design. Figure 3.4 shows the types of information required for each maintenance activity associated with a design. In the example shown, the "With Investigation" design has 9 activities. Activity 1 corresponds to the rehabilitation and activities 2 to 9 correspond to the subsequent maintenance treatments.



Alternative: 1

Alternative Description: With Investigation - Good terminal condition

Number of Activities: 9

Activity Description: Rehabilitation

Activity Cost and Service Life Inputs

Agency Construction Cost ($1000): 2379.9084

User Work Zone Costs ($1000):

Maintenance Frequency (years):

Activity Service Life (years): 4.11

Activity Structural Life (years): 11.69

Agency Maintenance Cost ($1000):

Activity Work Zone Inputs

Work Zone Length (miles): 2

Work Zone Capacity (vphpl): 1057.5

No of Lanes Open in Each Direction During Work Zone: 1

Work Zone Duration (days): 2.26670956

Work Zone Speed Limit (mph): 35

Traffic Hourly Distribution: Week Day 1

Work Zone Hours

	Inbound		Outbound	
	Start	End	Start	End
First Period of Lane Closure:	2000	2400	2000	2400
Second Period of Lane Closure:	0	600	0	600
Third Period of Lane Closure:				

Figure 3.14 Alternative-Level input in the RealCost Software

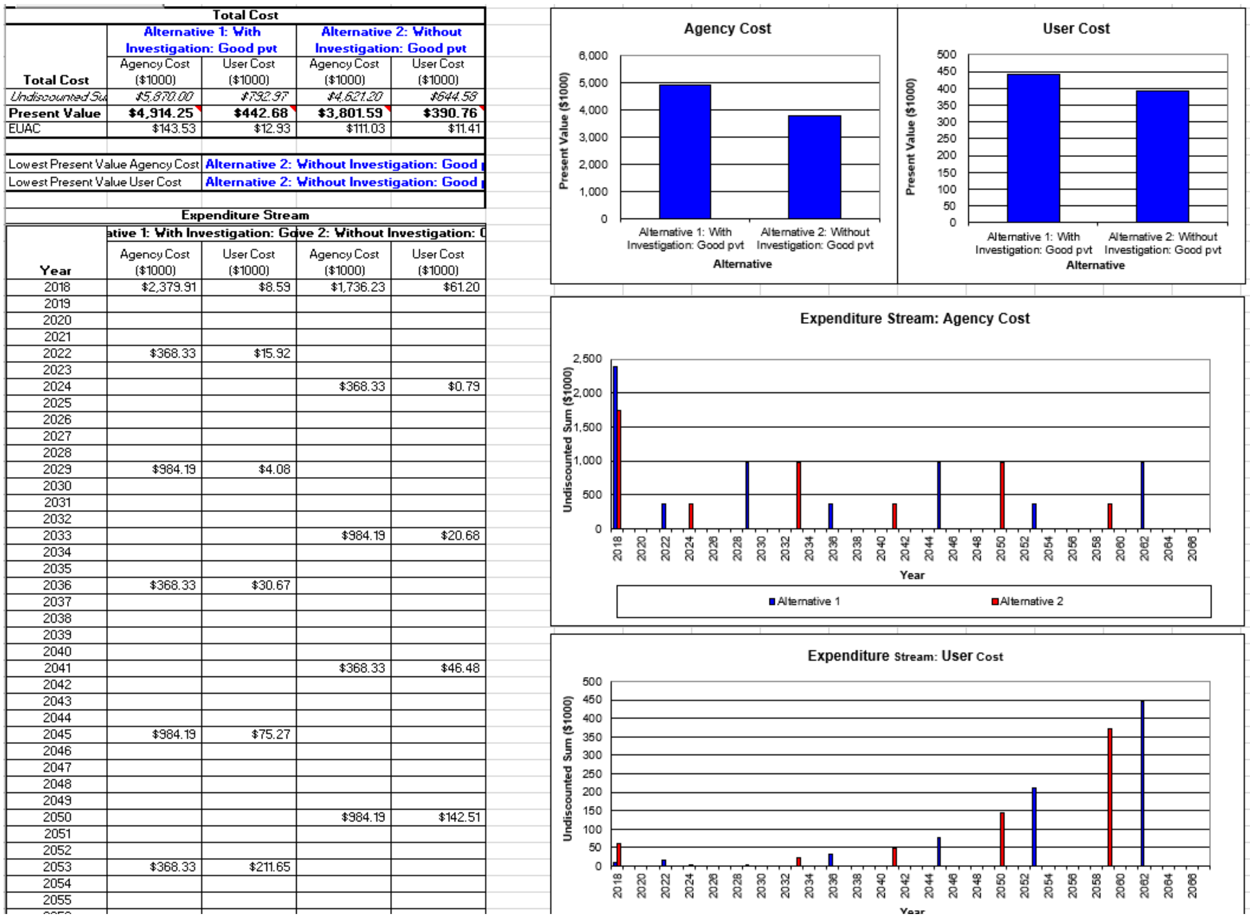
For each activity, the service life needs to be specified. In Realcost, the service life is the number of years between one maintenance activity and the next. The service life was assumed to follow the triangular probability distribution. The most likely value of the triangular distribution was calculated using Equation 2 as explained in section 3.4. The minimum and maximum values of the distribution are set to 80% and 120% of the most likely value, respectively.

As noted in Chapter 1, the life-cycle cost for each route was analyzed for three different service conditions, “Good”, “Fair,” and “Poor.” In this project, the assumed maintenance treatments for good, fair, and poor pavements are:

- **Good (PSI ≥ 3.0)** – Cycle 1: overlay 100 psy, Cycle 2: Mill 2” and overlay 200 psy. Repeat Cycle 1 and Cycle 2 within 50-year period.
- **Fair (PSI ≥ 2.0)** – Mill 2” (or 1”) and overlay to meet required SN.
- **Poor (PSI ≥ 1.0)** – 12” CMRB and overlay to meet required SN.

The other key input required for each activity is the cost of each construction line item (e.g., mill 2 inches, 8-inch full-depth patch, 200 psy overlay of Surface Type B). These line item costs were computed using the weighted average of actual bid amounts submitted by contractors. Note that the rehabilitation designs *with* investigation included the cost of traffic control, performing FWD tests, and taking core samples. The administrative and analysis costs were not considered.

Once both the project-level inputs and alternative-level inputs are provided, the user can compare the life-cycle costs between the different alternative designs using either deterministic cost method or probabilistic cost method. Figure 3.5 shows a sample output for generated by RealCost. In this project, the deterministic cost method was used and only the life-cycle agency cost was considered when evaluating the cost-effectiveness of field investigation.



Total Cost				
	Alternative 1: With Investigation: Good pvt		**Alternative 2: Without Investigation: Good pvt**	
Total Cost	Agency Cost ($1000)	User Cost ($1000)	Agency Cost ($1000)	User Cost ($1000)
Undiscounted Su	*$5,870.00*	*$792.97*	*$4,621.20*	*$644.58*
Present Value	**$4,914.25**	**$442.68**	**$3,801.59**	**$390.76**
EUAC	$143.53	$12.93	$111.03	$11.41

Lowest Present Value Agency Cost	**Alternative 2: Without Investigation: Good**
Lowest Present Value User Cost	**Alternative 2: Without Investigation: Good**

Expenditure Stream				
	ative 1: With Investigation: Go		**ive 2: Without Investigation: (**	
Year	Agency Cost ($1000)	User Cost ($1000)	Agency Cost ($1000)	User Cost ($1000)
2018	$2,379.91	$8.59	$1,736.23	$61.20
2019				
2020				
2021				
2022	$368.33	$15.92		
2023				
2024			$368.33	$0.79
2025				
2026				
2027				
2028				
2029	$984.19	$4.08		
2030				
2031				
2032				
2033			$984.19	$20.68
2034				
2035				
2036	$368.33	$30.67		
2037				
2038				
2039				
2040				
2041			$368.33	$46.48
2042				
2043				
2044				
2045	$984.19	$75.27		
2046				
2047				
2048				
2049				
2050			$984.19	$142.51
2051				
2052				
2053	$368.33	$211.65		
2054				
2055				

Figure 3.15 Deterministic cost output for route ID 1 generated by RealCost

3.7 Equivalent Uniform Annual Cost Analysis (EUAC)

The equivalent uniform annual cost (EUAC) was used to evaluate the cost-effectiveness of rehabilitation designs, *with* and *without* field investigation for fair pavements. The assumed economic period for the EUAC is 15 years. The EUAC calculation procedure is illustrated in Table 3.6 for the rehabilitation design *with* investigation for route ID 27. EUAC for each route was calculated using Equation 5.

$$EUAC = P\left[\frac{i(1+i)^n}{(1+i)^n - 1}\right] \tag{5}$$

Where,
P = Present Value
i = discount rate

The present value (P) in Equation 5 was calculated by subtracting the salvage value from the total NPV. To calculate the total NPV, all the future costs (F) of the design are converted to the Net Present Value (NPV) cost using Equation 6.

$$NPV = \frac{F}{(1+i)^n} \tag{6}$$

As shown in Table 3.6, the NPV of the first maintenance treatment at year 11.17 following the rehabilitation is $165.03. The total NPV is calculated by adding the cost of rehabilitation and the NPV of all maintenance treatments for a route. In this example, there is only one maintenance treatment; thus, the total NPV for route ID 27 is $552.35.

Table 3.6 EUAC calculation for route ID 27

Route id	Design Procedure	Design type	Rehab./ Maint. Year	Interval (Years)	Cumulative interval (Years)	Cost Per lane	NPV
27	With investigation	Rehab.	0	11.25	11.25	$387.32	$387.32
27		Maint. 1	11.17	8.92	20.17	$197.05	$165.03
						Total NPV	$552.35

The salvage value was determined using Equation 7 (Virginia DOT, 2020).

$$\textit{Salvage value} = \textit{last rehab./maint. cost at Year X} * \textit{Percentage of remaining life at year } 15 \tag{7}$$

The remaining life of last maintenance treatment design in Equation 7 was calculated using Equation 8.

$$\textit{Remaining life}(\%) = \frac{\textit{last maint. treatment year} + \textit{design life of maint. treatment} - \textit{economic period}}{\textit{design life of maint. treatment}} \tag{8}$$

As shown in Table 3.6, the last maintenance treatment (i.e., Maint. 1) was performed at year 11.17 for route ID 27. The design life of this maintenance treatment is 10 years. Thus, the remaining life of the maintenance treatment is 61.7% (i.e., remaining life = (11.17+10-15)/10 = 0.617). The salvage value of the pavement at the end of 15-year economic period is \$101.82 (i.e., salvage value = 197.05*0.617 = \$101.82).

The calculated value of "P" in Equation 5 is \$450.53 (i.e., \$552.35- \$101.82 = \$450.53). Using Equation 5, the EUAC per lane for route ID 27 was \$34.02. In both Equations 5 and 6, i represents the discount rate, which was assumed to be 1.6%.

3.8 Paired sample t-test

The paired t-test was used to determine whether the mean life-cycle cost (LCC) of the design *with* field investigation is significantly different from that of the design *without* field investigation. The hypothesis of the paired t-test for each route and pavement condition (good, fair, and poor) is:

$$H_0 : \mu_{with\_investigation} - \mu_{without\_investigation} = 0$$
$$H_0 : \mu_{with\_investigation} - \mu_{without\_investigation} \neq 0$$

Where

$\mu_{with\_investigation}$ = mean of LCC of designs *with* investigation

$\mu_{without\_investigation}$ = mean of LCC of designs *without* investigation

Given a sample size greater than 30, the difference between the means of the LCCs was assumed to be Normally distributed with mean μ_d and standard error $\frac{s_d}{\sqrt{n}}$. The test statistics, t^* was calculated using Equation 9.

$$t^* = \frac{\overline{d}}{\frac{s_d}{\sqrt{n}}} \tag{9}$$

With degrees of freedom, $df = n - 1$.

If the computed test statistic is greater than the t-value at the 5% significance level and degrees of freedom, then H_0 is rejected. The R version 4.0 (R Core Team, 2020) statistical software was used to perform the paired t-test.

3.9 Decision Tree Models

Decision trees are a machine learning method often applied to classification problems. In this project, they were used to obtain relevant variables and associated thresholds that determine when it would be more cost-effective for a project to conduct field investigation. A decision tree consists of three types of nodes: root node, decision nodes, and leaf nodes. A graphical representation of a simple decision tree is presented in Figure 3.15. This tree has three layers of nodes. The first layer is the root node. The circle in the second layer is the decision node. The three rectangles in the second and third layers are leaf nodes. The leaf nodes represent the outcomes, and the decision nodes represent factors affecting the outcomes. In this project, the route characteristics (i.e., AADT, AADTT, number of lanes, SSV) were factors considered to have an effect on whether field investigation is cost-effective or not. Thus, decision nodes represent variables related to route characteristics and leaf nodes represent the outcomes of field investigation (i.e., whether it is cost-effective).

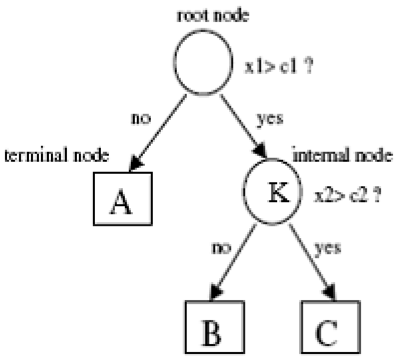


Figure 3.16 An illustration of simple decision tree model (Kim, 2005)

There are a few commonly used decision-tree algorithms. They differ from one another in how they select and split the decision nodes. The *Iterative Dichotomiser 3 (ID3)* algorithm developed by Quinlan (1986) uses the Gini Index as criterion. The *C4.5* algorithm is a successor to *ID3* and it was developed by Quinlan (1993) which uses Information Gain (IG) or Gain raitio as the criterion. *Classification and Regression Tree (CART*) was developed by Breiman et al. (1998) and it uses the Gini Index as the splitting criterion. The *Chi-squared Automatic Interaction Detector (CHAID)* which is based on the chi-square test of association was developed by Kass (1980). In this project, the 'rpart' package (Therneau, 2019) library in R was used to develop the decision tree. This package defines the impurity of an internal node, I(P) as shown in Equation 10.

$$I(P) = \sum_{i=1}^{C} f(p_{iK}) \tag{10}$$

Where,

p_{iK} = Proportion of sample in node P that belongs to i

C = number of class

$f(.)$ impurity function

The 'rpart' package uses two impurity function to find I(P)=0. The two functions are: information index, defined as $f(p) = -p\log(p)$ and Gini Index, defined as $f(p) = -p(1-p)$. These functions measure the impurity at decision node. Using this impurity measurements, 'rpart' package picks the variables that provide the maximum impurity reduction and results in purest subsequent nodes. This process is recursively performed starting from the root node until the stopping criteria are met and the tree is constructed.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Exploratory Data Analysis

The existing, required and resulting SNs from rehabilitation designs *with* and *without* investigation are shown in Table 4.1. The 10-year design SN *with* field investigation is higher than the required SN for the majority of routes (26 out of 31). The design SN *without* field investigation is higher than the required SN for only a little over half of the routes (18 out of 31). Moreover, the design SN *with* field investigation is higher than the one *without* field investigation for 15 of the 31 routes (i.e., routes 3, 4, 5, 9, 10, 13, 14, 15, 17, 18, 22, 23, 25, 26, 29); both designs had the same SN (5.03) for route 2. The 20-year design *with* investigation generally resulted in a higher SN than the 10-year design. It should be noted that 11 routes out of 31 have existing SNs that are greater than required SN for a 10-year rehabilitation design (i.e., 11, 16, 18, 19, 20, 21, 24, 27, 28, 30, 31).

Table 4.1 Comparison of rehabilitation designs with and without investigation

Route ID	Existing SN	Required SN (10-year Design)	Required SN (20-year Design)	SN after rehabilitation		
				Design with investigation (10-year Design)	Design without investigation (10-year Design)	Design with investigation (20-year Design)
1	3.28	4.14	4.61	4.36	4.68	4.82
2	4.75	4.87	4.87	5.03	5.03	5.03
3	2.93	4.65	5.16	4.63	4.01	5.25
4	2.16	3.77	4.22	3.82	3.76	4.52
5	2.74	4.10	4.58	4.10	3.30	4.62
6	3.72	4.48	4.97	4.52	4.70	5.32
7	3.62	4.10	4.62	3.90	5.32	4.70
8	4.71	4.78	5.30	4.99	6.41	5.39
9	2.73	4.09	4.56	4.62	3.92	4.72
10	2.47	3.72	4.16	4.10	3.51	4.32
11	4.51	4.20	4.68	4.32	4.62	5.39
12	3.84	4.58	5.08	4.52	4.67	5.17
13	3.95	5.44	6.02	5.49	4.72	6.23
14	3.21	4.28	4.77	4.32	3.98	4.72
15	2.12	3.89	4.34	3.92	2.38	4.52
16	5.40	4.36	5.08	5.68	5.71	5.68
17	2.07	4.21	4.69	4.52	4.46	4.72
18	4.57	3.89	4.50	5.13	4.88	5.13
19	8.17	4.83	5.36	8.45	8.97	8.45
20	5.63	4.96	5.49	5.91	6.19	5.91
21	7.43	4.06	4.53	8.13	8.23	8.13
22	2.81	4.13	4.60	4.41	2.81	4.81
23	2.86	3.44	3.85	3.54	3.21	3.94
24	4.70	4.11	4.58	4.70	4.98	4.70

Route ID	Existing SN	Required SN (10-year Design)	Required SN (20-year Design)	SN after rehabilitation: Design with investigation (10-year Design)	SN after rehabilitation: Design without investigation (10-year Design)	SN after rehabilitation: Design with investigation (20-year Design)
25	2.67	3.55	3.98	3.58	2.67	4.10
26	2.98	3.94	4.40	4.10	3.33	4.62
27	7.40	4.50	4.99	4.62	7.40	4.72
28	5.63	4.50	4.99	5.39	5.63	6.19
29	3.10	3.79	4.23	3.70	3.10	4.30
30	5.47	4.01	4.47	5.47	5.47	5.47
31	4.97	3.99	4.44	4.73	4.97	5.25

As shown in Figure 4.1, the 10-year design *with* field investigation is more consistent in providing a pavement structure that has the required SN than the one *without* (inter-quartile range of 15.54% versus 35.40%). Similarly, the 20-year design *with* field investigation is more consistent than the 10-year design with field investigation (inter-quartile range of 8% versus15.54%). These findings suggest that both the 10-year design and 20-year design *with* field investigation tend to produce a pavement that has the necessary depth and made up of higher strength pavement materials that bring its SN closer to the required value. Thus, rehabilitation designs *with* field investigation would enable the SCDOT to maximize the utilization of available resources and improve condition of more roadways.

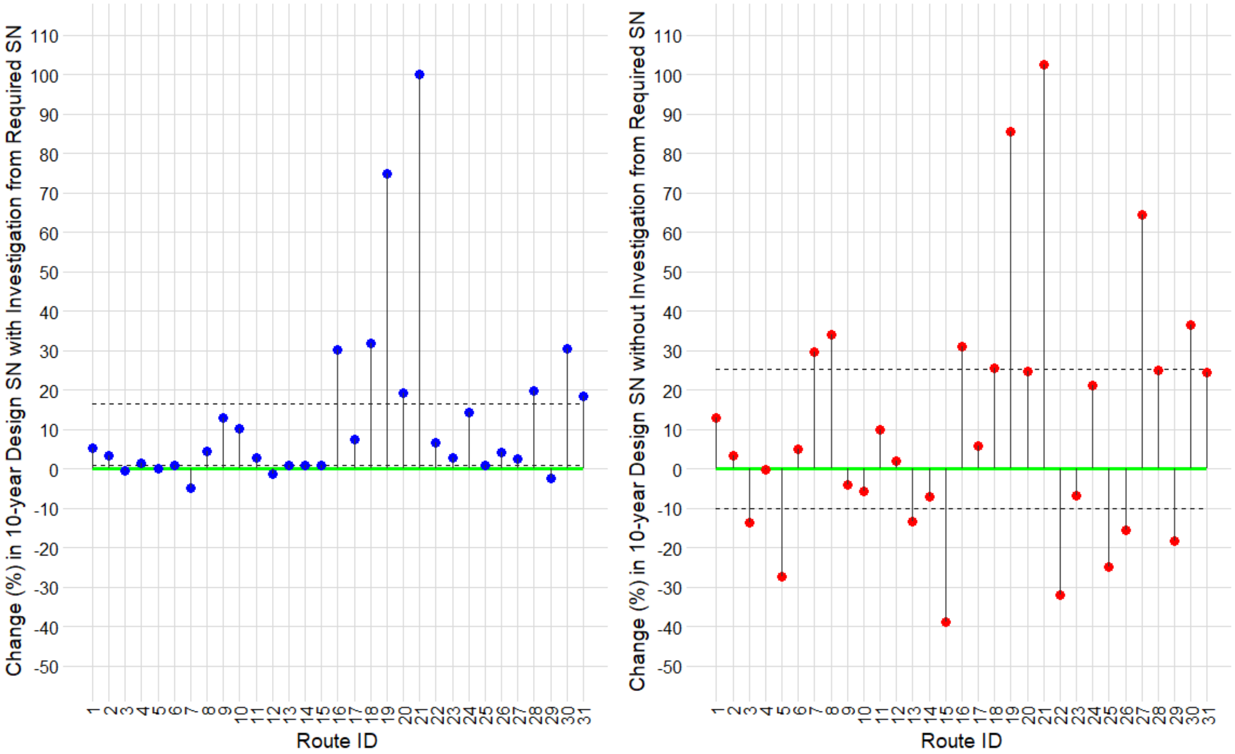


Figure 4.1 Percentage change in with and without investigation design SN from required SN for 10-year rehabilitation design

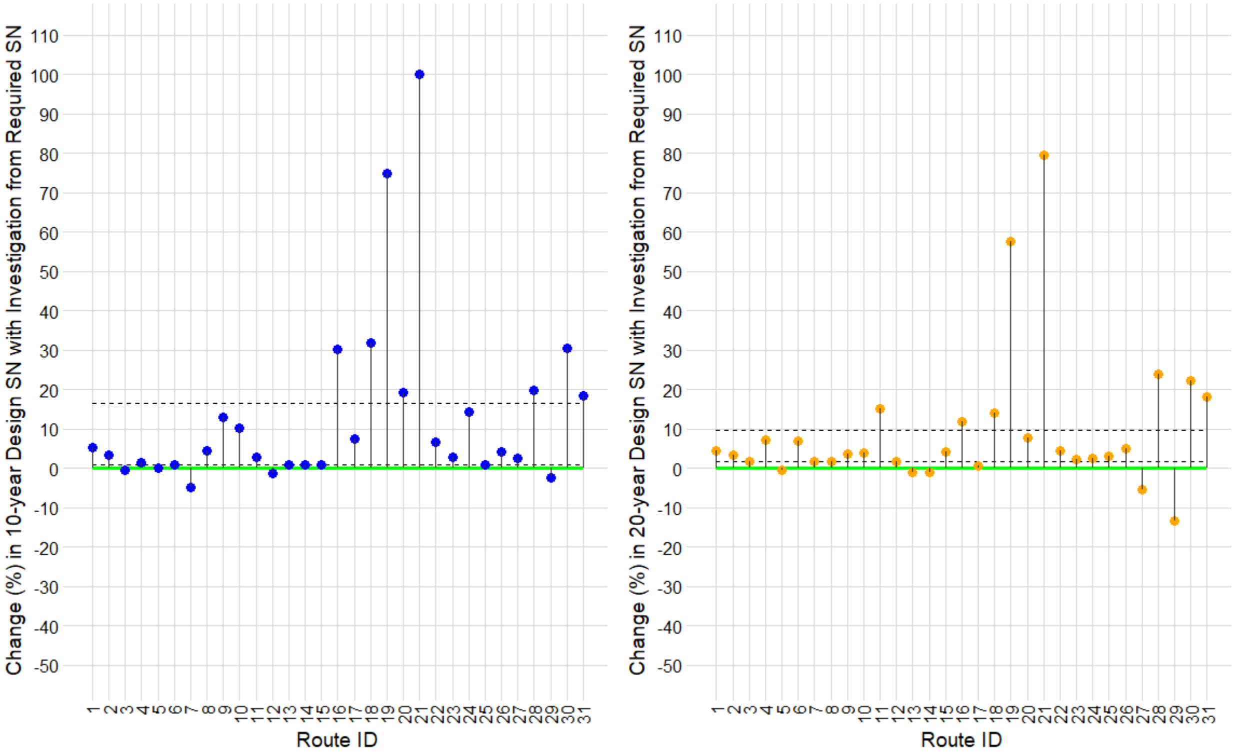


Figure 4.2 Percentage change in with investigation design SN from required SN for 10-year vs 20-year rehabilitation design

4.2 Evaluation of 10-year Rehabilitation Design with and without field investigation using LCC analysis

The difference in the number of maintenance treatments needed in a 50-year period between the designs *with* and *without* field investigation is shown in Table 4.2. Since both rehabilitation design methods, *with* and *without* field investigation, are assumed to have the same maintenance treatments discussed previously, the number of maintenance treatments needed for good, fair, and poor pavements is governed primarily by the service life of the rehabilitation design. As expected, the 10-year design *with* investigation require a higher or same number of maintenance treatments for good pavements compared to fair. The 10-year design *without* investigation shows similar results for good pavement compared to the fair pavement. Similarly, the number of maintenance treatments needed for fair pavements is higher or same compared to poor for the 10-year design *with* investigation. For the 10-year design *without* investigation, the number of maintenance treatments required is higher or same for majority (29 out of 31) of fair pavement compared to poor. For each type of pavement (good, fair, and poor), it is observed that for routes where the 10-year design *with* field investigation have higher SN than those *without* field investigation (i.e., routes 3, 4, 5, 9, 10, 13, 14, 15, 17, 18, 22, 23, 25, 26, 29), fewer or the same number of maintenance treatments is needed; only route 29 requires a higher number of maintenance treatments for good pavement. Conversely, for routes where the 10-year design *with* field investigation have lower SN than those *without* field investigation (i.e., routes 1, 6, 7, 8, 11, 12, 16, 19, 20, 21, 24, 27, 28, 30, 31), higher or the same number of maintenance treatments are needed; only route 8 requires higher number of maintenance treatments for poor pavement. This finding suggests that there is a correlation between the design SN and number of maintenance treatments needed. Specifically, the higher the design SN the fewer the number of maintenance treatments is required, and vice-versa. In other words, a properly designed pavement will require fewer maintenance treatments. Another very important finding is that designs *with* field investigation prolong the time when the first maintenance treatment is needed. This is particularly important for the SCDOT not only in terms of cost savings, but also reducing the number of concurrent resurfacing projects since there is a high demand for contractors in South Carolina.

Table 4.2 Comparison of number of maintenance treatments needed in a 50-year period for 10-year rehabilitation design with and without investigation

Route ID	**Good**		**Fair**		**Poor**	
	Design with investigation (10-year Design)	**Design without investigation (10-year Design)**	**Design with investigation (10-year Design)**	**Design without investigation (10-year Design)**	**Design with investigation (10-year Design)**	**Design without investigation (10-year Design)**
1	7	7	5	5	4	4
2	7	7	5	5	5	5
3	9	11	5	6	4	5
4	6	6	5	6	4	4
5	7	14	4	5	4	5
6	7	7	6	6	4	4
7	7	4	4	4	4	4
8	7	4	5	4	4	5
9	5	7	4	4	4	5
10	5	8	5	6	4	4
11	7	4	6	4	4	4
12	8	7	5	4	4	4
13	9	11	6	6	4	5
14	8	8	4	5	4	4
15	6	12	5	9	4	5
16	5	5	4	4	4	4
17	8	8	4	4	4	4
18	4	5	4	4	4	4
19	4	4	4	4	4	4
20	5	4	4	4	4	4
21	4	4	4	4	4	4
22	6	8	4	6	4	4
23	7	7	5	7	5	5
24	4	4	4	4	4	4
25	6	9	6	6	4	4
26	6	9	5	6	5	5
27	7	4	5	4	4	4
28	4	4	4	4	4	4

Route ID	Good		Fair		Poor	
	Design with investigation (10-year Design)	Design without investigation (10-year Design)	Design with investigation (10-year Design)	Design without investigation (10-year Design)	Design with investigation (10-year Design)	Design without investigation (10-year Design)
29	7	6	6	6	5	5
30	4	4	4	4	4	4
31	4	4	4	4	4	4
Totals	*190*	*206*	*145*	*154*	*128*	*134*

The difference in deterministic agency cost per lane for a 50-year analysis period between the designs *with* and *without* field investigation is shown in Table 4.3. The reported agency costs are in net present value. As a result of treatment types assumed in this study, for the 10-year design *with* field investigation, the life-cycle costs for two-thirds (20 out of 31) of good pavements are higher compared to fair pavements. However, for 10-year designs *with* field investigation, the life-cycle costs of fair pavements are lower compared to poor except for two routes (i.e., route 25, 29). For designs *without* field investigation and assumed treatment types, the life-cycle costs of good pavements are higher than fair for more than half of the routes (18 out of 31), and the life-cycle costs of fair pavements are lower compared to poor for all the routes. The total life-cycle cost per lane indicates that the design *with* field investigation is cost-effective for good, fair, and poor pavements (good: \$41,316.03 vs. \$45,459.19; fair: \$40,287.80 vs. \$42,160.88; poor: \$68,262.37 vs. \$73,987.05). Also, the total life-cycle cost per lane of rehabilitation design *with* field investigation is lowest for fair pavements (\$40,294.75) compared to good (\$41,316.03) and poor (\$68,262.37). These findings suggest that for the SCDOT, field investigation is cost-effective for fair and poor pavements. It is most cost advantageous when applied to fair pavements.

A paired t-test was performed to determine if the difference in life-cycle cost (LCC) is statistically different at the 95% confidence level. The null and alternative hypotheses are as follows.

$$H_0: LCC_{with\_investigation} - LCC_{without\_investigation} = 0$$
$$H_a: LCC_{with\_investigation} - LCC_{without\_investigation} \neq 0$$

The test results indicate that the null hypothesis cannot be rejected at the 95% confidence level for good pavements (*p-value = 0.081*), fair pavements (*p-value = 0.563*), and poor pavements (*p-value = 0.13*). In other words, while the design *with* field investigation has lower LCC than the one *without*, it is not statistically different.

Table 4.3 Comparison of deterministic agency cost (in thousands) in net present value for 10-year rehabilitation design

Route ID	Good		Fair		Poor	
	Design with investigation	Design without investigation	Design with investigation	Design without investigation	Design with investigation	Design without investigation
1	\$1,170.53	\$956.25	\$1,100.28	\$819.57	\$1,602.67	\$1,493.27
2	\$14.77	\$13.23	\$15.18	\$14.05	\$28.55	\$27.66

Route ID	**Good**		**Fair**		**Poor**	
	Design with investigation	**Design without investigation**	**Design with investigation**	**Design without investigation**	**Design with investigation**	**Design without investigation**
3	$536.30	$295.27	$469.74	$428.02	$585.93	$632.96
4	$313.84	$312.82	$289.32	$417.08	$372.59	$422.11
5	$22.62	$30.45	$15.92	$19.51	$26.23	$29.20
6	$2,465.08	$2,544.90	$2,396.76	$2,450.39	$3,518.52	$3,669.14
7	$3,618.81	$3,243.56	$2,886.96	$3,311.96	$5,242.51	$5,748.98
8	$675.18	$628.72	$717.89	$828.03	$1,074.88	$1,457.11
9	$3,124.26	$3,550.81	$1,635.88	$3,187.64	$4,532.72	$4,737.93
10	$2,393.02	$3,157.70	$2,510.35	$3,074.97	$3,321.29	$3,609.12
11	$5,121.98	$6,224.99	$5,067.07	$2,857.96	$6,183.99	$5,636.17
12	$178.84	$147.28	$114.15	$87.35	$146.83	$129.29
13	$160.18	$158.52	$107.08	$86.62	$139.56	$162.59
14	$106.42	$93.10	$68.11	$57.50	$100.99	$84.95
15	$265.71	$511.02	$138.05	$277.44	$241.43	$300.08
16	$93.26	$93.41	$56.16	$54.45	$147.02	$145.41
17	$403.19	$518.95	$235.60	$269.95	$369.49	$396.32
18	$132.30	$82.62	$153.99	$77.93	$219.15	$154.10
19	$673.86	$463.31	$610.40	$401.61	$3,570.15	$3,364.67
20	$836.20	$1,073.31	$364.96	$576.15	$2,384.06	$2,699.29
21	$595.09	$639.72	$518.17	$565.25	$3,383.91	$3,428.99
22	$3,520.82	$4,508.93	$5,555.26	$5,634.34	$7,640.61	$8,730.09
23	$6,859.90	$6,285.11	$5,897.41	$6,746.76	$8,241.18	$7,389.52
24	$249.38	$396.05	$284.36	$467.45	$926.71	$1,146.73
25	$504.95	$455.84	$1,116.64	$859.14	$1,084.16	$1,203.82
26	$3,234.37	$3,583.87	$2,981.12	$2,638.85	$4,638.12	$4,203.39
27	$838.82	$338.98	$772.02	$310.48	$1,032.32	$1,299.12
28	$324.90	$312.21	$408.32	$375.86	$966.18	$945.08
29	$1,621.90	$2,499.70	$2,004.80	$2,657.73	$339.01	$3,523.58
30	$580.09	$824.05	$626.17	$855.25	$2,971.36	$3,172.06
31	$679.51	$1,514.55	$1,169.75	$1,751.66	$3,230.32	$4,044.37
Total	*$41,316.03*	*$45,459.19*	*$40,287.75*	*$42,160.88*	*$68,262.37*	*$73,987.05*

4.3 Evaluation of 10-year and 20-year Rehabilitation Design with field investigation using LCC analysis

The difference in the number of maintenance treatments needed in a 50-year period between the 10-year design *with* field investigation and 20-year design *with* field investigation is shown in Table 4.4. As discussed in section 4.2, the 10-year design with investigation require a higher or same number of maintenance treatments for good pavements compared to fair and for fair pavements compared to poor. For the 20-year design *with* field investigation, the number of maintenance treatments required is higher or same for good pavements compared to fair and for fair pavements compared to poor. Table 4.4 shows that there is significant difference in the total number of maintenance cycles between the 10-year and 20-year designs *with* investigation for good and fair pavements (good: 190 vs. 169; fair: 145 vs. 125). For poor pavement, the number of maintenance cycles is nearly equal (poor: 128 vs. 126).

Table 4.4 Comparison of number of maintenance treatments needed in a 50-year period for 10-year vs 20-year rehabilitation design with investigation

Route ID	Good		Fair		Poor	
	Design with investigation (10-year Design)	**Design with investigation (20-year Design)**	**Design with investigation (10-year Design)**	**Design without investigation (20-year Design)**	**Design with investigation (10-year Design)**	**Design without investigation (20-year Design)**
1	7	6	5	4	4	4
2	7	6	5	4	5	4
3	9	8	5	4	4	4
4	6	5	5	4	4	4
5	7	6	4	4	4	4
6	7	7	6	4	4	4
7	7	6	4	4	4	4
8	7	8	5	4	4	6
9	5	4	4	4	4	4
10	5	4	5	5	4	4
11	7	6	6	4	4	4
12	8	7	5	4	4	4
13	9	8	6	4	4	4
14	8	6	4	4	4	4
15	6	5	5	4	4	4
16	5	5	4	4	4	4
17	8	6	4	4	4	4
18	4	4	4	4	4	4
19	4	4	4	4	4	4
20	5	4	4	4	4	4
21	4	4	4	4	4	4
22	6	5	4	4	4	4
23	7	5	5	4	5	4
24	4	5	4	4	4	4
25	6	5	6	4	4	4
26	6	5	5	4	5	4
27	7	7	5	4	4	4
28	4	4	4	4	4	4
29	7	6	6	4	5	4

Route ID	Good		Fair		Poor	
	Design with investigation (10-year Design)	**Design with investigation (20-year Design)**	**Design with investigation (10-year Design)**	**Design without investigation (20-year Design)**	**Design with investigation (10-year Design)**	**Design without investigation (20-year Design)**
30	4	4	4	4	4	4
31	4	4	4	4	4	4
Totals	*190*	*169*	*145*	*125*	*128*	*126*

The difference in deterministic agency cost per lane for a 50-year analysis period between the 10-year design *with* field investigation and 20-year design with field investigation is shown in Table 4.5. As discussed in section 4.2, for the 10-year design *with* field investigation using the assumed treatment types, the life-cycle costs per lane of good pavements are higher than fair for two-thirds of the routes (20 out of 31), and the life-cycle costs per lane of fair pavements are lower for all routes compared to poor except for two (i.e., routes 25 and 29). For 20-year designs *with* field investigation, the life-cycle costs per lane of good pavements are higher than fair for nearly three-fourths of the routes (21 out of 31), and the life-cycle costs per lane of fair pavements are lower for all routes compared to poor. The life-cycle cost per lane of good pavements is higher for 10-year design *with* field investigation compared to 20-year design *with* field investigation for more than half of the routes (18 out of 31). Similarly, the life-cycle cost per lane of 10-year design with field investigation is higher for a little over half of the routes (18 out of 31) routes for fair pavements and 11 routes for poor pavements, compared to 20-year design *with* field investigation. The total life-cycle cost per lane indicates that the 20-year design with field investigation is cost-effective for good and fair pavements (good: $41,316.03 vs. $38,529.36; fair: $38,647.08vs. $52,794.97) but not for poor (poor: $68,269.32 vs. $72,393.25). These findings suggest that for the SCDOT, using the 20-year design is more cost-effective than the 10-year design with field investigation when rehabilitation is performed to keep the pavement in good and fair condition. It should be noted here that the assumed maintenance treatments for both 10-year and 20-year designs *with* field investigation are the same for good, fair, and poor pavements; in practice, these designs might differ significantly.

A paired t-test was performed to determine if the difference in life-cycle cost (LCC) is statistically different at the 95% confidence level for 10-year and 20-year design with field investigation. The null and alternative hypotheses are as follows.

$$H_0\text{: } LCC_{10\text{-year\_design\_with\_investigation}} - LCC_{20\text{-year\_design\_with\_investigation}} = 0$$
$$H_a\text{: } LCC_{10\text{-year\_design\_with\_investigation}} - LCC_{20\text{-year\_design\_with\_investigation}} \neq 0$$

The test results indicate that the null hypothesis cannot be rejected at the 95% confidence level for good pavements (p-value = 0.389), fair pavements (p-value = 0.373), and poor pavements (p-value = 0.28). In other words, the LCC of the 10-year design *with* field investigation is not statistically different from the LCC of the 20-year design *with* field investigation.

Table 4.5 Comparison of deterministic agency cost (in thousands) in net present value for 10-year vs 20-year rehabilitation design with investigation

	Good		**Fair**		**Poor**	
Route ID	**Design with investigation (10-year Design)**	**Design with investigation (20-year Design)**	**Design with investigation (10-year Design)**	**Design without investigation (20-year Design)**	**Design with investigation (10-year Design)**	**Design without investigation (20-year Design)**
1	$1,170.53	$1,112.68	$1,100.28	$947.92	$1,602.67	$1,602.67
2	$14.77	$12.89	$15.18	$12.39	$28.55	$25.40
3	$536.30	$450.43	$469.74	$461.83	$585.93	$679.63
4	$313.84	$224.40	$289.32	$306.53	$372.59	$496.61
5	$22.62	$24.57	$15.92	$16.69	$26.23	$26.33
6	$2,465.08	$2,945.98	$2,396.76	$2,029.00	$3,518.52	$3,483.28
7	$3,618.81	$3,473.42	$2,886.96	$3,179.80	$5,242.51	$5,102.70
8	$675.18	$805.43	$717.89	$359.40	$1,074.88	$1,066.10
9	$3,124.26	$772.31	$1,635.88	$2,735.41	$4,532.72	$4,868.07
10	$2,393.02	$1,870.75	$2,510.35	$2,722.40	$3,321.29	$5,865.40
11	$5,121.98	$3,785.05	$5,067.07	$4,467.69	$6,183.99	$6,344.15
12	$178.84	$127.15	$114.15	$103.87	$146.83	$146.83
13	$160.18	$127.22	$107.08	$80.42	$139.56	$136.89
14	$106.42	$77.67	$68.11	$67.02	$100.99	$100.69
15	$265.71	$190.06	$138.05	$160.28	$241.43	$217.45
16	$93.26	$75.54	$56.16	$56.16	$147.02	$177.52
17	$403.19	$286.44	$235.60	$252.26	$369.49	$372.78
18	$132.30	$136.65	$153.99	$148.36	$219.15	$223.78
19	$673.86	$673.86	$610.40	$685.25	$3,570.15	$4,098.88
20	$836.20	$914.40	$364.96	$651.01	$2,384.06	$2,361.09
21	$595.09	$595.09	$518.17	$518.17	$3,383.91	$3,383.91
22	$3,520.82	$4,625.71	$5,555.26	$5,123.45	$7,640.61	$7,640.61
23	$6,859.90	$6,082.79	$5,897.41	$5,114.54	$8,241.18	$6,371.73
24	$249.38	$296.39	$284.36	$292.96	$926.71	$926.71
25	$504.95	$425.71	$1,116.64	$775.32	$1,084.16	$1,038.11
26	$3,234.37	$3,171.44	$2,981.12	$2,554.59	$4,638.12	$4,654.10
27	$838.82	$922.27	$772.02	$685.87	$1,032.32	$1,081.28
28	$324.90	$491.02	$408.32	$629.29	$966.18	$1,021.72
29	$1,621.90	$1,889.66	$2,004.80	$1,830.65	$339.01	2,213
30	$580.09	$935.09	$626.17	$626.17	$2,971.36	$2,951.58
31	$679.51	$1,007.34	$1,169.75	$1,052.45	$3,230.32	$3,714.32
Total	*$41,316.03*	*$38,529.36*	*$40,287.80*	*$38,647.08*	*$68,262.37*	*$72,393.257*

4.4 Evaluation of 10-year Rehabilitation Design with and without field investigation using EUAC analysis

The difference in the number of maintenance treatments and equivalent uniform annual cost per lane (EUAC) for fair pavements in a 15-year period between the 10-year designs *with* and *without* field investigation is shown in Table 4.6. Recall from Section 4.2 that both designs, *with* and *without* field investigation, were assumed to have the same maintenance treatments. Also, recall that for the EUAC cost analysis for fair pavements, the determination of service life was performed using the M-E method. For fair pavements, it is observed that the 10-year design *with* field investigation requires fewer or the same number of maintenance treatments for the majority of the routes compared to 10-year design *without* field investigation. Only routes 8 and 29 require a higher number of maintenance treatments. The total EUAC cost per lane-mile indicates that the 10-year design *with* field investigation is cost-effective for fair pavements (with investigation: $1,707 vs. without investigation: $2,010). These results confirm previous findings that a properly designed pavement require fewer maintenance treatments, a design *with* field investigation prolongs the time when the first maintenance treatment is needed, and field investigation is cost-effective for fair pavements.

Table 4.6 Comparison of deterministic agency cost (in thousands) of 15-year economic period in EUAC for 10-year rehabilitation design

Route ID	Number of cycles		EUAC 15-year period		Annual Cost Difference
	With investigation	Without investigation	With investigation	Without investigation	
1	1	3	$44.93	$46.74	$1.81
2	1	1	$0.38	$0.38	$0.00
3	1	1	$17.92	$17.92	$0.00
4	2	5	$14.31	$27.40	$13.09
6	1	1	$57.46	$68.83	$11.37
7	1	1	$64.69	$168.64	$103.95
8	2	1	$15.34	$14.95	-$0.39
9	1	2	$134.03	$199.51	$65.48
10	1	1	$146.37	$110.06	-$36.31
11	1	3	$264.52	$178.10	-$86.42
12	1	1	$14.76	$10.57	-$4.19
13	1	7	$3.90	$10.24	$6.34
14	1	2	$3.03	$2.51	-$0.52
15	2	2	$6.58	$13.67	$7.09
16	1	1	$2.40	$2.20	-$0.19
17	1	1	$10.84	$12.86	$2.03
18	1	1	$6.91	$2.70	-$4.21
19	1	2	$61.92	$40.83	-$21.09
20	1	1	$38.30	$64.57	$26.27
21	1	1	$44.70	$50.89	$6.19
22	1	2	$239.95	$266.47	$26.53

Route ID	Number of cycles		EUAC 15-year period		Annual Cost Difference
	With investigation	Without investigation	With investigation	Without investigation	
23	1	1	$173.82	$118.02	-$55.80
24	1	1	$0.17	$17.21	$17.03
25	3	3	$53.05	$32.98	-$20.07
26	1	3	$142.88	$137.86	-$5.03
27	2	9	$34.02	$84.19	$50.17
28	1	3	$15.46	$30.09	$14.63
29	2	1	$4.61	$73.37	$68.76
30	1	1	$0.17	$66.82	$66.65
31	1	1	$89.46	$139.15	$49.70
Total	*40*	*61*	*$1,706.88*	*$2,009.74*	*$302.86*

A paired t-test was performed to determine if the difference in equivalent uniform annual cost (EUAC) for fair pavement is statistically different at the 95% confidence level. The null and alternative hypotheses are as follows.

$$H_0: EUAC_{fair\_with\_investigation} - EUAC_{fair\_without\_investigation} = 0$$
$$H_a: EUAC_{fair\_with\_investigation} - EUAC_{fair\_without\_investigation} \neq 0$$

The test results indicate that the null hypothesis cannot be rejected at the 95% confidence level for fair pavements (p-value = 0.222).

4.5 Pavement Field Investigation Guide

Decision tree models were developed to identify route characteristics that have a tendency to yield lower LCC with field investigation. Figure 4.3 shows decision tree results using all the data presented in Table 4.2 (sample size of 93). This decision tree identified two key factors that affect the LCC of the design with field investigation: number of lanes and Annual Average Daily Truck Traffic (AADTT). The first variable selected for decision-making is number of lanes. When the number of lanes is 2, AADTT provided the most significant split at a cutoff level of 1,151. If AADTT is equal or higher than 1,151, no further splits are made, and field investigation is suggested. When AADTT is lower than 1,151, a second AADTT cutoff at 456 provides the best split, and field investigation is suggested for AADTT lower than 456. When the number of lanes is 4 and AADTT is lower than 1,151, no further splits are made, and field investigation is suggested. A simplified guide for performing field investigation from the decision tree results is presented below:

Rule		Decision
Number of lanes	AADTT	
2	≥ 1,151 or ≤ 456	Perform field investigation
4	< 1,013	Perform field investigation

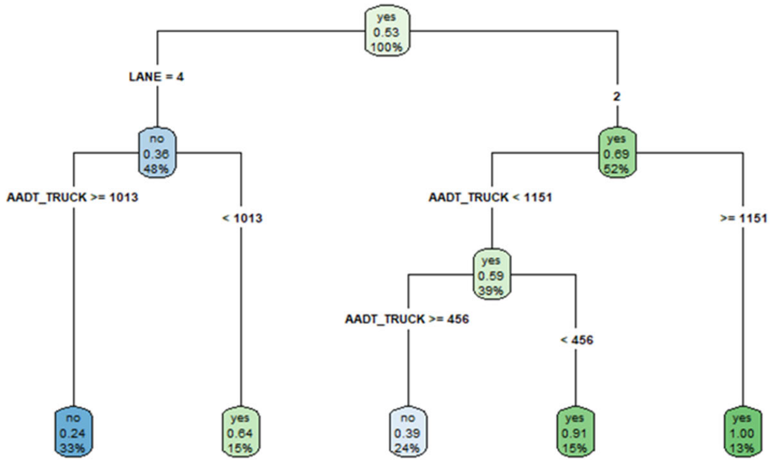


Figure 4.3 Decision tree model for routes to predict field investigation

Recall that two different methods were used to determine service life: SN and M-E. The decision tree presented in Figure 4.3 was based on the results obtained using the SN method. Figure 4.4 shows the decision tree results using the data presented in Table 4.6 (sample size of 30) which used the M-E method to determine service life. This decision tree identified Annual Average Daily Truck Traffic (AADTT) as the key factor that affects the LCC of the design *with* field investigation. If AADTT is equal to or higher than 1,325, no further splits are made, and field investigation is suggested. When AADTT is lower than 1,325, a second AADTT cutoff at 585 provides the best split, and field investigation is suggested for AADTT lower than 585. A simplified guide for performing field investigation from the decision tree results is presented below:

Rule	**Decision**
AADTT	
≥ 1,325	Perform field investigation
< 585	Perform field investigation

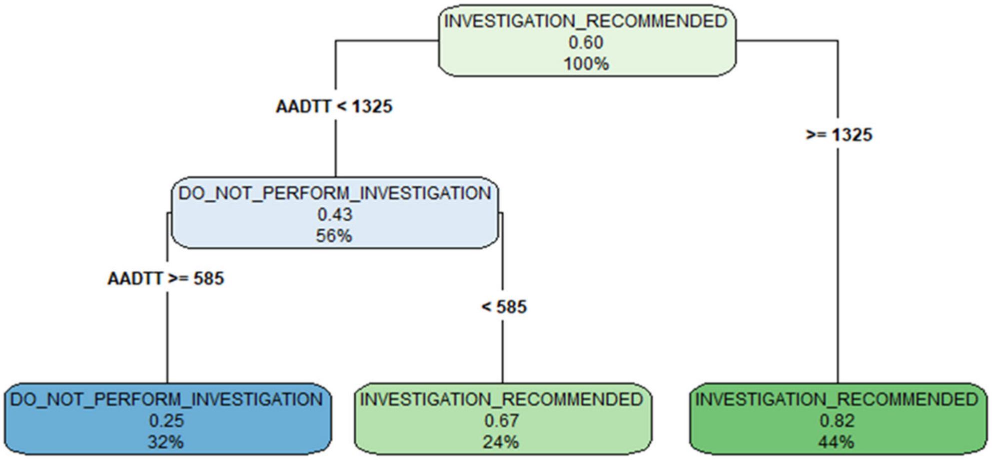


Figure 4.4 Decision tree model for fair pavement to predict field investigation

It should be noted that these decision tree models were developed using a very small sample size. Machine learning methods require a substantial number of observations for model training. Due to the low sample size, the performance metrics such as classification rate, positive predictive value, negative predictive value, sensitivity, and specificity for these decision tree models are not reported. The decision tree models developed in this project are intended to serve as a framework that can be further developed in future SCDOT-sponsored research.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

This study assessed the cost-effectiveness of performing field investigation at the rehabilitation design stage for non-interstate routes. The results indicated that the design *without* investigation will generally result in a higher number of maintenance cycles (i.e., shorter durations between maintenance activities) than the design *with* investigation. This is due to the design *without* investigation yielding a pavement structure that is less than the required structural number, and in a few instances, significantly less (i.e., ≥ 25% less than the required SN). With the current practice of using the design *without* investigation, if SCDOT does not perform timely maintenance on these pavement sections, then they would fall into the poor pavement category. If a greater percentage of pavements in the State falls into the poor category, it would contradict the SCDOT's 10-year plan of reducing the percentage of poor pavements from 45% to 16% for Non-Interstate NHS and from 61% to 37% for Non-NHS Primaries (SCDOT TAMP, 2019). Moreover, a pavement system that requires frequent rehabilitation would stress the construction labor force that is already in short supply in the State and it would be disruptive to the traveling public. There is also a negative perception associated with constant pavement repair.

The life-cycle cost analysis indicated that when the design *with* investigation is used instead of the design *without* investigation, the cost difference to maintain one lane-mile of pavement in good functional condition is -\$27,030, in fair functional condition is -\$12,220, and in poor functional condition is -\$37,348 over the 50-year analysis period; the negative cost difference indicates that the value is a savings to the SCDOT. These findings indicate that field investigation is generally cost-effective. It was found that at least 50% of the time, the design *with* investigation will result in a lower cost. While it may be cost advantageous to perform investigation on poor pavements, the intention of this study is not to identify when best to rehabilitate. It primarily focused on whether the SCDOT should conduct field investigation. The SCDOT rehabilitated about 280 centerline miles of primary routes in 2020; these pavement sections required at least 150 PSY of surface type B or C. Assuming 50% of these pavements were in poor condition and 50% in fair condition, the expected annual cost savings to the SCDOT would have been \$138,790 if field investigation had been performed and the design *with* investigation had been used. Therefore, it is recommended that the SCDOT should focus on performing field investigation on pavements that are in fair and poor conditions. It should be noted that on-going efforts (pooled fund study and SPR 748) will likely impact the investigation procedure for good pavements.

Field investigation should be strongly considered for each candidate project not only because of lower cost but also of higher quality design. That is, the design *with* investigation provides a more accurate design (i.e., providing the necessary SN) and it addresses both bottom-up and reflective cracking; thereby, prolonging the life of the pavement. The mechanistic-empirical design evaluation approach was found to provide a more accurate representation of the observed/actual pavement service life than the SN method which uses coefficient depreciation values based on visual inspection and age of pavement. An advantage of using the mechanistic-empirical approach to determine the pavement service life is that the SCDOT can alter the trigger value for percentage of fatigue cracking to enable a more precise quantitative approach for when a pavement should be rehabilitated.

5.2 Implementation Recommendations

The decision to perform field investigation should consider the available number of trained personnel to perform field investigation and traffic control. It should be noted that the cost of performing field investigation (i.e., coring, FWD) and traffic control will be higher if the SCDOT were to contract out this work to consultants. Current rates indicate that it will be about 5 to 7 times that of the in-house cost.

It is recommended that the State Pavement Engineer holds annual or bi-annual workshops to review and discuss the procedure for identifying which project requires field investigation with all district contract managers (DCMs). These workshops will allow the DCMs to provide feedback, and the dialogue between the DCMs and State Pavement Engineer will improve the identification procedure over time and ensure consistent application of the procedure across the state.

In the course of this project, it became clear that the SCDOT could benefit from having a pavement design decision support system (DSS). A Web-based and GIS-based pavement design DSS that integrates all of the SCDOT pavement design tools and roadway maintenance history would eliminate guesswork regarding existing pavement condition and facilitate the development of an appropriate reconstruction/rehabilitation/preservation treatment. The DSS should include a Web-based version of the SCDOT's current DOS-based backcalculation tool and Access-based Pavement Estimator. Making both of these tools Web-based will allow both SCDOT staff and consultants to use them in the office or at project site with different devices, including laptops, tablets and smartphones. The DSS should also include a Web-based version of the decision tree/flow chart that guides DCMs on when to employ field investigation. Such decision tree/flow chart should incorporate findings from this study and those from SPR 748 (Traffic Speed Deflectometer) project. Additionally, the DSS should provide the SCDOT staff and consultants the ability to enter criteria such as pavement rehabilitation/preservation information, material and layer properties, core sample images, and structural deflection data for a roadway segment, and be able to query for projects that meet one or more of the specified criteria.

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