OKLAHOMA TRANSPORTATION CENTER

ECONOMIC ENHANCEMENT THROUGH INFRASTRUCTURE STEWARDSHIP

QUANTIFYING THE COSTS AND BENEFITS OF PAVEMENT RETEXTURING AS A PAVEMENT PRESERVATION TOOL

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OTCREOS7.1-16-F

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16. ABSTRACT

The objective of the study is to build on the research done overseas and conduct a comparative field evaluation of various methods used to restore pavement skid resistance by retexturing the existing surface with either a surface treatment, chemical treatment or a mechanical process. In Phase 1, 16 field test sections were constructed on State Highway 77 between Oklahoma City and Norman. Monthly microtexture and macrotexture measurements were taken over a period of 22 months. The field data was reduced to create deterioration models based on loss of both micro and macrotexture over time. The models were then used to calculate effective service lives for each treatment which was then used as input for a life cycle cost analysis.

A new lifecycle cost analysis model for pavement preservation treatments based on equivalent uniform annual cost rather than net present value was developed and is used to process the pavement texture change data. This will allow pavement managers to have the required information to be able to make rational engineering design decisions based on both physical and financial data for a suite of potential pavement preservation tools. Each treatment alternative has been evaluated under the same conditions over the same period of time by an impartial research team. The project will continue for a third year under the Phase 2 OTCREOS9.1-21 contract. Upon its completion, a pavement preservation treatment toolbox for a total of 23 different treatments will be developed and furnished to ODOT for use by its division maintenance engineers in the state-wide pavement preservation program.

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SI (METRIC) CONVERSION FACTORS

Approximate Conversions to SI Units

Symbol	When you know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	25.40	millimeters	mm
ft	feet	0.3048	meters	m
yd	yards	0.9144	meters	m
mi	miles	1.609	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm
ft^2	square feet	0.0929	square meters	m^2
yd^2	square yards	0.8361	square meters	m^2
ac	acres	0.4047	hectares	ha
mi^2	square miles	2.590	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.0283	cubic meters	m^3
yd^3	cubic yards	0.7645	cubic meters	m^3
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.4536	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	degrees Fahrenheit	(°F-32)/1.8	degrees Celsius	°C
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.448	Newtons	N
lbf/in^2	poundforce per square inch	6.895	kilopascals	kPa

Approximate Conversions from SI Units

Symbol	When you know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.0394	inches	in
m	meters	3.281	feet	ft
m	meters	1.094	yards	yd
km	kilometers	0.6214	miles	mi
		AREA		
mm^2	square millimeters	0.00155	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.196	square yards	yd^2
ha	hectares	2.471	acres	ac
km^2	square kilometers	0.3861	square miles	mi^2
		VOLUME		
mL	milliliters	0.0338	fluid ounces	fl oz
L	liters	0.2642	gallons	gal
m^3	cubic meters	35.315	cubic feet	ft^3
m^3	cubic meters	1.308	cubic yards	yd^3
		MASS		
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.1023	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	degrees Celsius	9/5+32	degrees Fahrenheit	°F
		FORCE and PRESSURE or STRESS		
N	Newtons	0.2248	poundforce	lbf
kPa	kilopascals	0.1450	poundforce per square inch	lbf/in^2

Quantifying the Costs and Benefits of Pavement Retexturing as a Pavement Preservation Tool

Final Report

OTCREOS7.1-16

July 31, 2010

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

The objective of the study is to build on the research done in Australia (ARRB, 2001) and New Zealand (TNZ, 2002) and conduct a comparative field evaluation of various methods used to restore pavement skid resistance by retexturing the existing surface with either a surface treatment, chemical treatment, or a mechanical process. The goal is to assemble the technical engineering data for each treatment coupled with an economic analysis of the costs and benefits associated with each treatment. This will allow pavement managers to have the required information to be able to make rational engineering design decisions based on both physical and financial data for a suite of potential pavement preservation tools. Each treatment alternative will have been evaluated under the same conditions over the same period of time by an impartial research team.

Pavement preservation is the embodiment of infrastructure stewardship. Its central theme is using pavement technology to “keep good roads good.” There is a wide range of funding for pavement preservation and maintenance programs with the U.S., average ranging from a low of $15.0 million to a high of $1.7 billion per year (Tighe and Gransberg, 2010). In those agencies, like the Oklahoma Department of Transportation (ODOT) that are on the low end of the funding spectrum, the need for an aggressive pavement preservation program is critical to getting as much value out of each maintenance dollar as possible (Galehouse, 2003; NHI, 2007). Pavement preservation is inherently sustainable as it seeks to minimize the amount of natural resources consumed over a pavement’s life cycle (Geiger, 2005). Therefore, focusing on pavement preservation rather than reactive maintenance and repair, furnishes a broad foundation on which to build ODOT’s pavement sustainability program.

As part of this research project, a series of test sections were constructed on existing asphalt and concrete pavement sections on State Highway 77H (Sooner Road) between Norman and Oklahoma City, Oklahoma. Each test section is ¼ miles (400 meters) long and one lane wide. Each section has been retextured with a different type of pavement preservation process. There are a total of 23 different treatments that are

covered in the research. Of these, 14 were installed during the summer of 2008 as part of OTCREOS7.1-16, which is now complete. The remaining nine sections were installed during the summer of 2009 as a part of OTCREOS9.1-21. Because the two projects are integrated, it is difficult and confusing to attempt to discuss them as separate projects. Additionally, the test sections installed as part of 7.1-16 will continue to be sampled on a monthly basis for macrotexture and skid along with the 9.1-21 test sections. Table 1 shows the details of the test sections. Surface friction and pavement macrotexture were measured on each test section before the treatments and continue to be measured on a monthly basis for three years after application. Thus, changes in both skid resistance and pavement macrotexture will be recorded over time, and each treatment's performance can then be compared to all other treatments in the same traffic, environment, and time period.

Table 1 Oklahoma Pavement Preservation Test Sections

Asphalt Test Sections		
Surface Treatment	**Chemical Treatment**	**Mechanical Treatment**
• Fog seal • Microsurfacing • ODOT Standard 3/8" chip seal • ODOT Standard 5/8" chip seal • ODOT Standard 5/8" chip seal with a fog seal • Single size ½" chip seal • Novachip • Open Graded Friction Course • Open Graded Friction Course with a fog seal • Permeable friction course • 1" Hotmix Asphalt mill-inlay	• E-Krete pavement surface stabilizer • Asphalt penetrating conditioner with crack seal	• Pavement retexturing using shotblasting (48" width) • Pavement retexturing using abrading (72" width) • Pavement retexturing using abrading (72" width) with fog seal • Pavement retexturing using a flat headed planing (milling) technique with asphalt penetrating conditioner • Asphalt diamond grinding
Concrete Test Sections		
Surface Treatment	**Chemical Treatment**	**Mechanical Treatment**
	• Pavement retexturing using shotblasting treated (48" width) with Nanolithium densifier	• Pavement retexturing using shotblasting (48" width) • Pavement retexturing using abrading (72" width) • Diamond grinding • "Next Generation" diamond grinding

The project's major deliverable is a pavement surface texture maintenance guide that can be used by ODOT pavement managers to select the appropriate pavement preservation treatment to restore surface texture and skid resistance to various types of pavements throughout the state. This will constitute a surface retexturing "toolbox" that contains both the technical engineering information as well as the economic analysis of each treatment's efficacy. The idea is not to identify the "best" method but rather to quantify the benefits of all the treatments in a manner that then allows a pavement engineer to select the right pavement preservation "tool" for the specific issue that they need to address and satisfy the fundamental definition of pavement preservation: "put the right treatment, on the right road, at the right time" (Galehouse et al., 2003.)

This study is also demonstrating the value of long-term pavement preservation field research. It has shown the need to have the combination of both skid resistance and macrotexture measurements available to the maintenance engineer when pavement preservation treatments are selected. Combing these two measurements with financial information and life cycle cost analysis provides all the tools that are necessary to permit an informed engineering and management decision to be made.

This project demonstrates a robust partnership between the Oklahoma Transportation Center (OTC), the University of Oklahoma (OU), the Oklahoma Department of Transportation (ODOT), and members of the pavement preservation industry from six states. This project is not a competition between products. It is the start of an encyclopedia of pavement preservation comparative analyses, and projects of this nature could be instituted throughout the U.S. to provide the unique local performance information that only long-term field testing can generate. It is demonstrating the benefits of pavement preservation materials and means and methods in a manner that will not only be of value to ODOT and other Oklahoma public agencies but also to the rest of the nation. All the test sections were donated by either ODOT or the pavement preservation industry, and the fact that over $400,000 worth of pavement preservation treatments were donated as well as the in-kind contributions by ODOT in providing traffic control, skid testing, and engineer's time, shows the importance of pavement preservation research.

The project has drawn both national and international interest. Caleb Riemer, PE, the doctoral student, was appointed to the FHWA Pavement Preservation Expert Task Group (PPETG), a rare honor for such a young person. The MS student, Dominique Pittenger, was the only MS student of nine University Transportation Center graduate research assistants recognized by the Transportation Research Board (TRB) as the top graduate researchers in the nation. The other nine were doctoral candidates. She went on to write and win a TRB grant to support her doctoral work in extending this project's results and methodology to airport pavements. Also, she was named the *2010 OTC Student of the Year,* which is a very prestigious award. As a result of PPETG presentations made in New Orleans and Reno by Mr. Riemer and Ms. Pittenger, the Southeastern Pavement Preservation Partnership decided to hold its 2011 conference in Oklahoma City so that the OTC project could act as the conference centerpiece and possible spawn similar research in other states.

Drs. Gransberg and Zaman were invited to submit and present a paper on the project at the 1st International Conference of Pavement Preservation sponsored by TRB and the Federal Highway Administration (FHWA). After that event Dr. Gransberg was appointed as a peer of Natural Sciences and Engineering Research Council of Canada, their version of the US National Science Foundation, and he was subsequently invited to present this OTC project at an international airport pavement conference in Toronto and to deliver a guest lecture at the University of Waterloo in Ontario. He made invited presentations in August 2010 at the Universities of Canterbury and Auckland in New Zealand. Sarah Brockhaus was awarded a grant by the Oklahoma Asphalt Paving Association to complete her undergraduate honors thesis using the project's data. The award funded a trip for her to collect data and work in Dr. Susan Tighe's green pavements lab at the University of Waterloo in Canada. There are plans for one of Dr. Tighe's students to visit OU during the coming year and participate in the field testing. Finally, Bekir Aktas an ABD doctoral candidate in pavement engineering at Sulieman

Demirel University in Isparta, Turkey, was awarded a year-long research-abroad fellowship by his government to join Drs. Gransberg and Zaman's research team on this and other OU projects in the area of pavement preservation. Finally, articles on this project have been featured in *Roads and Bridges* and the *Journal of Pavement Preservation.*

To briefly summarize, this OTC project has gone beyond its expectations and made Oklahoma the clear leader in pavement preservation research at a period in our nation's economy where DOTs must wring every last bit of value out of their pavement management budgets. It has spun off research partnerships with engineering schools in Canada and Turkey, which will furnish a very rich environment for Oklahoma students to study pavement preservation in the future. The OTC project's student research assistants have won two national awards, two state awards, and an appointment to a national technical committee. The project was selected by the Western Association of State Highway and Transportation Officials (WASHTO) as its candidate for the AASHTO recognition as the nation's most influential state-funded research project and as a result of that recognition, this OTC project will be featured in a special informational report being developed by the US Congress to demonstrate the return on investment in transportation research.

INTRODUCTION

Pavement skid resistance is perhaps the most important engineering component of the road from a safety standpoint. Slippery pavements are the result of several causes, chief of which is the loss of pavement surface micro and macrotexture. A European study found that increasing the pavement's macrotexture not only reduced total accidents under both wet and dry conditions, but also reduced low speed accidents (Roe et al., 1998). As a result, pavement managers must not only manage the structural condition of their roads but also their skid resistance (Gee, 2007; NCHRP, 1989). In fact, it is possible for a structurally sound pavement to be rendered unsafe from a loss of skid resistance due to polishing of the surface aggregate, or in the case of chip seals, flushing of the binder in the wheel paths (Patrick et al., 2000). This results in a safety requirement to modify the pavement surface to restore skid resistance. Many of the possible tools for restoring skid resistance, like chip seals, are also used for pavement structural preservation. Thus, it seems that maintenance of adequate pavement skid resistance is also a pavement preservation activity (Moulthrop, 2003). This intersection of two requirements creates a technical synergy that a state like Oklahoma can leverage to stretch its pavement maintenance budget if it has the necessary technical and financial information to assist decision-makers in selecting the appropriate surface treatment tool for a given situation.

PROBLEM

There is a wealth of information on skid resistance in the literature (Voight, 2006; Patrick et al., 2000; Roe et al., 1998; Henry, 2000). However, most of the previous research has been in the safety realm developing the relationship between skid resistance and crashes. There is also a wealth of information on pavement surface treatments (NCHRP, 1989). However, a majority of previous studies has been in the laboratory and focused on the material science aspect. Very little substantive work has been done in the field regarding surface treatment performance, and most of the research in this area is focused on short-term performance (Owen, 1999). The FHWA Long Term Pavement Performance Program (LTPP) collects friction data as part of its standard protocol (Titus-Glover and Tayabji, 1999). However, the LTPP data largely relates to pavement mix design criteria and while it includes data for chip seals, it does not collect data for any of the other potential pavement preservation treatments. Additionally, the typical research project only examines a single surface treatment. Also, making it more difficult for DOT pavement managers, much of the published research is commercial in nature and while completely valid, contains a strong inherent bias toward showing the given product in its best light (ARRB, 2001; Vercoe, 2002; Bennett, 2007). Finally, with three exceptions, all completed by the authors of this proposal (Gransberg, 2009; Gransberg and Pidwerbesky, 2007; Gransberg and Zaman, 2005), virtually no research in this area has addressed the economic aspects of pavement retexturing in conjunction with the engineering aspects. Thus, the gap in the body of knowledge is the lack of engineering data correlated with a comparative economic analysis of different alternatives to restore skid resistance on a long-term basis.

BACKGROUND

Transportation agencies in the United States have procedures in place to identify and rectify skid resistance problems. However, the procedures are often empirical and tend to be reactive rather than proactive in nature. This is not the case in some other countries. For example, Austroads, the Australia/New Zealand equivalent to AASHTO, developed and has been successfully using a set of procedures to literally manage pavement macrotexture for the past three decades (Austroads, 2005). Austroads sees macrotexture as furnishing enhanced drainage to combat hydroplaning during wet periods as well as enhancing skid resistance. As such, they implemented an aggressive macrotexture-oriented program as part of their pavement management system. Therefore, it is not necessary to develop new procedures for the industry and the transportation agencies in this country. This project seeks to “customize” the Austroads model to suit American needs. The Austroads “Procedure to Identify and Treat Sites with Skidding Resistance Problems” uses the following five steps:

1. “Identify [possible] treatment [alternatives]”
2. Cost works and carry out economic evaluation
3. Shortlist schemes in priority order

4. Carry out short-term measures, if required
5. Program longer term measures" (Austroads, 2006).

From the aforementioned discussion, it is evident that pavement managers in Australia and New Zealand have not only the engineering technical data that they need to generate a set of technically feasible options for rectifying a loss of skid resistance, but they also have the economic data required to be able to place those alternatives in the context *of a limited maintenance budget*. It should be noted that this approach does not merely involve selecting the lowest cost alternative. Instead Austroads requires a *life cycle cost analysis* to accompany all public works and as a result, selects treatment alternatives on a basis of the lowest life cycle cost not the lowest construction cost (Austroads, 2005). As a result, a treatment alternative with a higher initial cost but which effectively extends the service life of a pavement for a longer period can be selected, and the long-term benefits to the agency's multi-year budgets can be accrued.

Additionally, Austroads advocates the use of both short and long-term measures. For example, a given pavement may lose its skid resistance during the winter months where it is climatically impossible to install a bituminous surface treatment due to low ambient air temperatures. Austroads has a machine called the ultra-high pressure watercutter that can literally go out in a limited area such as a slippery superelevated curve or a freeway ramp and restore pavement macrotexture in any weather (Vicroads, 2003). This would be a short-term measure. The long-term measure might involve installing microsurfacing or a new chip seal in the summer when the climatic conditions allow it. Both treatments would be included in the life cycle cost analysis used to justify the retexturing project.

OBJECTIVES

The primary objective of this study is to build on the research done in Australia and New Zealand. The on-going OTCREOS9.1-21 Phase 2 work will build on the OTCREOS7.1-16 Phase 1 work described in this report. The goal is to furnish pavement managers with the technical engineering data for each pavement preservation treatment coupled with a life cycle cost analysis of the costs and benefits associated with each treatment. This will allow ODOT pavement managers to have the required information to be able to make rational engineering design decisions based on both physical and financial data for a suite of potential pavement preservation tools, which were evaluated under the *same conditions* over the *same period of time* by an *impartial research team*. This project represents a true collaboration between ODOT, industry and university. Considering its importance, both ODOT and industry have committed significant resources toward this study.

SCOPE

The project's scope is best illustrated in the tabular form shown in Table 1. The table shows that the scope covers all three treatment types for asphalt pavements and two types for concrete.

Table 1 Oklahoma Pavement Preservation Test Sections

Asphalt Test Sections		
Surface Treatment	**Chemical Treatment**	**Mechanical Treatment**
• Fog seal • Microsurfacing • ODOT Standard 3/8" chip seal • ODOT Standard 5/8" chip seal • ODOT Standard 5/8" chip seal with a fog seal • Single size ½" chip seal • Novachip • Open Graded Friction Course • Open Graded Friction Course with a fog seal • Permeable friction course • 1" Hotmix Asphalt mill-inlay	• E-Krete pavement surface stabilizer • Asphalt penetrating conditioner with crack seal	• Pavement retexturing using shotblasting (48" width) • Pavement retexturing using abrading (72" width) • Pavement retexturing using abrading (72" width) with fog seal • Pavement retexturing using a flat headed planing (milling) technique with asphalt penetrating conditioner • Asphalt diamond grinding
Concrete Test Sections		
Surface Treatment	**Chemical Treatment**	**Mechanical Treatment**
	• Pavement retexturing using shotblasting treated (48" width) with Nanolithium densifier	• Pavement retexturing using shotblasting (48" width) • Pavement retexturing using abrading (72" width) • Diamond grinding • "Next Generation" diamond grinding

The test sections demonstrate how each of the 23 treatments performs when subjected to the same environment, same traffic, and same testing protocol over the same period. The 12 asphalt surface treatments and the concrete diamond grinding are commonly used by ODOT divisions across the state. The remaining ten test sections are treatments that are new to Oklahoma and represent an opportunity to expand the tools available to ODOT pavement managers.

Table 2 is taken from the FHWA Memorandum on Pavement Preservation (Geiger, 2005). It shows that pavement preservation treatments (shaded in green) are applied to extend the service life of a given road, NOT to enhance its capacity or structural strength. The treatments shown in Table 1 literally cover the spectrum of pavement preservation. They range from shotblasting which merely restores macro and microtexture and uses no new raw materials to a 1” (2.5cm) mill and inlay. The FHWA rules state that overlays that are less that 1.5” thick are not deemed to enhance structural capacity (Geiger, 2005). The economic importance of understanding the difference between pavement preservation and pavement maintenance is huge. Pavement preservation projects are eligible for Federal-aid funding, while maintenance projects must be entirely funded by the state. Therefore, this project personifies the OTC theme of “economic enhancement through infrastructure stewardship.” The results of this project will effectively expand the number of pavement preservation tools that can be used by ODOT and every single one of those tools brings federal aid eligibility along with it.

Table 2 Pavement Preservation Guidelines (after Geiger, 2005)

Pavement Preservation Guidelines					
	Type of Activity	**Increase Capacity**	**Increase Strength**	**Reduce Aging**	**Restore Serviceability**
	New Construction	X	X	X	X
	Reconstruction	X	X	X	X
	Major Rehabilitation		X	X	X
	Structural Overlay		X	X	X
Pavement Preservation	Minor Rehabilitation			X	X
Pavement Preservation	Preventive Maintenance			X	X
Pavement Preservation	Routine Maintenance				X
	Corrective (Reactive) Maintenance				X
	Catastrophic Maintenance				X

Table 2 also has “corrective/reactive maintenance” highlighted in yellow. This was done to show that some the treatments shown in Table 1 can also be used for this category. For example, shotblasting, skidabrading, and microsurfacing can all be applied to a structurally sound pavement that has become unsafe due to loss of skid resistance. However, if used for this purpose, federal funding will not be authorized.

TECHNOLOGY TRANSFER

Technology transfer has occurred continuously during this project. It has occurred at a number of levels. First, at the local level, Caleb Riemer, PE is a maintenance engineer in Division 3. He has already implemented the use of several new treatments, including the shotblasting and E-crete to his division. He has written specifications as a result and has shared those along with emerging test results with the other ODOT divisions during routine state-wide maintenance meetings. As previously stated, the scale and breadth of this project has drawn national and international attention. The research team has made 22 presentations in 24 months and published 17 journal and proceedings papers. Two technology transfer workshops were held in Norman as a part of a secondary education initiative to expose high school science teachers to engineering testing. Again, Caleb Riemer was the instructor at both. Dominique Pittenger led a day long workshop for top performing Oklahoma high school students in July 2010, which included a look at the test procedures used by pavement engineers in the field on this OTC project. Finally, research partnerships have been developed with the University of Waterloo in Canada and Suliyeman Demirel University in Turkey. An OU research assistant traveled to Canada last fall, and the project is benefitting from the work done by a Ph.D. student from Turkey who is spending a year working with the OU pavement preservation research team.

The body of the report is organized in four major sections, following the three primary areas in which the project is organized. Those sections are as follows:

- The science of pavement surface micro and macrotexture: Covers the information necessary to understand the field test results.

- Field test protocol and methodology: Describes the procedures used in the research and features the results of the treatments installed in 2008.
- Life cycle cost analysis: Presents a new model for calculating pavement preservation life cycle costs that differs from the classic model advocated by the FHWA and presents the life cycle cost output for the treatment installed in 2008.
- Field test results: The analysis of the two years of Phase 1 research (OTCREOS7.1-16) and emerging findings.

IMPORTANCE OF PAVEMENT SURFACE TEXTURE

Engineers must use every possible tool during design, construction and operations to make the road as safe as possible. The design/construction engineer has control over the geometry of the road, both in horizontal and vertical alignments, the speed of travel, the signage of the roadway system, the material properties of the surface course and over time as the pavement deteriorates, and the maintenance engineer can control the characteristics of that surface by selecting various pavement preservation and maintenance treatments. Ultimately, the physics of the moving vehicle will determine if the engineers who have been involved in the road's service life will determine whether or not the road can be safely traveled. Once the road is built, the only facet of the road that is truly controllable is its surface. No other factor of the complex three-dimensional equation that determines whether a moving vehicle will be able to safely remain on the surface of the road can be changed without a large relative commitment of resources to effect the desired change. As a result, the maintenance engineer's mission must be to preserve the road's structural capacity and to ensure that its surface frictional characteristics are sufficient to safely pass traffic for which it was originally designed.

Roadway crashes are complex events that are the result of one or more contributing factors. Such factors fall under three main categories: driver-related, vehicle-related, and highway condition-related (Noyce et al., 2005). This project addresses solutions for highway condition-related crashes. It does it by quantifying the rate at which 23 different pavement preservation treatments deteriorate over time. The comparative knowledge treatment deterioration rates is essential for maintenance engineers to select the appropriate treatment for a given pavement condition problem.

Surface Texture

Surface texture is the primary physical characteristic that can be measured after a traffic accident (Manion and Tighe, 2007). One author posits that the factors that cause loss of skid resistance can be grouped into two categories:

- mechanical wear and polishing action rolling or braking
- accumulation of contaminants (Neubert, 2006)

These two categories directly relate to the two physical properties of pavements that create the friction that produces a pavement's skid resistance. The first is called microtexture and it consists of the natural surface roughness of the aggregate as shown in Figure 1.

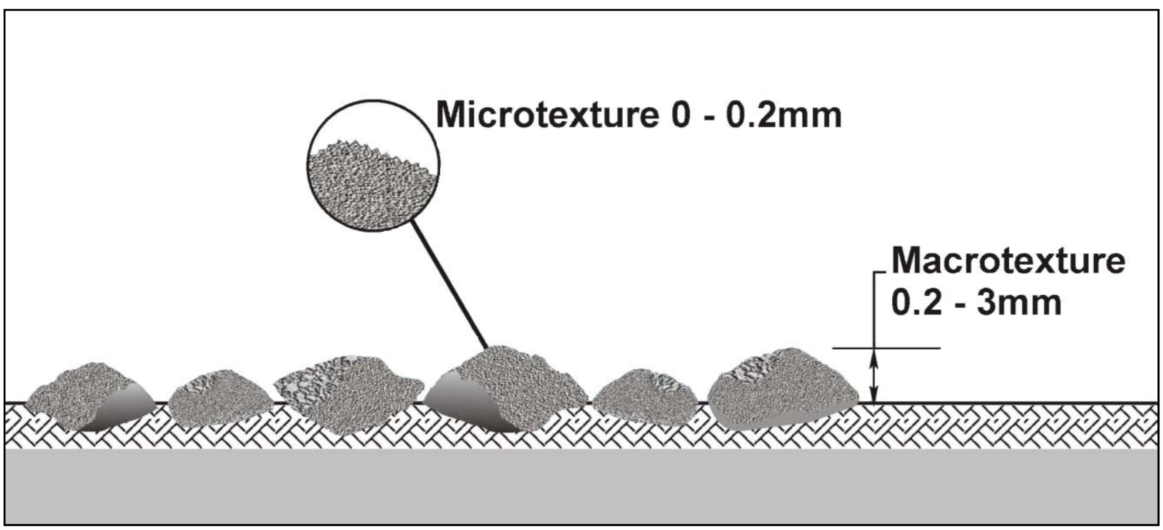


Figure 1: Pavement Surface Microtexture and Macrotexture (Pidwerbesky et al., 2006)

Microtexture is lost due to mechanical wear of the aggregate's surface as it is polished by repetitive contact with vehicle tires and gets smoother. The second is macrotexture and relates to the resistant force provided by the roughness of the pavement's surface. Macrotexture is reduced as the voids between the aggregate and either the cement or binder in the pavement's surface is filled with contaminants. This can happen in three possible ways:

1. Transient macrotexture loss from icing or mud tracked onto the surface
2. Persistent macrotexture loss from flushing or bleeding in the asphalt binder
3. Localized macrotexture loss from accumulation of tire rubber deposits from braking or skidding.

The skid resistance of a highway pavement is the result of a "complex interplay between two principal frictional force components—adhesion and hysteresis" (Hall, 2006). There are other components such as tire shear, but they are not nearly as significant as the adhesion and hysteresis force components. Figure 2 shows these forces and one can see that the force of friction (F) can be modeled as the sum of the friction forces due to adhesion (F_A) and hysteresis (F_H) per Equation 1 below:

$$F = F_A + F_H \qquad (1)$$

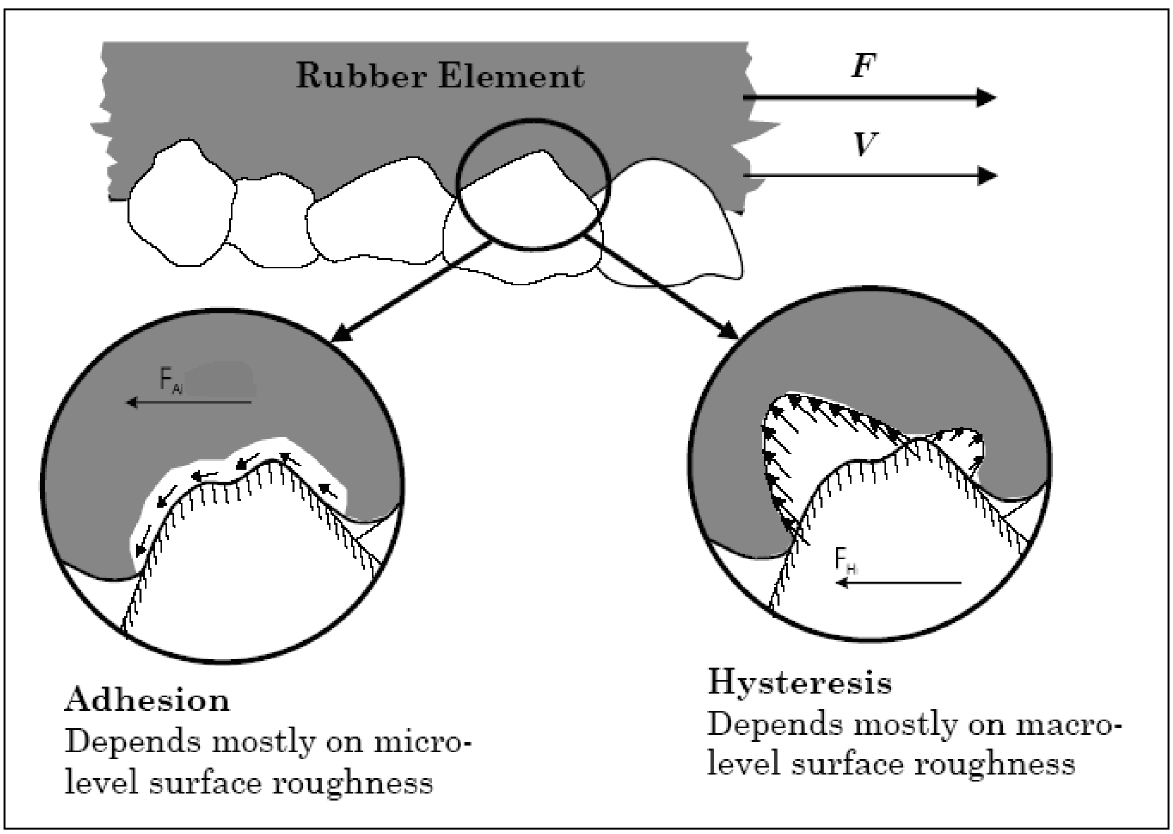


Figure 2: Pavement Friction Model (Hall, 2006)

Relating Figures 1 and 2, one can see that the frictional force of adhesion is "proportional to the real area of adhesion between the tire and surface asperities" (Hall, 2006), which makes it a function of pavement microtexture. The hysteresis force is "generated within the deflecting and visco-elastic tire tread material, and is a function of speed" making it mainly related to pavement macrotexture (Hall, 2006). Thus, if an engineer wants to improve skid resistance through increasing the inherent friction of the physical properties of the pavement that engineer should seek to improve *both* surface microtexture and macrotexture. This idea is confirmed in a 1984 study of the effect of rubber deposits on airport runway pavements that stated: "Rubber buildup alters the texture properties of the runway as well as the frictional coefficient" (Lenke et al., 1986).

In Australia and New Zealand extensive work has been done to manage macrotexture to control crash rates. In North America extensive work has been done to manage skid number, or microtexture, to control crash rates. Generally, US agencies believe that if an engineer could control wet weather related crashes then all crashes would be reduced. Therefore, most studies regarding crash rates versus surface characteristics, whether macrotexture, skid number, or microtexture, primarily focus on the reduction of wet weather crashes (NCHRP, 1989). To better understand exactly how to manage the surface characteristics over time, a thorough definition of each characteristic must be established in order to see the role each plays in contribution to safe travel.

Skid number is a critical component when analyzing road safety, making it one of the most widely studied surface characteristics. Skid number can be measured in a number of ways with the common method being ASTM E 274 skid tester equipped with either with a smooth tire or a ribbed tire. Other common methods are the SCRIM device, the grip tester device, and the mu-meter devices. For this research, the ASTM E 274 skid tester with a ribbed tire serves as the primary way of obtaining the skid number. The testing apparatus is towed behind a vehicle at the desired speed, 40 mph in this project which is the standard for ODOT skid testing. Water is then applied in front of the tire just before the tire's brakes force the tire to lock up. The resultant force is then measured and converted into a skid number value (ASTM, 2000).

Surface texture is separated into three components microtexture, macrotexture, and megatexture as shown in Figure 3. Each has a varying range of texture depth and influences to the pavement tire interactions. Microtexture is the grittiness of the surface; it is a function of the aggregate's geology and its ability to withstand polishing. The force normally associated with microtexture is “adhesion” which occurs from the shearing of molecular bonds formed when the tire rubber is pressed into close contact with pavement surface (Noyce et al., 2005).

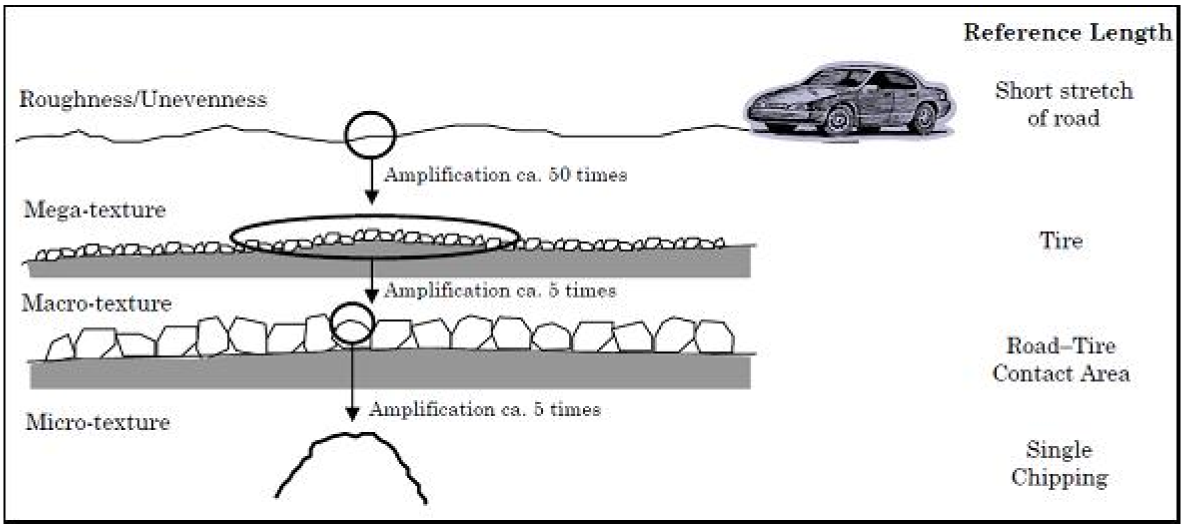


Figure 3: Pavement Texture Definitions (Evans, 2002)

Macrotexture can also be broken into two separate physical components: hysteresis and drainage. Good texture depth assists with drainage, preventing the formation of a water sheet across the surface with the resulting risk of hydroplaning. While hysteresis is the mechanical deformation of tire with the surface, good texture depth is needed to enable this mechanical deformation to occur, which then releases energy through heat (Cairney, 2005). The PIARC describes macrotexture as a surface roughness quality defined by the mixture properties, i.e. shape, size, and gradation of aggregate, of asphalt paving mixtures and the method of finishing or texturing used on concrete paved surfaces, such as dragging, tining, or grooving. Macrotexture's range is set at 0.5mm to 50mm, and it predominately controls the stopping ability on the roadway surface at speeds greater than 45 mph.

Megatexture is on a much larger scale than either microtexture or macrotexture and is in essence the irregularities of the road such as potholes, rutting, joints, cracks, raveling, and skin patches. These have a small effect on stopping ability. However, megatexture plays a significant role in how the driving public perceives the road, via the resultant road noise or poor ride quality. Another surface characteristic that accompanies microtexture, macrotexture, and megatexture, is ride quality or roughness measured by the International Roughness Index (IRI) number. Many DOTs use roughness measurements to portray the overall integrity of their roadway system (Li et al., 1974; Moulthrop et al., 1996; Zaniewski and Mamlouk, 1999). This project does not address megatexture or roughness. Its focus is on micro and macrotexture, the variables of interest for road surface safety.

Surface Texture as a Pavement Preservation Activity

Microtexture, macrotexture, megatexture, and roughness, taken together, summarize the universe of roadway surface defects that a maintenance engineer must address. If the road surface begins to ravel, rut, or develop base failures, megatexture will increase. If the road is found to be losing its skid resistance, measured microtexture will be found to be decreasing. If a section of road begins to experience crashes due to hydroplaning, its macrotexture will have decreased. The same is true if a chip sealed road does not retain its aggregate. All these scenarios are the direct result of the surface characteristics of the highway and can be used by the maintenance engineer to identify and select an appropriate pavement preservation or maintenance treatment for a given problem.

Pavement preservation's focus is placing" the right treatment, on the right road, at the right time" (Galehouse et al., 2003). If a road's megatexture or IRI become unacceptable, it is too late to attempt to "preserve" the pavement. These measures are indicative of inadequate structural capacity and will require major maintenance or reconstruction treatments to rectify the loss in ride quality and to recapture the pavement's structural capacity. Hence, understanding the relationships between microtexture and macrotexture deterioration over time, allows the engineer to establish "trigger points" that permit sufficient time to schedule pavement preservation before the pavement's structural capacity is permanently compromised.

A good example of a trigger point comes from the New Zealand Transport Agency (NZTA). NZTA uses macrotexture measurements as one of the key performance indicators (KPI) on its national highway network (Manion and Tighe, 2007). Much of that network is surfaced with a chip seal and the rainy climate found in New Zealand demands that pavement engineers manage macrotexture as a means to furnish the requisite surface drainage for safety. NZTA has established that if the average macrotexture of a road drops below 0.9mm (0.04 in) on roads with posted speed limits greater than 70 km/hr (43.5 mph) that pavement preservation by resealing is no longer an option and prescribes the removal and replacement of the surface course. With this failure criterion in mind, NZTA maintenance engineers have then developed individual trigger points based on local conditions that allow the programming of a pavement preservation seal before the macrotexture loss becomes critical (Pidwerbesky et al., 2006).

What pavement preservation often overlooks are other constraints a maintenance engineer also faces. These constraints are primarily budgetary in nature but also can include political or construction timelines. When an engineer determines that a roadway surface needs a treatment to address a surface characteristic deficiency, selecting the appropriate treatment is a critical decision. Currently, the engineer must rely on practical empirical data, gathered through experience in the field to estimate the impact of each treatment option and how long each treatment will last. The treatment's service life is important due to factors such as the availability of current and/or future funding or the timing of the next major reconstruction project. This information has historically been estimated through laboratory testing or left to the judgment of the engineer. The goal of this research is to standardize the pavement preservation treatment selection process, to assist the pavement maintenance engineers in making treatment selection decisions by quantifying the engineering properties of commonly available surface treatments, and applying that data to create short term deterioration models for each treatment based on actual field testing.

RESEARCH METHODOLOGY AND PROTOCOLS

When setting up a research project of this magnitude it is useful to study research projects of the past. One of the largest research projects in the field of surface-tire interaction occurred on Wallops Island, Virginia (Yager et al., 2000). It was designed to characterize the various testing methods and machines used to determine the skid number, microtexture, and macrotexture. In doing so, they set up a large number of pavement test sections that furnish a wide variety of surface treatments. By the end of the process, Yager et al. captured a number of important lessons on how to create test sections that support the technical objectives of the research (Yager et al., 2000).

The goal of this project is to create simple deterioration models for a wide variety of pavement preservation treatments to assist the maintenance engineer with selecting the most appropriate treatment given their situational needs. To do this a uniform test section for each treatment was developed. Conversely, the project needed to eliminate as many ancillary factors as possible. For all the asphalt test sections, it was determined that a stretch of a 4-lane state highway (SH77) would furnish a satisfactory location to build the test sections. It had an adequate length to install all the test sections in the same lane of traffic. It also facilitated safety and ease of testing, as active traffic could flow at normal speed while testing was being conducted under a single standard lane closure. The sections were placed in the outside, south-bound lane of travel with gaps between each to avoid major turning motions at intersections and driveways and to act as control sections. The length was predetermined to be 1320 feet (402 meters) which allowed three skid measurements per section but reduced the expense to the contractors donating and installing each section. To ensure uniformity the sections were also designed as full lane-width sections to not inadvertently create an uneven driving surface. The test section locations were determined before the treatments were applied and a baseline test of micro and macrotexture was completed for each section.

Test Section Development

In 2005, the Federal Highway Administration issued a memorandum that standardized the terminology for pavement preservation projects (Geiger, 2005). This document described those practices that are eligible for federal funding. The essence of that document was to restrict pavement preservation treatments to those that do not enhance or restore structural integrity. Subsequent guidance refined the definition to allow thin overlays up to 1.5 inches (3.7 cm) thick (Gee, 2007). Thus, authorized asphalt pavement preservation treatments range from minimal treatments such as shotblasting that merely restores microtexture and fog seals, to significant treatments like thin overlays on asphalt pavements. A similar range of possible treatments exists in concrete pavements which run from shotblasting through grinding and grooving to white-topping.

From the pavement preservation treatments approved by the FHWA, the researchers selected a series of pavement preservation treatments that spanned the spectrum of possible treatments and are shown in Figure 4. Phase 1 constructed nine asphalt test sections:

- 1” mill and inlay section
- 5/8” chip seal section
- 3/8” chip seal section
- fog seal section
- open graded friction course section
- asphalt penetrating conditioner section
- shot blasting section using a 4’ head
- shot blasting section using a 6’ head
- shot blast section using a 6’ head followed by a fog seal application.

There are two test concrete test sections: a shot blasting section using a 4’ head and a shot blasting section using a 6’ head. All sections were constructed in the summer of 2008, the asphalt sections were constructed in the southbound outside lanes of Oklahoma State Highway 77H and the concrete sections were constructed on the outside lanes of United States Highway 77, one in the southbound and one in the northbound outside lanes.

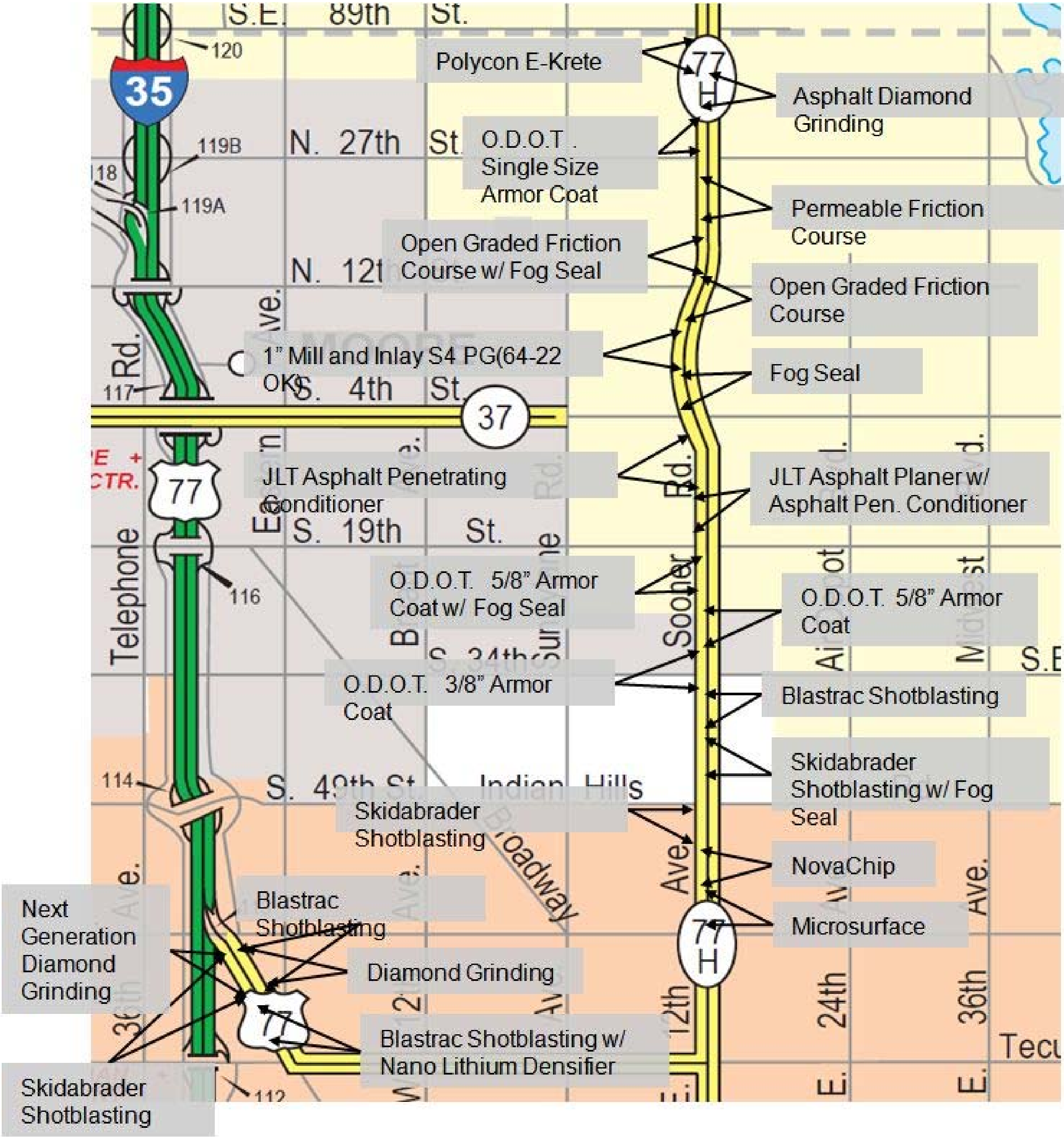


Figure 4: Phase 1 Test Site Locations

Asphalt Test Section Descriptions

The following are detailed descriptions of the test sections that were built on asphalt substrate:

- The 1 inch mill and inlay was constructed by contract forces using an Oklahoma DOT mix design classification of S4 PG (64-22 OK) which is a standard hot mix asphalt normally used in maintenance applications. The existing surface was milled to a depth of 1 inch and the HMA was then laid in the void.

- The 5/8ths inch chip seal used standard ODOT specifications in regards to the aggregate and oil. The oil, provided by Ergon, was Cationic High Float Rapid Set – 2P. This chip seal was installed by an ODOT chip seal crew.
- The 3/8ths inch chip seal used standard ODOT specifications in regards to the aggregate and oil. The oil, provided by Ergon, was Cationic High Float Rapid Set – 2P. This chip seal was installed by an ODOT chip seal crew.
- The fog seal was SS-1 oil diluted to a ration of 5:1 water to oil and applied to the surface at a rate of 0.1gal/sy across the entire lane of the test section.
- The open graded friction course was installed by a contractor with following the ODOT standard specifications.
- The asphalt penetrating conditioner is a proprietary product of JLT Corp. and was installed by their forces to their specifications.
- The shot blasting of asphalt using a 4 foot blasting head was conducted by Blastrac Inc. of Edmond, Oklahoma, using their specifications and recommended rates.
- The shot blasting of asphalt using a 6 foot blasting head was conducted by Skidabrader Inc. from Ruston, Louisiana, using their specifications and recommended rates.
- The shot blasting of asphalt using a 6 foot blasting head with an accompanying fog seal was jointly conducted by Skidabrader Inc. using their specifications and recommended rates for the shot blasting and by an ODOT contractor for the fog seal, using ODOT standards and specifications as described in the fog seal section above.

Concrete Test Section Descriptions

The following are detailed descriptions of the test sections that were built on a Portland cement concrete substrate:

- The shot blasting of concrete using a 4 foot blasting head was conducted by Blastrac Inc. using their specifications and recommended rates.

- The shot blasting of concrete using a 4 foot blasting head was conducted by Blastrac Inc. using their specifications and recommended rates and the newly textured pavement was then shot with a nanolithium densifer by Calumet Lubricants of Shreveport, Louisiana.
- The shot blasting of concrete using a 6 foot blasting head was conducted by Skidabrader Inc. Ruston, Louisiana using their specifications and recommended rates.
- Diamonding grinding by Penhall Diamond Grinding of Anaheim, California using their specifications and recommended rates.
- New Generation Diamonding grinding by Penhall Diamond Grinding of Anaheim, California using their specifications and recommended rates.

Skid Resistance and Macrotexture Measurements

Abrasion resistance and aggregate microtexture are the two characteristics that have the greatest impact on skid resistance. Therefore, prior to installation, aggregate samples were collected and characterized in the laboratory using both the Micro-Deval method to test for abrasion resistance as recommended by a FHWA report on pavement preservation (Beatty et al., 2002) and the Aggregate Imaging System (AIMS) (Bathina, 2005; Massad, 2001). The Aggregate Imaging System (AIMS) is used to provide a quantitative evaluation of the form, angularity and texture of coarse aggregates and angularity and form of fine aggregates used in surface treatment methods. All aggregates used in the research have been characterized in the same manner.

The field test section data consists of two types of macrotexture measurements. The volume outflow meter ASTM E2380/E2380M-09 (ASTM, 2009) and the New Zealand Transport Agency (NZTA) TNZ T/3 sand circle (TNZ, 1981). The TNZ T/3 testing procedure feeds the TNZ P/17 performance specification which can then be used as a metric to judge the success or failure of the surface treatments in their first 12 months based on a field-proven standard (TNZ, 2002). A recently completed pavement surface texture research project in Texas proved the validity of both the test procedure and the performance specification for use in the US (Gransberg, 2007). The purpose of taking two different types of measurements of pavement surface macrotexture is to allow a back-check by relative readings to be conducted and thus improve the accuracy of the discrete engineering property data collected as well as to enhance reproducibility.

The field test section data also consists of friction measurements using the ODOT's skid trailer using ASTM 274 test using a ribbed tire to produce three skid measurements per test section each month. The skid numbers are then averaged to calculate the average skid number for a given test section. Tests are all conducted on the outside wheel path. Figure 5 shows the skid trailer and the two field macrotexture tests being conducted in the field.

Figure 5: (Clockwise from the top) ODOT Skid Tester, Sand Circle Tests, and Outflow Meter/Sand Circle Testing in Progress

Each section is tested on a monthly basis to gather sufficient data to develop a deterioration model. There were three tests performed on each section:

1. First, the Oklahoma Department of Transportation (ODOT) determines the skid number for each section using its skid trailer,
2. Next, macrotexture is measured using a New Zealand sand circle test,
3. Lastly, a second macrotexture measurement is taken using a Hydrotimer outflow meter.

This allows an opportunity to compare and contrast two macrotexture measurements with the skid number from each section and develop a two-tiered deterioration model with failure criteria for both friction and macrotexture.

The New Zealand sand circle is completed on a monthly basis using the NZTA TNZ T/3 standard. Three sand circles are taken on the outside wheel path and averaged together to eliminate any irregularities caused due to slight variations in the test location. The NZTA sand circle test was chosen due to the unreliability of the ASTM sand patch as demonstrated in an early California DOT study (Doty, 1974) and a recent study conducted for the Texas DOT (Gransberg, 2007). There are limitations on the sand circle primarily on textures that have heavy negative texture as the surface will remain damp up to a day after a rain, turning the sand to mud and compromising the accuracy of the test. A wind shield is used to shelter the circle from winds and prevent loss of test sand during the test. The outflow meter is used to determine macrotexture in the outside wheel path. Four tests are taken and averaged together to provide the macrotexture measurement for a given test section.

The macrotexture data over time from each of the measurement methods is then compiled and reduced. The output is similar to the output shown in Figure 6. It shows how the macrotexture of a given road is gradually lost during the pavement preservation treatment's life cycle. This curve portrays the rate of deterioration of a given treatment and when coupled with an appropriate failure criterion allows the engineer to estimate the treatment's actual service life. From the analysis an actual deterioration rate can be used to furnish a realistic period of analysis to be used in life cycle cost analysis (LCCA).

For instance, NZTA uses 0.9mm of macrotexture as the failure criterion for chip seals. The two chip seal test sections shown in Figure 6 have not reached that point after 18 months of service. Regressing the data would yield an equation that would allow the extrapolation of the curves and the ability to find when each crossed the 0.9mm line. That point in time would be different for both binder types, and since the emulsion road appears to be losing its macrotexture more slowly than the AC road, it would have the longer service life and hence the lower life cycle cost. Thus, this method furnishes a means to compare a marginally higher cost pavement preservation alternative to a lower cost one and then select the treatment that has the lowest life cycle cost not merely the one that has the lowest initial cost, as ODOT must do today.

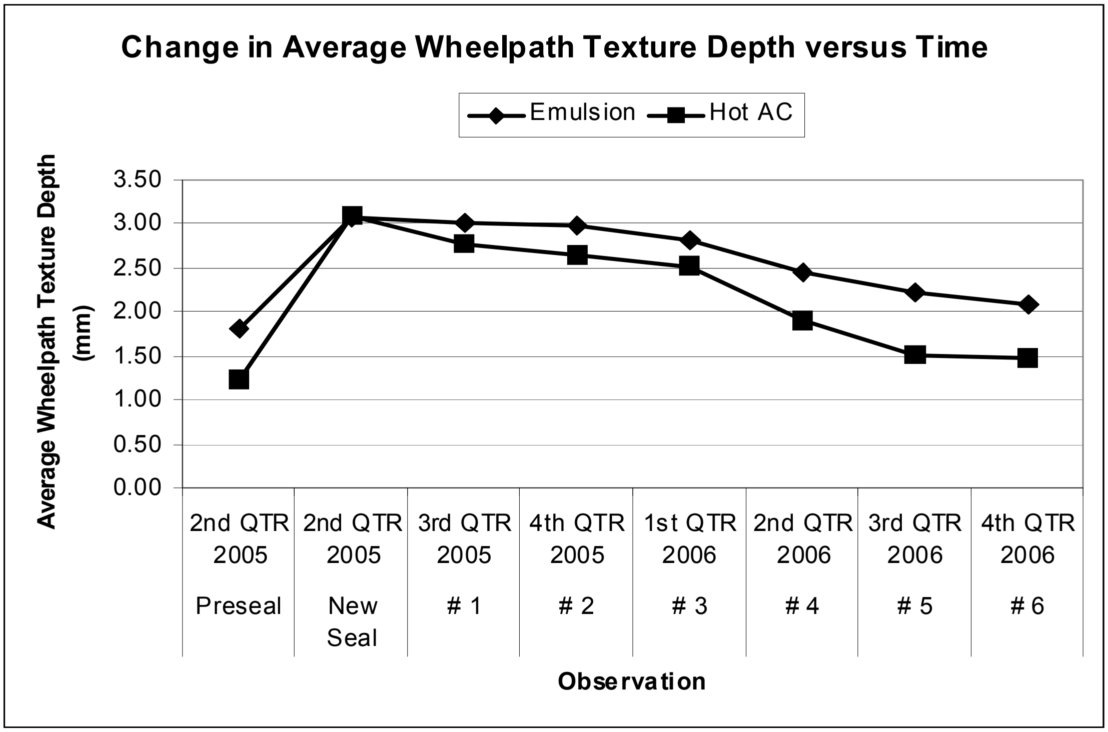


Figure 6: Change in Average Wheelpath Texture Depth Over Time in TxDOT Chip Seal Texture Project (Gransberg, 2007)

LIFE CYCLE COST ANALYSIS

Life cycle cost analysis (LCCA) provides a measure of a pavement preservation treatment's sustainability. Sustainability has become an issue as state transportation agencies are increasingly challenged with "high user demand, stretched budgets, declining staff resources, increasing complexity, more stringent accountability requirements, rapid technological change and a deteriorating infrastructure" (FHWA, 2007). According to FHWA, "[State transportation] agencies are focusing on maintenance and rehabilitation of existing infrastructure to a greater extent than ever before" (FHWA, 2002) and it is expected that *pavement preservation* will become the core of all future highway programs (FHWA, 1998). Oklahoma is certainly one of those agencies for which these statements apply, as evidenced by its latest Asset Preservation Plan that states: "The preservation of our existing transportation system is an absolutely critical part of the Department's mission" (ODOT, 2010). Preservation is especially critical in Oklahoma due to its relatively small transportation budget and correspondingly fragile maintenance budget (Riemer et al., 2010).

Unlike the reactive nature of traditional ‘Worst First’ pavement maintenance programs, pavement preservation is a proactive approach to treating pavements before they fall into disrepair (Geiger, 2005). In other words, preservation keeps good roads good (Galehouse et al., 2003). Theoretically, this proactive approach could reduce the amount of “costly, time consuming rehabilitation and reconstruction projects” and “provide the traveling public with improved safety and mobility, reduced congestion and smoother, longer lasting pavements” (Geiger, 2005). A pavement preservation program, according to the FHWA, consists primarily of three components: *preventive maintenance*, *minor rehabilitation* (non-structural) and some *routine maintenance* implemented for the purposes of slowing deterioration and restoring serviceability of a pavement (Geiger, 2005). Pavement preservation does not include *corrective (reactive)* or *catastrophic maintenance,* which only serve to restore serviceability (Geiger, 2005). Figure 7 shows how pavement preservation differentiates itself from corrective maintenance with its goal of extending the life of a pavement. It is not expected to increase strength or capacity like construction, reconstruction or rehabilitation (Geiger, 2005).

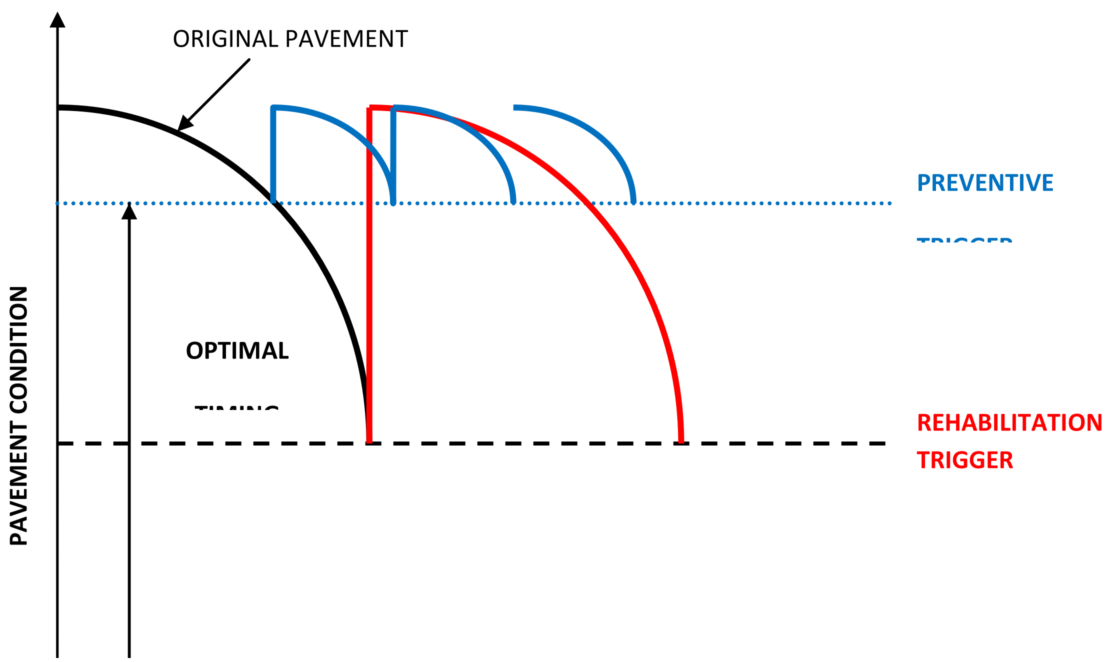


Figure 7: Proactive Approach versus Reactive Approach (Davies and Sorenson, 2000)

LCCA AND PAVEMENT PRESERVATION

The theoretical benefits resulting from pavement preservation is of supreme interest as state transportation agencies search for answers, but the information that would facilitate the widespread implementation of preservation programs is lacking (FHWA, 1998; Gransberg et al., 2010). As with any paradigm shift, there is a learning curve. According to the *Transportation System Preservation Research, Development, and Implementation Roadmap, January 2008,* there is a "need for a comprehensive, large scale Research & Development program" in the area of preservation. The following is an excerpt:

> "Preservation practices can extend service life and can provide better, safer, and more reliable service to users at less cost. These points reflect common sense and intuitive conclusions, but many aspects of preservation actions or their effect on service have not been demonstrated quantitatively. The tools for pavement and bridge preservation exist, but guidelines for their application are often limited. Research, development and implementation have historically focused on construction and rehabilitation activities and not on the topics of preservation and maintenance." (FHWA, 1998)

But as budget shortfalls and infrastructure needs increase to reach critical levels in the next two decades (FHWA, 2007), states are in search of how to spend their limited funds more effectively (AASHTO, 2001). "The core of transportation decision making is the evaluation of transportation projects and programs in the context of available funding" (Sinha, 2007). Economic analysis is a vital component to the new paradigm that is *Transportation Asset Management*, and specifically, *Pavement Preservation*, and its application has long been promoted by the FHWA to "highway project planning, design, construction, preservation, and operation" (FHWA, 2005), for cost-effectiveness evaluation and accountability (FHWA, 2007). "Considering the annual magnitude of highway investments, the potential savings from following a cost-effective approach to meeting an agency's performance objectives for pavements are significant" (Peshkin et al., 2004), thus, allowing agencies to stretch the budget to address sustainability needs in infrastructure and enhance stewardship.

Economic analysis is critical and encouraged at all levels of transportation, to include long term, midterm, and short term, although “models, methods and tools to construct and analyze economic tradeoffs are still being developed” (FHWA, 2007). The ‘long term’, or planning level, uses include evaluation at the design-level for the purpose of assisting engineers in the selection of the most cost-efficient design (FHWA, 2007). The ‘midterm’ uses include evaluation at the network-planning level for the purposes of determining cost-efficiency in budget allocation (FHWA, 2007). The ‘short term’, which is the programming implementation level, uses the focus of this research, which includes project-specific evaluation for the purpose of assisting pavement managers in pavement treatment selection (FHWA, 2007).

To be effective, every programming framework should include a mechanism for assessing the cost-effectiveness of alternatives considered for implementation (Sinha, 2007). Life cycle cost analysis (LCCA) is an engineering economic analysis tool that could be useful (FHWA, 2002), although it is not commonly being employed by ‘frontline’ pavement managers to determine the most cost-effective pavement preservation treatment alternative for a given project (Gransberg et al., 2010; Bilal et al., 2009; J. Hall et al., 2009; Monsere et al., 2009; Cambridge et al., 2005). The FHWA states the following purpose for LCCA use:

> “LCCA is an analysis technique that builds on the well-founded principles of economic analysis to evaluate the over-all-long-term economic efficiency between [mutually exclusive] competing alternative investment options. It does not address equity issues. It incorporates initial and discounted future agency, user, and other relevant costs over the life of alternative investments. It attempts to identify the best value (the lowest long-term cost that satisfies the performance objective being sought) for investment expenditures.” (FHWA, 1998)

LCCA can become quite complex, so an analyst should be judicious about the level of detail included (FHWA, 1998). The analysis can be simplified by including only differential costs, i.e. omitting those that cancel out, as well as disregarding those costs that contribute minimal or no impact on the final results (FHWA, 1998). The FHWA offers "LCCA Principles of Good Practice" in its *Life Cycle Cost Analysis in Pavement Design, Interim Technical Bulletin* released in 1998, such as in selecting a discount rate. 'Good Practice' is that *constant dollars* and *real discount* rate be used for the purposes of discounting future costs (i.e. omit inflation and effects). FHWA recommends a rate between 3-5% be used in analyses, which is consistent with the OMB Circular A-94. Other 'LCCA Principles of Good Practice' are integrated with the LCCA procedures/methodology.

LCCA PROCEDURES/METHODOLOGY

The following are LCCA procedures, as excerpted from the FHWA *Life Cycle Cost Analysis Primer* (FHWA, 2002) and the *Interim Technical Bulletin* (FHWA, 1998):

1. Establish design alternatives [and analysis period]
2. Determine [performance period and] activity timing
3. Estimate costs [agency and user]
4. Compute [net present value] life cycle costs
5. Analyze results
6. Reevaluate design strategies (FHWA, 2002; FHWA, 1998)

Design Alternatives and Analysis Period

The first step in the procedure involves establishing strategies, i.e. associated rehabilitation and maintenance activities associated with each alternative expected over the analysis period (FHWA, 1998). The analysis period can be selected by various methods when alternatives have differing performance periods for the purposes of comparing all alternatives over a 'common period of time', which is an engineering economic analysis principle (White et al., 2010). The general suggestion is that the analysis period be a standard length, such as 35-40 years (FHWA, 2002), and long enough to allow "at least one major rehabilitation activity" for each design alternative

(FHWA, 2002). The *net present value* (NPV) method is the preferred analysis method, with the *equivalent periodic annual cost* (EUAC) only being used as a re-statement of the NPV (FHWA, 1998).

Performance Period and Activity Timing

The second step involves determining the performance period (i.e. cash flow diagram) for an alternative, which is the period that covers one life cycle of that alternative and is generally determined by the analyst's judgment based on experience and historical data (FHWA, 1998). Activity timing includes the determination of maintenance and other activity frequency associated with a specific alternative strategy, as established in step 1 (FHWA, 1998). The performance period determination has a significant effect on the LCCA output, and should be considered with care (FHWA, 1998).

Agency and User Costs Estimation

The third step involves determining or estimating agency and user costs for each of the competing alternatives. Agency and user costs are determined for each of the competing alternatives and future costs are 'discounted' to determine the NPV. Agency costs are those costs directly incurred by the agency, such as costs for project supervision and administration, materials, labor and traffic control for the initial installation, as well as any associated rehabilitation and maintenance costs required over the life cycle of the alternative. These costs are generally based on current and/or historical costs.

According to the FHWA, *salvage value* is the value associated with each alternative determined at the point of analysis terminal and involves any *residual value* (value attributed to the reclaimed materials) or any *serviceable life* (value attributed to alternative 'life' that exists after analysis terminal) and should be attributed to alternatives appropriately for the purposes of analysis (FHWA, 1998). *Sunk costs*, which are costs occurring pre-analysis, should not be included in the analysis unless they specifically apply to the alternatives that are to be compared (FHWA, 1998).

User costs relate to costs incurred by the traveling public in both *work-zone* and *non-work-zone* phases for a given extent of road for which alternatives are being compared (FHWA, 1998). Generally, the user costs incurred during *non-work-zone* phases are disregarded in LCCA due to a lower likelihood of difference among alternatives (FHWA, 2002). Differing [work zone] user costs among alternatives are pertinent to the analyses, and generally include "[time] delay, vehicle operating, and crash costs incurred by the users of a facility" (FHWA, 1998).

> "User costs are heavily influenced by current and future roadway operating characteristics. They are directly related to the current and future traffic demand, facility capacity, and the timing, duration, and frequency of work zone-induced capacity restrictions, as well as any circuitous mileage caused by detours. Directional hourly traffic demand forecasts for the analysis year in question are essential for determining work zone user costs."
> (FHWA, 1998)

It is suggested that "different vehicle classes have different operating characteristics and associated operating costs, and as a result, user costs should be analyzed for at least three broad vehicle classes: Passenger Vehicles, Single-Unit Trucks, and Combination Trucks" (FHWA, 1998). Unit costs are generally translated into monetary terms (for the purposes of analysis) and can be ascertained from various sources, and those costs escalated with the use of the transportation component of the *Consumer Price Index (CPI)* (FHWA, 1998). *Delay* costs are calculated by multiplying the unit of 'wait' time attributed to each alternative's work-zone timings by the monetary unit (FHWA, 1998). *Vehicle operating costs* (VOC) are calculated by multiplying the vehicle-related cost factors attributable to each alternative's work-zone timings by the monetary unit (FHWA, 1998). Crash costs are calculated by multiplying the number of specific types of crashes by their respective monetary unit (FHWA, 1998). User costs as a result of detours are typically assigned a cents-per-mile rate, such as that used by the Internal Revenue Service for mileage allowance (FHWA, 1998).

Compute Life-Cycle Costs (NPV)

As excerpted from FHWA's LCCA Interim Technical Bulletin:

> "Economic analysis focuses on the relationship between costs, timings of costs, and discount rates employed. Once all costs and their timing have been developed, future costs must be discounted to the base year and added to the initial cost to determine the NPV for the LCCA alternative. The basic NPV formula for discounting discrete future amounts at various points in time back to some base year is:
>
> $$\text{NPV} = \text{Initial Cost} + \sum \text{Rehab Costs}\,[1 \div ((1 + i)^n)] \qquad (2)$$
>
> Where: i = discount rate, *n* = year of expenditure and $[1 \div ((1 + i)^n)]$ = PV formula" (FHWA, 1998).

Analyze Results

LCCA has two possible computational approaches: *deterministic* and *probabilistic* (FHWA, 1998). The deterministic approach involves using discrete input values and a single output value (FHWA, 2002). A *sensitivity analysis* should be conducted so that the analyst may determine the level of variability of a given input value relative to the output (FHWA, 1998). For example, an analyst chooses a 4% discount rate to do the LCCA, which results in output (a preferred alternative). The sensitivity analysis will allow the analyst to conduct a '*What if*' scenario to determine if choosing a 5% discount rate would result in different output (different preferred alternative). The sensitivity analysis is limited in application with regard to being unable to analyze simultaneous variability (FHWA, 2002).

The probabilistic approach involves analyzing input value probability based on the full range of '*What if*' scenarios allowed by sensitivity analysis by providing a 'distribution of PV results' (FHWA, 2002). It is generally accompanied with a *risk analysis,* which unlike sensitivity analysis, does allow the analyst to determine the level of certainty with regard to simultaneous variability in all input parameters (FHWA, 1998).

Reevaluate Design Strategies

LCCA results should be coupled with other decision-support factors such as "risk, available budgets, and political and environmental concerns" (FHWA, 2002). The output from an LCCA should not be considered the 'answer', but merely an indication of the cost –effectiveness of alternatives (FHWA, 1998). Considering cost-effectiveness without also considering treatment effectiveness (and vice versa), or the 'economic efficiency' of a treatment, may not provide the 'whole picture' either and may result in not selecting the 'best' alternative (Bilal et al., 2009).

LCCA RESEARCH APPROACH

As pavement preservation becomes increasingly vital to sustainability in infrastructure, it has become apparent that economic analysis, specifically life cycle cost analysis, could be an essential tool in assisting ODOT pavement managers in the selection of cost-effective alternatives that may yield extended service lives of Oklahoma pavements. Figure 8 shows that the LCCA research is the synthesis of three independent sources of information:

- A comprehensive literature review,
- A survey of Oklahoma Department of Transportation (ODOT) pavement managers
- Pavement preservation treatment field trial data.

Additionally, a pilot study was conducted to validate the models created for this portion of the research. The surveys were deployed in an effort to define the current processes used by ODOT pavement managers when making decisions regarding pavement treatment selection, and the literature review was conducted to determine the current processes used by other state highway agencies. The survey data, combined with literature review and the field trial data associated with this project, was also collected for the purpose of defining the input values and other parameters with regard to costs (user, construction, etc.) and time (analysis period, service life, etc.) associated to the specific trial pavement preservation treatments. This research aims to develop, complete and report economic and life cycle cost analysis using deterministic engineering economic analysis so that models (one for concrete and the other for asphalt pavement preservation treatments) may be created that can produce standardized results relevant to pavement managers when comparing pavement preservation alternatives.

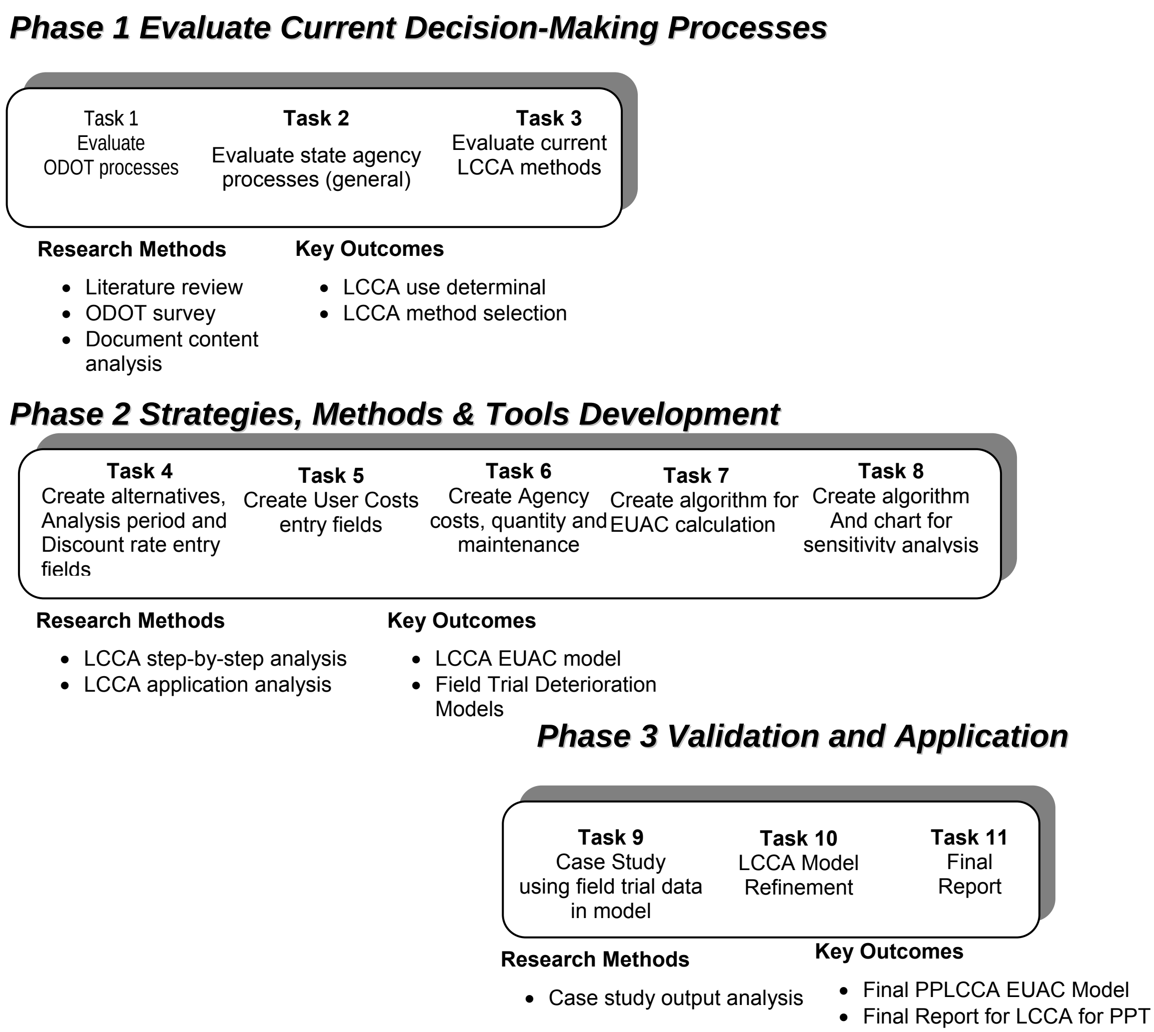


Figure 8: Research Approach

Research Instruments

This research employed the following:

1. Analysis of current state transportation agencies decision-making processes
2. Survey of ODOT pavement managers (Table 3)
3. Case study analysis from field trials

Table 3 ODOT Survey Responses

ODOT Survey Responses	Response #1	Response #2	Response #3	Response #4	Response #5
LCCA used in current decisions	No				
Current decision-making system		judgement	judgement	judgement	
Importance of decision-making factors					
(ranking, 1 - most important, 5-least/not important)					
initial cost of pavement treatment (PT)	2	1	1	1	1
safety	1	3	3	2	1
traffic volume	3	3	5	2	2
existing surface condition	1	4	1	2	2
service life of PT	4	3	4	3	2
availability of PT	3	2	5	5	5
availability of trained crew to install PT	5	4	5	3	4
weather constraints for PT	4	3	2	4	3
past experience with PT's effectiveness	1	5	3	2	2
Pavement preservation differentiated from maintenance	Yes				
Percent of annual allocation for good/fair condition surfaces					
asphalt		50%	40%	60%	
concrete		15%		35%	
Three most common ODOT preservation treatments (SL)*	HMA (10)				
*(Avg. service life based on pavement condition/traffic volume)	chip seal (5)			microsurface	chip seal (5)
	fog seal		crack seal (3)	UTBWC	
Three most common ODOT preservation treatments	HMA overlay ($70/ton)				
(average cost)*	chip seal ($1.77/SY)			microsurface	chip seal
	fog seal		crack seal ($3	UTBWC	
Average Production Rate chip seal	45k SY/day	6 lane-mi/day	80k SY/day	8 lane-mi/day	
HMA	700 tons/day		1800 tons/day	4 lane-mi/day	

Surveys for this study were developed in accordance with the methodology specified by Lehtonan and Pahkinen (2004). The responses indicated that initial cost plays a primary role when deciding which pavement treatment to employ and that long-term cost or cost-effectiveness of a treatment selection is not considered, i.e. LCCA is not conducted. The survey also yielded information about other decision making factors, as well as the types of preservation and maintenance treatments typically employed in Oklahoma, and each treatment's cost range, productivity range and typical service life range based on factors such as average annual daily traffic (AADT), percent truck traffic and pavement condition, as shown in Table 3.

LCCA Procedures/Methodology, Equivalent Uniform Annual Cost Method

The following are LCCA procedures, as excerpted from the FHWA *Life Cycle Cost Analysis Primer* (FHWA, 2002) and the *Interim Technical Bulletin* (FHWA, 1998) and discussed in the *Background and Motivation* section of this writing. The steps will serve as a guide for the development of this model.

1. Establish design alternatives [and analysis period]
2. Determine [performance period and] activity timing
3. Estimate costs [agency and user]
4. Compute [net present value] life cycle costs
5. Analyze results
6. Reevaluate design strategies (FHWA, 2002 and 1998)

LCCA Step 1: Establish [pavement treatment] alternatives [and analysis period]

According to the survey deployed for this study, ODOT pavement managers consider the *pavement quality index (PQI), percent truck traffic and AADT*, among other things, when establishing alternatives. The model created for this research can simultaneously analyze up to six established alternatives. According to the literature review, the analysis period selection is especially subject to sensitivity. Because the *Equivalent Uniform Annual Cost* (EUAC) method seemingly bypasses the analysis-period selection process and neutralizes the sensitivity issue based on a non-treatment-relevant basis, it was selected for the model created for this research (see Figure 9). The analyst does not have to select an analysis period based on any of the six selection methods listed in the literature review section that can be problematic because of the adjust-to-fit requirements and other cited issues, such as the requirement to understand underlying engineering economic theory garnered from *economist* experience.

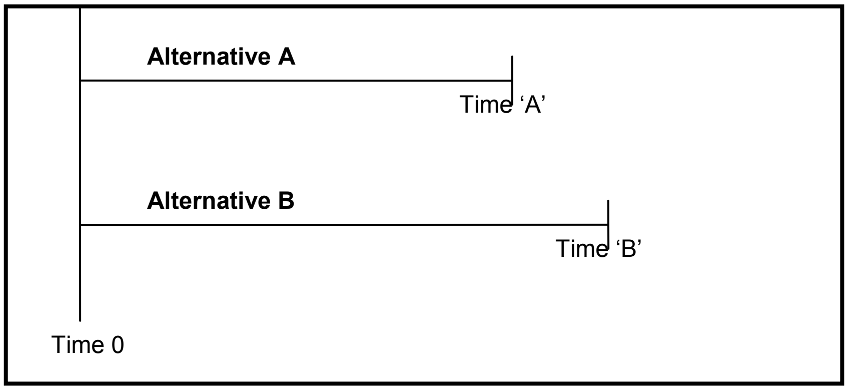


Figure 9: Equivalent Uniform Annual Cost for Unequal-Life Alternatives

LCCA Step 2: Determine [service life and] activity timing

The analyst, instead, goes to the next step of entering service-life length for each alternative (shown in Figure 10 below), which is garnered from *pavement-manager* experience, and will serve as the basis for the EUAC calculations. Replacing analysis period input with treatment-relevant input, such as service life and pavement extension, allows the pavement manager to intuitively analyze LCCA results.

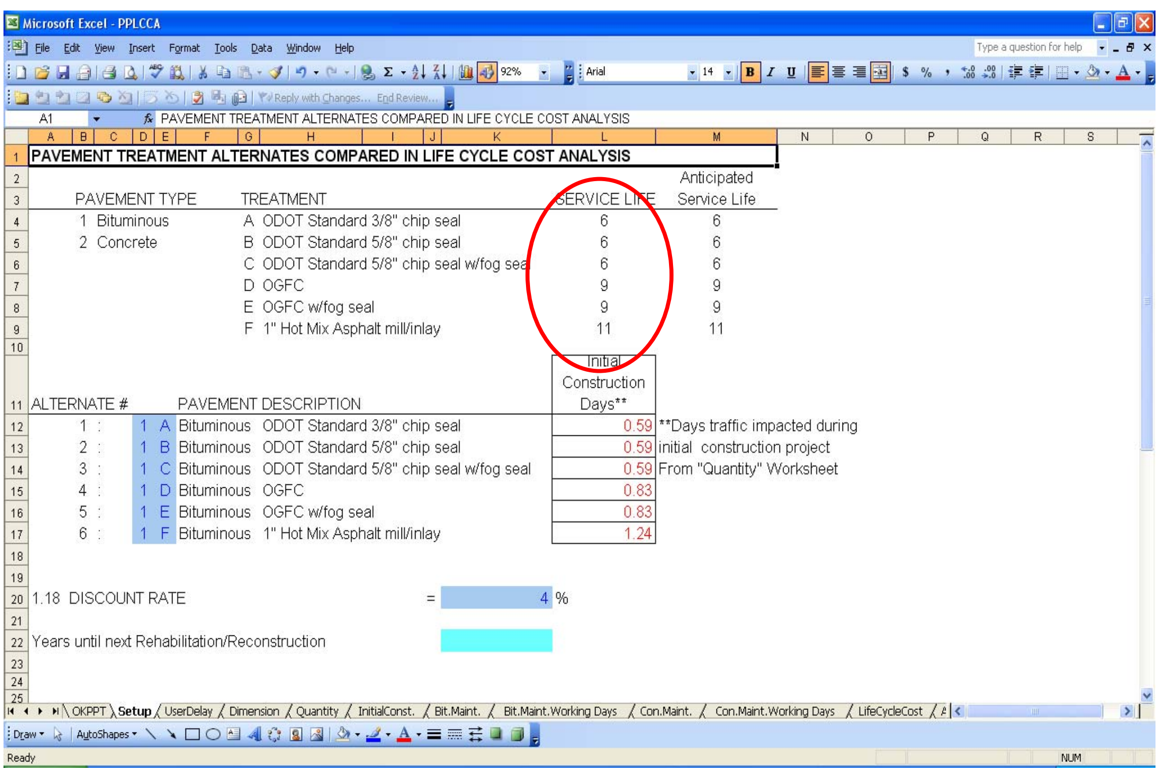


Figure 10: Service Life as Analysis Period

According to the FHWA's LCCA Primer, "allowing analysis periods to vary among design alternatives would result in the comparison of alternatives with different total benefit levels, which is not appropriated under LCCA" (FHWA, 2002). Although it may appear on the surface that using EUAC is violating the engineering economic principle of "analyzing alternatives over a common period of time" due to the differing-service-lives-as-analysis-period input, it in fact is not due to the relationship that exists between EUAC and the PW, least-common-multiple method. In other words, EUAC can be considered a "covert" PW least-common-multiple method due to the fact that both calculations for a given data set are proportionately equal, allowing the substitution of EUAC (White et al., 2010). Furthermore, when one adjusts alternatives' residual value(s) in accordance with FHWA's "good practices" (FHWA, 1998) as previously discussed, the output, or preferred alternative should be the same regardless of EUAC or PW method employed. EUAC also accommodates the short term, as well as the continuous nature of pavement treatments and does not unnecessarily truncate lives (Lee, 2002). EUAC allows a straightforward comparison of each pavement treatment alternative based on a cost-versus-service-life function. EUAC has been suggested as being appropriate in this type of application (Pittenger, 2010; Sinha and Labi, 2007).

Maintenance funding is authorized on an annual basis making comparing alternatives on an annual cost basis more closely fit the funding model than using NPV which would assume availability of funds across the treatment's entire service life. Since pavement managers typically consider several alternatives with varying services lives based on available funding rather than technical superiority, the FHWA LCCA method based on NPV creates more problems than it solves.

The pavement manager will be faced with one of two scenarios in the short-term implementation level of decision making: the year of the *next expected* rehabilitation or reconstruction will either be known (i.e. terminal state (Lee, 2002)) or it will not (i.e. continuous state (Lee, 2002)). In the terminal state, the pavement manager generally chooses the "do nothing" option. There may be occasions, however, when a pavement manager must employ treatment to extend the life of the pavement until the next rehabilitation or reconstruction is expected. To avoid the common "mistake" associated with employing the EUAC method, the analyst must consider the encroachment (White et al., 2010). In the instant case, when the year of the *next expected* rehabilitation or reconstruction is known (i.e. terminal state (Lee, 2002)), it must be addressed for engineering economic principles adherence. The model for this OTC research, as illustrated in Figure 11 below, has been built to accommodate the terminal state and engineering economic principles.

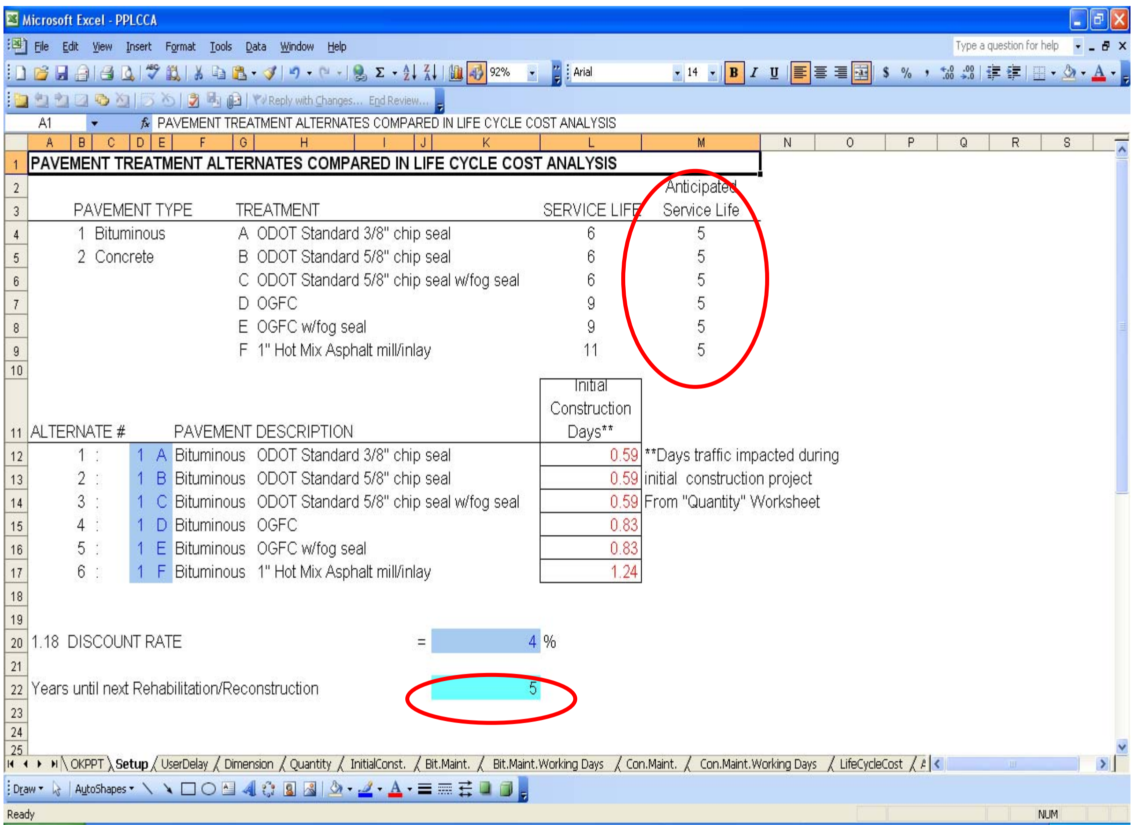


Figure 11: Anticipated Service Life

In continuous state when the next rehabilitation/reconstruction is unknown, the "Years until next Rehabilitation/Reconstruction" cell is left blank and the calculations are based on each alternative's respective service life, as shown in Figure 10. However, as illustrated in the Figure 11, when the next rehabilitation/reconstruction is expected in, for example, five years, "5" is entered into the cell. The model automatically sets the analysis period to five years and truncates each service life accordingly, which is notated as the *anticipated service life*. The residual value is considered to be "0" since the alternatives are not expected to serve in the pavement-treatment capacity at the time of the rehabilitation or reconstruction, as per the literature review section. Pavement preservation treatments and the associated pavement-life-extending properties are currently being researched (Peshkin et al., 2004).

If the terminal state exists and the "Years until next Rehabilitation/Reconstruction" cell contains a value that creates a gap for one or more alternatives, the model is built to ignore the gap and calculate all alternatives with the EUAC method. This situation, although rare due to the "do nothing" preference and very short-term nature of the terminal state, may not explicitly adhere to the specific "common period of time" engineering economic principle, but does not warrant it because the gap will most likely be filled with another "do nothing" option. In this scenario, if the analyst were to choose the shortest-life alternative to set the analysis period and the other longer-life alternatives were adjusted to fit in accordance with FHWA straight-line-depreciation-like method, the LCCA should still yield the same preferred alternative as the EUAC method. As per the literature review, this type of calculation would likely favor the shortest-life alternative.

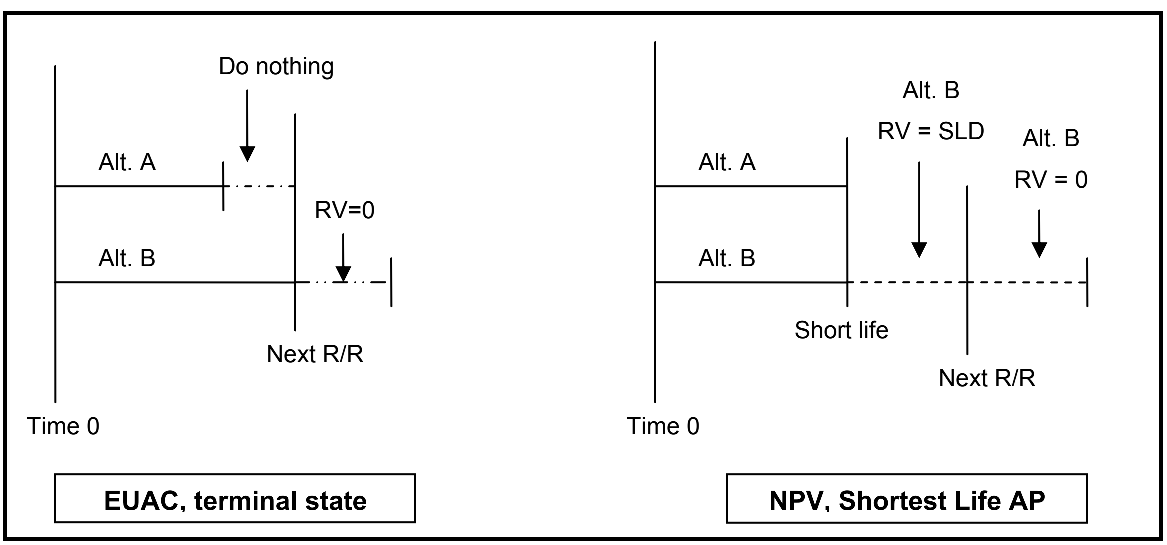


Figure 12: Two Methods, Same Preferred Alternative

The only other analysis period setting option that would accommodate this scenario would be to set all alternatives lives to the next expected rehabilitation/reconstruction, which would require filling the gap. This option would be less palatable than shortest-life and EUAC methods because it would require a repetition of the shortest-life alternatives in an effort to fill the gap. Couple the issues associated with filling the gap from the literature review and the fact that "do nothing" will be the choice selected if possible, filling the gap may result in faulty output. If the next expected rehabilitation/reconstruction period is expected in seven years, leaving a one-year gap for a six-year service life alternative, if the gap is filled with a repetitive treatment, keeping in mind that the residual value will equal zero, then the long-life alternatives may be favored. This would be especially problematic when the gap will realistically be filled with "do nothing", as illustrated in Figure 13.

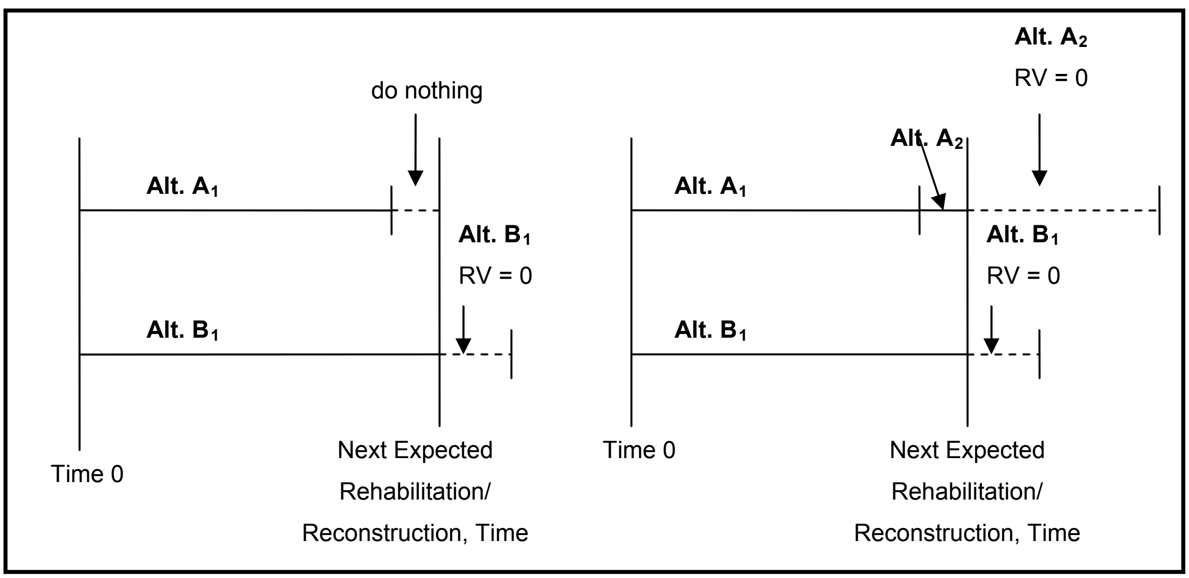


Figure 13: Do-Nothing Scenario vs. Fill-the-Gap Scenario

On the other hand, the analyst could figure the "do nothing" and use the seven-year period for the six-year alternative, i.e. a *one-shot* investment in which the six-year alternative would be figured over the seven-period, but the treatment may require some cost in that gap year. All analysis-period selection methods, when applied to this scenario, have inherent issues, so one must decide which method would yield the best information for the pavement manager. EUAC would tend to be the compromise between treating the short life alternative like a one-shot option or repeating it to fill the gap. The shortest-life method would adhere to the “common period of time” engineering economic principle while EUAC would overtly not. But because of the same preferred alternative being yielded from both methods, for the purposes of a consistent model, and with all of the previously-cited issues with the analysis period, using EUAC, even in this rare situation, would appear to be a covert short-life method and provide the pavement manager with relevant decision-making information based on cost, service life and the real possibility of “do nothing” during this state.

Essentially, when the EUAC “standalone” model is used for decision making regarding pavement treatments in the continuous state, it functions similar to present value in least-common-multiple mode. Furthermore, “instead of employing a rule of thumb for establishing [an analysis period]”, one should consider the nature of the investment when establishing an analysis period (White et al., 2010). Since ODOT maintenance budgets are annual in nature, then it follows that pavement preservation and maintenance treatment LCCA should use EUAC. The screen captures shown above in Figures 10 and 11 come from the LCCA model developed specifically for this project and are currently available for use by ODOT maintenance engineers to assist in pavement treatment selection analysis. The model’s logic is shown graphically in the flow chart found in Figure 14.

The final component of this research is a life cycle cost comparison of pavement preservation treatments exhibited in field trials associated with this research. The application of the EUAC, Pavement Preservation (PP) LCCA model developed for this research will be demonstrated using extrapolated field data. The format of this section will be similar to the LCCA steps outlined in previous sections. Input values are based upon field trial, vendor and ODOT survey data, literature review results and bid tabulations. The output is manually verified. The EUAC model ranking results will be compared to present value alternative ranking results for verification. The model is validated when it produces standardized results.

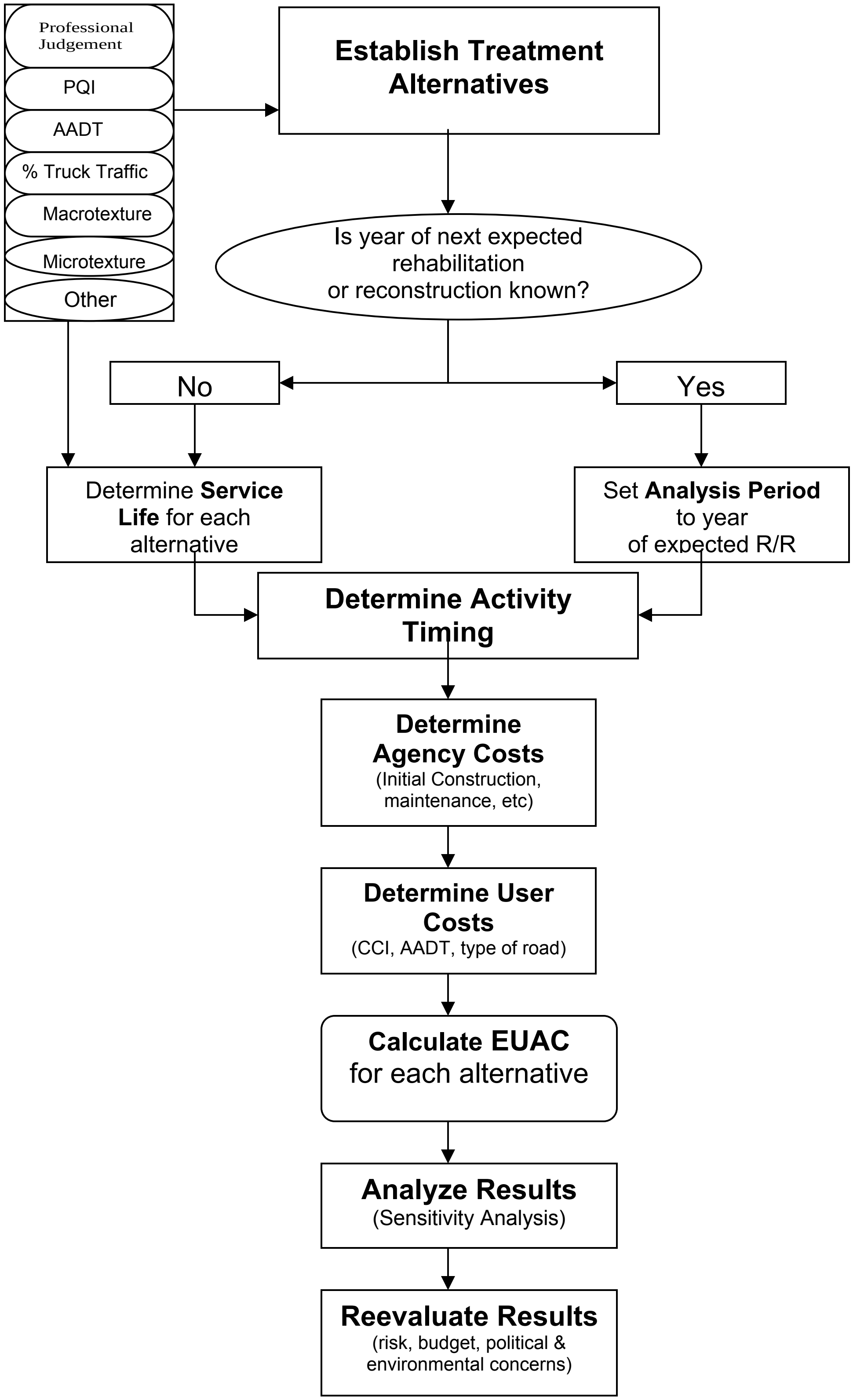


Figure 14: Pavement Preservation LCCA Model Logic

LCCA MODEL DEMONSTRATION, CONTINUOUS STATE

To better document the pavement preservation model developed and proposed in the previous section, two versions of the LCCA model will be demonstrated using the actual field data from the OTCREOS7.1-16 project. The purpose of this section is to show how the pavement micro and macrotexture deterioration models can be used within the newly developed pavement preservation treatment LCCA model.

LCCA Step 1: Establish Pavement Treatment Alternatives and Service Life

Five pavement preservation treatments from the field tests associated with this research serve as the selected alternatives in Table 4. They range from a minimal treatment, shotblasting, to the heaviest treatment, the overlay. As discussed in the previous section, instead of choosing an analysis period consistent with the present value (PV) method, each alternative's service life is selected consistent with the equivalent uniform annual cost (EUAC) method.

Table 4 Pavement Treatment Service Life Estimation

Pavement Preservation Treatment	ODOT/Lit. Review Service Life (years)
1" Hot Mix Asphalt Mill & Inlay (HMA)	10 (avg)
Open Graded Friction Course (OGFC)	10 (avg)
5/8" Chip Seal	5 (avg)
Pavement Retexturing, Abrading	2 (avg)
Pavement Retexturing, Shotblasting	2 (avg)

Linear regression was applied to the field trial microtexture and macrotexture data to approximate the deterioration rate and extrapolate the remaining service life of each treatment as summarized and illustrated in the following figures. These were then compared to failure criteria found in the literature. Service life was determined by identifying the time it took each treatment to deteriorate to each failure criterion. The failure criterion for macrotexture was 0.9mm, which is consistent with TNZ P/12 performance specification (TNZ, 2002). The failure point considered for microtexture was a skid number less than 25. The resulting approximate service life for each alternative was compared to the ODOT survey and literature review results (Stroup-Gardiner and Shatnawi, 2008; FHWA, 2005).

This methodology for estimating pavement preservation treatment service from local field data reduces the uncertainty of selecting the service life from experience or the literature, and literally enhances the analog because the data is taken in the same environment that the selected treatment must function. Figure 15 illustrates the deterioration of microtexture experienced in current OTC field trial data for the 1" Hot Mix Asphalt mill and inlay (HMA).

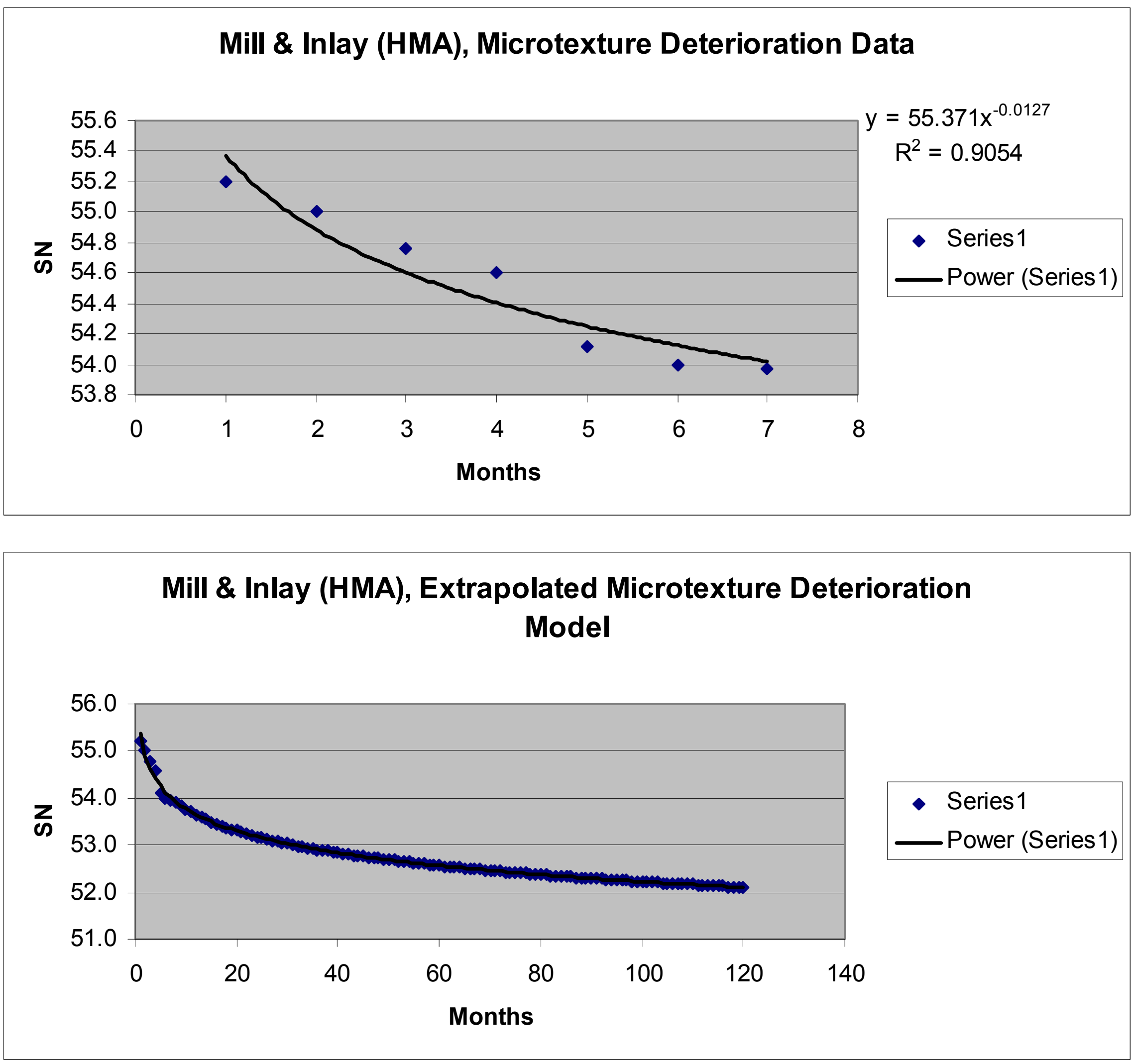
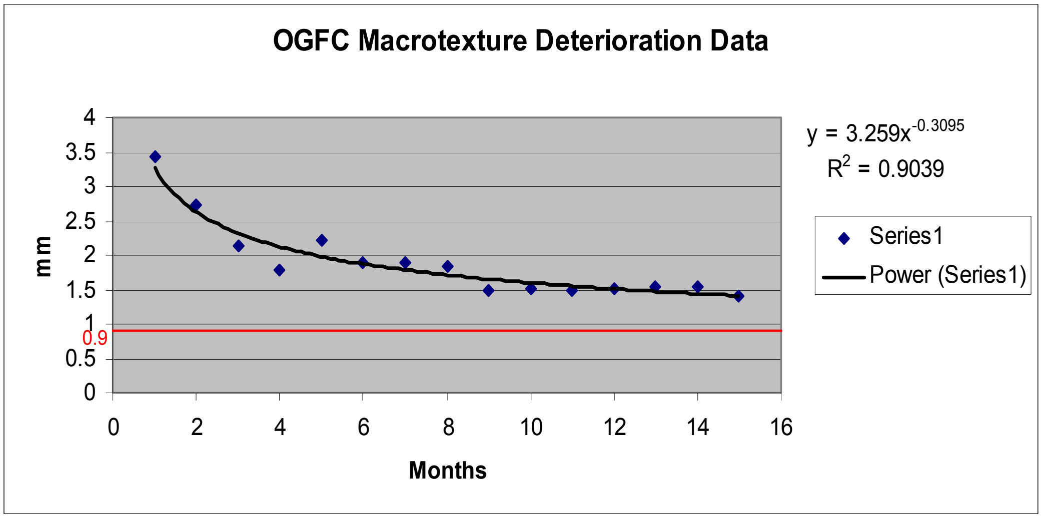


Figure 15: 1" Hot Mix Asphalt Mill & Inlay Microtexture Deterioration Model

The HMA's loss of microtexture was plotted over time and the linear regression for the change in microtexture over time was conducted. The equation shown in the upper right-hand corner of the figure was derived and the coefficient of determination (R^2) was calculated to be 0.9054. The regression equation was then used to calculate the deterioration rate beyond the available data. These values were added to the actual data points to extrapolate the curve out to 120 months (i.e. 10 years) as shown in Figure 15. Based upon this procedure and a failure criterion of 25, it appears that the HMA will not fail due to a loss of skid resistance over this period. Since this treatment is HMA, macrotexture does not apply due to the inherent properties of the material, which is not designed to provide measurable macrotexture.

Open graded friction course (OGFC) is a treatment whose service life can be determined using analysis of both macro and microtexture. The extrapolation methodology described above was used for this and the other treatments. As illustrated in Figures 16 and 17, OGFC falls below the critical level for macrotexture at around 64 months with a coefficient of determination of 0.90, but would retain sufficient skid resistance at the time it fails due to loss of macrotexture.



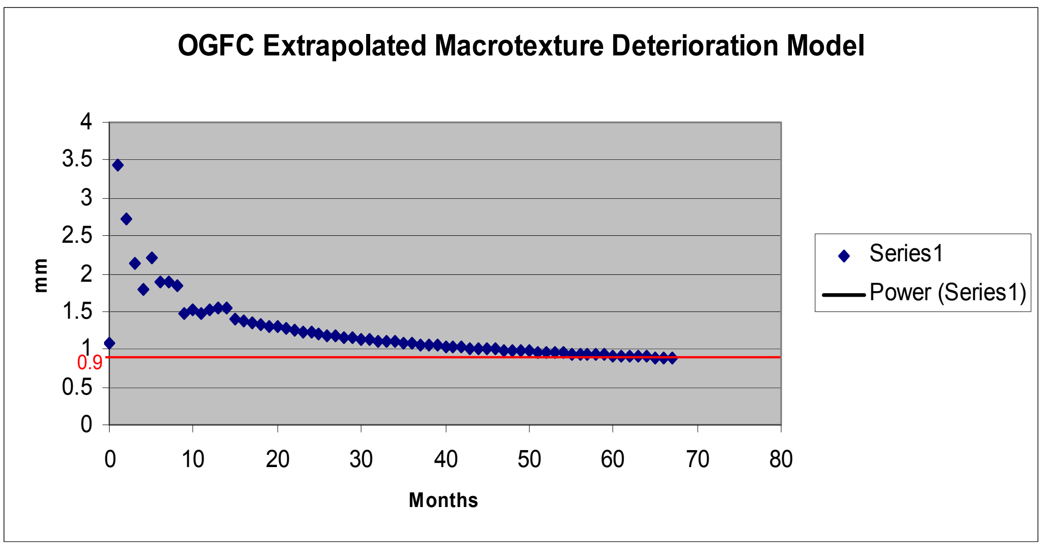
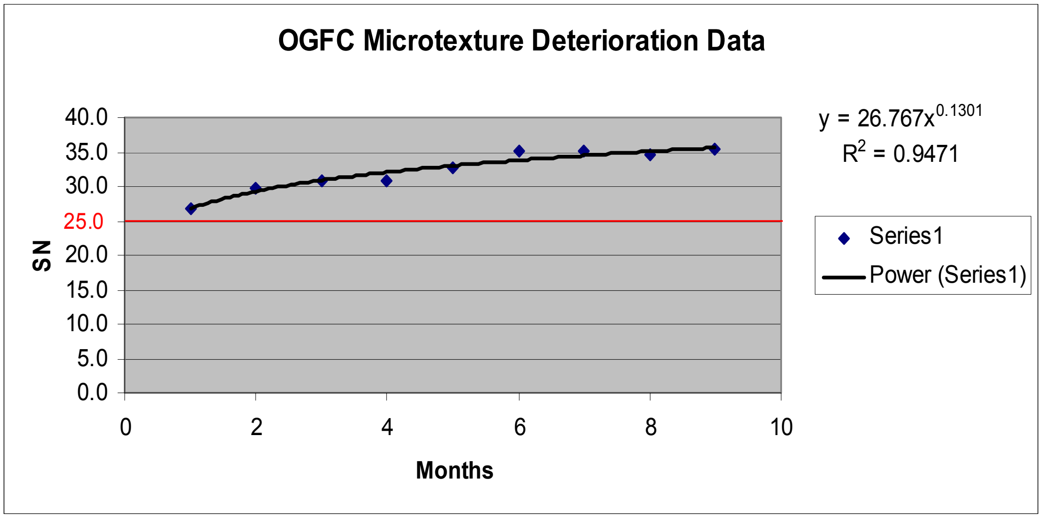


Figure 16: Open Graded Friction Course Macrotexture Deterioration Model



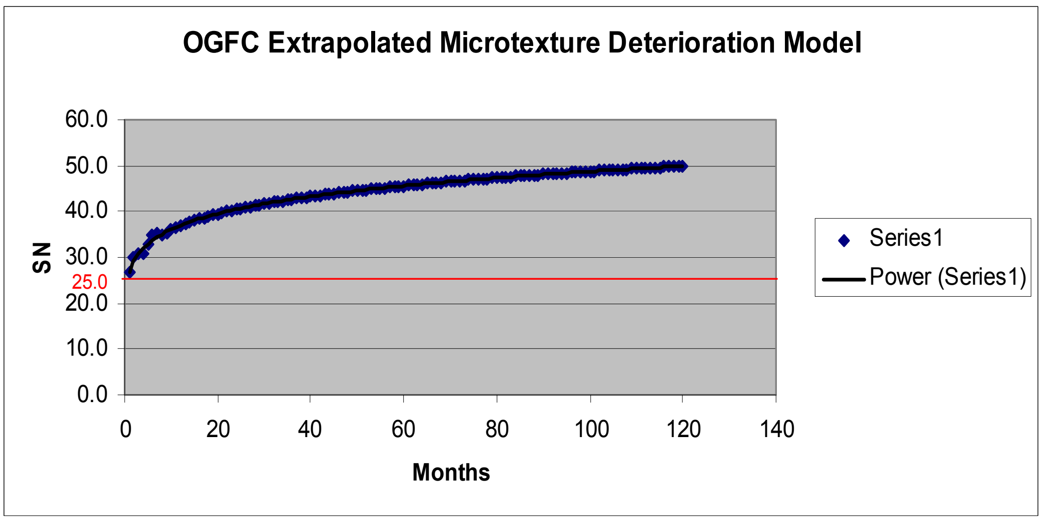


Figure 17: Open Graded Friction Course Microtexture Deterioration Model

As illustrated in Figures 18 and 19, the 5/8” Chip Seal falls below the failure criteria for macrotexture and microtexture at around 21 months and 46 months respectively.

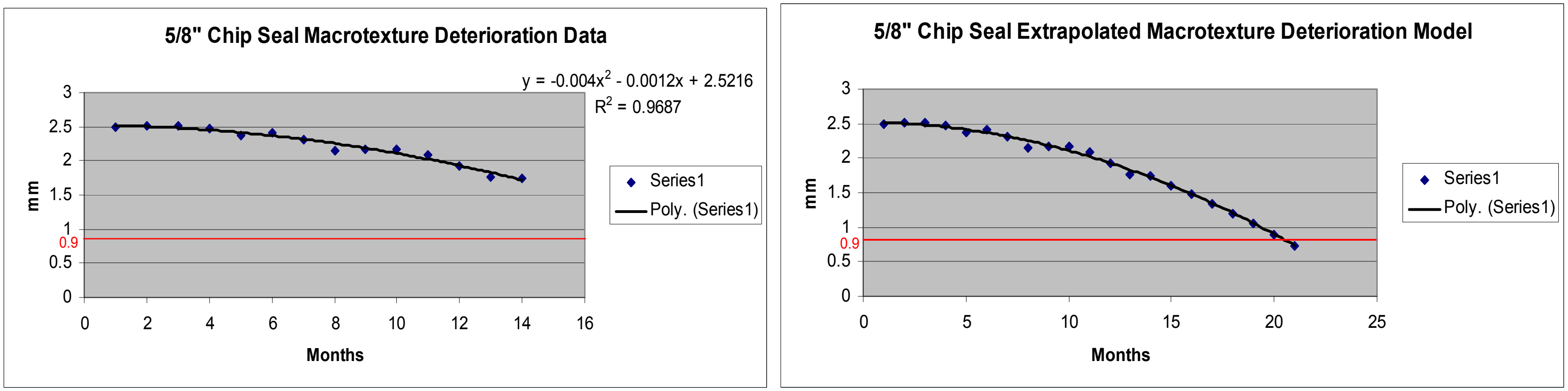


Figure 18: 5/8” Chip Seal Macrotexture Deterioration Model

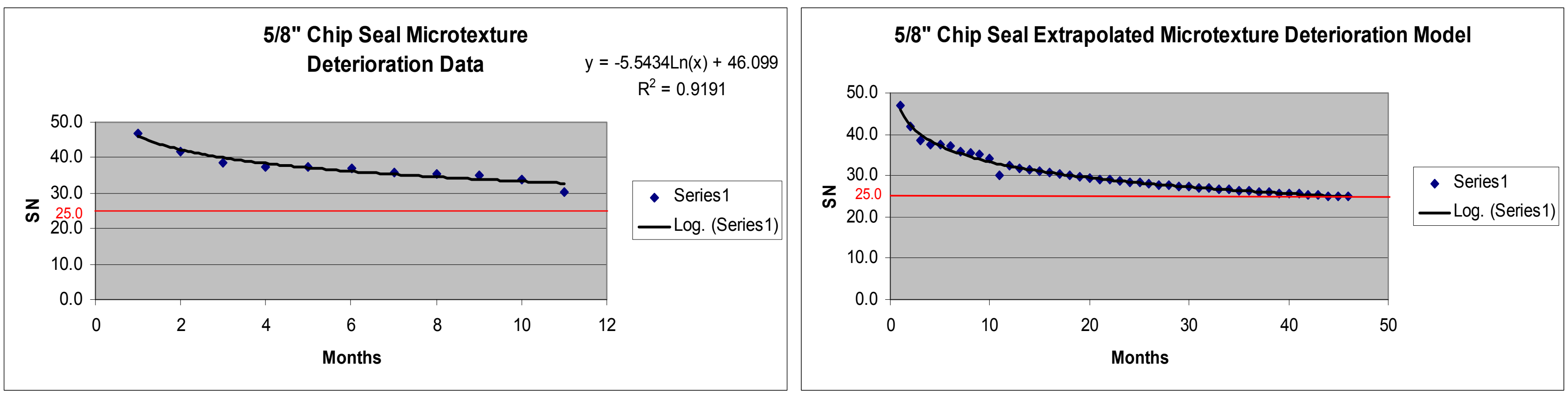


Figure 19: 5/8” Chip Seal Microtexture Deterioration Model

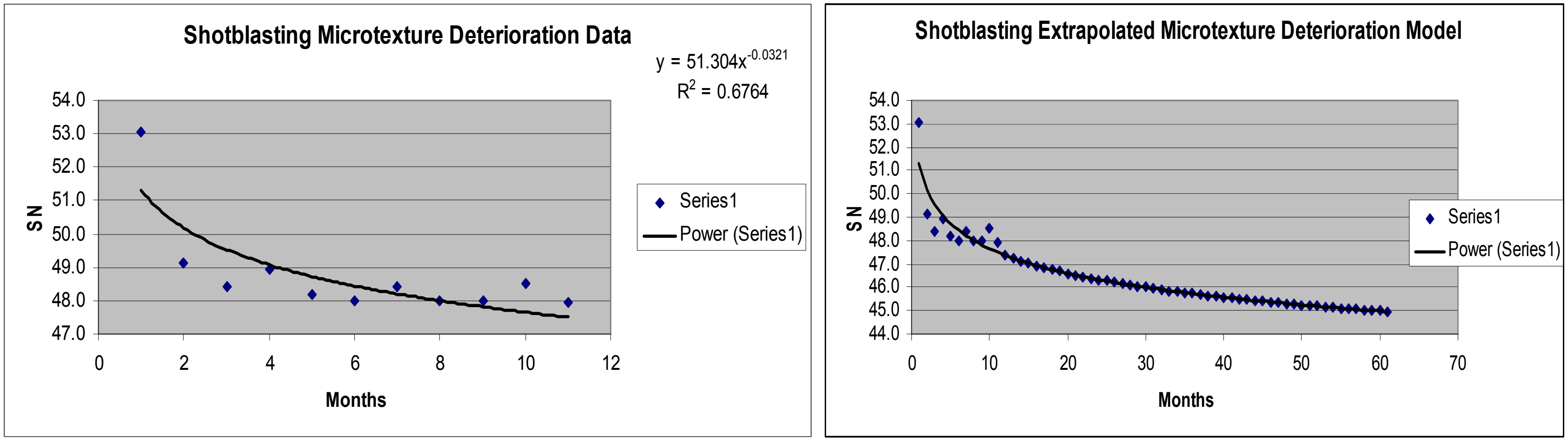


Figure 20: Pavement Retexturing - Shotblasting Microtexture Deterioration Model

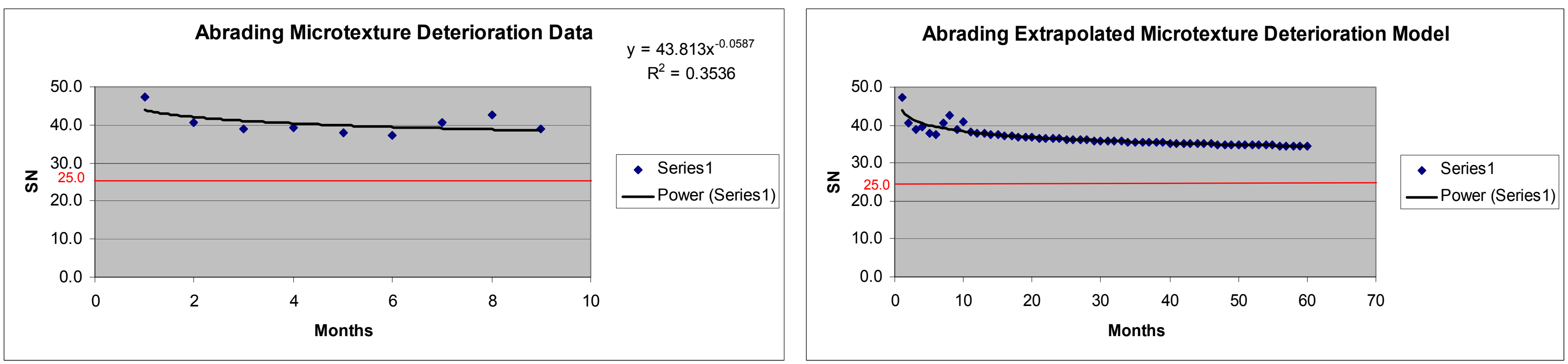


Figure 21: Pavement Retexturing - Abrading Microtexture Deterioration Model

The analysis of the field data, coupled with literature and ODOT survey information, can be used to select an appropriate service life value as shown in Table 5 and gauge the sensitivity for each treatment being evaluated.

Table 5 Treatment Service Life Based on Extrapolated Field Data

Pavement Preservation Treatment	Service Life (years)			
	Microtexture	Macrotexture	ODOT & Lit. Review	Minimum
1" Hot Mix Asphalt Mill & Inlay (HMA)	> 10	N/A	10	10
Open Graded Friction Course (OGFC)	> 10	5.3 years	10	5.3
5/8" Chip Seal	3.8	1.8	5	1.8
Pavement Retexturing, Abrading	>5	N/A	2	2
Pavement Retexturing, Shotblasting	>5	N/A	2	2

The selected alternatives and the corresponding minimum service life values from Table 5 were entered into the model, as well as other items required for LCCA as illustrated by Figure 22. The initial construction installation time is represented by days, to two significant digits, to capture the differences between alternatives for user cost calculations. Production rates came from the ODOT survey and vendor data. The discount rate selected for the demonstration of the model is 4%. No value was entered in the "Years until next Rehabilitation/Reconstruction" because of the analysis assumes the continuous state, so the "Service Life" is equal to the "Anticipated Service Life" for all alternatives. Project length is one lane-mile.

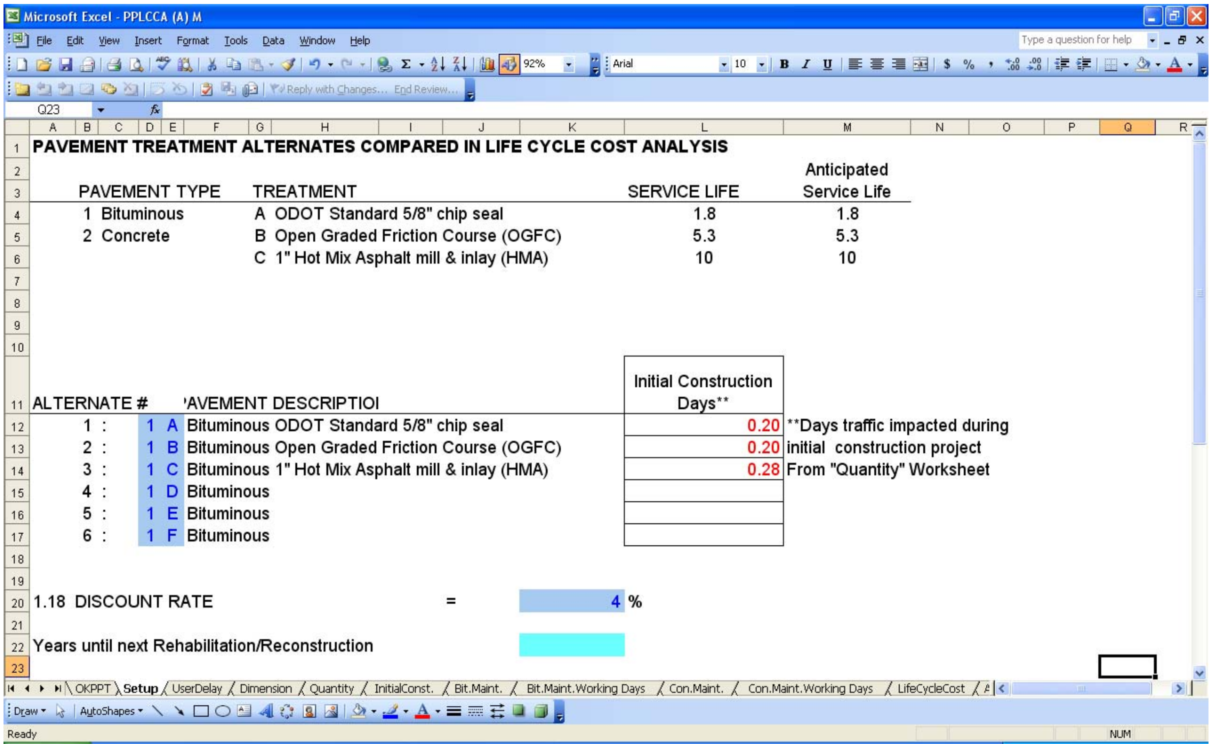


Figure 22: LCCA Step 1: Establish Alternatives and Each Service Life

LCCA Step 2: Determine [Performance Period and] Activity Timing

Step 2 of the LCCA process is illustrated in Figure 23. Performance period, or service life, was determined in Step 1 to be the analysis period, as modified by this research. Activity timing will include maintenance, which will be a crack seal and 2%-of-total-area patching with a three-year frequency for all asphalt treatments.

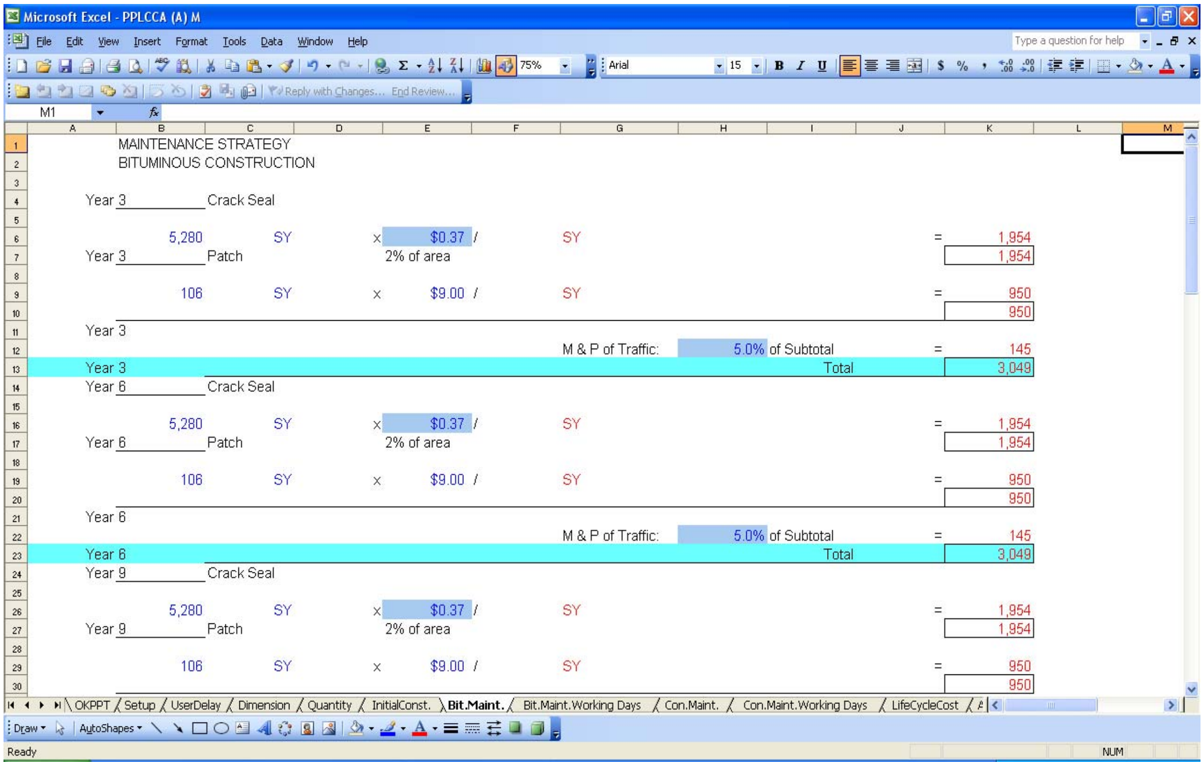


Figure 23: LCCA Step 2: Determine Activity Timing

LCCA Step 3: Estimate Agency & User Costs

The average cost for treatments and maintenance shown in Table 6 came from the ODOT survey and was verified by field trial donor data, literature review results (Stroup-Gardiner and Shatnawi, 2008; FHWA, 2005, Bausano et al., 2004), and ODOT bid tabulations. It is used as shown in Figures 24 and 25.

Table 6 Average Pavement Treatment Cost

	PAVEMENT TREATMENTS	Average Cost/SY
Asphalt	ODOT Standard 5/8" chip seal	1.77
Asphalt	Open Graded Friction Course (OGFC)	3.75
Asphalt	1" Hot Mix Asphalt mill/inlay (HMA)	4.00
Asphalt	Crack Seal	0.34
Concrete	Pavement Retexturing using shotblasting (48" Width)	3.00
Concrete	Pavement Retexturing using abrading (72" Width)	2.00

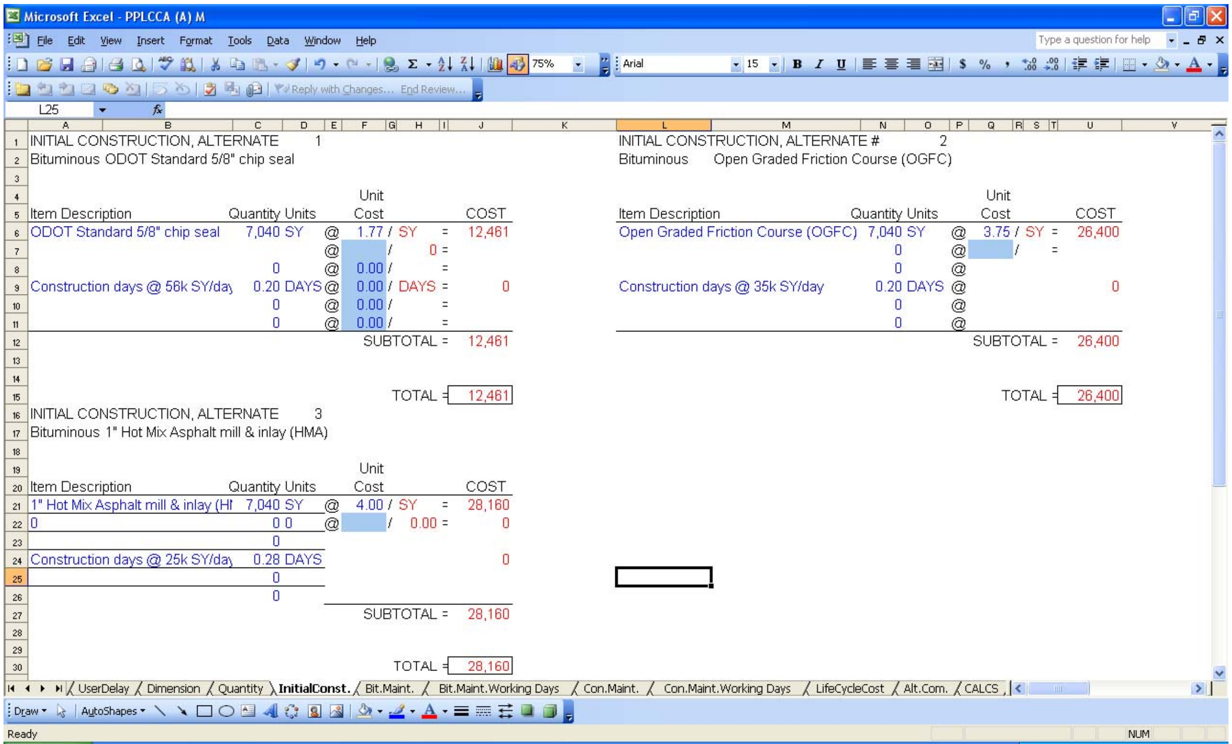


Figure 24: LCCA Step 3: Determine Agency Costs, Construction

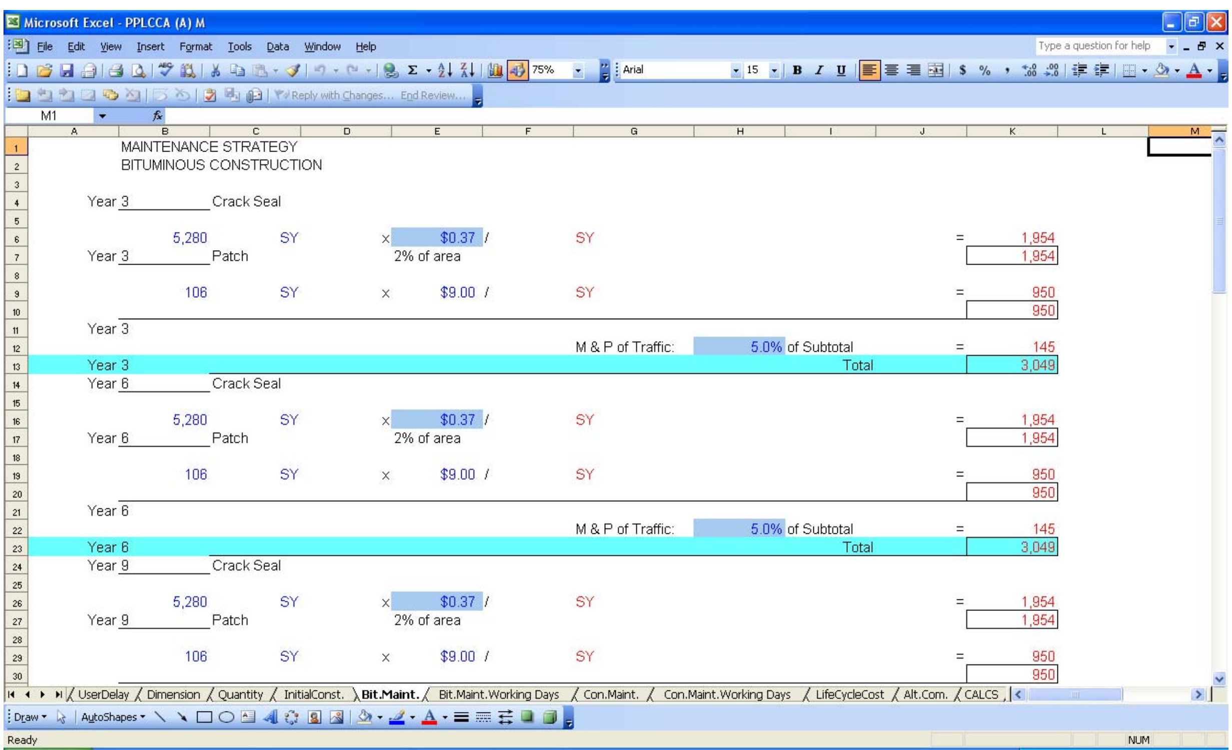


Figure 25: LCCA Step 3: Determine Agency Costs, Maintenance

According to ODOT, the traffic volume for the section of Sooner Road containing the asphalt test sections is 16,900 (AADT); the traffic volume for the section of Highway 77 containing the concrete test sections is 19,500 (AADT). For the given road sections, ODOT anticipates a 2% traffic growth every two to three years for the remaining pavement design life of ten years. Traffic is expected to be comprised of 92% vehicle and 8% truck traffic split 50/50. The routes are classified as "5: Urban Minor Arterial or Collector". The May 2010 Construction Cost Index (CCI) is 8677 (ENR, 2010). These user costs input were entered into the model as illustrated by Figures 26 and 27.

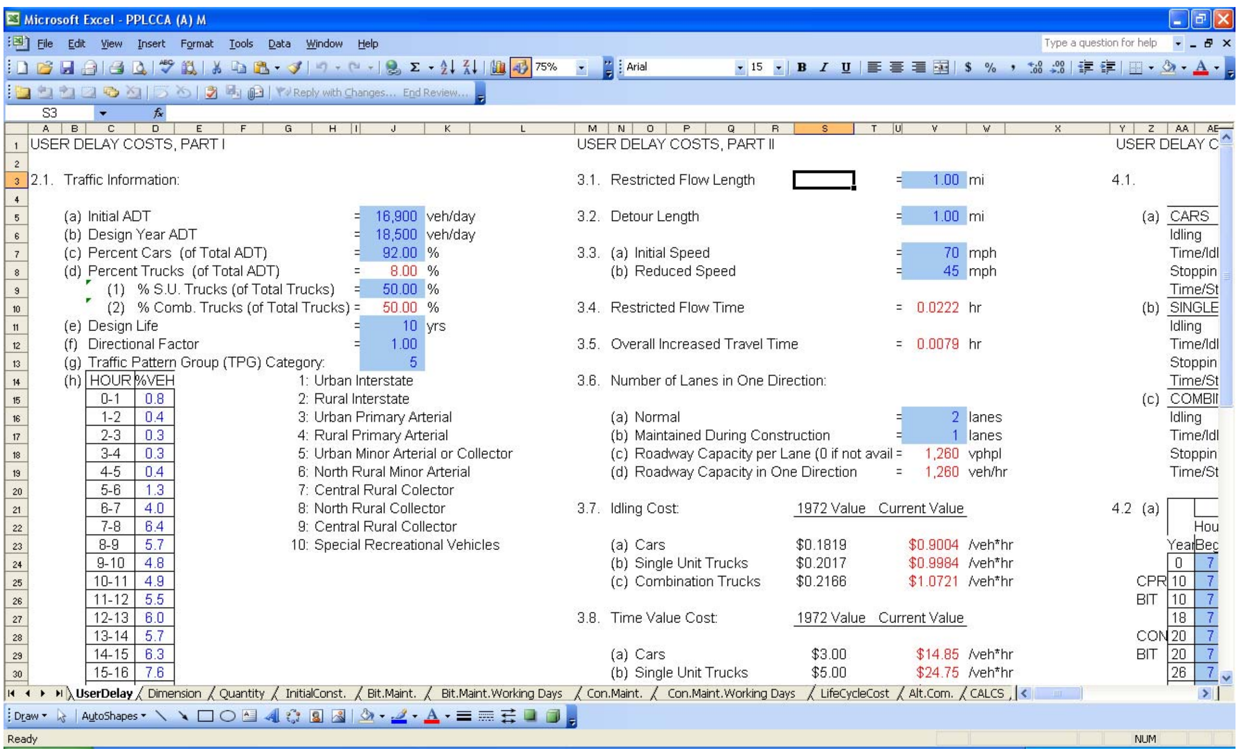
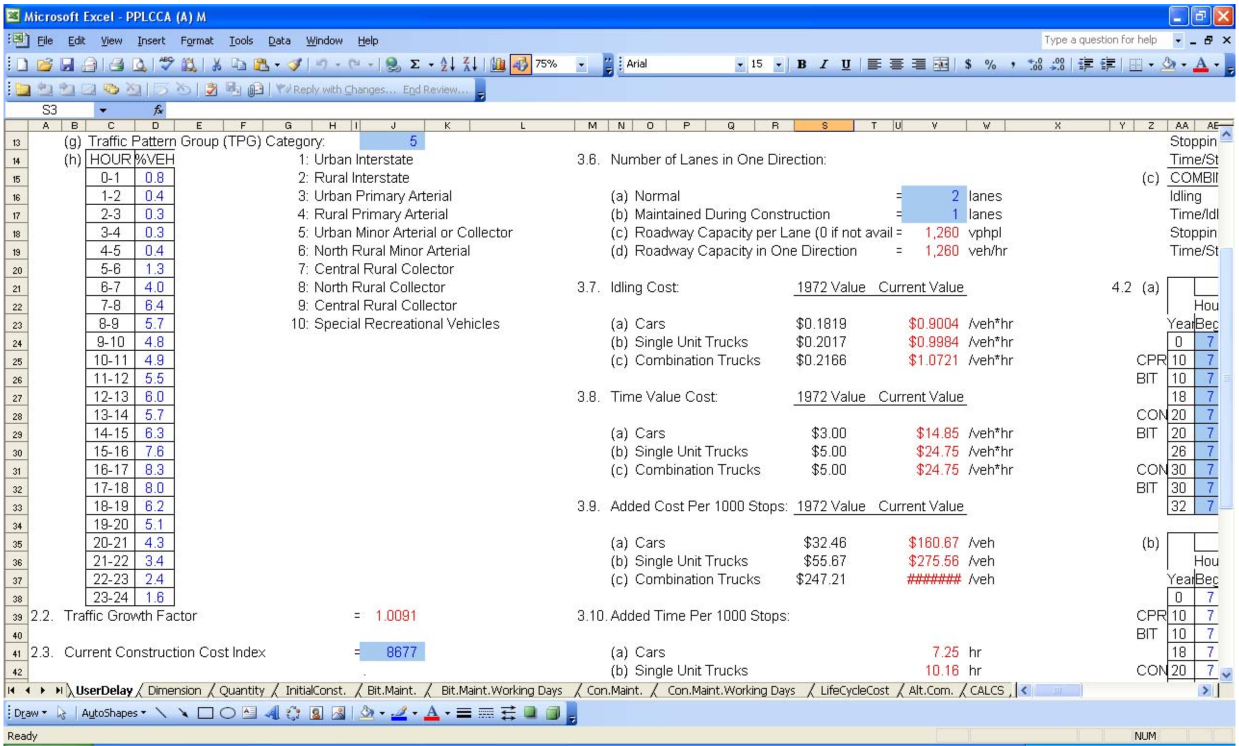


Figure 26: LCCA Step 3: Determine User Costs



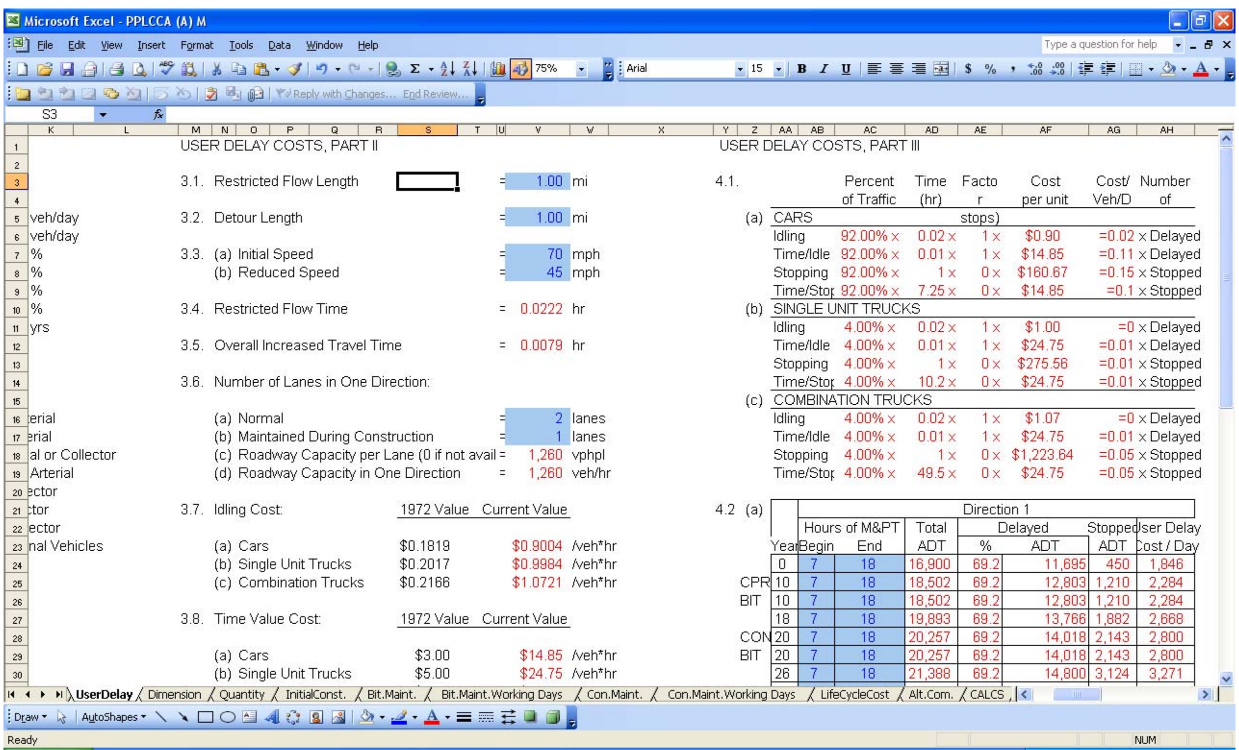
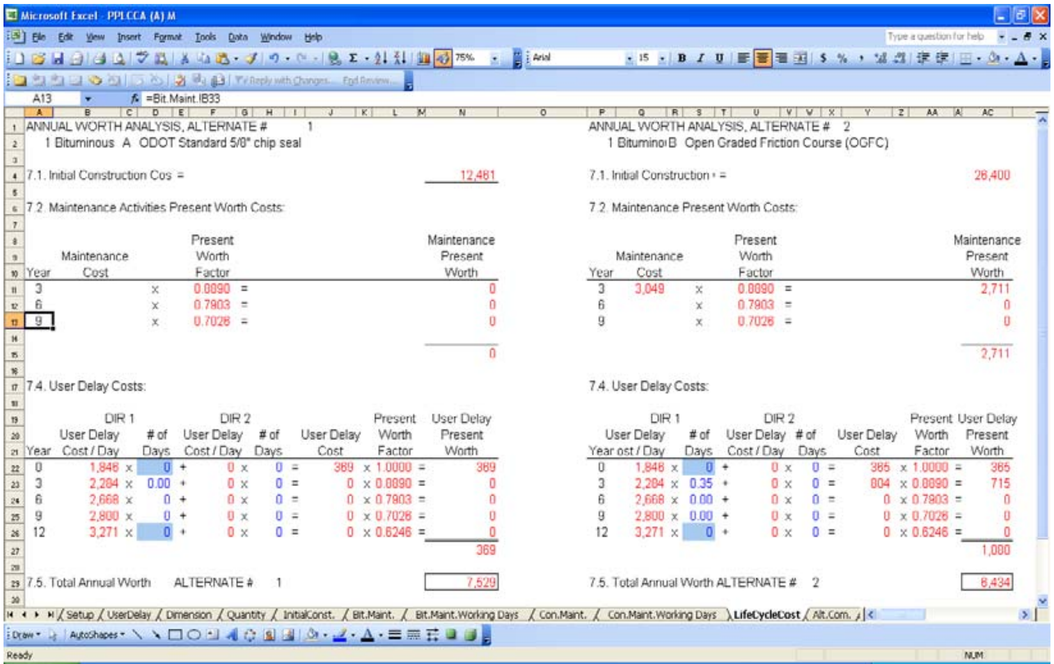


Figure 27: LCCA Step 3: Determine User Costs (Continued)

LCCA Step 4: Compute Life Cycle Costs, Asphalt Model

The life cycle cost calculations were conducted to determine the EUAC of each alternative as shown in Figure 28. The results were manually verified. Although the HMA alternative has the highest initial cost ($28,160), it has the lowest EUAC ($4,696) when service lives are set to the minimum value, as demonstrated in Figure 29.



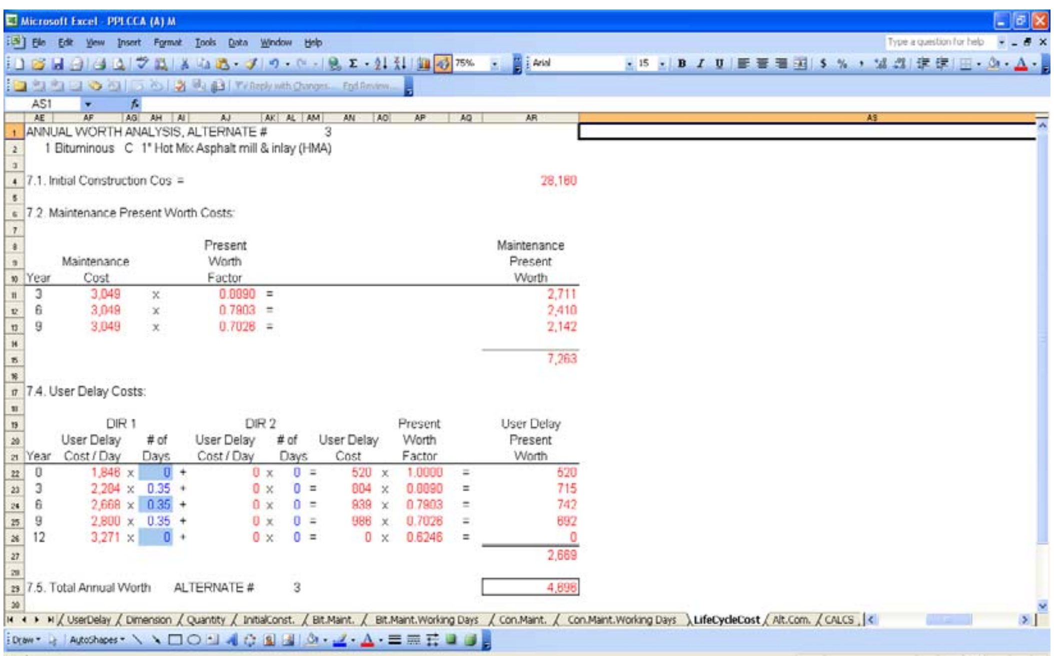
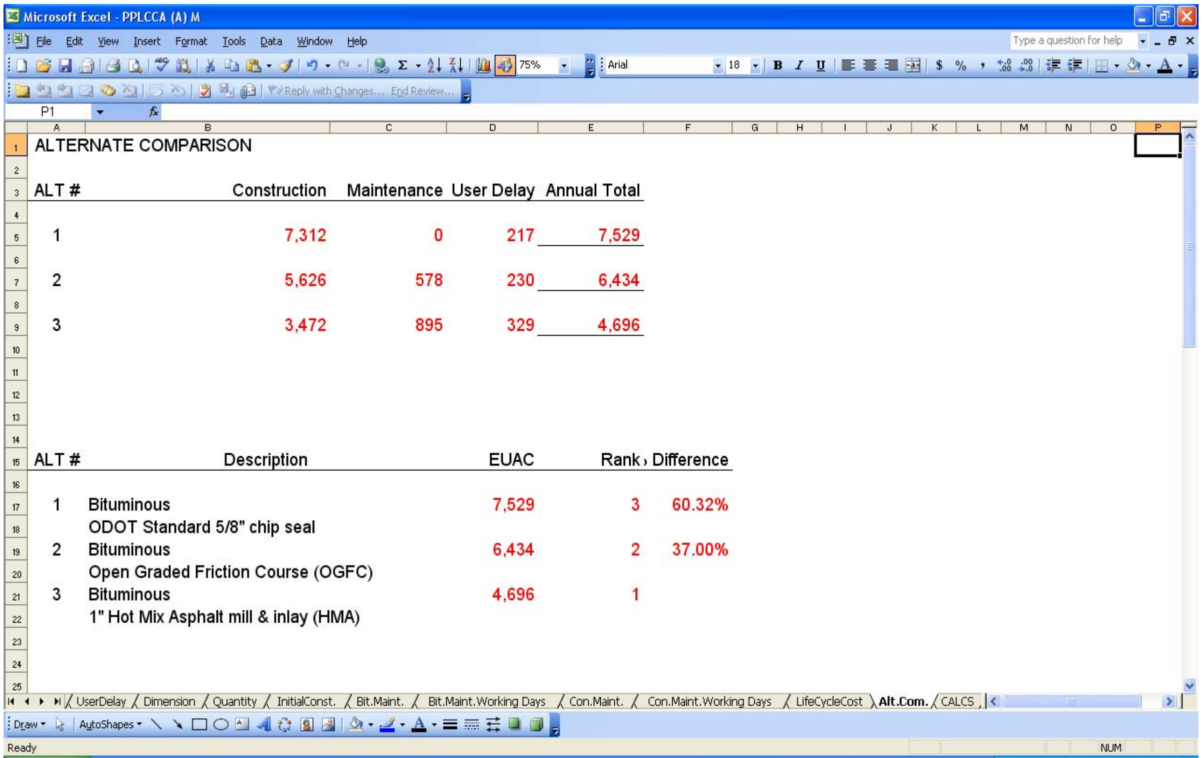


Figure 28: LCCA Step 4: Calculate EUAC, Asphalt Model



ALTERNATE COMPARISON

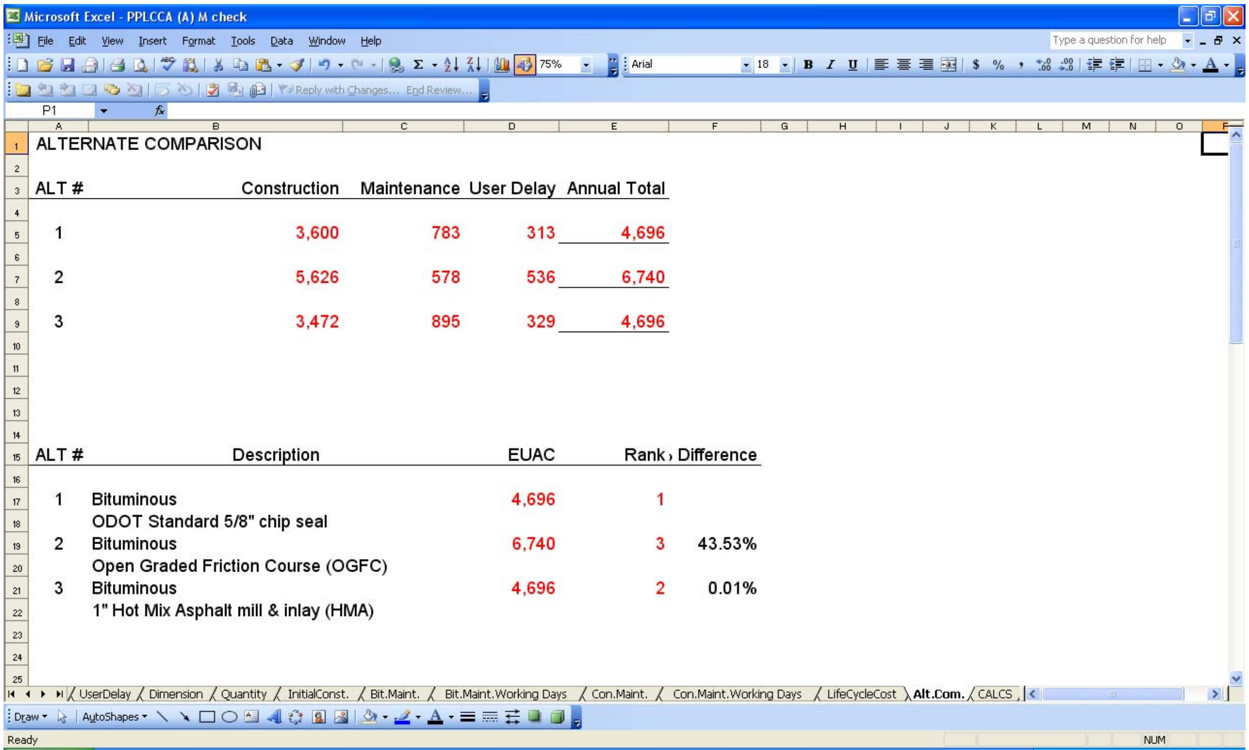
ALT #	Construction	Maintenance	User Delay	Annual Total
1	7,312	0	217	7,529
2	5,626	578	230	6,434
3	3,472	895	329	4,696

ALT #	Description	EUAC	Rank	Difference
1	Bituminous ODOT Standard 5/8" chip seal	7,529	3	60.32%
2	Bituminous Open Graded Friction Course (OGFC)	6,434	2	37.00%
3	Bituminous 1" Hot Mix Asphalt mill & inlay (HMA)	4,696	1	

Figure 29: EUAC Comparison, Asphalt Model

LCCA Step 5: Analyze the Results, Asphalt Model

Service life and discount rate values can be sensitive parameters, so both are analyzed for sensitivity. Both macrotexture and microtexture values are routinely collected by ODOT, so these parameters, as well as the ODOT expected service life values (as stated in Table 5) will be used to verify the sensitivity of the service life value in the life cycle cost analysis as demonstrated in Figure 30. When a service life of 3.8 years (microtexture extrapolation) is entered for chip seal, its life-cycle cost becomes equal to that of the HMA alternative. Essentially the pavement manager could choose either on a life cycle cost basis at a 4% discount rate.



ALTERNATE COMPARISON

ALT #	Construction	Maintenance	User Delay	Annual Total
1	3,600	783	313	4,696
2	5,626	578	536	6,740
3	3,472	895	329	4,696

ALT #	Description	EUAC	Rank	Difference
1	Bituminous ODOT Standard 5/8" chip seal	4,696	1	
2	Bituminous Open Graded Friction Course (OGFC)	6,740	3	43.53%
3	Bituminous 1" Hot Mix Asphalt mill & inlay (HMA)	4,696	2	0.01%

Figure 30: LCCA Step 5: Service Life Sensitivity Analysis, Microtexture-Based

A sensitivity analysis (Figure 31) reveals that this life-cycle cost analysis *is* sensitive to the discount rate, however. Selecting a *discount rate less than 4%* results in the HMA having a lower EUAC ($4,580) than chip seal ($4,643). When *using a discount rate higher than 4%*, the HMA has a higher EUAC ($4,814) than chip seal ($4,749). This means that the selection of a discount rate could effectively drive the pavement preservation design decision between these three alternatives. Therefore, the classic notion that alternatives can be compared equitably using the same discount rate (Walls and Smith, 1998) is disproven for application in the pavement preservation treatment LCCA (Gransberg and Scheepbouwer, 2010). This will not always be the case based on the relative differences between alternatives' installation costs (Reigle and Zaniewski, 2002). However, it shows that if a low discount rate is used, it favors the higher cost, longer lived alternative. The converse is true if a high discount rate is used.

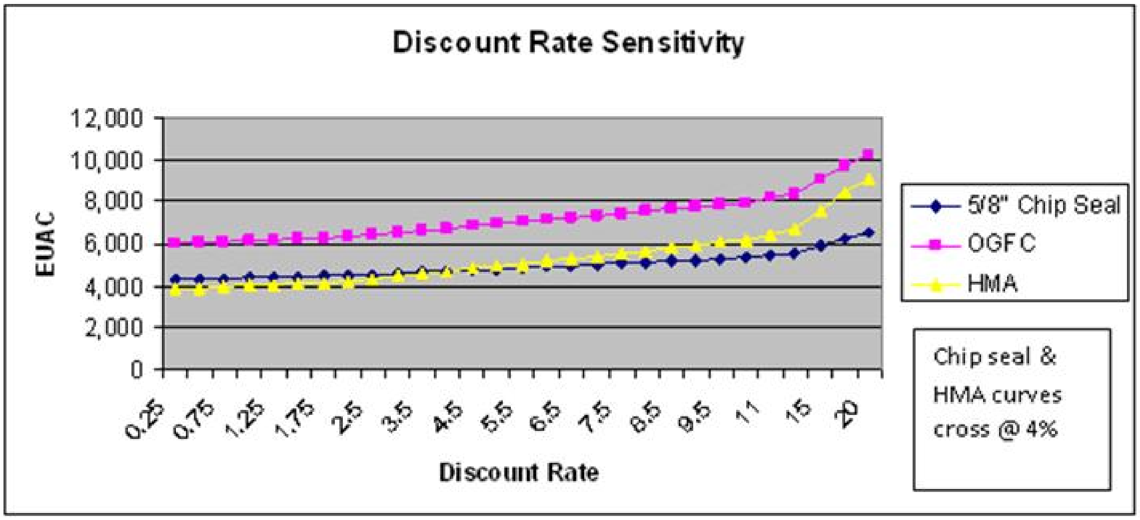


Figure 31: LCCA Step 5: Discount Rate Sensitivity Analysis, Microtexture-Based

When all service lives are set to ODOT expected values, the chip seal becomes the preferred alternative, while the OGFC moves to 2nd place (Figure 32). This proves that using field data derived deterioration curves and performance-based failure criteria provides a more accurate result than the empirical values for service life in use for the current FHWA-approved LCCA process.

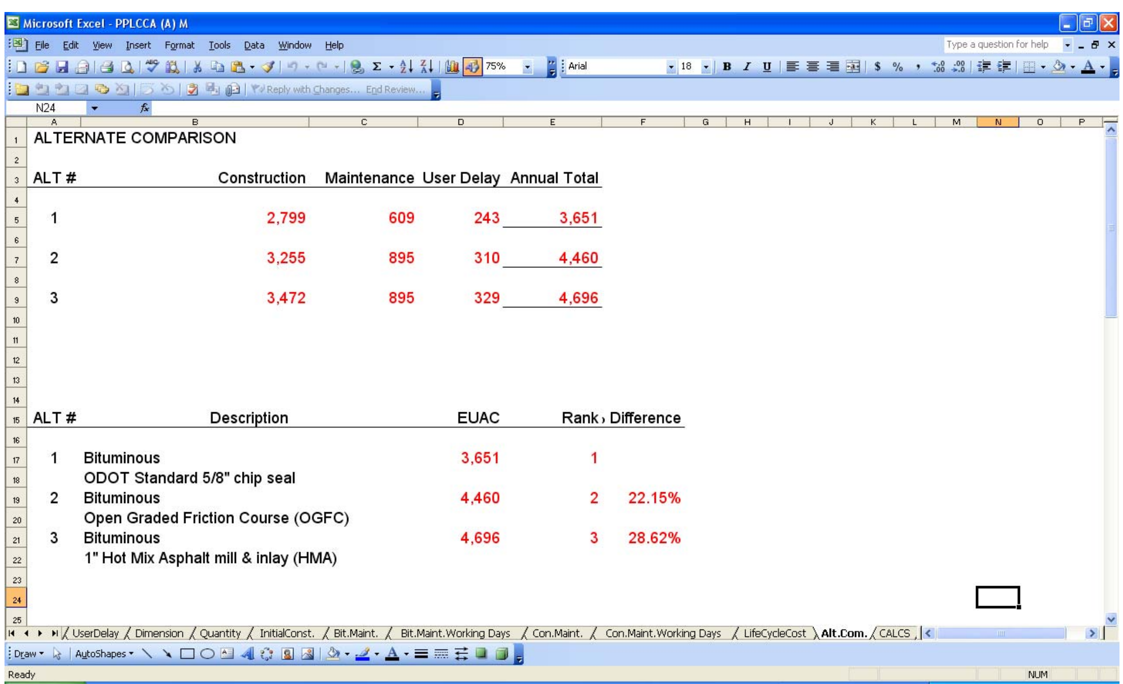


Figure 32: LCCA Step 5: Service Life Sensitivity Analysis, Expectation-Based

Based on this data, the service life parameter is sensitive because an alternative's service life and cost are directly correlated in LCCA. By changing the service life input value of chip seal from 1.8 years to 3.8 years and then to 5 years, its rank changes from 3 to tied with HMA to 1, respectively. The discount rate, in the instant case, is not sensitive. In other words, using a different discount rate will not change the preferred alternative, as illustrated by Figure 33.

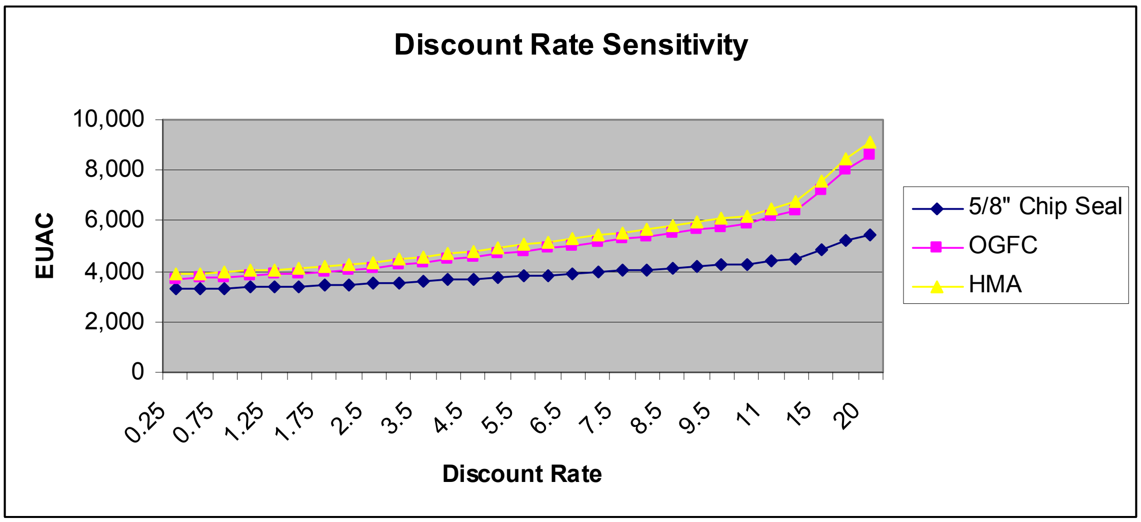
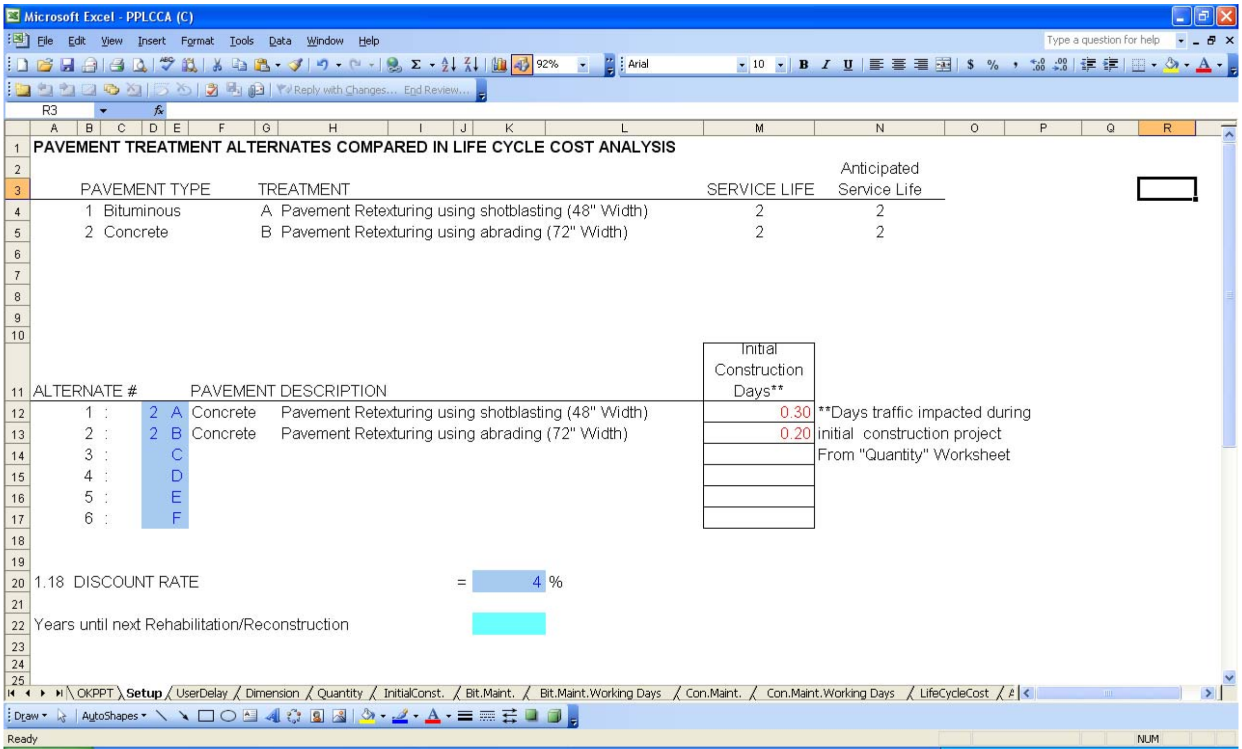


Figure 33: LCCA Step 5: Discount Rate Sensitivity Analysis, Asphalt Model

LCCA Step 4: Compute Life Cycle Costs, Concrete Model

The same LCCA steps are applied to demonstrate the concrete model using the information from the service life and cost Tables 5 and 6, and all other parameters remaining the same, with the exception of the exclusion of a maintenance strategy on these two-year treatments (Figure 34).



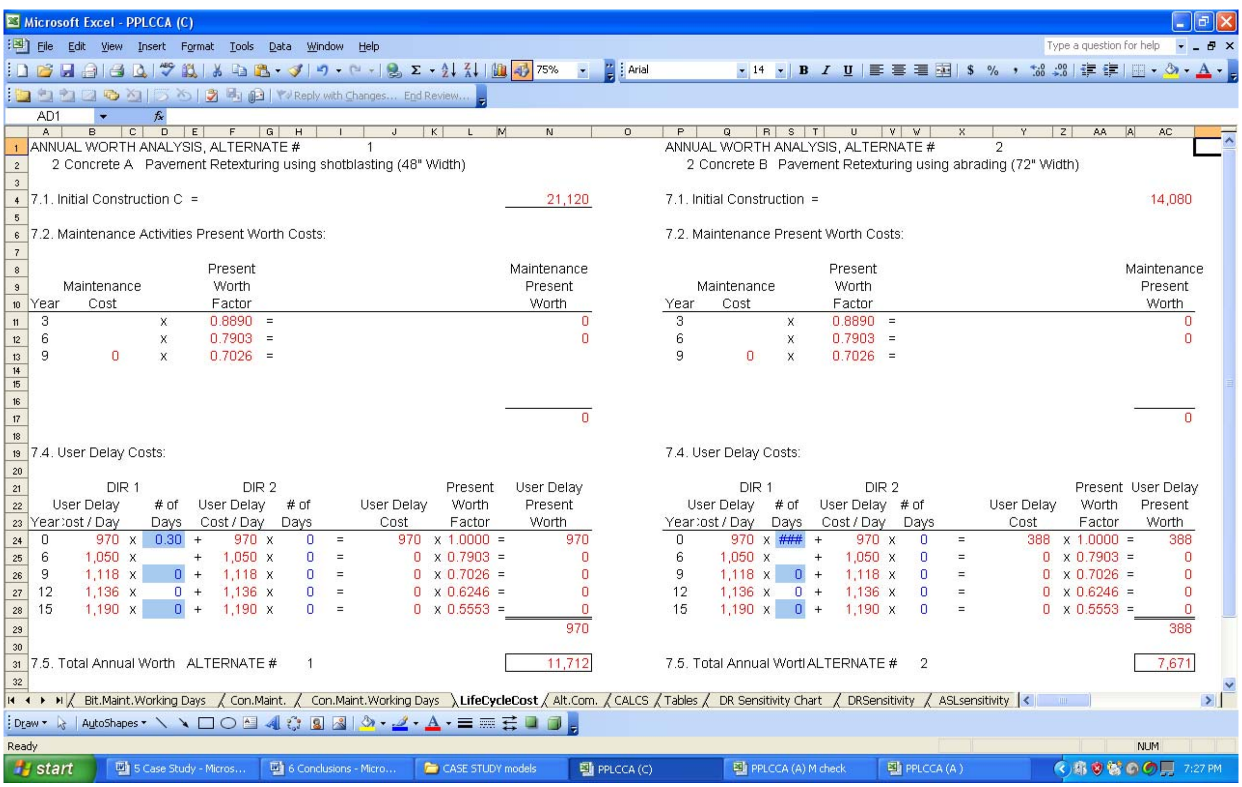


Figure 34: LCCA Step 4: Calculate EUAC, Concrete Model

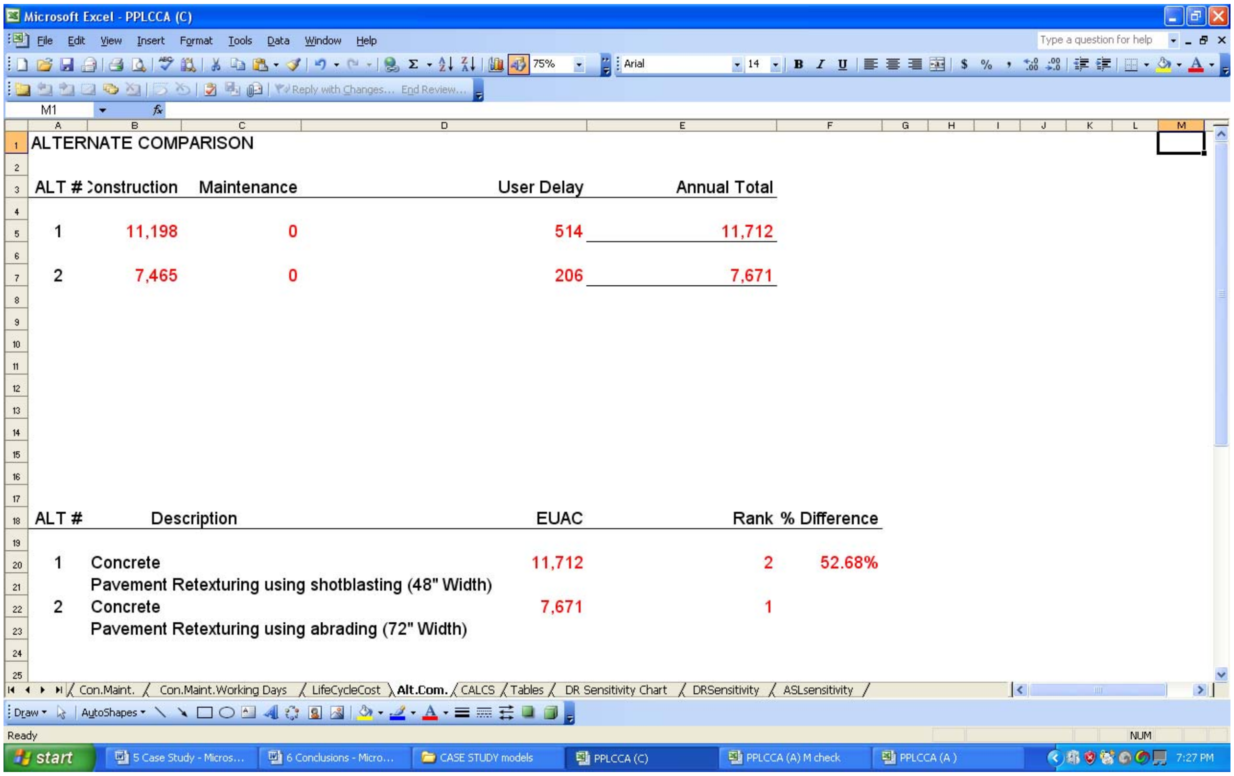


Figure 35: EUAC Comparison, Concrete Model

Based on the given data, the pavement retexturing using abrading alternative would be preferred because it has a lower initial cost and EUAC.

LCCA Step 5: Analyze the Results, Concrete Model

A sensitivity analysis shown in Figure 36 reveals that the alternative selection in the previous is not sensitive to the discount rate (Figure 37).

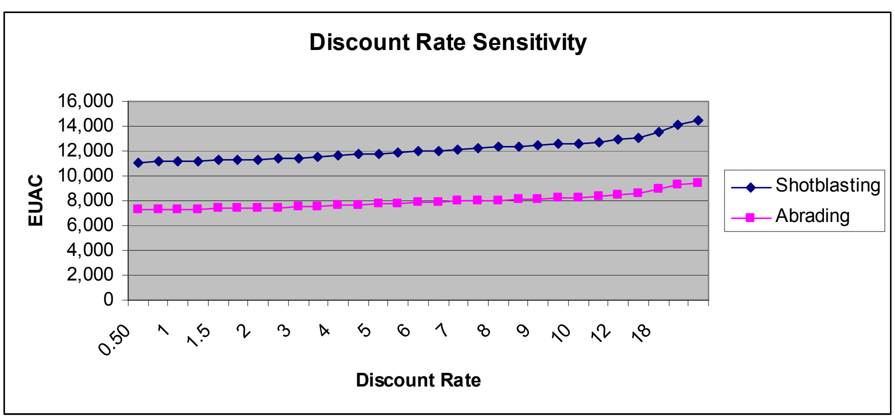


Figure 36: LCCA Step 5: Discount Rate Sensitivity Analysis, Concrete Model

COMPARABLE PW CALCULATIONS, CONTINUOUS STATE

Keeping a good road good could be a perpetual task. The model was developed to accommodate this type of decision making and will operate mainly in this continuous mode. To verify the model, EUAC and present values were calculated to demonstrate that all should yield the same preferred alternative when gaps and residual values are addressed as discussed and cited as appropriate in the previous sections. The standard analysis period was set to twenty years, consistent with an FHWA case study on project-level planning (FHWA, 2005). Twenty years is also the least common multiple of lives. User costs were omitted for simplification. All methods returned the same ranking, as illustrated in Table 7, in support of validating EUAC "standalone" as a valid pavement preservation LCCA method. This illustrates the point that using different analysis periods corresponding with the differing service lives of alternatives in a life cycle cost analysis does not remove the "fairness" nor does it result in differing benefits; it does, however, bypass the commonly problematic analysis period selection, associated adjust-to-fit requirements and well-cited sensitivity issues for that parameter. The service life selection and corresponding sensitivity can be obscured by the analysis period in present value calculations, but are exposed by the EUAC model. This allows for the sensitivity to be moved from the analysis period parameter, which may be arbitrary and uncontrollable, to the service life parameter, which allows the pavement manager to intuitively adjust and account for service life selection and sensitivity based on professional judgment.

Table 7 Comparable EUAC and PV Rankings, Continuous State

PAVEMENT TREATMENTS	Agency Costs	Analysis Period	Rank
EUAC			
ODOT Standard 5/8" chip seal (5-yr)	3,408	5	1
OGFC (10-yr)	4,150	10	2
1" Hot Mix Asphalt mill/inlay (10-yr)	4,367	10	3
Present Value - Shortest Life			
ODOT Standard 5/8" chip seal (5-yr)	15,172	5	1
OGFC (10-yr)	20,463	5	2
1" Hot Mix Asphalt mill/inlay (10-yr)	21,343	5	3
Present Value - Longest Life			
ODOT Standard 5/8" chip seal (5-yr)	30,344	10	1
OGFC (10-yr)	33,663	10	2
1" Hot Mix Asphalt mill/inlay (10-yr)	35,423	10	3
Present Value - Standard Period & LCM			
ODOT Standard 5/8" chip seal (5-yr)	60,688	20	1
OGFC (10-yr)	67,326	20	2
1" Hot Mix Asphalt mill/inlay (10-yr)	70,846	20	3

MODEL DEMONSTRATION, TERMINAL STATE

To demonstrate the LCCA model's ability to accurately depict all possible modes, the following will show its use in terminal state, where the next major rehabilitation or reconstruction for a given pavement is known.

LCCA Step 4: Compute Life Cycle Costs

The model should rarely be operated in terminal mode due to a pavement manager's propensity to "do nothing" when the next rehabilitation/reconstruction is known. However, if "do nothing" is not an option, the model can be used to determine the preferred alternative in this short-term period. Although it can yield the same preferred alternative as PV regardless of analysis period selected as exhibited in Table 8, it can be sensitive to the analysis period selection depending on the input data. In an analysis-period-sensitive situation, the EUAC will function like PV when setting the analysis period consistent with the shortest-life alternative. For example, if the next expected rehabilitation/reconstruction is in six years, "do nothing" would be the pavement manager's first choice. If "do nothing" is not an option, then "6" would be entered into the appropriate cell, truncating the longer service lives of the OGFC and HMA, but leaving a one-year gap filled implicitly with "do nothing" for the chip seal, as illustrated in Figure 37. The residual value equals zero at the time of the encroachment, so the OGFC and the HMA will have analysis periods of six years.

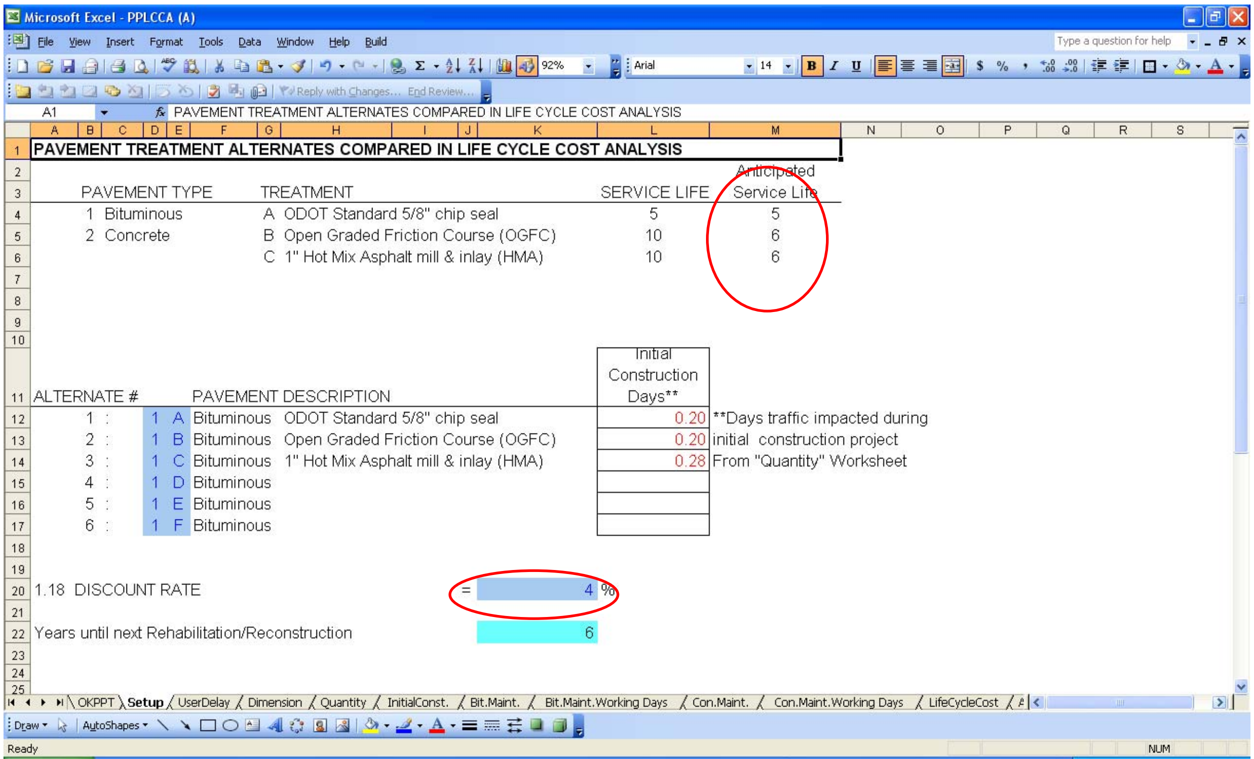
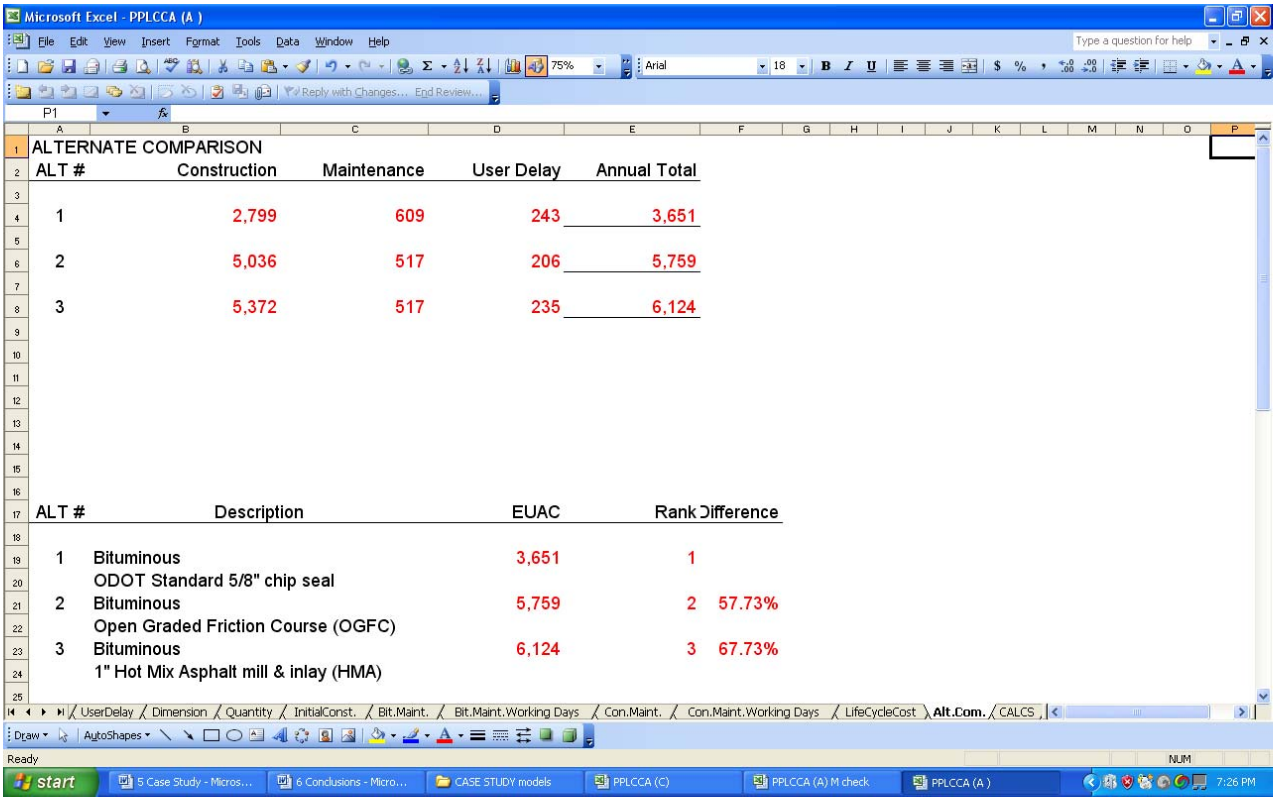


Figure 37: LCCA Step 4: Calculate EUAC, Terminal State



ALTERNATE COMPARISON

ALT #	Construction	Maintenance	User Delay	Annual Total
1	2,799	609	243	3,651
2	5,036	517	206	5,759
3	5,372	517	235	6,124

ALT #	Description	EUAC	Rank	Difference
1	Bituminous ODOT Standard 5/8" chip seal	3,651	1	
2	Bituminous Open Graded Friction Course (OGFC)	5,759	2	57.73%
3	Bituminous 1" Hot Mix Asphalt mill & inlay (HMA)	6,124	3	67.73%

Figure 38: LCCA Step 4: Compare EUAC, Terminal State

Figure 38 shows the preferred alternative to be chip seal. It would also be the intuitive choice because it would efficiently fill the gap.

LCCA Step 5: Analyze the Results

Chip seal is also the preferred alternative with a 3.8-year service life input value consistent with the microtexture extrapolation, but is not preferred with a 1.8-year service life value extrapolated from the macrotexture data as illustrated in Figures 39 and 40. This situation illustrates the value of exposing the service life sensitivity versus obscuring it with PV so that the pavement manager can intuitively analyze the results. The EUAC makes evident to the pavement manager that the 3.8-year chip seal, coupled implicitly with “do nothing” for 2.2 years, is the preferred alternative to fill the 6-year window until terminal and can decide based on professional judgment whether or not that is realistic.

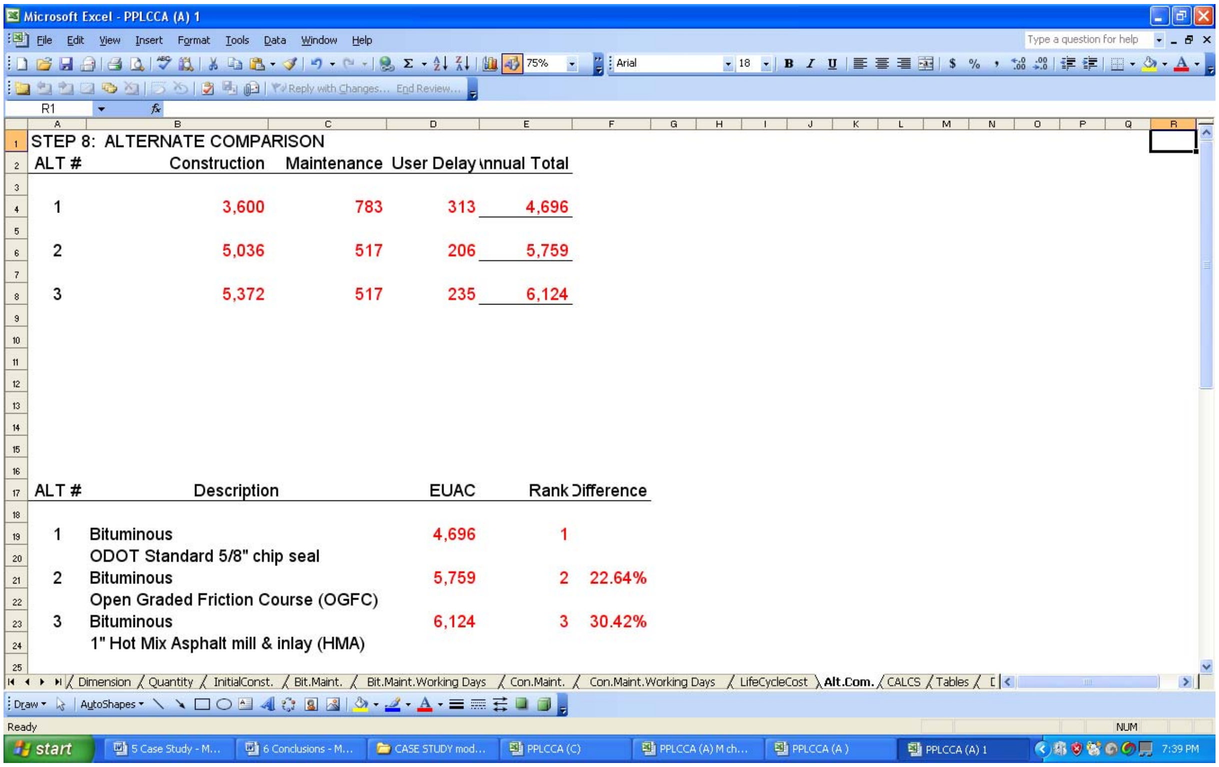


Figure 39: LCCA Step 5: Service Life Sensitivity, Terminal – Microtexture-Based

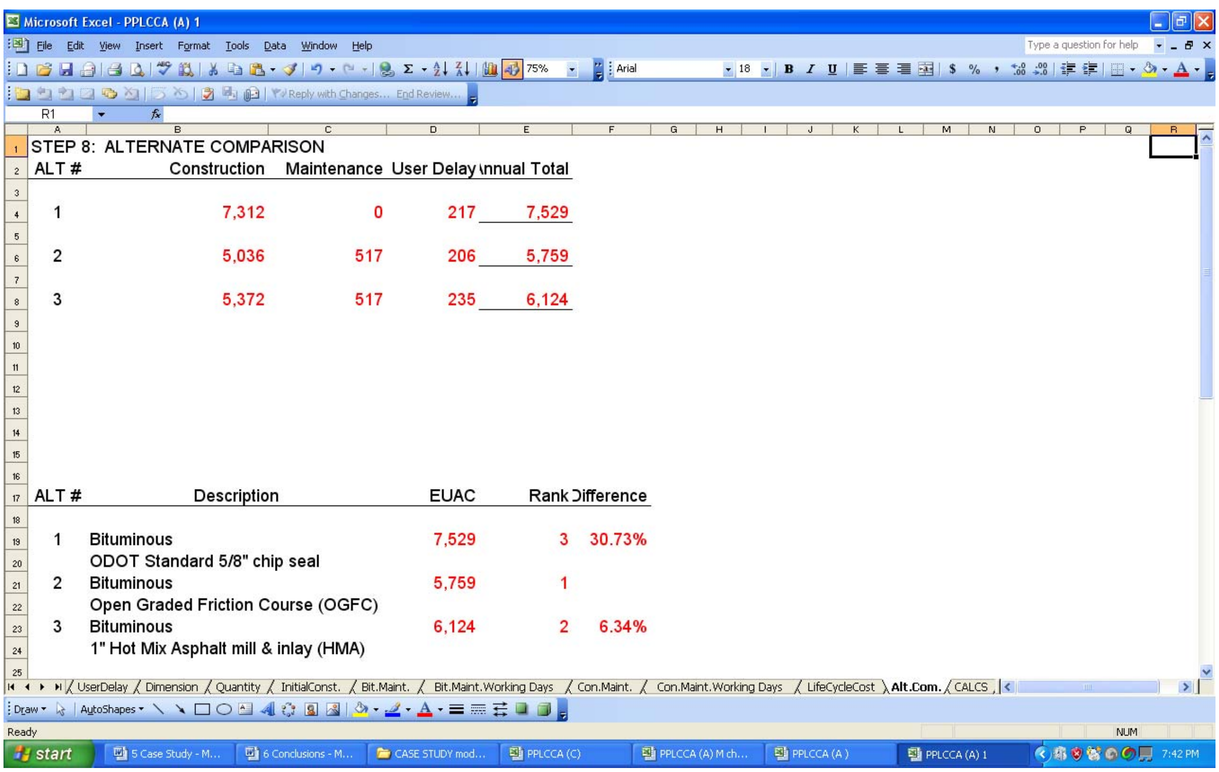


Figure 40: LCCA Step 5: Service Life Sensitivity, Terminal – Macrotexture-Based

It is also prudent to analyze the effect of pavement-life extending possibilities on alternative ranking by those alternatives whose service lives were truncated by the next expected rehabilitation/reconstruction. This is accomplished by changing the value in the next expected rehabilitation/reconstruction cell to the expected or possible service life value for given alternatives. In the instant case, when the cell is set to “10”, which is consistent with the expected life of HMA and OGFC, the preferred alternative does not change, meaning there is no sensitivity to the pavement-life extension parameter. This calculation is identical to the one conducted in Figure 32. If, on the other hand, the pavement-life extension parameter is sensitive, the pavement manager may ascertain the effect by intuitively adjusting the R/R cell until the preferred alternative changes, within the expected limits of service life for alternatives.

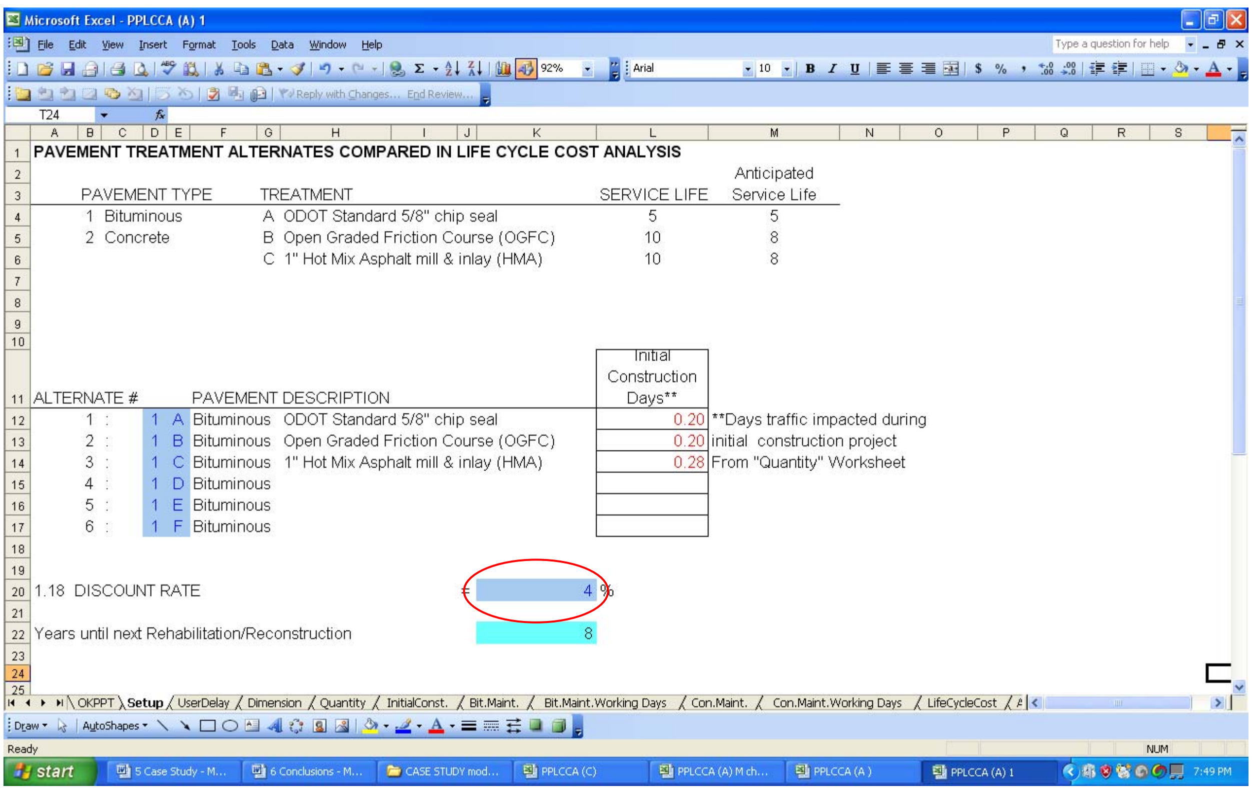


Figure 41: LCCA Step 5: Pavement Life Extension Sensitivity, Terminal State

COMPARABLE PW CALCULATIONS, TERMINAL STATE

Table 8 below illustrates that even in terminal state, EUAC can yield the same results as PV when service lives are truncated to accommodate the next expected rehabilitation/reconstruction. The situation to avoid would be to fill the 1-year gap before terminal with another chip seal. Although there is no change in preferred alternative when this was calculated in the following Table, the PV values are close and could result in faulty output in other situations because although a pavement manager would not realistically fill a 1-year gap with another 5-year chip seal, the PV method may default to and obscure that calculation in the LCCA.

Table 8 EUAC and PV Results (no user costs), Terminal State at 6yrs

PAVEMENT TREATMENTS	Agency Costs	Analysis Period	Rank
EUAC			
ODOT Standard 5/8" chip seal (5-yr)	3,408	5	1
OGFC (10-yr)	5,553	6	2
1" Hot Mix Asphalt mill/inlay (10-yr)	5,889	6	3
Present Value - Shortest Life			
ODOT Standard 5/8" chip seal (5-yr)	15,172	5	1
OGFC (10-yr)	29,111	5	2
1" Hot Mix Asphalt mill/inlay (10-yr)	30,871	5	3
Present Value - Rehab year, Fill the gap for Chip Seal			
ODOT Standard 5/8" chip seal (5-yr)	27,633	6	1
OGFC (10-yr)	29,111	6	2
1" Hot Mix Asphalt mill/inlay (10-yr)	30,871	6	3

EUAC does yield the same decision support as PV in continuous mode, as cited in the literature (White et al., 2010). It is also likely to yield the same decision support as PV in the rarer terminal mode and would function like PV (shortest-life) method. EUAC disallows the repetitive fill-the-gap treatment which is not appropriate in pavement preservation/terminal scenario because the more common choice is “do nothing”. By explicitly displaying service life and pavement extension values and corresponding sensitivity, the pavement manager is given information vital to determining cost effectiveness of competing alternatives. Therefore, its use is appropriate and has been suggested for transportation decision making (Gransberg and Scheepbouwer, 2010; Sinha and Labi, 2007).

LCCA Step 6: Reevaluate the Results

Armed with field data, expertise and the LCCA results for a continuous or terminal scenario, a pavement manager would have enough information to make decisions about which treatment to employ. This information should be coupled with other decision-support factors such as “risk, available budgets, and political and environmental concerns” (FHWA, 2002). The output from an LCCA should not be considered the “answer”, but merely an indication of the relative cost effectiveness of alternatives (FHWA, 1998) and a rough measure of each treatment’s sustainability as compared to the other options.

FIELD TEST RESULTS

The test sections associated with the Phase 1 project will continue to be tested on a monthly basis for another 12 months. At this writing there have been up to 22 observations made on the sections that were installed first. The prime objective of the research is to build simple deterioration models that can be used as demonstrated in the LCCA section of the report to predict pavement preservation treatment service life and assist ODOT maintenance engineers in making an informed treatment selection decision.

DETERIORATION MODEL DEVELOPMENT

Furnishing micro and macrotexture deterioration model based on field test data will allow maintenance engineers to use them to calculate a rational value for the service life of pavement preservation treatments under consideration for a given project (Austroads, 2000; TNZ, 2005). Once the models are proven, they can then be used in conjunction with rationally developed failure criteria to permit LCCA as an additional treatment selection decision parameter. At this point in the research, the models do not contain sufficient data to be reliable. Therefore, the detailed discussion of this feature of the research will be reserved for inclusion in the OTCREOS9.1-21 Phase 2 final report in 2011. The remainder of this section will discuss the emerging trends and findings that the research is observing, as well as how the team will use the information in the final project deliverables. Figures 42 through 48 are derived from a nonlinear regression of the monthly macrotexture measurements derived from the TNZ T/3 sand circle test.

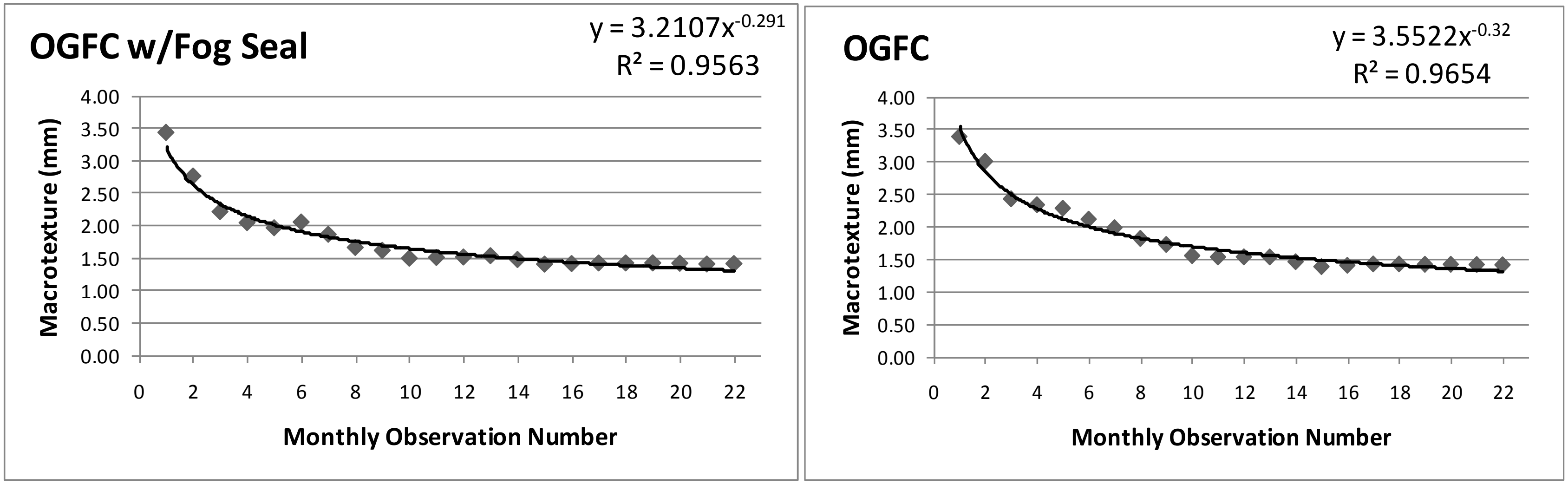


Figure 42: Open Graded Friction Course Test Results: With and Without a Fog Seal

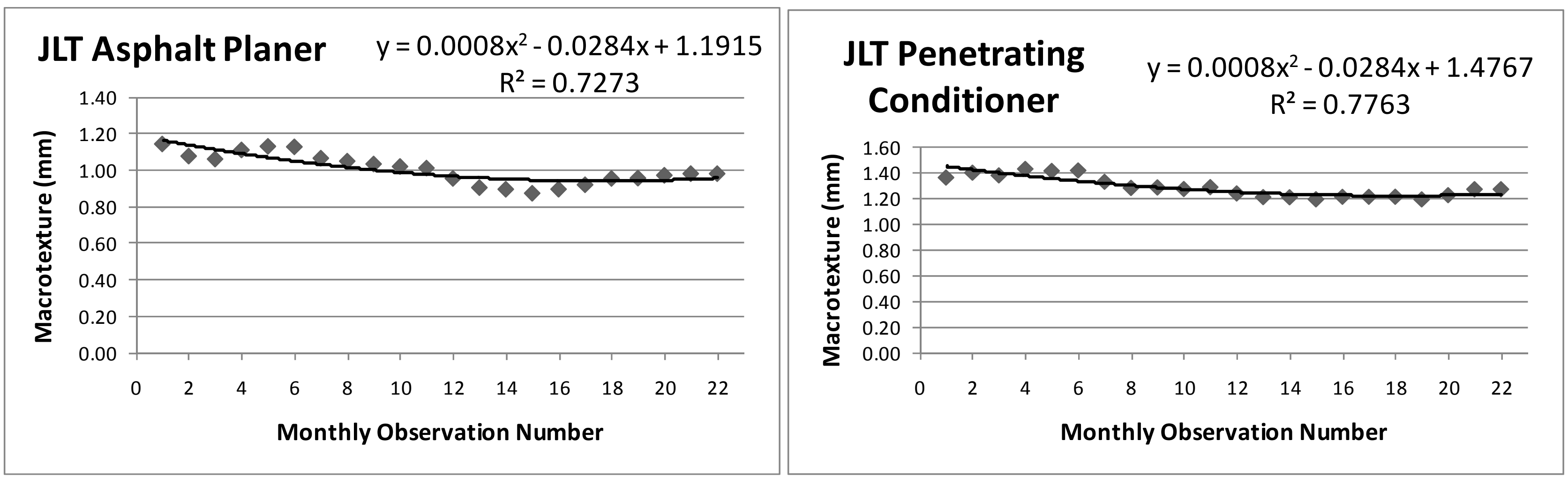


Figure 43: JLT Penetrating Conditioner on Planed and Unplaned Asphalt Surface

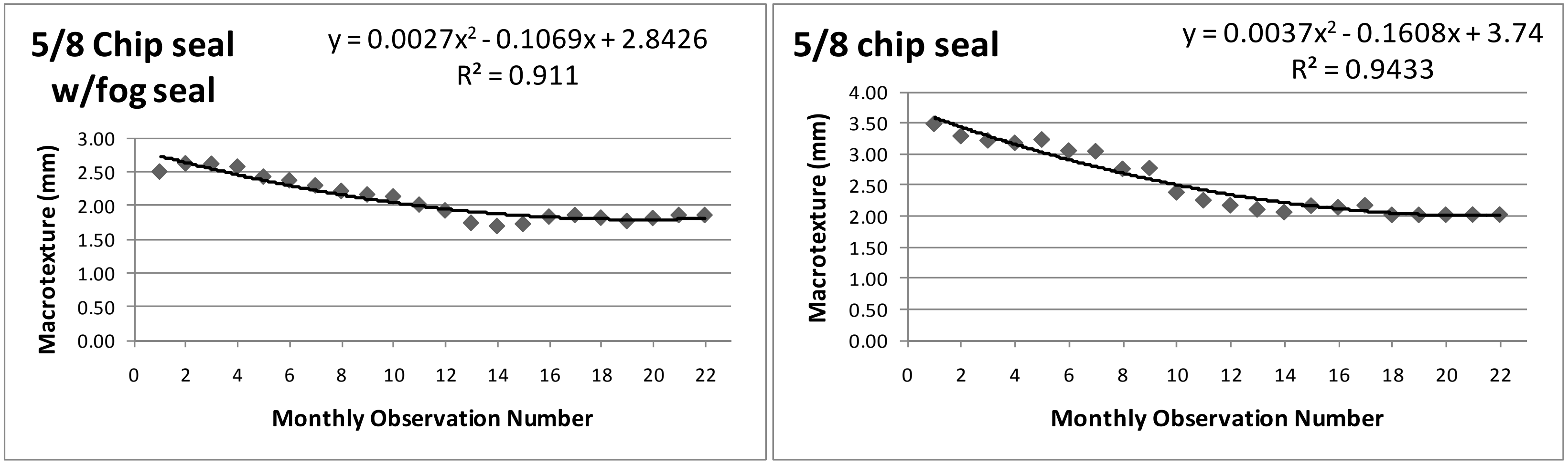


Figure 44: 5/8” Chip Seal With and Without Fog Seal

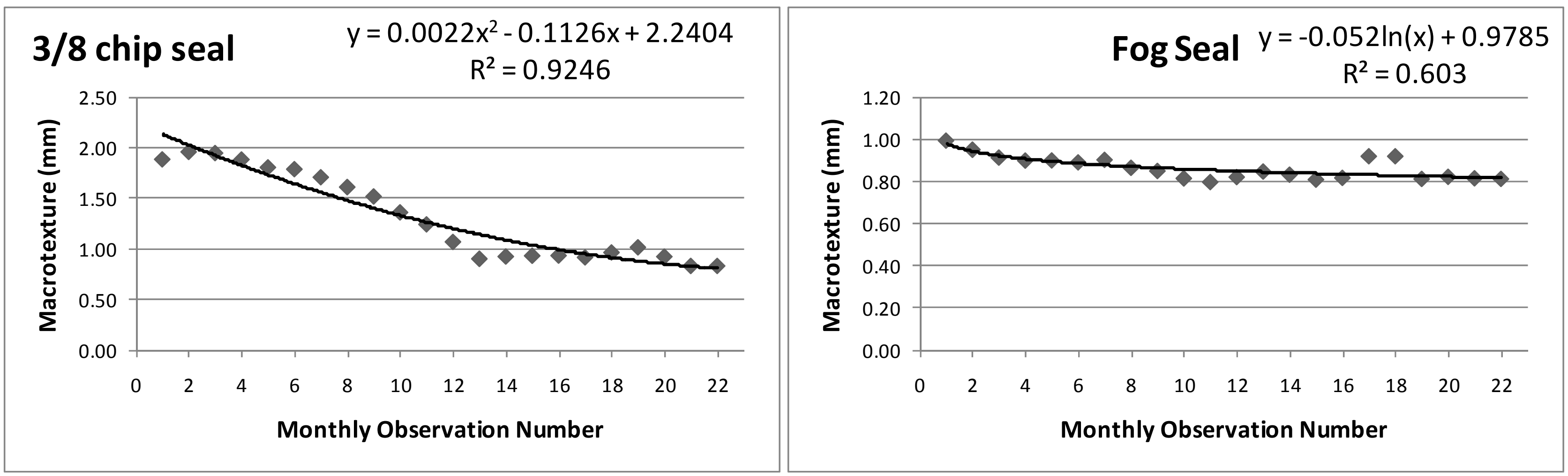


Figure 45: 3/8” Chip Seal and Fog Seal Alone

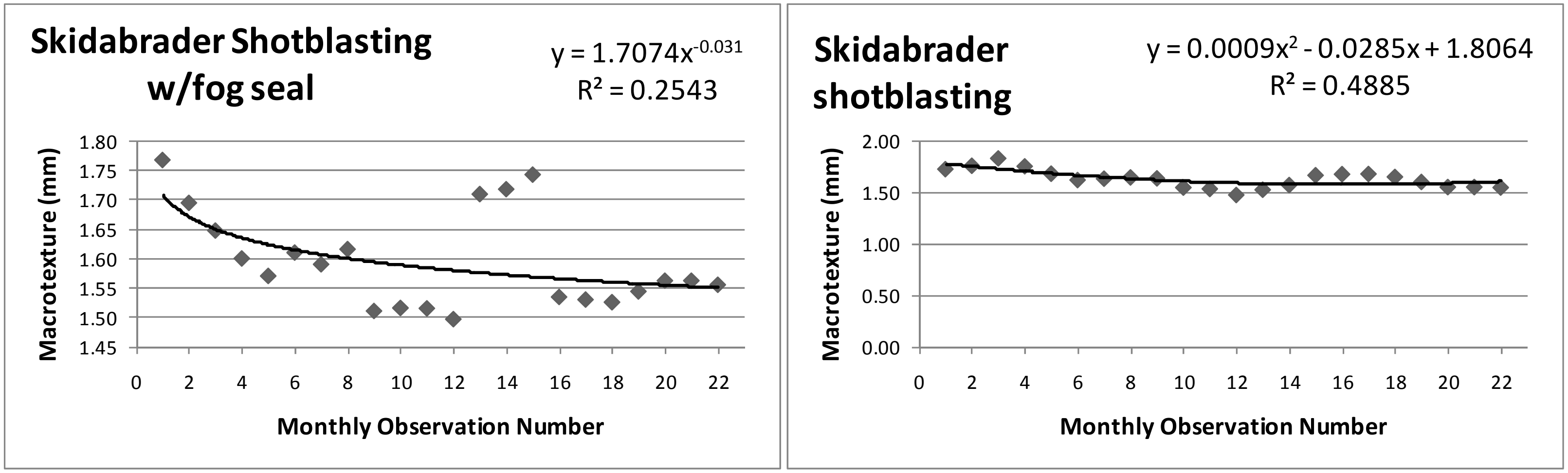


Figure 46: Skidabrader Shotblasting on Asphalt With and Without Fog Seal

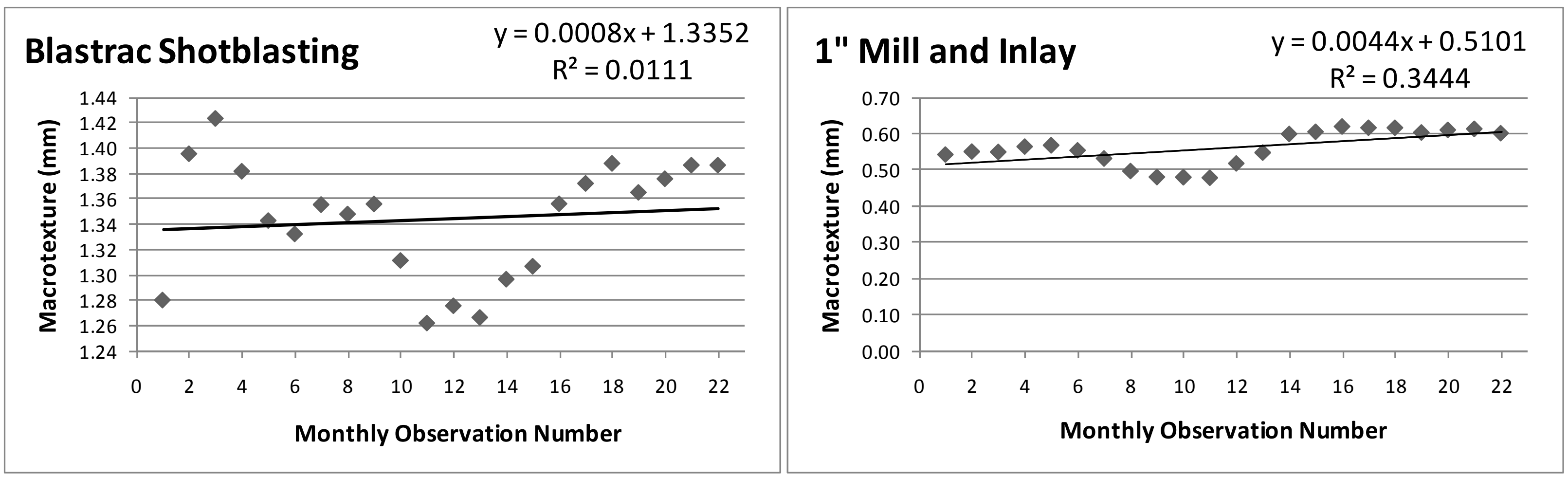


Figure 47: Blastrac Shotblasting on Asphalt and 1” Mill and Inlay

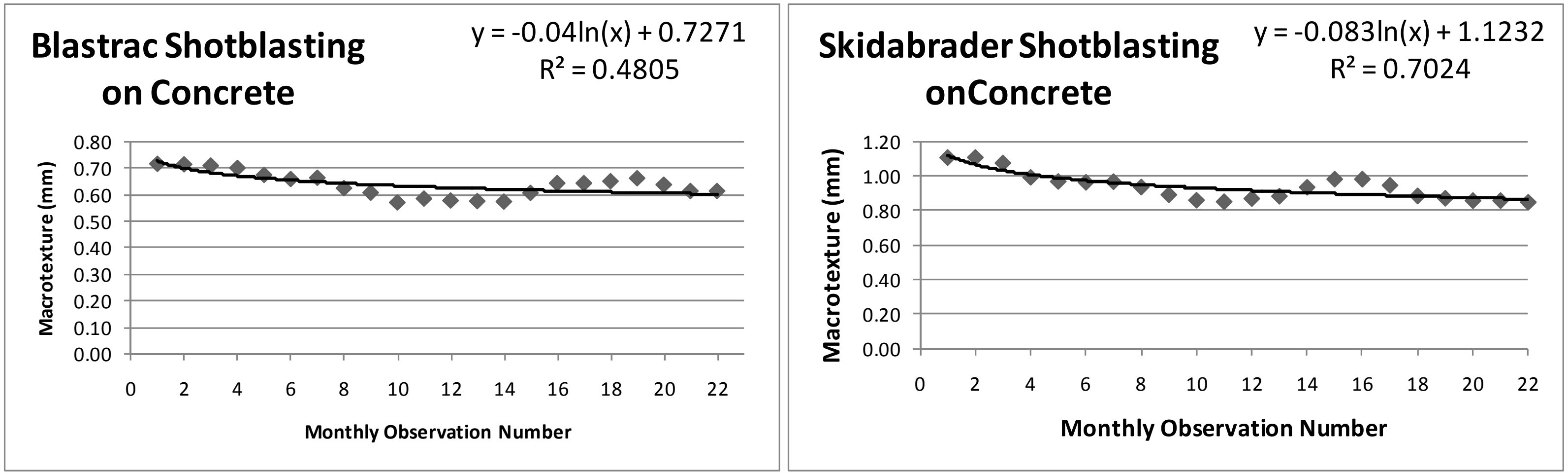


Figure 48: Blastrac and Skidabrader Shotblasting on Concrete

TRENDS IN MACROTEXTURE DETERIORATION

The TNZ T/3 sand circle test monthly macrotexture data was chosen for this particular report because it can be directly compared with the Australian and New Zealand research upon which the project is building. One aspect of that research is a performance specification for chip seals that measures macrotexture after 12 months and compares it to a value that is derived from a deterioration model for a specific design life. A performance specification is defined as a measurement of "how the finished product should perform over time" (Chamberlain, 1995). Specification of design life expectations is an effective means of determining long-term chip seal performance. The entire TNZ specification is based on this deterioration model and is founded on the assumption that long-term chip seal service life is ultimately determined by the consequence of texture loss due to flushing (a condition also called bleeding in the US literature) (TNZ, 2002).

Chip Seal Deterioration

The chip seal performance specification is New Zealand's P/17, *Notes for the Specification of Bituminous Reseals* (TNZ, 2002). The philosophy behind the P/17 specification is that the texture depth after twelve months of service is the most accurate indication of the performance of the chip seal for its remaining life. The New Zealand specification also contends, "the design life of a chip seal is reached when the texture depth drops below 0.9 mm (0.035 inches) on road surface areas supporting speeds greater than70 km/h (43 mph)" (TNZ, 2002). The deterioration models developed in New Zealand have directed the P/17 Specification to require the minimum texture depth one year after the chip seal is completed using the following equation.

$$Td_1 = 0.07\ ALD \log Y_d + 0.9 \qquad (3)$$

Where: Td_1 = texture depth in one year (mm)

Y_d = design life in years

ALD = average least dimension of the aggregate (mm)

Figures 42 through 48 can be seen to exhibit some very different behavior over time. First, it must be stated that only the chip seal test sections shown in Figures 43 and 45 can be evaluated by the model shown in equation 3. Table 9 shows the output from that analysis. One can compare the TNZ failure criterion of 0.9mm with the preseal measured macrotexture that the existing substrate was a mere 0.04mm above failing. After 12 months of service, the 3/8" chip seal has failed the P/17 12- month criterion at all possible design lives, and at 22 months it drops below the ultimate failure criterion of 0.9mm. The opposite is true for the two 5/8" chip seal sections. The table also shows that the treatment with a fog seal's macrotexture is less than the one without the fog seal. When viewed the macrotexture standpoint, the fog seal marginally fills the new seal's voids with bitumen and therefore intuitively, it must reduce the macrotexture has observed in Table 9.

Table 9 TNZ P/17 Performance Specification Comparison

Treatment	**P/17 12-month Minimum Macrotexture at Given Design Life**			**Before Seal Macrotexture**	**Actual 12-month Macrotexture**	**Actual 22-month Macrotexture**
	4-year	**5-year***	**6-year**			
3/8 Chip Seal No Fog Seal	1.17	1.29	1.37	0.94	1.07	0.83
5/8 Chip Seal No Fog Seal	1.43	1,68	1.85	0.94	2.18	2.04
5/8 Chip Seal w/Fog Seal	1.43	1.68	1.85	0.94	1.93	1.86
* Average design life for chip seals cited in ODOT survey						

The next point that can be found in Figures 43 and 45 is the high coefficient of determination (R^2) of the regression equation that represents the deterioration model for the three treatments. The classic definition for R^2 states that it is a measure of "the proportion of variability in a data set that is accounted for by the statistical model" and describes "goodness of fit of the curve derived from the regression analysis" (Draper and Smith, 1998). Therefore based on this definition, the curves shown in Figures 44 and 45 account for over 90% of the variation in chip seal macrotexture loss. Said another way, the age of the chip seal is the major factor in its loss of macrotexture, and the regression equations for each treatment will be able to reliably predict the loss of macrotexture over time to a $\pm$ 10% degree of accuracy. This makes the deterioration models for the three chip seal treatments reasonably reliable.

Open Graded Friction Course (OGFC) Deterioration Models

The R^2 values shown in Figure 42 for the two OGFC test sections were greater than the chip seal values. Therefore, using the same logic, these deterioration models will also be highly reliable. There is no previously established performance failure criterion for OGFC macrotexture in the literature. So the analysis shown in Table 9 cannot be conducted for this treatment. However, the analysis shown in Figure 16 for OGFC to determine is service life as input to the LCCA model can be viewed as a possible solution. That analysis uses the NZTA ultimate failure criterion of 0.9mm as the point at which the service life ends. While that specific number comes from chip seal research and is not directly relatable to OGFC, it does indicate that given research to measure how much macrotexture is required for OGFC to perform as designed that a performance failure criterion could be determined. That is beyond the scope of this project and is a future research need that may be considered by OTC and ODOT in the years to come.

Deterioration Models for Remaining Treatments

Table 10 is a consolidation of the macrotexture deterioration models for the Phase 1 test sections sorted by coefficient of determination. Looking at those that were used on the asphalt substrate the table shows that time is the primary factor in macrotexture loss for the OGFC and chip seals, all of which had R^2 values above 0.9. Next the two JLT penetrating pavement conditioner test sections show that time only accounts for roughly 75% of the variation in macrotexture loss. The difference between the two sections was whether or not the surface had been planed prior to applying the conditioner. The planing operation removed a small amount (~1/8”) of existing surface that theoretically “opened” the surface to permit a greater penetration of the conditioner. Figure 43 shows that the planer actually removed about 0.2mm of average macrotexture and as a result, the planed test section is literally hovering slightly above the 0.9mm failure criterion. Thus, if restoring macrotexture is the goal for a given asphalt pavement, then planing is not a good option for the maintenance engineer to select.

Table 10 Summary of Regression-based Pavement Preservation Treatment Macrotexture Deterioration Models

Pavement Preservation Treatment on Asphalt Substrate	Deterioration Model	Coefficient of Determination (R^2)
Open Graded Friction Course	$y = 3.5522x^{-0.32}$	$R^2 = 0.9654$
Open Graded Friction Course w/Fog Seal	$y = 3.2107x^{-0.291}$	$R^2 = 0.9563$
ODOT 5/8" Chip Seal	$y = 0.0037x^2 - 0.1608x + 3.74$	$R^2 = 0.9433$
ODOT 3/8" Chip Seal	$y = 0.0022x^2 - 0.1126x + 2.2404$	$R^2 = 0.9246$
ODOT 5/8" Chip Seal w/Fog Seal	$y = 0.0027x^2 - 0.1069x + 2.8426$	$R^2 = 0.9110$
JLT Penetrating Asphalt Conditioner	$y = 0.0008x^2 - 0.0284x + 1.4767$	$R^2 = 0.7763$
JLT Asphalt Planer w/Conditioner	$y = 0.0008x^2 - 0.0284x + 1.1915$	$R^2 = 0.7273$
Fog Seal	$y = -0.052\ln(x) + 0.9785$	$R^2 = 0.6030$
Skidabrader Shotblasting	$y = 0.0009x^2 - 0.0285x + 1.8064$	$R^2 = 0.4885$
1" Mill and Inlay	$y = 0.0044x + 0.5101$	$R^2 = 0.3444$
Skidabrader Shotblasting w/fog	$y = 1.7074x^{-0.031}$	$R^2 = 0.2543$
Blastrac Shotblasting	$y = 0.0008x + 1.3352$	$R^2 = 0.0111$
Pavement Preservation Treatment on Concrete Substrate	**Deterioration Model**	**Coefficient of Determination (R^2)**
Skidabrader Shotblasting	$y = -0.083\ln(x) + 1.1232$	$R^2 = 0.7024$
Blastrac Shotblasting	$y = -0.04\ln(x) + 0.7271$	$R^2 = 0.4805$

Looking at the fog seal model in Table 10, the R^2 value indicates that treatment age accounts for only 60% of the variation. A fog seal is merely a diluted coat of bitumen sprayed on the substrate and as such does nothing to change the macrotexture other reducing it a bit by filling the existing voids in substrate's preseal macrotexture. Once again, this treatment shows itself to be a poor choice if the engineer needs to enhance macrotexture. The remaining asphalt test sections have coefficients of determination less than 0.5 which indicates than some factor other than treatment age is the predominate reason for macrotexture change over time.

The two concrete test sections in Phase 1 utilize essentially the same mechanism for retexturing the surface. However, the two technologies are substantially different. The Skidabrader can shotblast a 6.0' section in a single pass. Whereas the Blastrac technology's maximum head width is 4.0'. The difference means that Blastrac takes three passes to retexture a standard 12.0' lane and the Skidabrader takes two. Thus, the variability of the larger shotblaster will be less than the smaller one and this fact is confirmed by the R^2 value for the larger machine being higher than the same value for the smaller unit. Figures 46, 47, and 48 shows the same relationship on the asphalt sections as the concrete sections, i.e. the Skidabrader deterioration model has higher R^2 values than the Blastrac model. This leads to the conclusion that the Skidabrader technology produces a more uniform transverse macrotexture due to its ability to cover a lane in fewer passes.

It must be remembered that concrete pavement is designed to develop its drainage characteristics from the tining in its surface. Therefore, the macrotexture measurements include the effect of the tining. Airport pavement managers have reported that shotblasting can damage the grooves put in runway pavements to reduce hydroplaning on landings if not done properly (Speidel, 2002). These grooves are typically deeper and wider than the tines on concrete highway pavements. Thus, it seems that highway pavements would be less prone to tine damage than airport pavements. During the initial shotblasting, both operators remarked on the seeming softness of the aggregate in the concrete test sections and predicted that the retexturing's would be less than expected from pavement with higher quality aggregates. Figure 48 shows a nearly linear rate of macrotexture loss for both test sections. The regularity of the deterioration models confirms the visual sense of the experienced shotblasters and leads to the conclusion that shotblasting's service life will be dependent on the abrasion resistance of the aggregate in the pavement on which it is applied.

TRENDS IN MICROTEXTURE DETERIORATION

The project is measuring pavement microtexture using the ODOT skid trailer. It conducts monthly tests on all test sections and generates skid numbers as its primary output. A peer-review of the microtexture methodology by Dr. Thomas Yager, Director of the NASA Wallops Island Pavement Testing Facility, revealed that the use of the treaded tire on the ODOT skid trailer may be inducing variation into the sample output that could obscure the true rate of microtexture deterioration. As a result of that valuable assistance, the team purchased the smooth tire recommended by Dr. Yager for the trailer and altered the test protocol to take measurements using both types of tires. As a result, the output for this portion of the research is not in proper shape to analyze in the manner the macrotexture deterioration models were discussed in the previous section. That being said, an abbreviated set of data can be shown to demonstrate the type of analysis that will be completed on all 23 test sections in the Phase 2 final report next year. Table 11 illustrates the type of information that will be contained in the final pavement preservation toolbox for each pavement preservation treatment and its goodness of fit for a range of five different treatments on both asphalt and concrete substrates. These treatments all have reasonably good R^2 values. However, this is not expected to be the case for all 23 treatments. Figure 47 and 48 are illustrative of what is expected for some of the treatments.

Table 11 Deterioration Models for Five Selected Treatments based on Data Collected in a Single 12-month Period

Treatment	Microtexture (Skid Number)	Macrotexture (Outflow Meter)	Macrotexture (Sand Circle)
Asphalt Substrate			
OGFC	$y = -0.1x^2 + 2.051x + 26.389$	$y = -0.259\ln(x) + 2.5665$	$y = -0.657\ln(x) + 3.0798$
	$R^2 = 0.8907$	$R^2 = 0.8599$	$R^2 = 0.9519$
1" Mill & Inlay	$y = -0.1187x^2 + 0.7658x + 53.644$	$y = 0.0044x^2 - 0.0373x + 0.7417$	$y = -0.0031x^2 + 0.0241x + 0.5162$
	$R^2 = 0.8117$	$R^2 = 0.9478$	$R^2 = 0.9311$
JLT Conditioner	$y = 5.0393\ln(x) + 31.518$	$y = 0.0028x^2 - 0.0557x + 1.9113$	$y = -0.0015x^2 + 0.0051x + 1.393$
	$R^2 = 0.918$	$R^2 = 0.6266$	$R^2 = 0.7998$
JLT Planed	$y = 4.9882\ln(x) + 30.726$	$y = -0.0066x^2 + 0.0906x + 1.0948$	$y = -0.0018x^2 + 0.0099x + 1.0939$
	$R^2 = 0.94$	$R^2 = 0.9284$	$R^2 = 0.8507$
Concrete Substrate			
Blastrac Shotblasting	$y = -0.0372x^3 + 0.756x^2 - 4.6024x + 56.512$	$y = 0.0014x^2 - 0.0205x + 0.9361$	$y = -0.0007x^2 - 0.0068x + 0.7327$
	$R^2 = 0.8125$	$R^2 = 0.7695$	$R^2 = 0.9532$
Skidabrader Shotblasting	$y = -0.0843x^3 + 1.675x^2 - 9.8058x + 55.132$	$y = 0.0043x^2 - 0.064x + 1.4369$	$y = 0.0009x^2 - 0.037x + 1.159$
	$R^2 = 0.7711$	$R^2 = 0.7592$	$R^2 = 0.9413$

Figure 49 illustrates the results found in Table 11 in a graphical manner. One can see that the OGFC's microtexture actually increased over time. This is to be expected as traffic wears off the film of new bitumen that will be present immediately after construction. The figure also shows that the sand circle macrotexture measurements are compatible with the outflow meter macrotexture measurements, confirming either test can be used with reasonable consistency on this treatment.

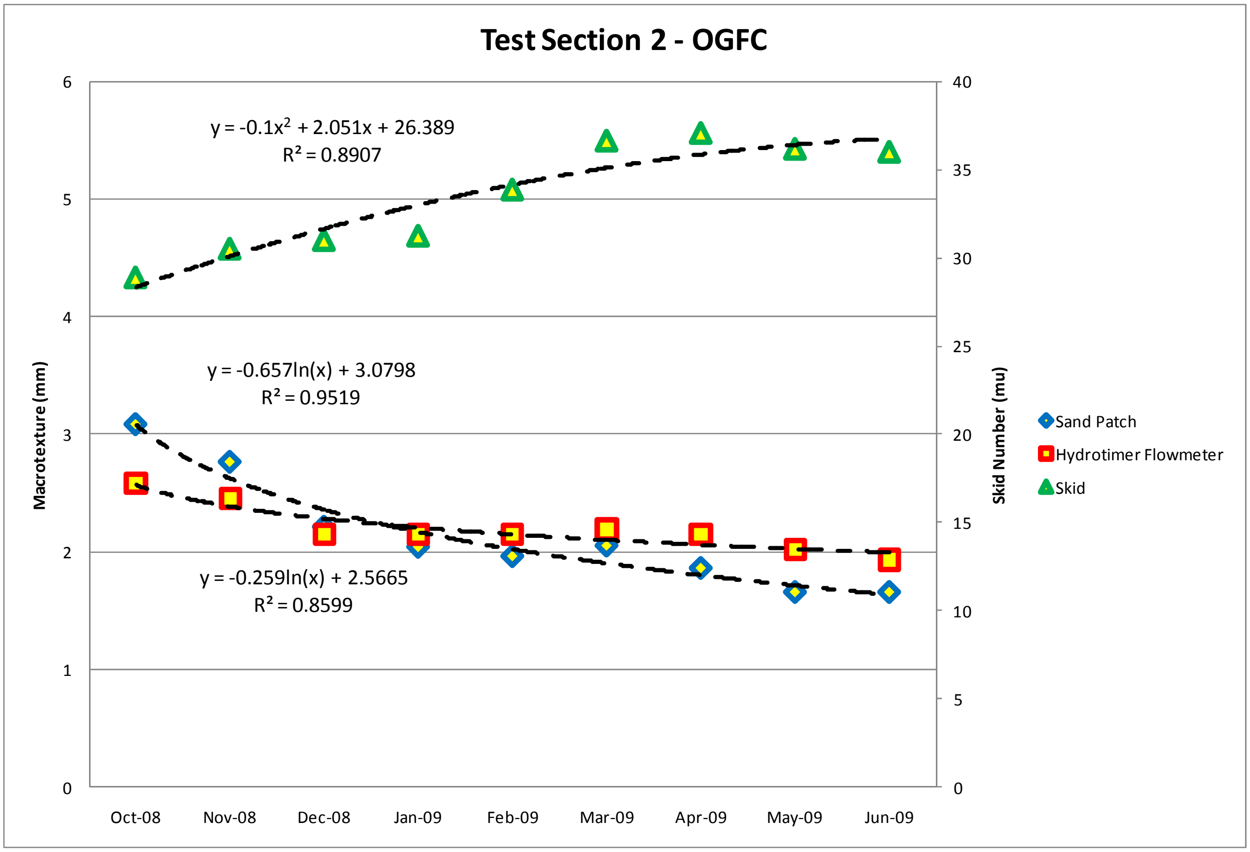


Figure 49: Open Graded Friction Course Comparison of Microtexture (Skid Number) and Macrotexture Measurements Made by Two Methods

ANALYSIS OF PROJECT TO DATE

At this writing, the project has gone smoothly and will carry on for one more year. With regard to OTCREOS7.1-16, the project has produced every deliverable it promised to in the proposal. The most important research finding to date deals with the limitations of the two macrotexture test procedures. The research team observed that each procedure seemed to be more accurate on certain treatments. Macrotexture depths and relative differences between both methods taken in November 2009 are shown in Figure 50. In Figure 50, macrotexture values between the two methods are given as a percentage. As is seen in this figure, the largest relative difference between the test methods are on TS8, TS9, TS10, TS11, TS21, and TS22. Those test sections showed a difference between the two test methods that is greater than 30 %. The test sections, TS8, TS9, TS10, TS21 and TS22, are all chip sealed surfaces, which have greater macrotexture depths than the other surface treatments. Thus, the outflow meter test outflow times are very low, which yields calculated macrotexture depths that are excessive. Chip seal surface smoothness that is not regular due to different aggregate dimensions, creates a situation where the bottom surface of the outflow meter test device cannot completely cover the road surface causing the water to flow out very quickly. In many cases the outflow time was one second or less. This creates a limitation within the equipment since the smallest measurable unit of time is one second. For these reasons, the calculated macrotexture depth differences are great when compared to the sand circle. TS11 consists of shotblasting on hot mix asphalt. This section has structural and capillary cracks on the road's surface, which affect the outflow time by providing a channel for the water to pass that is not related to macrotexture. This explains the high relative difference between the two methods on this test section

In other test sections, the relative macrotexture value differences between the two test methods were less than 30%. The lowest differences occurred in test sections 2, 3, 6, 7, 12, 13, 14, 16, 18, and 23. These test sections had macrotexture depths between 1.00 – 2.00 mm (0.04 – 0.08 in.) and the difference in the two test methods is less than 25%. In test sections 1, 5, 15, 17 and 20, macrotexture depths are less than 1.00 mm (0.04 in.) and the difference between the two methods is between 25% and 30%. In TS4 the macrotexture depth is less than 1.00 mm (0.04 in.) and the difference is 18.6%.

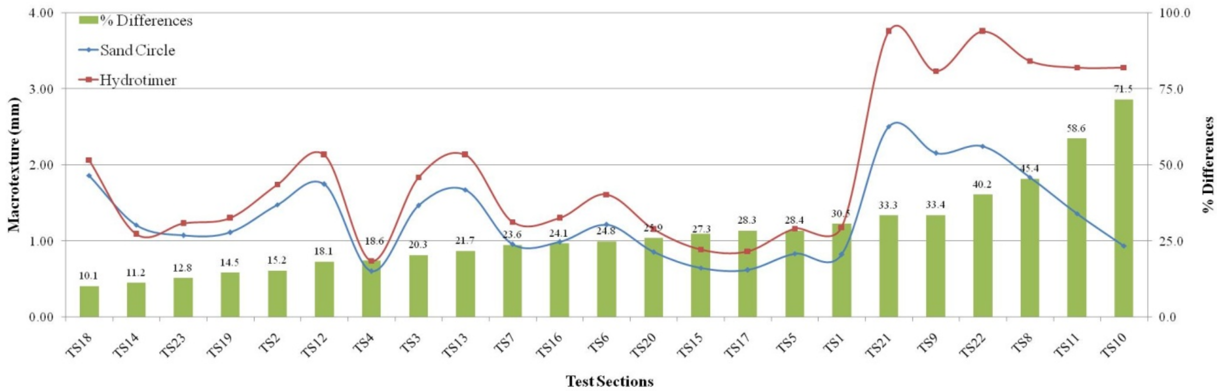


Figure 50: Test Sections Macrotexture Results and Differences of Two Test Methods in November 2009

Figure 51 illustrates the average macrotexture results and differences between the two test methods in the test sections over a total of 24 months. This graph's results are similar to the results shown in Figure 50, the results for a single month. Therefore, Figure 51 validates the Figure 50 trend showing differences between the two methods are high on surfaces where macrotexture depth is high (roughly greater than 1.5 mm (0.06 in.)) and low (roughly less than 1.00 mm (0.04 in.)). This leads to the conclusion that each method has its own inherent functional limitations. The outflow meter is not ideal for high macrotexture surfaces because it cannot measure outflow times less than one second. The sand circle's limitation is for low macrotexture surfaces. The limitation here is the ability of the engineer to be able to reliably observe when all the voids have been filled and stop expanding the sand circle. On a totally smooth surface such as glass, the circle would be one grain of sand deep and could be theoretically expanded to infinity since there are no voids to fill. In fact, NZTA (TNZ, 2005; TNZ, 1981) specifies the functional limit of sand circles to be 300 mm (11.8 in.) in diameter or less. Any larger measurements are deemed to be unreliable. The results of these analyses indicate that neither test method is appropriate for all surfaces.

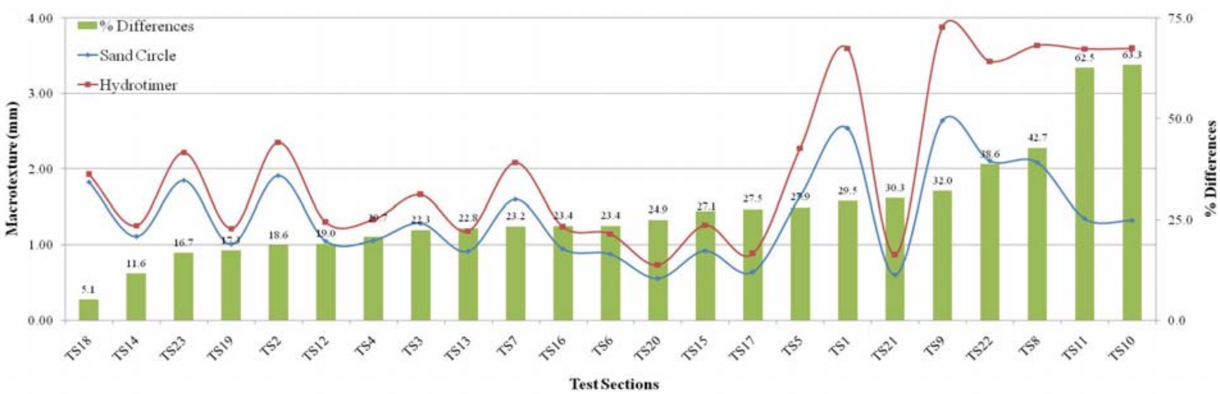


Figure 51: Average Macrotexture Results and Differences between Two Test Methods Over 24 Months

Figure 52 shows the percentage difference in calculated macrotexture values versus outflow time. It shows that the relative change in macrotexture is very high in the initial seconds of the outflow meter test. For instance, if the outflow time were to be 0.1 second, which cannot be measured by the current device, then the calculated macrotexture is 31.7 mm (1.25 in.), and if outflow time is 1.0 second then macrotexture is calculated 3.75 mm (0.15 in.). The difference between those values is 88.20%. Since the device cannot measure outflow times of less than 1.0 seconds, the engineer will get the same outflow time value across the range from 3.7mm to 31.8 mm (0.15 in. to 1.25 in.). Since macrotexture values decrease as the outflow time increases, this trend continues until the curve flattens out. For instance, the calculated macrotexture value changes 41.52 % between 1-2 seconds, 23.67% between 2-3 seconds, 15.50% between 3-4 seconds, and 11.01% between 4-5 seconds. If outflow time is more than 5 seconds, macrotexture changes per second of outflow time are less than 10 %. This leads to the conclusion that the 5^{th} second of outflow time portrays a functional limiting point past which the calculated macrotexture values become more reliable. Taking this information, one can infer that the outflow meter method should not be used on surfaces that result in outflow times less than 5 seconds. This translates to a macrotexture value of 1.26 mm (0.05 in.) or more.

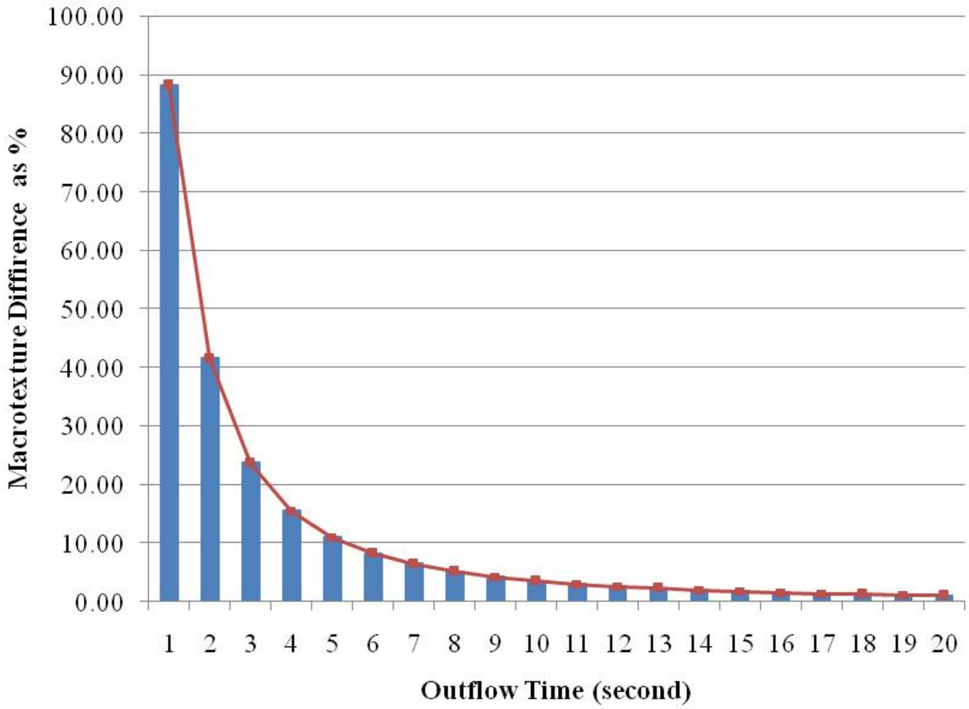


Figure 52: Macrotexture Percentage Differences between Seconds in Outflow Meter Test

Macrotexture curves that are derived from outflow meter and sand circle methods are shown as a theoretical curve in Figure 53. It shows that across the initial 5 seconds in the outflow meter test the macrotexture curve is steep which means measurements will be unreliable. Hence, if outflow time is less than 5 seconds then the sand circle method should be used for macrotexture measurements. The outflow meter and sand circle curves cross at 0.79 mm (0.03 in.) macrotexture value. This value is equal at the 20th second in outflow meter method and a sand circle with a diameter of 265 mm (10.4 in.). The sand circle diameter is large because the surface's macrotexture values are low. This value is close the NZTA specified maximum diameter of 300mm (11.8 in.). The difficulty of creating a large circle during the testing, results in a testing error and reproducibility. The outflow meter method is faster and easier than the sand circle test and should be used on surfaces where the macrotexture value is less than 0.79 mm (0.03 in.).

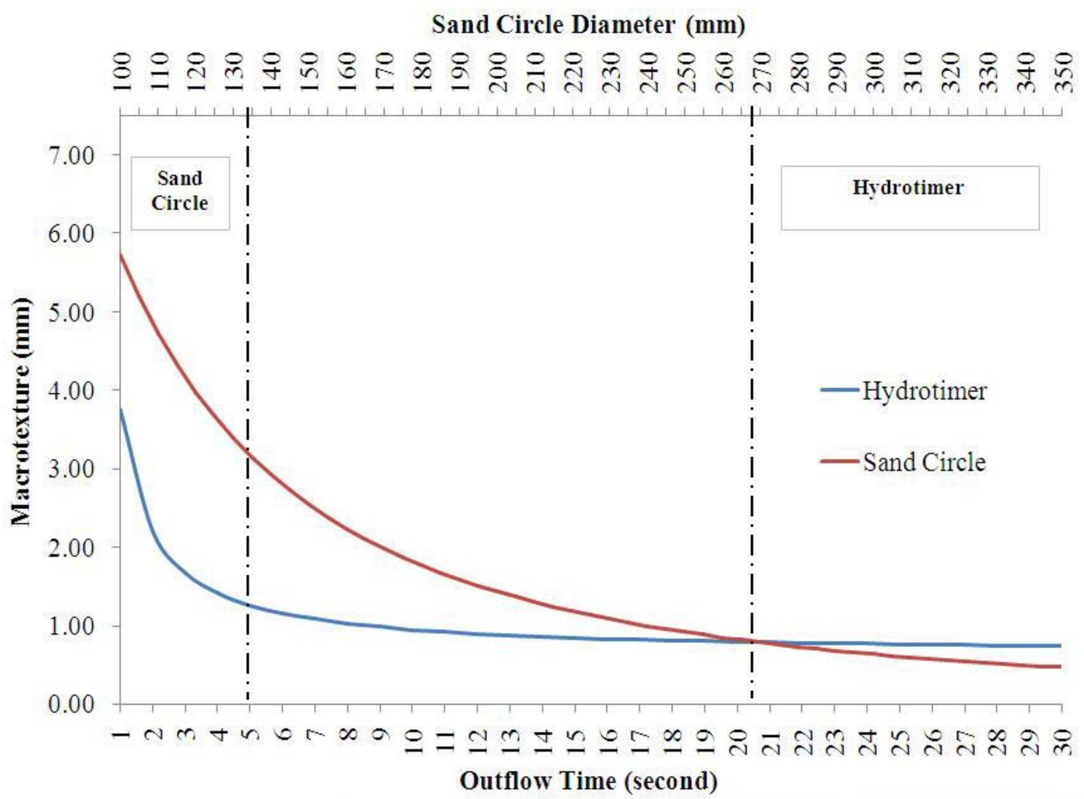


Figure 53: Theoretical Curves of Outflow meter and Sand Circle Tests

Determining macrotexture on pavement correctly and quickly is important for safety and economy in pavement preservation testing. This study investigated and compared two methods commonly used to determine macrotexture on pavement surfaces: the outflow meter and the sand circle test. The research and analysis results show that there are functional limitations in each method's ability to accurately measure pavement macrotexture. The outflow meter provides users with results measured in seconds. It is portable, practical on wet surfaces, inexpensive, and fast, but the measured outflow time can be inaccurate for pavement preservation treatments with high macrotextures. The opposite is true for the sand circle method which should be avoided on surfaces with low macrotexture. This results in the following recommendations for appropriate use of each test method:

- If macrotexture < 0.79mm (0.03 in.), use the outflow meter only.
- If macrotexture > 0.79mm (0.03 in.) and < 1.26mm (0.05 in.), either test is appropriate
- If macrotexture > 1.26mm (0.05 in.), use the sand circle test only.

Previous studies have been conducted to establish relationships of various test methods to measure macrotexture. However, those typically looked at a single surface treatment and as a result did not create an opportunity to observe the relative differences between two or more macrotexture measurement methodologies. The results discussed above are the first to give quantitative guidance to researchers and practitioners regarding trigger points where the two test methods become most appropriate for differing pavement surfaces. It is recommended that the macrotexture limitations for each test method should be contained in specifications for each test to ensure that those agencies that use these tests are made aware of each test's functional limitations.

CONCLUSIONS

This project has accomplished a number of research milestones. First, it developed a robust protocol for field test research that is both consistent and repeatable. The research produced a previously unpublished model for the LCCA of specific pavement preservation treatments and that EUAC-based model is the major contribution to the body of knowledge in pavement economics. The research also developed a methodology for developing pavement preservation treatment-specific deterioration models and demonstrated how these provide a superior result to those based on empirical service lives. Finally, the research demonstrated how the new model could be utilized to assist an ODOT maintenance engineer in selecting the most cost efficient pavement preservation treatment for a given pavement management problem.

Other contributions are as follows:

- EUAC-based LCCA models for both asphalt and concrete pavements using conspicuous service life and short-term cost efficiency analysis
- Developed the concepts continuous state LCCA for maintenance treatments based on individual service life as analysis period and terminal state which automatically truncates service life due to next expected rehabilitation or reconstruction encroachment and corresponding sensitivity analysis

- A model which can minimize analysis period selection issues and their associated sensitivity
- Microtexture and macrotexture deterioration model data usage to reduce service life selection sensitivity based on local conditions
- Quantifying the range of macrotexture where the sand circle and the outflow meter are most appropriate.

The Equivalent Uniform Annual Cost (EUAC) method was found to be the most efficient method to determine the cost effectiveness of treatment alternatives. Specific pavement-preservation LCCA adaptability issues were addressed, and subsequently the research contribution has made, by building LCCA asphalt and concrete models based on EUAC "standalone", the process less complex, more consistent with investment level, more efficient, and provides relevant decision-making information for the pavement manager applicable to the short term window of pavement treatment operations based on treatment-relevant input. Maintenance funding is authorized on an annual basis making comparing alternatives on an annual cost basis more closely fit the funding model than using NPV which would assume availability of funds across the treatment's entire service life. Since pavement managers typically consider several alternatives with varying services lives based on available funding rather than technical superiority, the FHWA LCCA method based on NPV creates more problems than it solves.

Deterioration models for the three chip seal test sections account for over 90% of the variation in chip seal macrotexture loss. Said another way, the age of the chip seal is the major factor in its loss of macrotexture The R^2 values for the two OGFC test sections were greater than the chip seal values. Therefore, using the same logic, these deterioration models will also be highly reliable. Models for other treatments were not as highly correlated. This leads to the conclusion that factors other than treatment age have more impact on micro and macrotexture deterioration. The project did not attempt to determine what those factors were, but it can be speculated that they are the same as for any pavement, traffic, weather, etc.

Economic and engineering technical data gathered from pavement preservation field trials can be quantified and correlated to produce meaningful, standardized economic and life cycle cost analysis (LCCA) information that would assist pavement managers in selecting an alternative that would yield extended service lives of Oklahoma pavements. Life cycle cost analysis can be correlated with engineering field data to assist Oklahoma Department of Transportation (ODOT) pavement managers in determining the “right treatment” component of the “right treatment for the right road at the right time” (Galehouse et al., 2003) pavement preservation strategy and increase the effectiveness of budget expenditure resulting in decision making validation and justification and enhanced stewardship.

RECOMMENDATIONS

This analysis uses the NZTA ultimate failure criterion of 0.9mm as the point at which the service life ends. While that specific number comes from chip seal research and is not directly relatable to OGFC, it does indicate that given research to measure how much macrotexture is required for OGFC to perform as designed that a performance failure criterion could be determined. That is beyond the scope of this project and is a future research need that may be considered by OTC and ODOT in the years to come.

IMPLEMENTATION/TECHNOLOGY TRANSFER

Technology transfer has occurred continuously during this project. It has occurred at a number of levels. First, at the local level, Caleb Riemer, PE is a maintenance engineer in Division 3. He has already implemented the use of several new treatments, including the shotblasting and E-crete. He has written specifications as a result and has shared those along with emerging test results with the other ODOT divisions during routine state-wide maintenance meetings. As previously stated, the scale and breadth of this project has drawn national and international attention. The research team has made 22 presentations in 24 months and published 17 journal and proceedings papers. Two technology transfer workshops were held in Norman as a part of a secondary education initiative to expose high school science teachers to engineering testing. Again, Caleb was the instructor at both. Dominique Pittenger, led a day long workshop for top performing Oklahoma high school students in July 2010 which included a look at the test procedures used by pavement engineers in the field on this OTC project. Finally, research partnerships have been developed with the University of Waterloo in Canada and Suliyeman Demirel University in Turkey. An OU research assistant traveled to Canada last fall, and the project is benefitting from the work done by a PhD student from Turkey who is spending a year working with the OU pavement preservation research team. Listed below are the products produced by the research team in the past two years.

JOURNAL AND PROCEEDINGS PAPERS

The team has produced a total 14 publications in two years. They are as follows:

1. Gransberg, D.D., "Preseal Surface Texture as a Chip Seal Performance Predictor," *Pavement Preservation Journal,* Foundation for Pavement Preservation, Summer 2008, p 13.

2. Gransberg, D.D., "Comparing Hot Asphalt Cement and Emulsion Chip Seal Binder Performance Using Macrotexture Measurements, Qualitative Ratings, and Economic Analysis," *2009 Transportation Research Board*, Paper #09-0411 January 2009.

3. Gransberg, D.D., "Surface Retexturing with Shotblasting is a Pavement Preservation Tool," *Roads and Bridges*, April 2009, p.44.

4. Gransberg, D.D. and M. Zaman**,** "Qualitatively Describe Precoat Status to Track Performance of Chip Seals," *Pavement Preservation Journal,* Foundation for Pavement Preservation, Fall 2009, pp. 37-38.

5. Gransberg, D.D., "Life Cycle Cost Analysis of Surface Retexturing with Shotblasting as a Pavement Preservation Tool," *Transportation Research Record 2108,* Journal of the Transportation Research Board, National Academies, December 2009 pp. 46-52.

6. Gransberg, D.D. and E. Scheepbouwer, "Performance Based Construction Contracting: The US versus the World," *2010 Transportation Research Board,* Paper # 10-0093, National Academies, Washington, D.C., January 2010, pp.

7. Gransberg, D.D., E. Scheepbouwer and S.L. Tighe, “Performance-Specified Maintenance Contracting: The New Zealand Approach to Pavement Preservation,” *Proceedings, 1st International Conference on Pavement Preservation,* Transportation Research Board Newport Beach, California, April 2010, pp103-116.

8. Riemer, C., D.D. Gransberg, M. Zaman, and D. Pittenger, “Comparative Field Testing of Asphalt and Concrete Pavement Preservation Treatments in Oklahoma,” *Proceedings, 1st International Conference on Pavement Preservation*, Transportation Research Board, Newport Beach, California, April 2010, pp.447-460

9. Gransberg, D.D., and E. Scheepbouwer “Infrastructure Asset Life Cycle Cost Analysis Issues,” *2010 Transactions*, AACE, International*,* Atlanta, Georgia, June 2010, pp. CSC.03.01- CSC.03.8.

10. Gransberg, D.D., and S. Mueller, "Key Findings from NCHRP Synthesis 342: *Chip Seal Best Practices,*" *Pavement Preservation Journal,* Foundation for Pavement Preservation, Spring 2010, pp. 18-19.

11. Aktas, B., D.D. Gransberg, C. Riemer, and D. Pittenger, “Comparative Analysis of Macrotexture Measurement Tests for Pavement Preservation Treatments, *Transportation Research Record*, *Journal of the Transportation Research Board,* National Academies, (Submitted July 2010; in review).

12. Pittenger, D., “Sustainable Airport Pavement Practices,” *2011 Transportation Research Board*, *Journal of the Transportation Research Board,* National Academies, (Submitted July 2010; in review).

13. Pittenger, D., D.D. Gransberg, M. Zaman, and C. Riemer, Life cycle Cost-Based Pavement Preservation Treatment Design,” *2011 Transportation Research Board*, *Journal of the Transportation Research Board,* National Academies, (Submitted July 2010; in review).

14. Pittenger, D. “Life Cycle Cost Analysis for Pavement Maintenance,” *2011 Transactions*, AACE, International, Orlando, Florida, June 2011, (Submitted August 2010; in review).

TECHNOLOGY TRANSFER

A total of 22 presentations across a range of local, national, and international venues have been made by the research team. They are listed below:

1. “Using Macrotexture to Measure Pavement Preservation Treatment Performance,” Invited guest lecture, Iowa State University, Ames Iowa, April 2010.
2. “Cost Engineering Applied to Pavement Preservation: The Value of Sustainable Infrastructure,” Invited guest lecture, North Carolina State University, Raleigh,

North Carolina, April 2010.

3. “Cost Model for Sustainable Asphalt Pavements,” Oklahoma Asphalt Paving Association, Oklahoma City, OK February 2010.
4. “Performance Based Construction Contracting: The US versus the World,” Transportation Research Board, National Academies, Washington, D.C., January 2010.
5. “Project Delivery Method Issues of Different Transportation Modes: One Size Does Not Fit All,” Transportation Research Board, National Academies, Washington, D.C., January 2010.
6. “Comparative Field Testing of Asphalt and Concrete Pavement Preservation Treatments in Oklahoma,” Transportation Research Board, National Academies, Washington, D.C., January 2010.
7. “Pavement Preservation Through Retexturing: Status Report,” FHWA Pavement Preservation Expert Task Group, Reno, Nevada, December 2009.
8. Achieving Sustainability Through Integrated Project Delivery,” DBIA National Conference, Washington DC, November 2009.
9. “Cost Engineering Applied to Green Pavements: Measuring the Value of Sustainable Infrastructure,” Department of Civil Engineering, University of Waterloo, Waterloo, Ontario, Canada September, 2009.
10. “Airport Runway Rubber Removal: Preserving Pavements by Restoring Friction,” Canadian Airport Association Annual Conference, Toronto, Canada, September 2009.
11. “Chip Seal Binder Research in Texas: 15 Years of Progress,” Ergon Asphalt and Emulsions, Inc. Mid-Continent Sales Conference, Dallas, Texas, September 2009.
12. “Achieving Sustainability Through Integrated Project Delivery,” DBIA National Conference, Washington DC, October 2009.
13. “Chip Seal Binder Research in Texas: 15 Years of Progress,” Ergon Asphalt and Emulsions, Inc. Mid-Continent Sales Conference, Dallas, Texas, October 2009.
14. “Sustainable Pavement Performance: Cost Engineering Justification,” Invited Lecture, College of Engineering, University of Waterloo, Waterloo, Ontario, Canada, September, 2009.
15. “Building Good Roads and Keeping Them Good: A Case Study,” AACE, International, Oklahoma Section, Oklahoma City, Oklahoma, September, 2009.
16. “Performance Contracting Success in New Zealand,” AASHTO Subcommittee on Construction, Chicago, Illinois, August 2009.
17. “Pavement Preservation Research in Oklahoma,” University of Canterbury, Christchurch, New Zealand, June 2009.
18. “Quantifying the Costs and Benefits of Pavement Retexturing as a Pavement Preservation Tool” FHWA Pavement Preservation Expert Task Group, New Orleans, LA May 2009.
19. “Sustainable Pavement Preservation Treatments,” Fulton Hogan Technical Group Meeting, Christchurch New Zealand, April 2009
20. “Comparing Hot Asphalt Cement and Emulsion Chip Seal Binder Performance Using Macrotexture Measurements, Qualitative Ratings, and Economic Analysis,” Transportation Research Board, Washington, DC, January 2009.

21. "Life Cycle Cost Analysis of Surface Retexturing with Shotblasting as a Pavement Preservation Tool," Transportation Research Board, Washington, DC, January 2009.
22. "Quantifying the Costs and Benefits of Pavement Retexturing as a Pavement Preservation Tool" OTC Research Day, Oklahoma City, OK October 2008

TECHNOLOGY TRANSFER EVENTS

Caleb Riemer has led the team's technology transfer event effort. He developed a 2-day module based on the field and laboratory research and has delivered it once each year to the Oklahoma Science Teachers Engineering Program.

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