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

A DISSERTATION APPROVED FOR THE DEPARTMENT OF ENGINEERING

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1.0 INTRODUCTION

"The mission of the Oklahoma Department of Transportation is to provide a safe, economical, and effective transportation network for the people, commerce, and communities of Oklahoma" (1).

To provide a safe, economical and effective transportation network should be the goal of any department of transportation (DOT). However, with less revenue from a sluggish economy, and a national transportation trust fund at a point where it needs a major transfusion just to stay alive, a responsible DOT must begin to place major emphasis on pavement preservation (2, 3). This research seeks to provide guidance for pavement preservation by investigating the characteristics of different pavement preservation techniques as they relate to driver safety and to the economics behind the implementation of these treatments.

1.1 BACKGROUND AND RESEARCH NEED

Research relating the safety aspects of the surface of the road has been conducted both abroad and within the United States, but previous studies have been focused on either macrotexture alone or microtexture alone (4, 5, 6). The focus of this research is to analyze both mechanisms as they relate to different pavement preservation treatments. The research will quantify pavement preservation treatment macrotexture and microtexture deterioration over time. This is being done to establish the effective service life of each treatment based on the time it takes for each treatment to reach recognized macrotexture and microtexture failure criteria.

Additionally, the research will add to the body of knowledge of pavement economics by applying macrotexture and microtexture deterioration models for pavement preservation treatments for use as service life inputs to life cycle cost analysis (LCCA). While there is a rich body of research on pavement LCCA, little specifically addresses preservation treatments themselves. Therefore, this research also explores the use of life cycle cost models as tools for selecting pavement preservation treatments from an economic standpoint.

This research is needed to enhance the idea that pavement preservation is the embodiment of infrastructure stewardship. Its central theme is using pavement technology to “keep good roads good.” (4) There is a wide range of pavement preservation and maintenance program funding levels among US DOTs that range from a low of $15.0 million to a high of $1.7 billion per year (5). 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 (4, 5). Pavement preservation is inherently sustainable as it seeks to minimize the amount of natural resources consumed over a pavement’s life cycle (6). Therefore, focusing on pavement preservation rather than reactive maintenance and repair furnishes a broad foundation on which to build ODOT’s pavement sustainability program. With this foundation constructed ODOT can easily become a national standard for other DOT’s to use as an example of how to implement as system of their own.

1.2 OBJECTIVE OF RESEARCH

The objective of this research was to leverage research done abroad in Australia and New Zealand, as well as research conducted within the United States to determine the role pavement preservation treatments have on safety aspects, pavement skid number and pavement macrotexture, of the highway system (7, 8, 9). Methods for pavement preservation range in variety from a simple chemical treatment, like a fog seal, to a more complex surface treatment, like a chip seal or overlay, to the sophisticated mechanical treatments, like shot-blasting. To meet the objective of this study, certain data was gathered for each pavement preservation treatment included for analysis. This data included microtexture measurements, and since it was deemed unreasonable to utilize the British Pendulum Tester considering the variability and difficult nature of field research, the American Society for Testing and Material's (ASTM) E274 skid tester was used to create an index for microtexture (10). Two separate tests were used to determine the macrotexture values for each treatment; they are the Transit New Zealand T/3 sand circle test (11) and the ASTM E965 outflow meter tester (12). A thorough anaylsis of available life cycle cost models was needed to establish economic data to each pavement preservation treatment, thus meeting the primary objective of this study. 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.

1.3 LITERATURE REVIEW

Skid resistance of pavement is an 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 (13). As a result, pavement managers must not only manage the structural condition of their roads but also their skid resistance (14, 15). In fact, it is possible for a structurally sound pavement to become 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 (16). 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 maintenaning adequate pavement skid resistance is also a pavement preservation activity (17). 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.

1.3.1 Previous Studies

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 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 (18). 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 monitoring and measurement 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" (18).

It is evident from the above discussion that pavement managers in Australia and New Zealand have 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 infrastructure projects and as a result, selects treatment alternatives on a basis of the lowest life cycle cost not the lowest construction cost (18). 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 (19). 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.

1.3.2 Point of Departure

There is a wealth of information on skid resistance in the literature (13, 16, 20, 21). 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 (15). However, a majority of previous studies has been laboratory-based and focused on the material science aspect. Very little substantive work has been done in the field regarding surface treatment performance. Also, most of the research in this area is focused on short-term performance (22). The FHWA Long Term Pavement Performance Program (LTPP) collects friction data as part of its standard protocol (23). 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 valid, it may contain a inherent bias toward showing the given product in its best light (7, 24, 25). Finally, with three notable exceptions (26, 27, 28), 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.

1.4 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 in 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 mission of a maintenance engineer must be to preserve the structural capacity of the road and to ensure that its surface frictional characteristics are sufficient to safely handle the traffic load 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 (9). This project addresses solutions for highway condition-related crashes. The project does this by quantifying the rate at which the surface texture of different pavement preservation treatments deteriorates over time. The comparative knowledge of treatment texture deterioration rates is essential for maintenance engineers to select the appropriate treatment for a given pavement condition problem.

1.4.1 Surface Texture

Surface texture is one of the primary physical characteristic that can be measured after a traffic accident (29). 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. (30)

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 1.1.

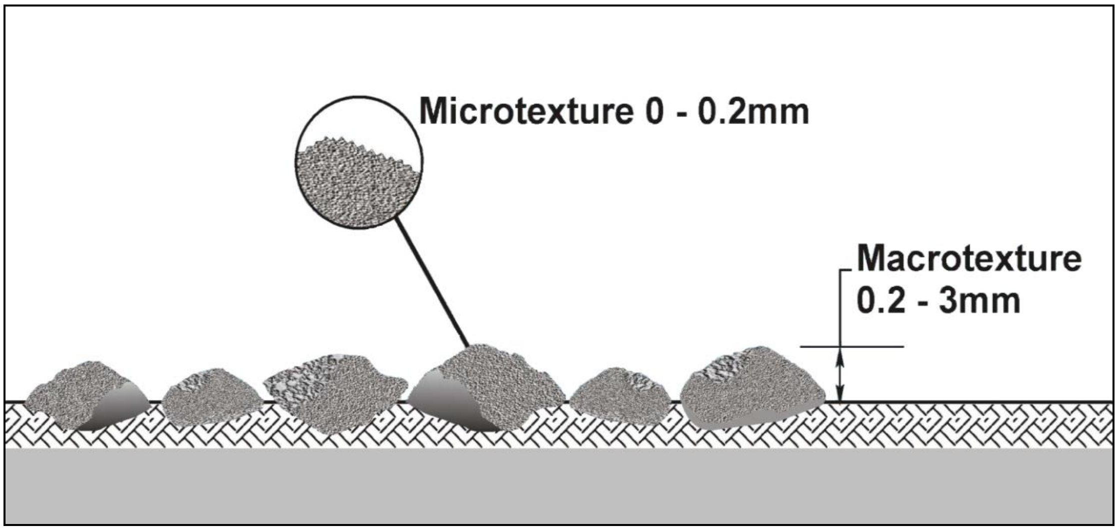

Figure 1.1 Pavement Surface Microtexture and Macrotexture (31)

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” (32). There are other components such as tire shear, but they are not nearly as significant as the adhesion and hysteresis force components. Figure 1.2 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 1.1 below:

$$F = F_A + F_H \qquad \text{Eq. 1.1}$$

Relating Figures 1.1 and 1.2, one can see that the frictional force of adhesion is “proportional to the real area of adhesion between the tire and surface asperities,” which makes it a function of pavement microtexture (32). 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 (32). Thus, if an engineer wants to improve skid resistance through increasing the inherent friction of the physical properties of the pavement they 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” (33).

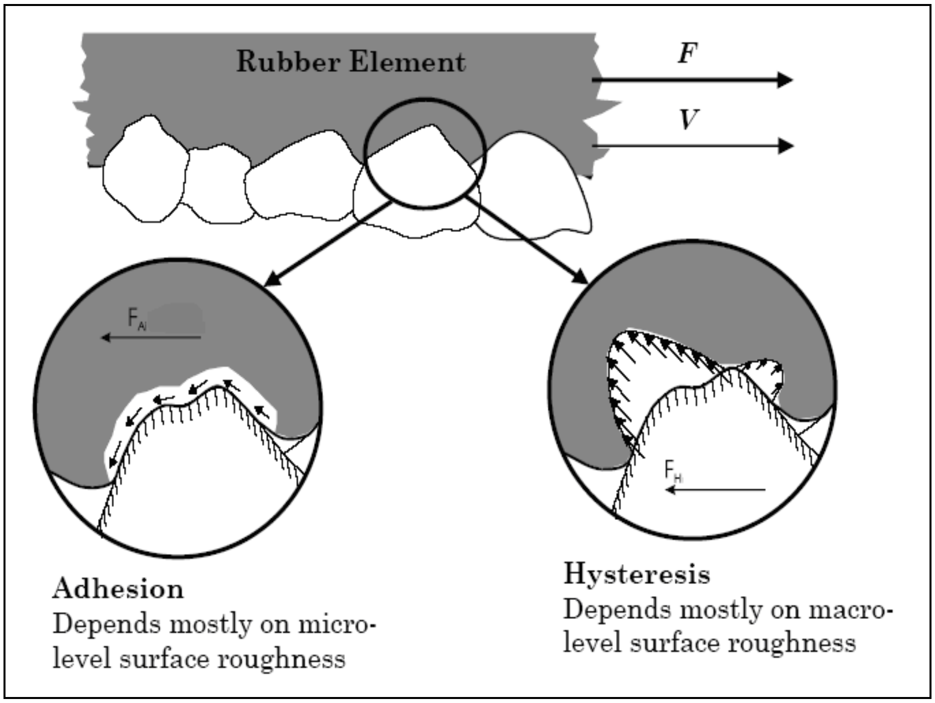

Figure 1.2 Pavement Friction Model (37)

In Australia and New Zealand extensive work has been done to manage macrotexture to control crash rates (6, 7, 34). In North America extensive work has been done to manage skid number, or microtexture, to control crash rates (9). 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 (i.e. macrotexture, skid number, or microtexture) primarily focus on the reduction of wet weather crashes (32). 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 (10). Other common methods are the Sideway-force Coefficient Routine Investigation Machine (SCRIM) device, the grip tester device, and the mu-meter devices (35). For this research, the ASTM E 274 skid tester with a ribbed tire serves as the primary way of obtaining the skid number (10). The testing apparatus is towed behind a vehicle at the desired speed, 40 mph which is the standard for ODOT skid testing. Water is then applied in front of the tire just before the trailer's brakes force the tire to lock up. The resultant force is then measured and converted into a skid number value (36).

Surface texture is separated into three components microtexture, macrotexture, and megatexture, as shown in Figure 1.3. 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 (9).

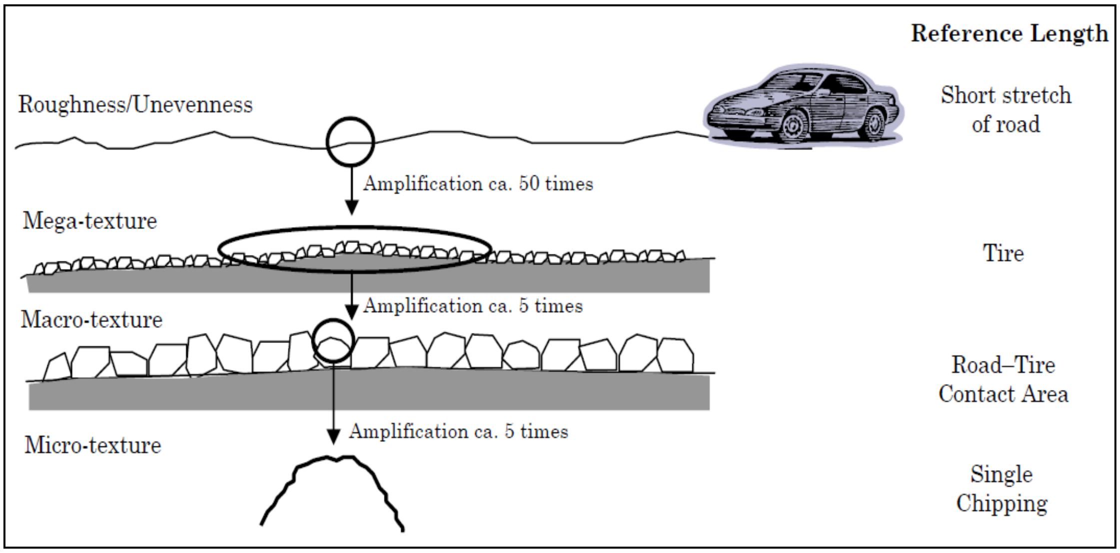

Figure 1.3 Pavement Texture Definitions (37)

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 (34). The World Road Association 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 of a vehicle on the roadway surface at speeds greater than 45 mph.

Megatexture is on a much larger scale than both microtexture and macrotexture and is in essence the irregularities of the road such as potholes, rutting, joints, cracks, raveling, and skin patches (4). 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 (4). Many DOTs use roughness measurements to portray of the overall integrity of their roadway system (38, 39, 40). The focus of this research is on microtexture and macrotexture, which are the variables of interest for road surface safety; it does not address megatexture or roughness.

1.4.2 Surface Texture as a Pavement Preservation Activity

Microtexture, macrotexture, megatexture, and roughness, taken together, summarize the universe of roadway surface defects that the maintenance engineer must address in their pavement management program. 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.

The focus of pavement preservation is placing" the right treatment, on the right road, at the right time" (4). If a road's megatexture or IRI becomes 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 (29). 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 with posted speed limits greater than 70 km/hr (43.5 mph) that pavement preservation by resealing is no longer an option. If this occurs, the NZTA calls for the removal and replacement of the surface course (8). 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 (31).

1.5 PAVEMENT ECONOMICS

What pavement preservation research projects often overlook are the other constraints a maintenance engineer 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 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 by quantifying the engineering properties of commonly available surface treatments. To assist the pavement maintenance engineers in making treatment selection decisions, this research will apply that data to create short term deterioration models for each treatment based on actual field testing.

1.5.1 Investment Decision Making in Transportation

The use of economic analysis, specifically Life Cycle Cost Analysis (LCCA), to achieve the cost-effectiveness and return on investment that supports transportation decision-making is one way to promote sustainability in transportation (41, 42). State agencies generally reserve LCCA application for the long-term, strategic planning process. LCCA could be used by DOTs for evaluating pavement-type selection (i.e., concrete or asphalt), determing strategies, and determining design specifications. It may be reserved for major projects only (41, 43). This research is interested in the implementation of LCCA at the pavement preservation treatment projects level of decision-making by the pavement manager. The literature review in that subject area has a limited amount of information regarding life cycle cost analysis procedures employed at the pavement manager's level (44, 45, 46). The goal of this research project in regards to the economic analysis of pavement preservation treatments was to create a modeling system that would be user friendly to all pavement managers. However, the literature review found that, "The emphasis upon economic cost analysis principles is recent, so models, methods, and tools to construct and analyze economic tradeoffs are still being developed" (47). "Creating a tool that can be readily used by all agencies is difficult due to variations in agency practices, such as condition rating systems, data availability, and data quality" (48). This led to a more expanded scope on how pavement preservation projects are related to LCCA.

1.5.2 Life Cycle Cost Model

As the nation's infrastructure deteriorates, sustainability within the confines of operating and maintenance budgets becomes a contentious issue. Considering only the initial project cost may result in the selection of a maintenance alternative that is more costly over the long run, burdening an ever-shrinking transportation budget as the overall quality and safety of the network decline (48, 49). A sustainable solution, pavement preservation, is currently being pursued and will be instrumental in addressing pavement system needs by keeping good roads good (4) instead of allowing them to deteriorate to the point of no return.

Although LCCA is a powerful project economic evaluation tool, there is no commonly accepted method in use by state agencies to conduct economic analysis at the pavement preservation level (32, 43, 45, 46). In general, LCCA is not wide-spread in transportation decision making, possibly due to the complexity and challenges associated with engineering economic theory (41). The current issues with LCCA application methods may be resulting in its limited use, especially at the implementation-level, where it may not be used at all (32, 42, 43, 45, 46, 50, 51, 52). Current LCCA models, such as the Federal Highway Administration's (FHWA) *RealCost*, are complex and intended for large-scale pavement design decisions and do not adequately address pavement preservation treatment evaluation and its short-term nature (50, 52, 53).

No solid answer was gathered from the literature review on how to implement LCCA at the pavement preservation and maintenance level, possibly because the "emphasis upon economic cost analysis principles is recent, so models, methods, and tools to construct and analyze economic tradeoffs are still being developed" (47). The FHWA suggests, however, that the level of LCCA detail "should be consistent with the level of investment" (54). The level of investment of some activities at the implementation level can somewhat be inferred by the following FHWA statement: "When discounted to the present, small reactive maintenance cost differences have negligible effect on Net Present Value (NPV) [of pavement design alternatives] and can generally be ignored." (54) Therefore, the one goal of this research became to analyze the steps and procedures of LCCA and determine if current LCCA application employed at the long-range-planning level is appropriate at the short-term-treatment-implementation level.

1.6 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 at the NASA test complex on Wallops Island, Virginia (35). 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, the NASA experiment captured a number of important lessons on how to create test sections that support the technical objectives of this research (35).

The goal of this research 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 (SH77H) 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 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. It is important to note that while this section of state highway was the best location to conduct this test, it would not have been considered a candidate highway for some of the treatments applied.

1.6.1 Test Section Development

In 2005, the FHWA issued a memorandum that standardized the terminology for pavement preservation projects (6). 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 thick (14). 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, as well as cover some that weren’t highlighted by the

FHWA but were available. The asphalt sections are shown in Table 1.1 and the concrete sections are shown in Table 1.2.

All sections included in Phase One were constructed in the summer of 2008, and all sections included in Phase Two were constructed in the summer of 2009. All the asphalt sections were constructed in the southbound outside lane of Oklahoma State Highway 77H and the concrete sections were constructed on United States Highway 77, two in the southbound outside lane, one in the southbound inside lane, one in the northbound outside lane, and one in the northbound inside lane. A map of the locations is shown in Figure 1.4.

The construction of each test section was orchestrated by both the researchers and the contractor donating the material, time and labor. Test sections for the most part were donated by participating contractors; however a conscious effort was made on the part of the researchers to incorporate a broad spectrum of pavement preservation treatments. The best way to describe the test sections is to go one by one and explain the process and treatment section.

Table 1.1 Asphalt Test Sections

Asphalt Test Sections	
Phase One (Completed Summer 2008)	**Phase Two (Completed Summer 2009)**
Chip Seal (5/8″)	E-krete
Chip Seal (5/8″) with Fog Seal	Chip Seal (Single Size)
Chip Seal (3/8″)	Chip Seal (Single Size) With Calupave
Open Graded Friction Course (OGFC)	Calupave Seal
OGFC with Fog Seal	Novachip
1″ Mill and Inlay	Microsurfacing
Asphalt Pentrating Conditioner (APC)	
APC with Asphalt Planer	
Fog Seal	
Shotblasting (Skidabrader)	
Shotblasting (Skidabrader) with Fog Seal	
Shotblasting (Blastrac)	

Table 1.2 Concrete Test Sections

Concrete Test Sections	
Phase One (Completed Summer 2008)	**Phase Two (Completed Summer 2009)**
Shotblasting (Skidabrader)	Shotblasting (Blastrac) with Densifier
Shotblasting (Blastrac)	Diamond Grinding
	Next Generation Diamond Grinding

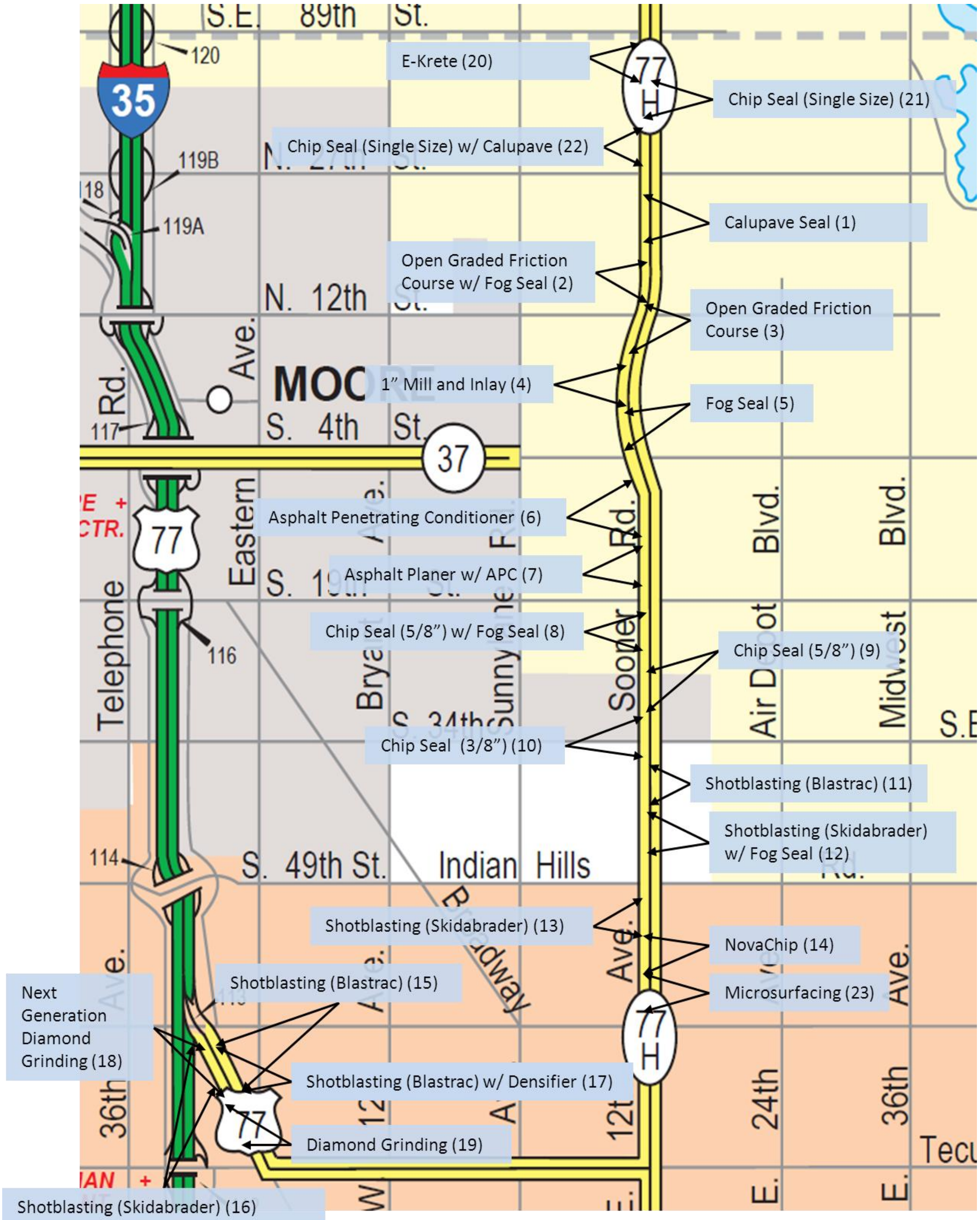

Figure 1.4 Map of Research Test Sections

Test Section #1 was constructed in Phase 2 to replace a Phase 1 section that was unexpectedly withdrawn. This section was then given to Calumet Specialty Products to apply a low penetration fog seal they call “Calupave.” This acts and looks very similar to a standard fog seal, however, visually it was much darker and held its color much longer than the traditional fog seal. This can be seen by comparing Figure 1.5 and Figure 1.9.

Figure 1.5 Test Section #1 –Calupave Seal

Test Section #2 shown below in Figure 1.6 is of Open Graded Friction Course (OGFC) with a Fog Seal. It seems weird to place a fog seal on an open graded surface; however the researchers wanted to determine if this process would produce a longer life cycle than just normal OGFC of Test Section #3, as shown in Figure 1.7. Open Graded Friction Course exhibits a negative macrotexture which means that it is porous and allows water to flow through the surface thus increasing drainage. Both OGFC sections were part of Phase 1.

Figure 1.6 Test Section #2 – Open Graded Friction Course w/ Fog Seal

Figure 1.7 Test Section #3 – Open Graded Friction Course

Test Section #4 shown in Figure 1.8 is that of a 1″ Mill and Inlay, which in practice requires the removal of 1″ of existing surface material and replacement of that material with new asphalt. In this case the researcher used a standard Oklahoma Department of Transportation (ODOT) mix design. This treatment serves as a good bench mark to compare all other treatments. It is probably the most commonly used treatment by ODOT maintenance engineers and as such was included in Phase 1.

Figure 1.8 Test Section #4 – 1″ Mill and Inlay

Test Section #5 was a standard fog seal placed according to ODOT specifications. This treatment applies a small amount of emulsion to the surface to help oxidized material. It was included in Phase 1 and shown below in Figure 1.9.

Figure 1.9 Test Section #5 – Fog Seal

Test Sections #6 and #7 were installed by the same contractor, JLT Inc. Test section #6 was a product called an Asphalt Penetrating Conditioner which works as a rejuvenator for asphalt pavements. In theory, it penetrates the asphalt, reacts with the bitumen and then hardens sealing and giving life to an older oxidized pavement. This research was only focused on determining the effects this product had on texture and therefore, did not test any penetration. Test Section #7 was placed using a special machine developed by the contractor to plane the surface of the roadway, removing any humps, ruts, or inconsistencies. After that process was complete the contractor then uses the Asphalt Penetrating Conditioner to seal the surface. Both of these test sections are shown below in Figures 1.10 and 1.11, and were included in Phase 1.

Figure 1.10 Test Section #6 – Asphalt Penetrating Conditioner

Figure 1.11 Test Section #7 – Asphalt Planer w/ Asphalt Penetrating Conditioner

Test Section #8 and #9 are identical chip seals using ODOT specification 3C (5/8″) gradation for aggregate and the same rate and type for binder, with the only difference being that Test Section #8 had fog seal applied after construction. A close up of the texture can be seen in Figure 1.12 and Figure 1.13. Test Section #10 is a chip seal using ODOT specification 2 (3/8″) gradations for aggregate and the same rate and type for binder, its texture is shown in Figure 1.14.

Figure 1.12 Test Section #8 – Chip Seal (5/8″) w/ Fog Seal

Figure 1.13 Test Section #9 – Chip Seal (5/8″)

Figure 1.14 Test Section #10 – Chip Seal (3/8″)

The next three test sections, #11, #12, and #13, all consist of a technique called shotblasting. This consists of shooting steel balls, called shot, at the roadway surface at high speeds, when the shot impacts the surface the road it removes excess bitumen roughening up and exposing aggregate, thus creating new texture. This product is promising due to the fact that it has no temperature constraints for application and its application process requires no aggregate or binder material. Test Section #11, shown in Figure 1.15, was installed by Blastrac using a single directional shot pattern and 4′ wide head. Test Sections #12 and #13, shown in Figure 1.16 and Figure 1.17, respectively, were shotblasted by Skidabrader using a multidirectional shot pattern and 6′ wide head with the only difference between the two sections being that section #12 had a fog seal applied after the shotblasting application.

Figure 1.15 Test Section #11 – Shotblasting (Blastrac)

Figure 1.16 Test Section #12 – Shotblasting (Skidabrader) w/ Fog Seal

Figure 1.17 Test Section #13 – Shotblasting (Skidabrader)

Test Section #14, shown in Figure 1.18, is an example of an ultra-thin bonded wearing course, in this case it is called Novachip. This section was supplied by Haskell Lemon Construction and Hall Brothers. It is a 3/4" thick mixture of well-graded aggregate, polymerized Performance Grade binder, and mineral fillers that is mixed at an asphalt plant and delivered to the project. It is then placed at the project using a material transfer device and a spray paver.

Figure 1.18 Test Section #14 – Novachip

Test Sections #15, #16, and #17 are shotblasting sections on a concrete roadway surface. Test Sections #15 and #17, shown in Figure 1.19 and Figure 1.21, respectively, were shotblasted by Blastrac using a single directional shot pattern and 4′ wide head with the only difference between the two sections being that section #17 had a nanolithium densifier applied to the surface after the shotblasting application to test the extent a denisfying agent has on the life of the shotblasted surface. Test Section #16, shown in Figure 1.20, was installed by Skidabrader using a multidirectional shot pattern and 6′ wide head.

Figure 1.19 Test Section #15 – Shotblasting (Blastrac)

Figure 1.20 Test Section #16 – Shotblasting (Skidabrader)

Figure 1.21 Test Section #17 – Shotblasting (Blastrac) w/ Densifier

Test Sections #18 and #19 were installed by Penhall, Inc and consist of next generation diamond grinding and traditional diamond grinding, respectively both of which were placed on a concrete roadway surface. Diamond grinding is a process where a drum-size cylinder compiled of many diamond tipped discs is pressed into the pavement while the cylinder is spinning, effectively grinding the surface of the roadway and adding texture. With the next generation diamond grinding technique grooves are installed into the pavement surface by systematically placing larger diameter discs around the spinning cutter drum. These treatments can be seen in Figure 1.22 and Figure 1.23.

Figure 1.22 Test Section #18 – Next Generation Diamond Grinding

Figure 1.23 Test Section #19 – Diamond Grinding

Test Section #20 is a proprietary product called E-Krete produced by Polycon. This product is in essence a Portland cement based slurry seal which is placed on the road at a thickness of 1/8″. This product can then either be dragged or tined to produce the desired texture. This treatment can be seen in Figure 1.24.

Figure 1.24 Test Section #20 – E-Krete

Test Sections #21 and #22 are both chip seal that incorporate the same aggregate and the same rate and type of emulsion. The only differences between these sections and Test Sections #8 and #9 are that these sections utilized a more uniform gradation of aggregates. Test Section #22, shown in Figure 1.26, varies from Test Section #21, shown in Figure 1.25, by the fact that it was treated with Calupave which is the same low penetration fog seal material that was used in Test Section #1.

Figure 1.25 Test Section #21 – Chip Seal (Single Size)

Figure 1.26 Test Section #22 – Chip Seal (Single Size) w/ Calupave

The last test section in this research project is a microsurfacing process shown in Figure 1.27 as Test Section #23. Microsurfacing is a mixture of well-graded aggregate, polymerized asphalt emulsion, fillers, additives, and water that is mixed on the project.

Figure 1.27 Test Section #23 – Microsurface

As pictured in Figures 1.5 - 1.27, there were a total of 23 test sections constructed in two separate phases, all section where tested monthly. These sections also covered a wide range of possible pavement preservation techniques.

1.6.2 Microtexture Testing Protocols

Testing protocols for microtexture involved monthly testing of microtexture using the ODOT skid tester as shown in Figure 1.28. This tester throughout the course of the project measured skid number, using the ASTM E274 testing standard using a ribbed tire, on a monthly basis for each of the 23 test sections (10). This value then was used as an index of the amount of microtexture present on the surface of the test section.

Figure 1.28 ODOT Skid Tester

1.6.3 Macrotexture Testing Protocols

There are a number of different tests that can be used to measure macrotexture of each test section but the most methods have been mostly volumetric methods, with one of the most common being the ASTM E-965 Sand Patch Method (12). However, the sand patch method as demonstrated in an early California DOT study and a more recent Texas DOT study has a reliability issue due to grain size and volume amount (55, 56). In the later study, it was found that the TNZ T/3 Sand Circle testing method produced more reliable results, thus was the test of choice on this research project. This test is a volumetric test, preformed by placing a known volume of sand, in this case 45 ml, which is then spread by revolving a straight edge untensil in a circle until the sand is level with the tops of the surface aggregate and can no longer be moved around (11). Once the known volume has been spread in a circle on the surface of the roadway and can no longer be moved, two measurements are taken to determine the average diameter of the circle, this value is then plugged into Equation 1.2.

$$Mean\,Texture\,Depth\,(mm) \;=\; \frac{57{,}300}{Diameter\;\;(mm\,)^2} \qquad \text{Eq. 1.2}$$

Since the surface texture is inversely porportional to the diameter of the circle produced on the surface, one can deduce that the smaller the circle the greater the macrotexture. This testing protocol is relatively simple but, it is susceptible to operator inconsistency, environmental issues with rain and wind, and roadway imperfections such as abnormal aggregate hieghts on the surface of the road. The results vary from wheel path to between wheelpath, and the test is slow and cumbersome requiring forward planning, good time management and adequate traffic control. This technique is not suited for routine monitoring of the road surface texture over a large road network (18).

The second test used in this study for determining macrotexture is an outflow meter as specified by ASTM E2380/E2380M (57). This method does not measure the texture depth directly; it measures the ability of the depth and interconnected nature of the voids in the surface to let water pass through the road’s surface. It is based on a known volume of water, under a standard head of pressure, which is then allowed to disperse through the gaps, or macrotexture, between a circular rubber ring and the road surface. The time it takes to pass the known volume of water, i.e. the outflow time, is measured. The outflow meter test quantifies the connectivity of the texture as it relates to the drainage capability of the pavement through its surface and subsurface voids. The technique is intended to measure the ability of the pavement surface to relieve pressure from the face of vehicular tires and thus is an indication of hydroplaning potential under wet conditions. A faster outflow time indicates a thinner film of water may exist between the tire and the pavement, thus more macrotexture is exposed to indent the face of the tire and more surface friction is available to the tire. To calculate mean texture depth the following equation is used.

$$Mean\ Texture\ Depth\ (mm) = \frac{3.114}{Outflow\ \ Time\ \ (sec)} + 0.636 \qquad \text{Eq. 1.3}$$

The outflow meter testing apparatus is shown below in Figure 1.29.

Figure 1.29 Outflow Meter Testing Apparatus

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:

- First, the Oklahoma Department of Transportation(ODOT) determines the skid number for each section using its skid trailer

- Next, macrotexture is measured using a New Zealand sand circle test
- Lastly, a second macrotexture measurement is taken using a Hydrotimer outflow meter.

These tests are again shown in Figure 1.30.

Figure 1.30 Test Method Order

1.7 Limitations of Testing Procedures

Within this research process limitations were discovered to exist in the testing practices, however, these limitations were explored and accounted for by the way the testing procedures were designed. The major limitation was with repeatability of testing at the same location for each testing cycle. This was overcome within the testing standards by taking multiple readings in the designated area and then averaging those readings together for the measured aggregate value. This limitation occurred in both the New Zealand Sand Circle test as well as the Hydrotimer Outflow meter test.

The second limitation discovered was a temperature limitation related to the use of water for the Hydrotimer Outflow meter and the ASTM 274E Skid Tester. This made testing using these two techniques very difficult if not at times impossible when the temperature at the test site locations fell below freezing.

The last limitation discovered through this research involved the timing mechanism for the Hydrotimer Outflow meter. In Chapter 3, this is further explored giving way to a new testing protocol as to when to use which macrotexture testing apparatus.

1.8 Organization of the Dissertation

The focus of this dissertation is the development of the relationships between the change in surface texture over time and relating that to the engineering and economic measures that can be used by pavement managers to make decisions in their pavement preservation programs. The remainder of the dissertation presents the findings of this research project formatted into five journal publications (two published, one accepted for publication, and two submitted for publication). Subsequent chapters (2 to 6) contains a single journal paper. Chapter 7 is composed of overall conclusions and recommendations for future research.

Chapter 2 entitled "Comparative Field Testing of Asphalt and Concrete Pavement Preservation Treatments in Oklahoma," discusses the preliminary results of the Phase 1 field testing. This chapter validates the need for the research and begins to lay the foundation needed create deterioration models for various pavement preservation treatments.

Chapter 3 entitled "Comparative Analysis of Macrotexture Measurement Tests for Pavement Preservation Treatments" presents a critical analysis of the macrotexture test protocols and presents the limitations that must be recognized when using each test. This paper resulted in the manufacturer of the Hydrotimer modifying its equipment to overcome the limitations found in this study. However, due to the nature of this limitation, future use of the outflow meter was appropriately not used in analysis of deterioration models.

Chapter 4 is entitled "Life Cycle Cost-Based Pavement Preservation Treatment Design." It presents a new LCCA model that was developed for pavement preservation treatments in this study. The model is currently being implemented by the FHWA as a new chapter in its pavement LCCA manual. This chapter presents a solution to common LCCA problem among maintenance engineers related to the short durations needed for pavement preservation treatments and the possible do nothing approach.

Chapter 5, "Modeling Pavement Texture Deterioration as a Pavement Preservation Management System Tool," presents a pavement preservation deterioration modeling method based on time series analysis. This modeling method permits a rigorous statistics-based procedure to validate pavement surface deterioration and to compute tigger points for pavement preservation treatment scheduling.

Chapter 6 is entitled "Preservation of Concrete Pavement Using a Nano-Lithium Densifier and Shotblasting: A Life Cycle Cost Analysis," and furnishes a discussion of a previously unrecognized pavement preservation treatment for concrete pavements. The paper combines this project's findings regarding microtexture deterioration with research using the same technology completed by the California Department of Transportation to demonstrate the potential of using nano-lithium densifer and shotblasting to increase the service lives of concrete pavements that are subject to abrasion from studded tires and snow plowing.

Chapter 7 summarizes the major contributions of this research and offers recommendations for future research.

2.0 COMPARATIVE TESTING OF ASPHALT AND CONCRETE PAVEMENT PRESERVATION TREATMENTS IN OKLAHOMA[1]

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.

2.1 Paper Synopsis

This paper was the initial foray into the world of pavement preservation for this research project, kind of a here I am statement to the professionals within the pavement preservation industry. It stated the number of test sections that were installed, as illustrated in Figure 1.4, and focused on those test sections that were installed in Phase One, as shown in Table 1.1 and Table 1.2. The use of Phase One test sections in this paper was due to the fact that initial trends were starting to become evident and clues as to what may be coming as more data is collected could be hypothesized. This paper was written to show the importance of long term pavement preservation and to show the need for both microtexture measurements and macrotexture measurements in analyzing the effectiveness of pavement preservation techniques. This paper also began to lay the framework for investigating new methods to handle the economics of pavement preservation life cycle costing.

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[1] The original paper has been reformatted to make it consistent with the other published papers in this document.

2.2 Results of the Study

At the time this paper was written only phase one sections had provided enough date to report on their performance. So, a few examples are provided that illustrate the emerging findings of the project. The fundamental objective involves measuring the change in macrotexture and skid number over time. A previous study found that “the skid number gradient with speed is inversely proportional to the pavement macrotexture” (59). Thus, as this study is focused on pavement preservation, it is important to be able observe the change over time for each measurement on each test section treatment. Figures 2.1 and 2.2 show the observed changes to date (11 months) for a concrete pavement retextured using the Blastrac shotblasting technology and an asphalt pavement that was covered with an open-graded friction course (OGFC). The concrete pavement is one with very low macrotexture but high microtexture which produces a high skid number. Figure 2.1 shows that the macrotexture of this test section remained virtually constant over the year. The skid dropped from the initial value but since then has remained basically constant. It must be noted that the test protocol was established to reduce as much variation in test locations as possible. However, all three tests are inherently variable as it is functionally impossible to take the measurements in exactly the same spot. Thus, it is the trends over time that are important rather than the individual measurements.

2.2.1 Measurements for Year-1

The next example is a test section that was treated with an asphalt penetrating pavement conditioner (i.e. one of the chemical treatments). This treatment was recommended as a pavement preservation treatment for structurally sound asphalt pavements whose primary distress is oxidation. No surface retexturing was done on this section, and this is seen in the two macrotexture test measurements remaining relatively constant in Figure 2.3. However, the conditioner had an initial negative impact on skid number. However, this immediate loss in skid resistance dissipated as the surface film was worn away by traffic. The project has a second test section that used the same product after milling 1/8″ off the surface. It too suffered a short-term loss of skid but it had increased macrotexture. This is the type of information that is currently missing in the body of knowledge. This shows that while there is a loss in skid number initially, it takes roughly 3 months to reach a level of 35 and then stays above that level for at least the remainder of the year. A maintenance engineer can now make a rational decision as to the viability of this pavement preservation treatment.

Figure 2.4 shows an example of a thin 1″ hot-mix asphalt overlay that has very low macrotexture by high skid numbers. This is the most expensive of the pavement preservation treatments. It is also the one with the least macrotexture;

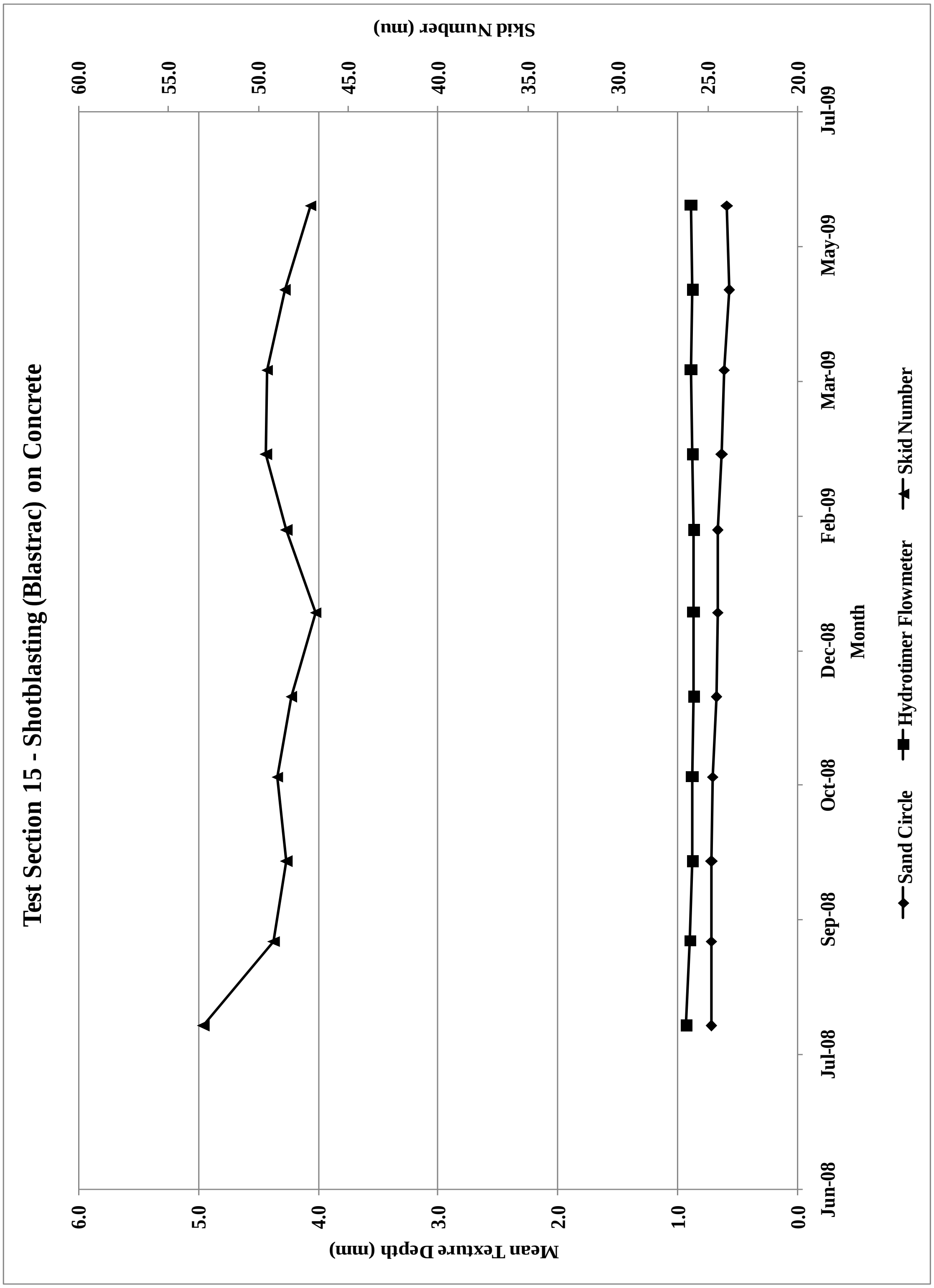

Figure 2.1 Test Section 15, Skid Number and Macrotexture

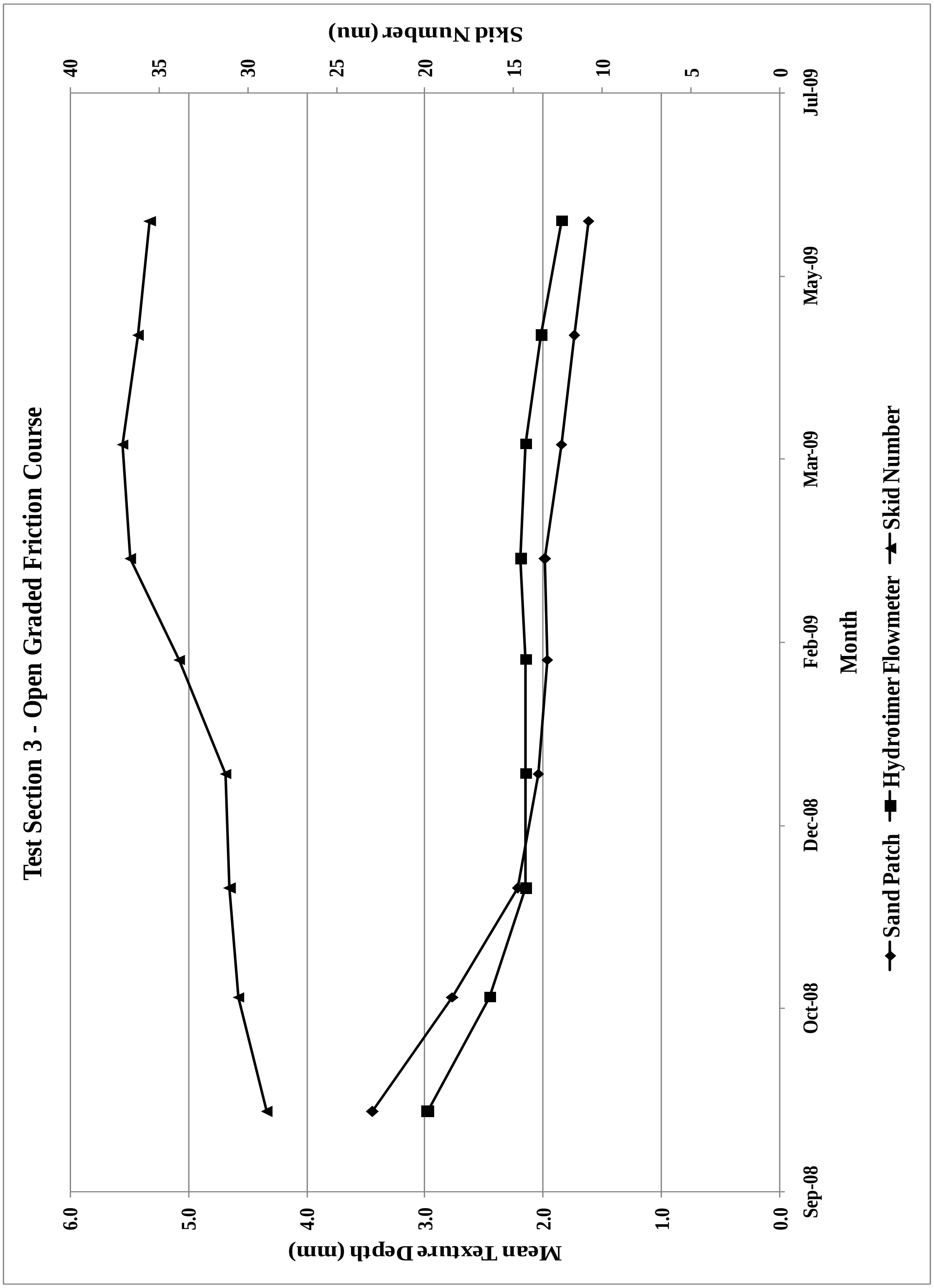

Figure 2.2 Test Section 3, Skid Number and Macrotexture

note that its initial skid numbers are quite high. Given the research by Flintsch et al (2003) that shows that macrotexture is important to pavement drainage and the reduction of hydroplaning, this treatment would be best used in areas where climatic conditions and pavement geometry do not lend themselves to periods of wet pavement (59). If this does not apply to the problem at hand then a treatment such as a chip seal would be a better choice.

Figure 2.5 shows the comparison with the above mill and inlay test section and a chip seal test section. First it should be noted that the inlay test section was constructed 2 months after the chip seal test section, hence the different periods shown in the graph. This example graphically shows the trade-off that must be made by a maintenance engineer when deciding to which pavement preservation treatment is most appropriate for a given problem on the highway. A later phase of this research project will set to measuring cost effectiveness based on actual field performance. The technique that will be used will be cost index number theory (60). This technique allows the analyst to measure the “bang for the buck.” In this case, the following equation can be used to calculate the Skid Number Cost Index for each treatment alternative (28).

$$SNCI_i = \frac{TC_i}{Ave\ SN_i} \qquad \text{Eq. 2.1}$$

where: $SNCI_i$ = Skid Number Cost Index of Treatment “i”

$Ave\ SN_i$ = Average Skid Number of Treatment “i”

TC_i = Total Cost per Lane-mile of Treatment “i”

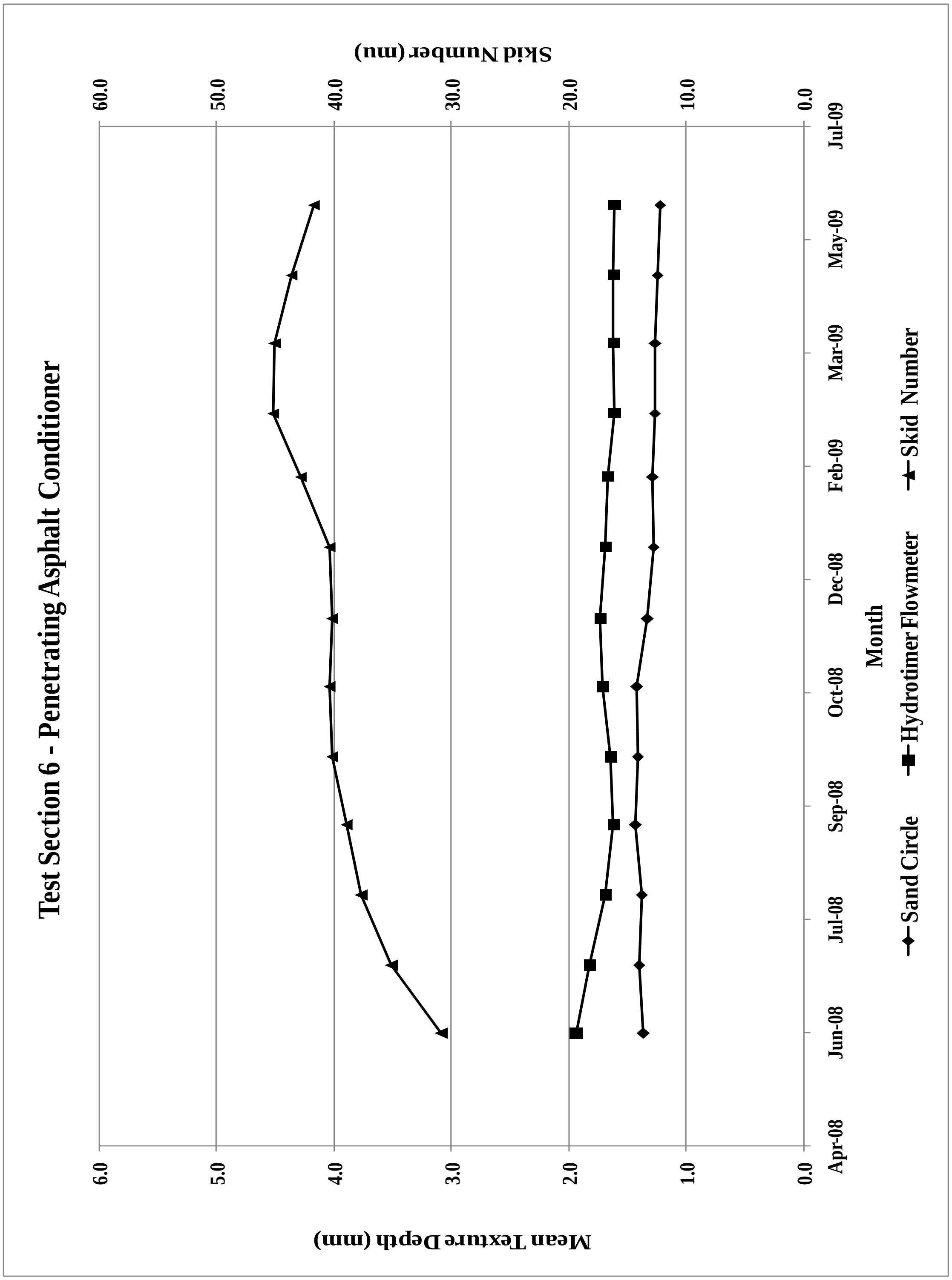

Figure 2.3 Test Section 6, Skid Number and Macrotexture Measurements for Year-1

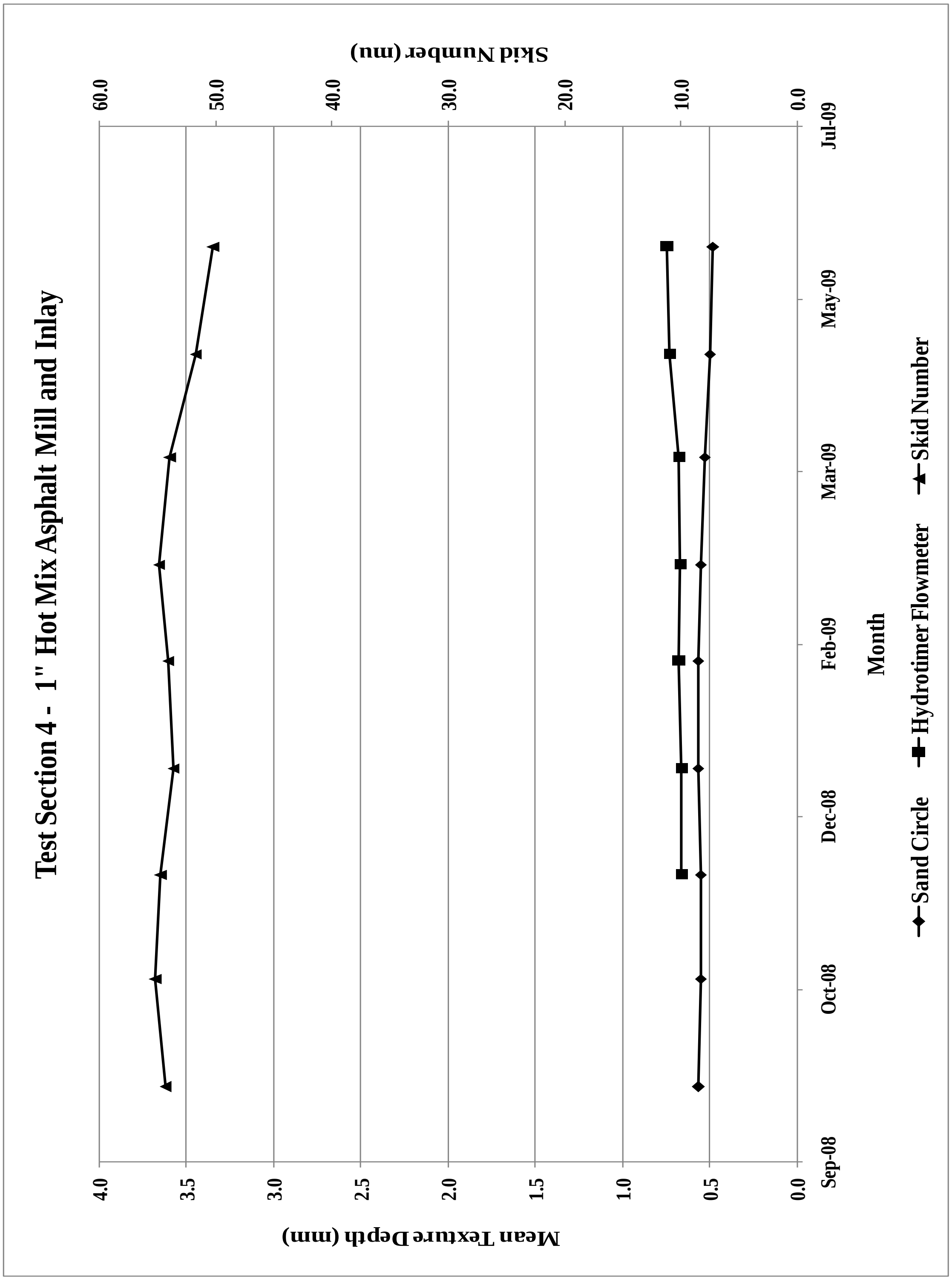

Figure 2.4 Test Section 4, Skid Number and Macrotexture Measurements for Year-1

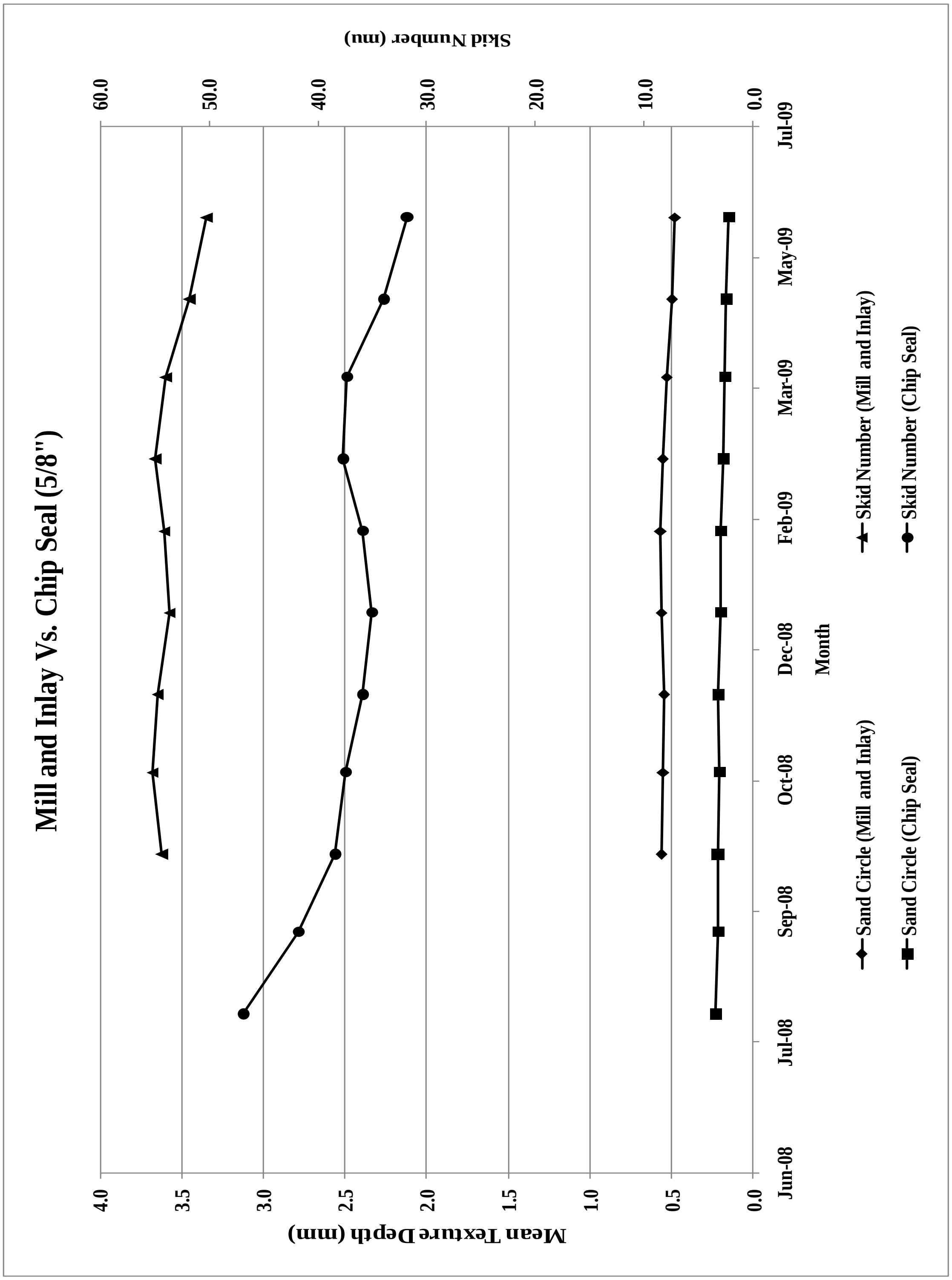

Figure 2.5 Comparison of Skid Number and Macrotexture Measurements, Mill and Inlay versus Chip Seal.

Using the July 2008 prices from the Oklahoma Department of Transportation, which is the period in which these two treatments were installed, the results are obtained and shown in Table 2.1. The alternative with the lower cost index number is the more cost effective option. So given the information on skid change, macrotexture and the financial facts, the maintenance engineer can now determine if spending six times as much per lane mile is justified by a 40% increase in skid number. The location and traffic level of the road in question would also play into this decision. The idea is to change the decision criterion from “minimize cost” to “maximize value” by having all the necessary decision-making information in one place.

Table 2.1 Skid Number Cost Index Analysis of Treatment Alternatives

Treatment	Unit Price (July 2009)	Total Cost per Lane-Mile	Average Skid Number	Skid Number Cost Index
1” Mill and Inlay	$8.52/SY	$59,981	52.6	1,141.28
Emulsion Chip Seal	$1.51/SY	$10,630	37.6	282.45
1 SY = 0.84 SM; 1 Lane-mile = 5,890 SM				

2.3 Conclusions

This study shows that the value of long-term pavement preservation field research. It also shows the need to have the combination of both skid resistance and macrotexture available to the maintenance engineer when pavement preservation treatments are selected. The combination of these two measurements with financial information and 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 government, academia, and industry. The fact that over $400,000 worth of pavement preservation treatments were donated as well as the in-kind donations of ODOT in providing traffic control, skid testing, and engineer’s time, shows the importance of research in pavement preservation. This project is not a competition between products. It is the start of an encyclopedia of pavement preservation comparative analysis, and projects of this nature should be instituted throughout the US to provide the unique local performance information that only long-term filed testing can generate.

3.0 COMPARATIVE ANALYSIS OF MACROTEXTURE MEASUREMENT TESTS FOR PAVEMENT PRESERVATION TREATMENTS [2]

Aktas, B., C. Riemer, D.D. Gransberg, and D. Pittenger, “Comparative Analysis of Macrotexture Measurement Tests for Pavement Preservation Treatments,“ *2011 Transportation Research Record*, *Journal of the Transportation Research Board* National Academies, (Accepted for publication in 2011). (61)

3.1 Paper Synopsis

This paper reports the results of field pavement preservation research regarding two accepted methods for measuring pavement macrotexture. The project has been ongoing for two and a half years and has used the outflow meter ASTM STP 583 and the Transit New Zealand TNZ T/3 sand circle to measure macrotexture on 23 asphalt and concrete pavement preservation treatments. As a result of the protocol which calls for monthly texture measure in the field, the researchers have observed that there are functional limitations regarding macrotexture depth on both standard tests. The differences are a function of the physical mechanics of the two methods. The paper furnishes guidance to researchers and practitioners with regard to the pavement textures where each test method is most appropriate. Essentially, the paper finds that the sand circle should be used on pavements with macrotexture greater than 0.79 mm

[2] The original paper has been reformatted to make if consistent with the other published papers in this document.

and the outflow meter should be used on pavements with textures less that 1.26 mm. Both tests can be used accurately in the 0.79 mm to 1.26 mm range.

3.2 Results of the Study

In this study, macrotexture data has been analyzed in 23 Test Sections (TS). Sand circle and outflow meter tests were completed on each test section once a month and macrotexture depths on the road surfaces were calculated. Macrotexture depths and relative differences between both methods for only one month, taken in November 2009, are shown in Figure 3.1. In Figure 3.1, 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 times are very low, which yields calculated macrotexture depths that are excessively high. 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. Test Section #11 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 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 and the difference between the two methods are between 25% and 30%. In TS4 the macrotexture depth is less than 1.00 mm and the difference is 18.6%.

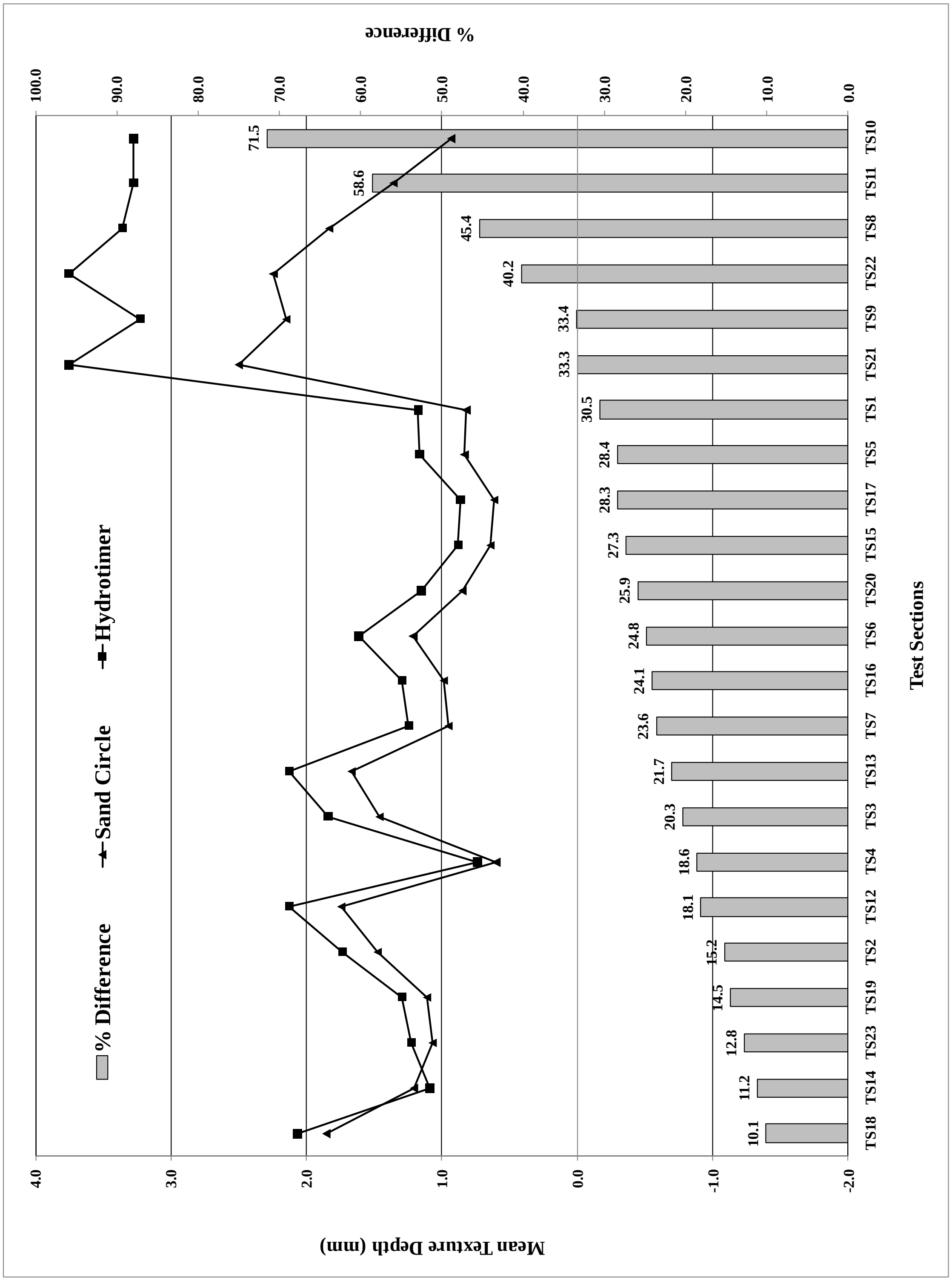

Figure 3.1 Test Sections Macrotexture Results and Differences of Two Test Methods in November 2009.

Figure 3.2 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 3.1, the results for a single month. Therefore, Figure 3.2 validates the Figure 3.1 trend showing differences between the two methods are high on surfaces where macrotexture depth is high (roughly greater than 1.5 mm) and low (roughly less than 1.00 mm). 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 limitation of the sand circle 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 (62) specifies the functional limit of sand circles to be 300 mm 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.

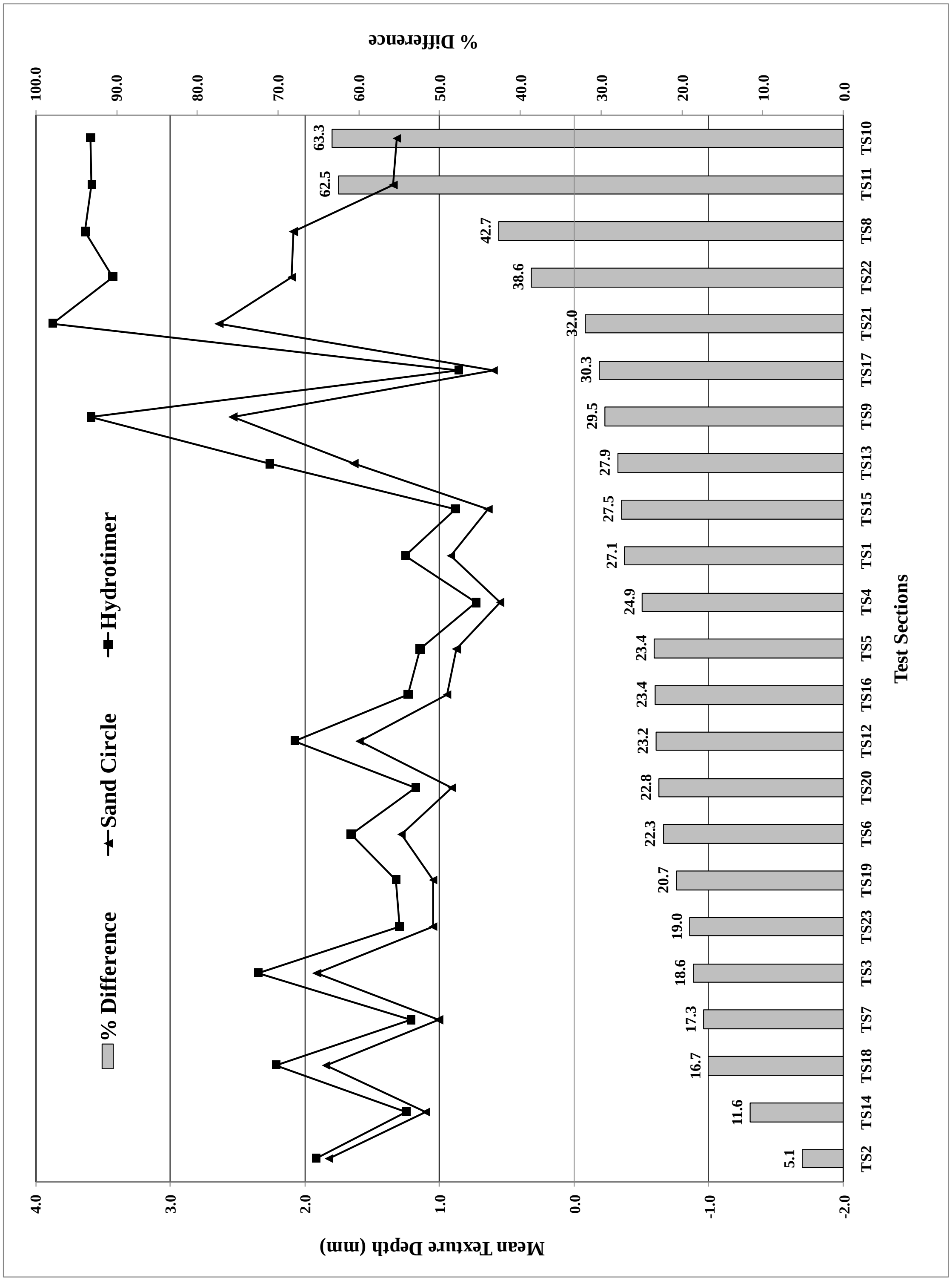

Figure 3.2 Average Macrotexture Results and Differences between Two Test Methods Over 24 Months

Figure 3.3 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, and if outflow time is 1.0 second then macrotexture is calculated 3.75 mm. 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 3.7 mm to 31.8 mm. 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 5th 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 or more. Macrotexture curves that are derived from outflow meter and sand circle methods are shown as a theoretical curve in Figure 3.4. 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 macrotexture value. This value is equal at the 20th second in outflow meter method and a sand circle with a diameter of 265 mm. 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. 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.

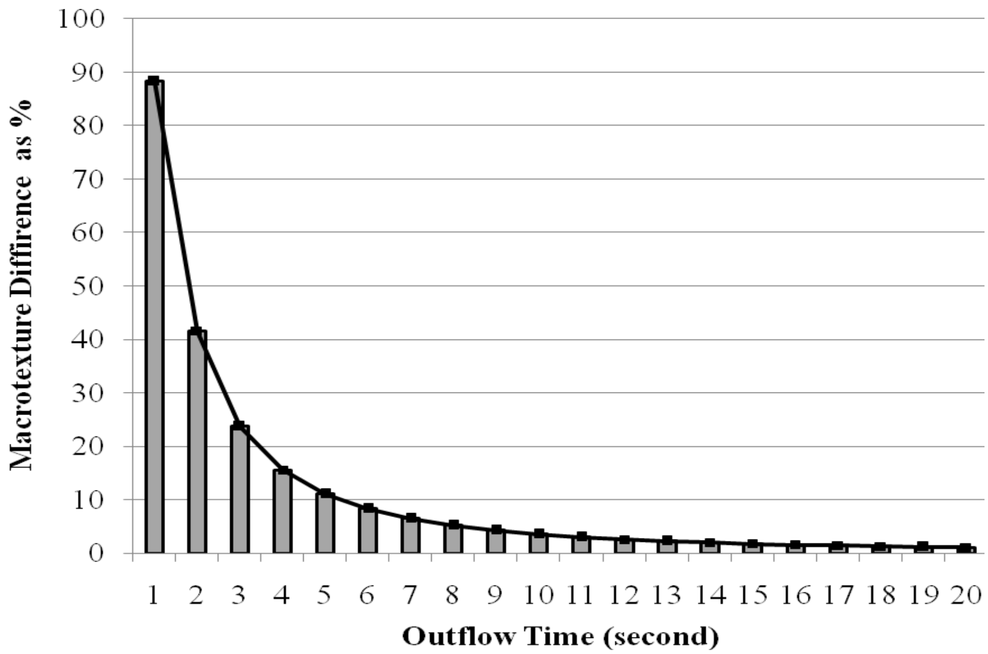

Figure 3.3 Macrotexture Percentage Differences between Seconds in Outflow Meter Test

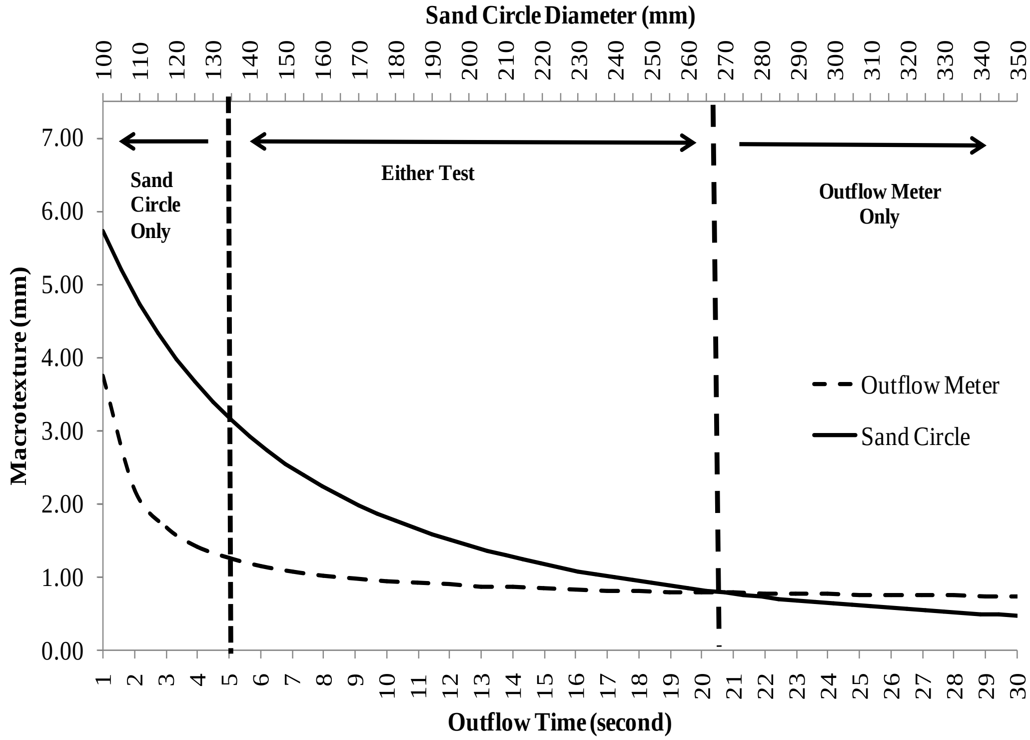

Figure 3.4 Theoretical Curves of Outflow meter and Sand Circle Tests

3.3 Conclusions

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, use the outflow meter only
- If macrotexture > 0.79mm and < 1.26mm 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 be contained in specifications for each test to ensure that those agencies that use these tests are made aware of the functional limitations of each test.

4.0 LIFE CYCLE COST-BASED PAVEMENT PRESERVATION TREATMENT DESIGN[3]

Pittenger,D.M., D.D. Gransberg, C. Riemer, and M. Zaman, "Life Cycle Cost-Based Pavement Preservation Treatment Design," *2011 Transportation Research Record, Journal of the Transportation Research Board* National Academies, (Accepted for publication in 2011).

4.1 Paper Synopsis

Classic engineering economic theory was developed to furnish the analyst a tool to compare alternatives on a basis of life cycle cost (LLC). However, tools used to apply theory to transportation focus on new construction projects with relatively long service lives. These tools do not accurately model the economic aspects of short-lived alternatives such as those that pavement managers must evaluate when seeking the most cost effective pavement preservation treatment. The field of pavement preservation seeks to "keep good roads good" and hence, pavement preservation treatments are applied to extend the functional service life of the underlying pavement. No significant research has been done to quantify the actual service lives of the pavement preservation treatments themselves nor a model been furnished to analyze their LCC. This paper addresses those two gaps in the pavement economics body of knowledge by proposing a methodology for using field test data to quantify the service

[3] The original paper has been reformatted to make it consistent with the other published papers in this document.

lives of pavement preservation treatments for both asphalt and concrete pavements. Additionally, it concludes that a LCC model based on equivalent uniform annual cost, rather than net present value, specifically addresses the relatively short term nature of pavement preservation treatments and allows the engineer to better relate treatment LCC output to annual maintenance budgets.

4.2 LCCA Issues

LCCA is used to compare pavement design alternatives, but there are issues regarding the real value of LCCA output (54, 63, 64). According to the FHWA, issues regarding the appropriate performance period and AP, among other things, can create obstacles in conducting LCCAs (41). This can create issues regarding “fairness”, resulting in “controversy” and doubt as to whether LCCA can be applied consistently and correctly to determine which alternative is truly the most cost effective (65). An analyst that is not thoroughly acquainted with underlying engineering economic analysis theory may inadvertently choose input values that create invalid output, especially when “asset alternatives have radically different technical aspects and dissimilar service lives” (65, 66).

4.2.1 Analysis Period, Net Present Value Method

One important input value is the analysis period (AP). Its selection is based on either a mandated value or the analyst’s judgment. The AP is often selected arbitrarily because conventional theory states that if two options are evaluated over the same period of time using the same discount rate, then the comparison is fair (65, 66).

While this may be true in theory, if the LCCA output effectively makes the pavement design decision (i.e. the engineer selects the one with the lowest value), then using an AP mandated by public entity for all analyses is tantamount to allowing an economist to practice pavement engineering (65).

Selecting an AP for alternatives with differing service lives, often the case in pavement treatment alternatives is necessary in determining the net present value (NPV) of competing alternatives so that cost differences can be assessed and results fairly compared (64) and engineering economic analysis principles upheld (66). The methods for selecting an AP to determine the NPV of competing alternatives are as follows (66):

1. set AP equal to the shortest life among alternatives
2. set AP equal to the longest life among alternatives
3. set AP equal to the least common multiple of the lives of the various alternatives
4. use a standard AP, such as 10 years
5. set the AP equal to the period the best suits the organization's need for the investment
6. use an infinitely long AP.

There is no consensus on which method is the "best" for selecting an AP, but the decision should be based on the investment scenario at hand (66). As a default, if the "best" method is not obvious, the use of a standard AP, if logical considering the investment scenario, is preferred (66). This default selection is evidenced in the FHWA's *Interim Technical Bulletin*, "LCCA Principles of Good Practice" section (54). The FHWA does suggest a standard AP chosen from the range of 35 to 40 years for pavement design decisions (53). But selecting an appropriate AP can be problematic due to its sensitivity, meaning that with all other inputs held constant, changing the AP can result in different alternative rankings (66, 67).

It is suggested that setting the AP equal to the shortest life can easily result in the shortest-life alternative being favored over the other longer-life alternatives (63). It has also been suggested that setting the AP equal to the longest life alternative is preferred and that an AP be "sufficiently long to reflect significant differences in performance among the different strategy alternatives," but not so long that it becomes unreasonable (54, 63). The issues with setting the AP consistent with methods 1, 2 and 4 are that gaps and/or residual values must be addressed for all alternatives whose service lives are shorter or longer than the AP, respectively, and are unacceptably sensitive to the input value (65).

If the analyst intends to assume that costs and service life lengths will remain constant over time, then only mathematical adjustments of gaps and residual values for AP accommodation, consistent with FHWA's *Interim Technical Bulletin*, "LCCA Principles of Good Practice," are required (54). The analysis method selected, in this case, would be irrelevant because all should yield the same decision support (66). In other words, the same outcomes can be rendered regardless of AP chosen so long as gaps and residual values are proportionately spread so as to be consistent with the fully crediting the treatment in accordance with FHWA "good practices," then the analysis can be considered "fair" and supported by engineering economic principles (54, 65, 66). Hence, setting the AP consistent with the shortest life, longest life or using a standard AP, which require adjusting alternatives to fit the same AP can yield the same ranking of alternatives as using the least common multiple of alternatives and an infinite period, which do not require the adjust-to-fit mechanisms, rendering the "arbitrarily truncated lifetime unnecessary" (66, 68). However, it is unreasonable to assume that costs and service lives will remain constant over time, especially when a specific pavement or treatment has its service life expressed as a range (63, 65).

4.2.2 Equivalent Uniform Annual Cost

Equivalent Uniform Annual Cost (EUAC) is an alternative method that avoids issues associated with NPV, such as determining the least common multiple of service lives to compare alternatives and others previously mentioned. Furthermore, "instead of employing a rule of thumb for establishing [an AP]", one should consider the nature of the investment (66). EUAC has been suggested as proper to use in transportation decision making when service lives differ in length for given alternatives (65) (69).

The EUAC model created for this research calculates the life cycle cost for each alternative based on the EUAC method. All incurred costs expected throughout the service life of an alternative are brought to a base year, summed, and then annualized according to the treatment's service life as determined by field data and pavement manager professional judgment. In other words, the AP for each treatment alternative is equal to its own anticipated service life (ASL):

$$ASL_{alt} = \text{analysis period}_{alt} \qquad \text{Eq. 4.1}$$

In NPV models, the annualization is based on the common AP. This model is unique because it seemingly bypasses the common-AP selection process. It determines the EUAC based on each alternative's respective anticipated service life by using the following EUAC calculation:

$$EUAC\ (i\%) = \left[\sum P\right]\left[\frac{i(1+i)^n}{(1+i)^n - 1}\right] \qquad \text{Eq. 4.2}$$

where: i = discount rate

P = present value

n = pavement treatment anticipated service life

The EUAC model is tailored to pavement-management decision-making. It considers the short-term, limited scenarios (continuous and terminal) that the pavement manager encounters. The pavement manager is able to intuitively analyze the LCCA results because they are displayed within the context of the pavement manager's expertise. Treatment-relevant input values, such as service life, are utilized. In contrast, other (NPV) models obscure these pavement-manager relevant values in a possibly arbitrary AP selection (41). Thus, EUAC minimizes the associated sensitivity and complexity issues. Because maintenance funding is authorized on an annual basis, comparing alternatives on a EUAC basis better fits 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. Furthermore, the EUAC method simplifies the LCCA process and results in the same ranking of alternatives as the NPV method, all else held constant, rendering the problematic AP irrelevant (66).

4.2.3 Continuous and Terminal Scenarios

A road segment (asset) is generally intended to remain in service indefinitely and pavement treatments are expected to be applied continuously over the life of the asset, although the service life of a treatment is finite (68). The pavement manager will encounter 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 (terminal scenario) or it will not (continuous scenario) (68). When using EUAC, the "mistake" occurs when the planning horizon, or terminal scenario, is not considered or acknowledged for the investment (66). In other words, if the encroachment of the next expected rehabilitation or reconstruction on the service lives of treatment alternatives is expected to have a material effect with regard to the treatment of residual value for one or more of the treatment alternatives, this encroachment must be addressed in the calculations (66). The intent of using EUAC as the basis of the model was to address both scenarios with its "covert" flexibility, which is recommended in economic analysis, while maintaining its efficient, "overt" inflexibility with regard to disallowing common AP selection (66). The continuous feature in the model disallows the "unnecessary truncating of [service] lives" while the "automatic truncate" terminal feature is built in to ensure adherence to engineering economic principles (68). This fixed flexibility reduces the negative impact associated with standard new pavement LCCA complexities and the possibility of faulty output.

4.2.4 EUAC Model, Continuous Feature

EUAC accommodates the continuous, short-term nature of pavement preservation treatment application because the next expected rehabilitation or reconstruction of the pavement is commonly unknown, i.e. is not on the current work plan. The pavement manager must plan to continuously maintain, preserve or "do nothing" to the pavement in the undefined interim. Because encroachment is not expected in the continuous mode, the material or mathematical adjustments to cost or service life lengths are not required and the pavement manager avoids the "unnecessary truncating of lives" (68). Therefore, the input value of each treatment's service life will be equivalent to its anticipated service life (n), which is the value used in EUAC calculations in this model to determine life cycle cost.

4.2.5 EUAC Model, Terminal Feature

In the terminal scenario, the pavement manager generally chooses the "do nothing" option. In other words, the pavement manager usually defers maintenance because the pavement is scheduled to be rehabilitated or reconstructed according to the work plan. Therefore, the decision essentially *is* to ignore pavement preservation on a given pavement knowing that it will be "fixed" in the near future. This permits the reprogramming of those funds to preserving other pavements in the network.

To avoid the common "mistake" associated with employing the EUAC method, the pavement manager must consider the encroachment upon (i.e. materially alter) treatment service lives to adhere to LCCA principles (66). For example, if the next rehabilitation is scheduled in two years and the pavement manager cannot defer maintenance due to safety concerns, any treatment service life that is expected to extend past two years must be truncated for the purpose of analysis, consistent with the “organization’s need for the investment” (66). If one of the alternatives is expected to have a four-year service life, it may not be able to realize the last two years of service life because its cash flow profile would have to be materially altered to accommodate the rehabilitation in two years. In other words, the residual value would equal zero at time two for the four-year alternative because it can no longer be considered continuous. It ceases having value (or remaining service life) as a pavement treatment because it will be removed when the road is rehabilitated (64, 68). In a terminal scenario, it has been argued that a pavement treatment’s material salvaged from removal can have salvage value, but then the analyst must quantify the cost of removal and value what has been salvaged (68).

The model has been built to accommodate the terminal scenario and engineering economic principles. The input value of each treatment’s service life that extends past the year of the next expected rehabilitation/reconstruction is automatically truncated to coincide with the year of the next rehabilitation or reconstruction. This truncated value becomes the treatment’s anticipated service life (n), which is the value used in EUAC calculations in this model to determine life cycle cost.

Pavement preservation theory asserts that proactively applying treatment extends the life of the pavement, allowing for the deferment of the expected rehabilitation/reconstruction (48). In this case, a sensitivity analysis is useful to determine the relative impact of the possibility of pavement life extension and encroachment of the rehabilitation activity on truncated treatment service life.

If, on the other hand, the pavement manager considers employing a one-year treatment in this example, a one-year gap would exist between the treatment's service life and the year of the expected rehabilitation/reconstruction. The EUAC model is built to ignore the gap in terminal mode and calculate EUAC for all alternatives. This situation, although rare due to the "do nothing" preference and very short-term nature of the terminal scenario, 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. All analysis-period selection methods, when applied to this scenario, have inherent issues as previously stated, so one must decide which method would yield the best information for the pavement manager. The shortest-life method would adhere to the "common period of time" engineering economic principle while EUAC would overtly not. However, if the pavement manager were to choose the shortest-life alternative to set the AP 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. Because the same preferred alternative is yielded from both methods, for the purposes of a consistent model, and with all of the previously-cited issues with the AP, EUAC was selected as the appropriate terminal scenario method. Even in this rare situation, EUAC behaves essentially like a covert short-life method and can provide the pavement manager with relevant decision-making information based on cost, service life and the real possibility of “do nothing” during this state.

4.2.6 Pavement Treatment Service Life Input Value

As pavement preservation emerges as a possible solution to the aging infrastructure problem, research has shown that coupling cost efficiency and treatment effectiveness, termed economic efficiency may be the key to determining the optimal preservation timing (46, 48). Microtexture and macrotexture data is routinely collected by the Oklahoma Department of Transportation (ODOT). Incorporating this type of localized performance data into LCCA may reduce the level of inherent uncertainty associated with [service life] “guesses” and can yield insight to a treatment’s effectiveness and cost-effectiveness (67). If treatment effectiveness (performance) is not considered when determining cost effectiveness, the results may be biased (46).

4.3 Results of Study

A commonly used approach to determine a treatment’s expected service life (effectiveness) is to extrapolate data based on surface condition such as microtexture and macrotexture data (46). This is the approach used in this research and applied to pavement preservation treatments exhibited in field trials (44). Linear regression was applied to the treatments’ microtexture and macrotexture data to approximate the deterioration rate and extrapolate the remaining service life of each treatment. 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 P12 performance specification. The failure point considered for microtexture was a skid number less than 25.

Demonstrating this methodology, Figure 4.1 shows the deterioration of microtexture over time experienced in current research field trial data for chip seal. Linear regression was applied. 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 0.836. 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 50 months (i.e. 4+ years) as shown in Figure 4.2. Based upon this procedure and a failure criterion of 25, it appears that the chip seal will fail due to a loss of skid resistance around the 46-month (3.8-year) mark.

Using the same methodology outlined for microtexture data regression, chip seal macrotexture data was extrapolated (Figures 4.3 & 4.4). The chip seal is expected to fall below the failure criteria for macrotexture around 36 months (3 years).

The resulting approximate service life input values for each alternative were compared to the ODOT survey and literature review results (51, 70, 71). The average cost for treatments and maintenance came from the ODOT survey and was verified by field trial and vendor data, literature review results (51, 70, 71) and bid tabulations. These values are displayed in Table 4.1.

Table 4.1 Treatment Service Life and Average Cost

Pavement Preservation Treatments on Asphalt Pavement	Service Life (years)				Average Cost
	Microtexture	Macrotexture	ODOT & Lit. Review	Minimum	$/SY
1” Hot Mix Asphalt Mill and Inlay (HMA)	>10	N/A	10	10	4.00
Open Graded Friction Course (OGFC)	>10	5.3	10	5.3	3.75
Chip Seal (5/8”)	3.8	3	5	3	1.77

The service life input value for each treatment for EUAC LCCA would be the minimum service life value represented in Table 4.1 and is expressed:

SL_{alt} = MIN<Mi, Ma, Ex>

where the service life input for a treatment alternative (SL_{alt}) equals the MIN (minimum value) of the Mi (microtexture deterioration model output), Ma (macrotexture deterioration model output), and the Ex (pavement manager’s expectation of treatment service life).

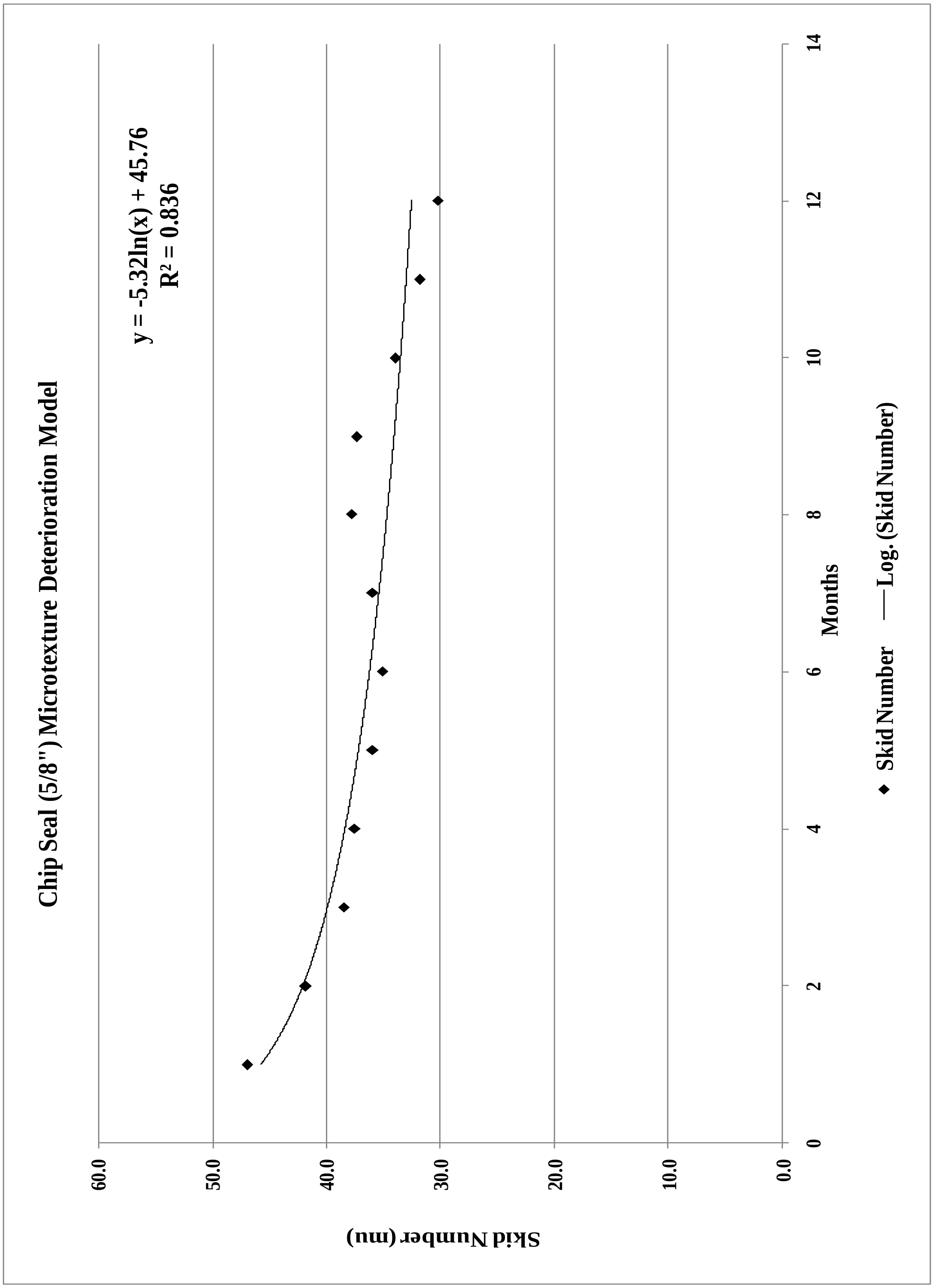

Figure 4.1 Chip seal microtexture field trial performance data.

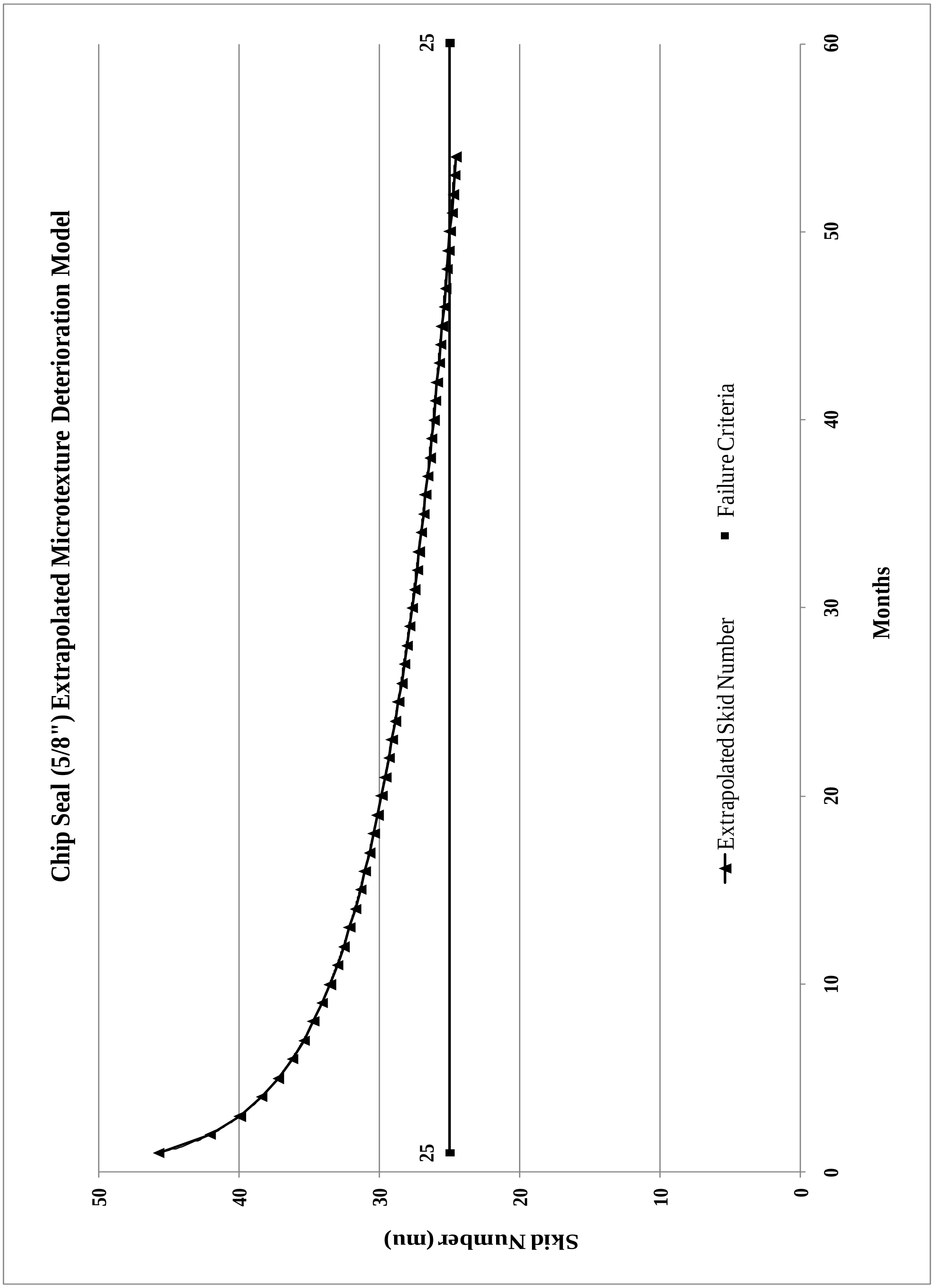

Figure 4.2 Chip seal microtexture deterioration model.

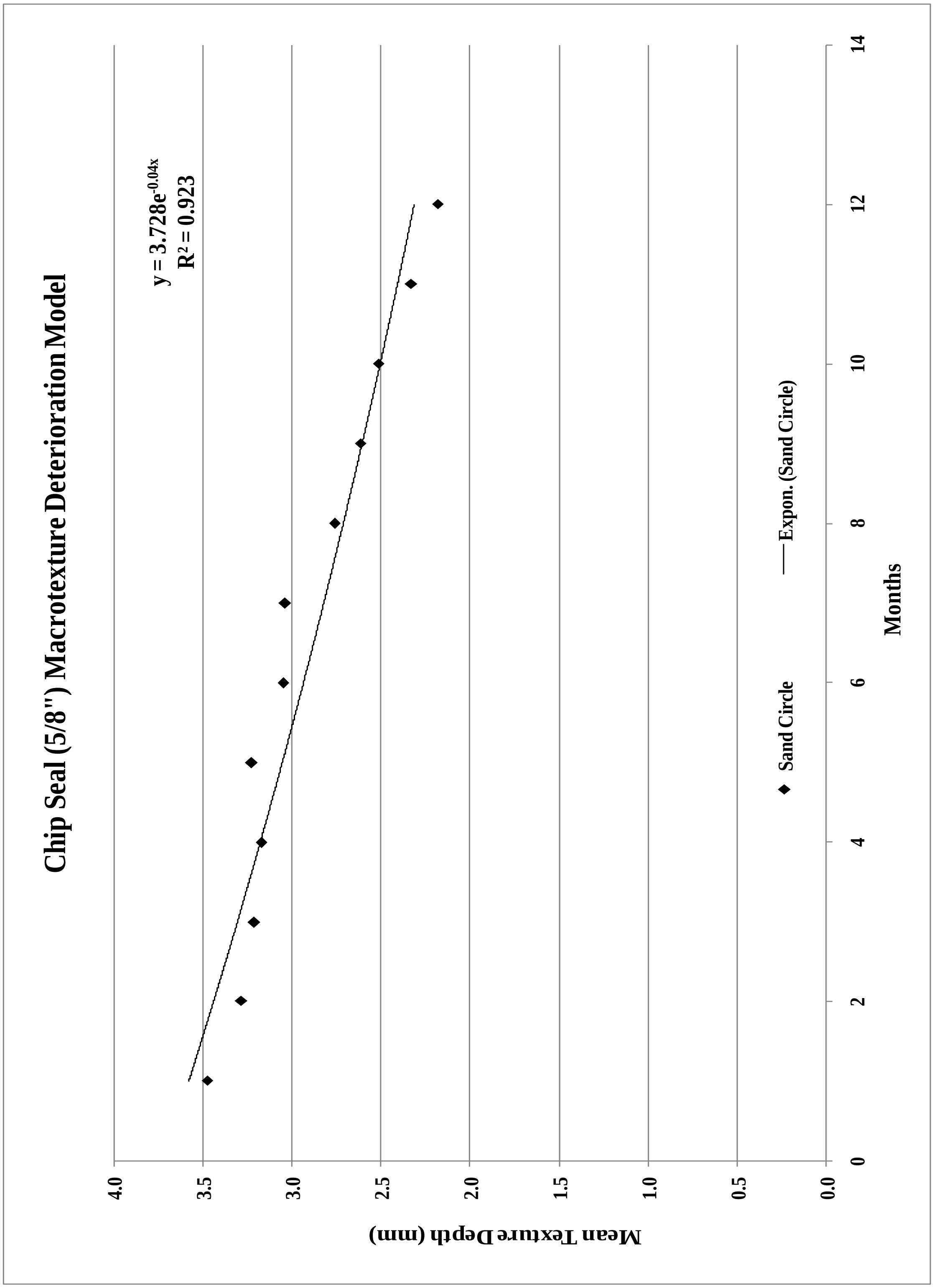

Figure 4.3 Chip seal macrotexture field trial performance data.

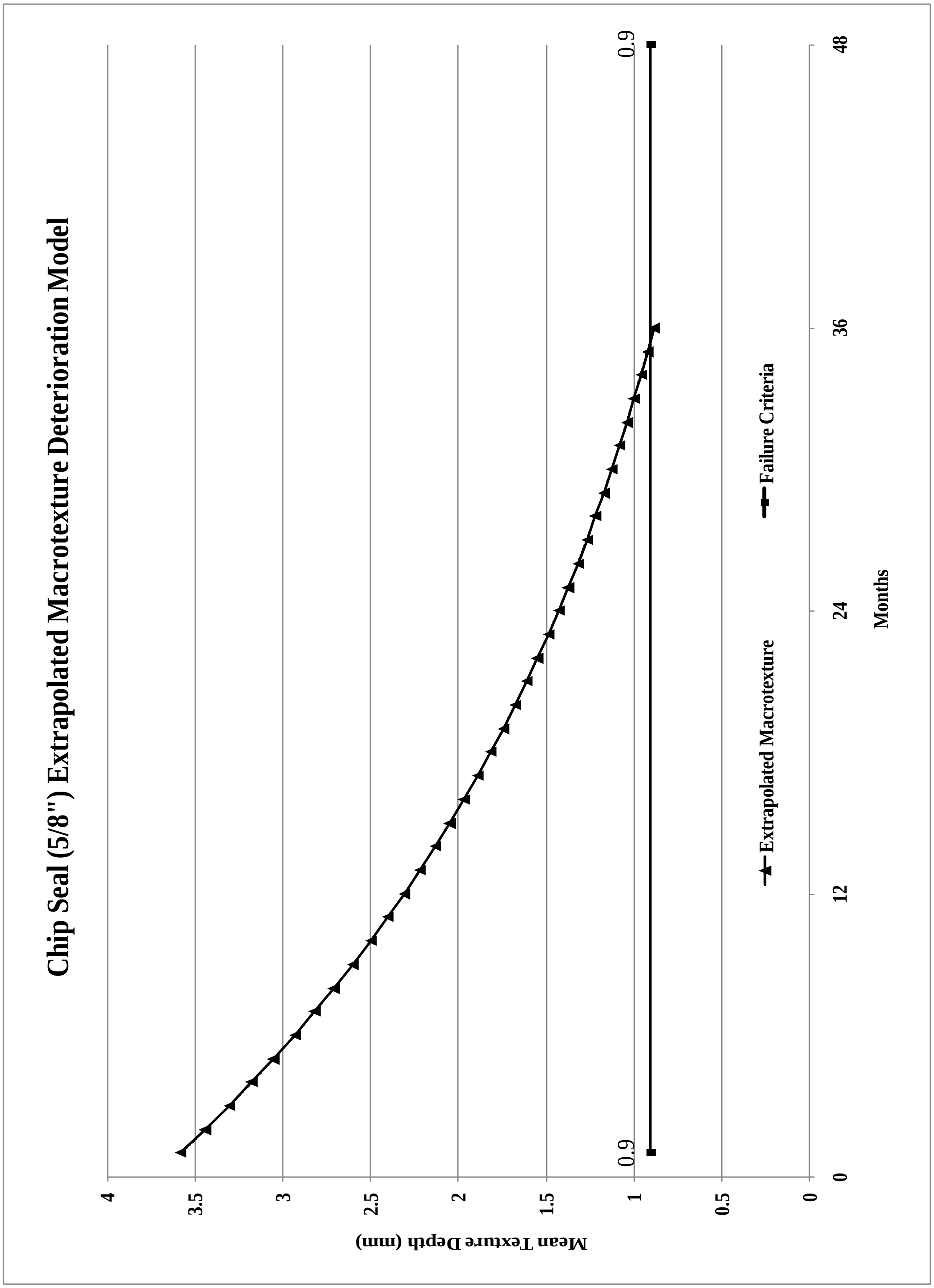

Figure 4.4 Chipseal macrotexture deterioration model.

4.3.1 Conducting EUAC Life Cycle Cost Analysis on Selected Treatments

Cost-effectiveness evaluation of treatments based on engineering economic principles was conducted on the pavement preservation treatments listed in Table 4.1. The FHWA suggests the following LCCA procedures when evaluating design alternatives (54, 64):

1. Establish design alternatives [and AP]
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. Re-evaluate design strategies.

This study has demonstrated that FHWA LCCA procedures 1, 2 & 4 in the above list do not adequately address pavement preservation treatment evaluation and need to be adapted so that it can be used as a frontline tool by the pavement manager to determine pavement treatment cost effectiveness. To recap, EUAC LCCA procedures include:

1. Establish [treatment] alternatives, where a treatment's anticipated service life equals its AP: Equation 4.1
2. Determine [performance period and] activity timing, where the service life of an alternative equals the minimum value of microtexture and macrotexture deterioration model outputs and engineering judgment:

3. Compute [EUAC] life cycle costs, where n is each treatment's anticipated service life: Equation 4.2 and
4. The anticipated service life is further adjusted as necessary by the terminal feature of the EUAC model.

FHWA LCCA procedures 3, 5 and 6 are incorporated into the EUAC evaluation. Initial construction costs and associated future maintenance costs were estimated for the alternatives being analyzed. Activity timing includes maintenance, which is a crack seal and 2%-of-total-area patching with a three-year frequency for all asphalt treatments. The selected alternatives and the corresponding minimum service life values from Table 4.1 were entered into the model, as well as other items required for LCCA.

User costs have been shown to potentially contribute a notable difference between the life cycle costs of preservation treatment alternatives so they were included in this analysis (32, 46). 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%, in accordance with FHWA recommendation (54). In this calculation, the continuous state is assumed, so each treatment's service life is equal to its anticipated service life. Project length will be one lane-mile. The pavement treatment alternative with the lowest EUAC should be considered for selection. EUAC results for the treatments were manually verified and are listed in Table 4.2.

Table 4.2 EUAC LCCA Results, Continuous Mode

Pavement Preservation Treatment on Asphalt Pavement	Microtexture Service Life	Macrotexture Service Life	Expected Service Life
	EUAC, $/lane-mile	EUAC, $/lane-mile	EUAC, $/lane-mile
1″ Hot Mix Asphalt Mill & Inlay (HMA)	4,696	4,696	4,696
Open Graded Friction Course (OGFC)	4,460	6,434	4,460
Chip Seal (5/8″)	4,696	7,529	3,651

The FHWA suggests that a sensitivity analysis be included in LCCA (Procedure 5). The sensitivity of the service life input value for treatments is exhibited in Table 4.2. Based on this data, the service life parameter is sensitive, as one should expect, because an alternative's service life and cost are directly correlated in LCCA. By changing the service life input value of chip seal from 3 years (Mi) to 3.8 years (Ma) and then to 5 years (Ex), its rank changes from 3 to tied with HMA to 1, respectively.

Essentially, EUAC allows for the sensitivity to be moved from the AP 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. In this case, the pavement manager can consider whether or not the chip seal is expected to remain in service for at least 3.8 years to justify the chip seal decision. Using NPV, the pavement manager would only be able to adjust an arbitrary "common period of time" to assess sensitivity, and the service life sensitivity would be obscured. Extensive economist training would be required to determine service life sensitivity and creates an LCCA implementation obstacle.

This proves that using field data derived deterioration curves and performance based failure criteria in an EUAC setting provides a more accurate result than the empirical values for service life in an NPV setting in use for the current FHWA-approved LCCA process. The sensitivity analysis tool, coupled with deterioration models, can yield information that would satisfy "What if" scenarios pertinent to pavement managers and gives the pavement manager the enhanced ability to truly identify, then justify, the most cost-effective pavement treatment for a given project, enhancing stewardship.

The pavement manager would need to put the LCCA results into context, and then reevaluate the results in accordance with FHWA "good practices" (Procedure 6). LCCA results should be coupled with other decision-support factors such as "risk, available budgets, and political and environmental concerns" (64). The output from an LCCA should not be considered the answer, but merely an indication of the cost effectiveness of alternatives (54).

If the next expected rehabilitation/reconstruction was expected in six years and was entered into the model, the model would automatically switch to terminal mode. The HMA and OGFC service lives would be automatically truncated from 10 years to 6 years. Thus, the anticipated service life for both would be 6 years. With a 5-year service life, the chip seal EUAC would remain $3,651 as shown in Table 4.2. With 6-year anticipated service lives, the HMA and the OGFC would have

EUAC values of $6,124 and $5,759, respectively. In this case, chip seal would be the preferred alternative. It would also be the intuitive choice because it, with a short "do nothing" period, would efficiently fill the gap. A quick sensitivity analysis, conducted in accordance with FHWA LCCA Procedure 5, reveals that even if HMA or OGFC were expected to extend the life of the underlying pavement by its full, 10-year service life, chip seal would still have the lowest EUAC, as shown in Table 4.2. If, on the other hand, the pavement-life extension parameter was sensitive, the pavement manager may ascertain the effect by intuitively adjusting the year when the next rehabilitation is expected, which will automatically adjust a treatment's anticipated service life value until the preferred alternative changes, within the expected limits of service life for alternatives. As in the continuous scenario, the pavement manager is able to intuitively analyze model results in terminal mode because input and output are both in the realm of the pavement manager's expertise.

4.3.2 Comparable NPV Calculations, Continuous Mode

To verify the model, EUAC and NPV 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 (66). The standard AP was set to twenty years, consistent with an FHWA case study on project-level planning (51). User costs were omitted for simplification. All methods returned the same ranking, as illustrated in Table 4.3, in support of validating the EUAC model as an appropriate pavement preservation LCCA method. This illustrates the point that using different APs 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 AP selection, associated adjust-to-fit requirements and well-cited sensitivity issues for that parameter.

Table 4.3 Comparable EUAC (Continuous Mode) & NPV Rankings

Pavement Treatments	Agency Costs	Analysis Period	Rank
Equivalent Uniform Annual Cost			
Chip Seal - 5/8″ (5-yr)	$ 3,408	5	1
Open Graded Friction Course (10-yr)	$ 4,150	10	2
1″ Hot Mix Asphalt Mill and Inlay (10-yr)	$ 4,367	10	3
Present Value – Shortest Life			
Chip Seal - 5/8″ (5-yr)	$ 15,172	5	1
Open Graded Friction Course (10-yr)	$ 20,463	5	2
1″ Hot Mix Asphalt Mill and Inlay (10-yr)	$ 21,343	5	3
Present value – Longest Life & LCM			
Chip Seal - 5/8″ (5-yr)	$ 30,344	10	1
Open Graded Friction Course (10-yr)	$ 33,663	10	2
1″ Hot Mix Asphalt Mill and Inlay (10-yr)	$ 35,423	10	3
Present Value – Standard Period			
Chip Seal - 5/8″ (5-yr)	$ 60,688	20	1
Open Graded Friction Course (10-yr)	$ 67,326	20	2
1″ Hot Mix Asphalt Mill and Inlay (10-yr)	$ 70,846	20	3

4.3.3 Comparable NPV Calculations, Terminal Mode

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 NPV regardless of AP selected as exhibited in Table 4.4, it can be sensitive to the AP selection depending on the input data. In an AP-sensitive situation, the EUAC will function like NPV when setting the AP consistent with the shortest-life alternative.

Table 4.4 EUAC (Terminal Mode-Year 6) & NPV Results

Pavement Treatments	Agency Costs	Analysis Period	Rank
Equivalent Uniform Annual Cost			
Chip Seal - 5/8” (5-yr)	$ 3,408	5	1
Open Graded Friction Course (10-yr)	$ 5,553	6	2
1” Hot Mix Asphalt Mill and Inlay (10-yr)	$ 5,889	6	3
Present Value – Shortest Life			
Chip Seal - 5/8” (5-yr)	$ 15,172	5	1
Open Graded Friction Course (10-yr)	$ 29,111	5	2
1” Hot Mix Asphalt Mill and Inlay (10-yr)	$ 30,871	5	3
Present value – Longest Life & LCM			
Chip Seal - 5/8” (5-yr)	$ 27,633	6	1
Open Graded Friction Course (10-yr)	$ 29,111	6	2
1” Hot Mix Asphalt Mill and Inlay (10-yr)	$ 30,871	6	3

4.4 Conclusions

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 information that furnishes pavement managers measurable failure criteria to estimate extended service lives of pavements. This research produced a previously unpublished EUAC-based model for LCCA that specifically addresses the nature of pavement preservation treatments and develops LCCA-based pavement preservation treatment design. The fixed flexibility of the model offered via continuous and terminal scenario allows it to adhere to engineering economic principles and provide the pavement manager project-level evaluation within a wider spectrum of pavement manager expertise. 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 a pavement manager in selecting the most economically efficient pavement preservation treatment for a given pavement management problem.

5.0 MODELLING PAVEMENT TEXTURE DETERIORATION AS A PAVEMENT PRESERVATION MANAGEMENT SYSTEM TOOL[4]

Riemer, C. and D.M. Pittenger, "Modeling Pavement Texture Deterioration as a Pavement Preservation Management System Tool," *2012 Transportation Research Record*, *Journal of the Transportation Research Board* National Academies, (Submitted for publication in August 2011).

5.1 Paper Synopsis

This paper examines the change of pavement surface treatment microtexture and macrotexture over time, and presents deterioration models for six commonly used pavement preservation treatments. The data for the models was developed from a 3-year field trial that exposed all six treatments to the same traffic and environmental conditions on an identical substrate. Monthly measurements of microtexture and macrotexture were taken during the test. The modeling of a pavement performance is an essential activity in all pavement management systems. These models play a crucial role in several aspects of a successful pavement management system, such as financial planning and budgeting as well as pavement design and life-cycle economic analysis (72). It is essential that a deterioration model include, as completely as possible, all the factors that affect the condition of the pavement and accurately represent the effect of maintenance on pavement condition (73). These models play

[4] A modified version of this paper has been submitted to the 2012 Transportation Research Board for publication in TR News, August 2011.

important role in pavement preservation by providing pavement managers with the critical treatment timing information needed to “put the right treatment, on the right road, at the right time” (4). However, pavement deterioration models have historically been focused on only distress types and traffic characteristics, combining multiple different variations of defects and traffic data to compute some form of pavement condition rating/score such as the Pavement Serviceability Index (PSI) (72, 73). These models fail to include the safety aspect of the pavement management process. The focus of this paper is on surface texture, its ability to be modeled, and it importance in pavement management systems. This paper seeks to determine if deterioration models of surface texture can be established to furnish safety performance criteria for various pavement preservation techniques to enhance the current pavement management systems that currently don’t account for any safety criteria.

5.2 Model Results

Tests for both microtexture and macrotexture were conducted on a monthly basis for three years on each pavement preservation test section and remain ongoing. The data gathered was then analyzed using time series analysis (74). The information shown in Table 5.1 is used to determine whether a deterioration model is reliable for a given texture, by examining the model’s coefficient of determination (R^2) value (72). Unlike laboratory research, the researchers engaged in field research are unable to exercise total control over all the variables. Therefore, based on the definition of the R^2 value and the reported experience of a similar study of skid resistance, the team determined that if the independent variable (time) could account for 50% or more of the variation in the dependent variable (texture) that the given deterioration model added value to the pavement preservation management process (75, 76). Thus, a model whose R^2 value is above 0.50 the model is considered reliable and if the R^2 is above 0.70 the model is highly reliable. Using this standard, one can look at the Table 5.1 and determine the treatments which have a reliable model.

There are certain attributes within the equation of the model that must be explained to better understand what one could expect from the model's predictions. For the macrotexture deterioration models, it was determined that logarithmic functions best modeled deterioration, by comparing the coefficients of determination of several different regression equations for the list of pavement preservation treatments and selecting the function that produced the highest R^2 value. When analyzing the macrotexture deterioration models it is important to ensure that the regression output is realistic by checking to see if the sign in front of the equation, negative, which means that the equation represents deterioration (i.e., the microtexture decreases over time). The second check is the constant at the end of the equation to ensure that it roughly equals the initial macrotexture for the given section. For instance, in the Table 1 macrotexture deterioration model for the Chip Seal (3/8″) test section, the equation is $y = -0.509 \ln(x) + 2.4198$. Therefore, the equation shows that the initial macrotexture should be approximately 240 mm, the rate of deterioration is -0.509 ln(x) and the R^2 value is 0.85.

Table 5.1 Summary of Time Series Data

Pavement Preservation Treatment	Macrotexture Deterioration		Microtexture Deterioration	
	Logarithmic Equation	R^2 Value	Power Equation	R^2 Value
Open Graded Friction Course	y = -0.499ln(x) + 2.9017	0.77	$y = 29.67x^{0.0724}$	0.49
Open Graded Friction Course w/ Fog Seal	y = -0.625ln(x) + 3.2829	0.77	$y = 28.597x^{0.08}$	0.56
Mill and Inlay	y = 0.038ln(x) + 0.4864	0.23	$y = 56.652x^{-0.046}$	0.47
Fog Seal	y = -0.034ln(x) + 0.95	0.21	$y = 41.347x^{0.0418}$	0.45
Penetrating Asphalt Conditioner (P.A.C.)	y = -0.084ln(x) + 1.4699	0.52	$y = 34.135x^{0.0839}$	0.70
P.A.C. w/ Asphalt Planer	y = -0.077ln(x) + 1.1715	0.56	$y = 32.82x^{0.0974}$	0.79
Chip Seal (5/8″) w/ Fog Seal	y = -0.386ln(x) + 2.8431	0.90	$y = 36.399x^{-0.071}$	0.38
Chip Seal (5/8″)	y = -0.636ln(x) + 3.8985	0.85	$y = 44.065x^{-0.115}$	0.71
Chip Seal (3/8″)	y = -0.509ln(x) + 2.4198	0.85	$y = 54.729x^{-0.162}$	0.77
Shotblasting (Blastrac)	y = 0.0028ln(x) + 1.3458	0.001	$y = 52.16x^{-0.031}$	0.27
Shotblasting (Skidabrader) w/ Fog Seal	y = -0.064ln(x) + 1.7158	0.34	$y = 49.868x^{-0.023}$	0.12
Shot-blasting (Skidabrader)	y = -0.054ln(x) + 1.7522	0.21	$y = 51.286x^{-0.031}$	0.27
Shotblasting (Blastrac) on Concrete	y = -0.03ln(x) + 0.7103	0.28	$y = 49.115x^{-0.008}$	0.03
Shotblasting (Skidabrader) on Concrete	y = -0.075ln(x) + 1.1123	0.56	$y = 39.681x^{0.01}$	0.02

The power function was selected for microtexture modeling because it produced the best R^2 values. Within these regression equations, the coefficient in front of the variable is now the initial value of the microtexture index value, (i.e. the initial skid number), and the exponent is the rate of or deterioration. Again using the microtexture deterioration model for the Chip Seal (3/8″), the equation is $y = 54.729\ x^{-0.162}$. Therefore, the initial measurement should be about 55, the rate of deterioration is $x^{-0.162}$, and the R^2 value is 0.79. This method helps determine the likelihood that a given pavement preservation treatment has a viable model to help predict its service life based on loss of texture (i.e., safety performance characteristics).

5.3 Test Section Evaluation

The next step is to determine which pavement preservation techniques provide deterioration models that are reliable, and then to determine their predicted service lives based on their safety performance characteristics. This is accomplished by again analyzing their time series analysis and extrapolating the resultant regression equation to estimate service life of each treatment. There are three possible outcomes for the different pavement preservation treatments in the field trial:

1. Viable deterioration model
2. No model: R^2 value is to low or equation constants are unrealistic
3. A constant model: Macro or microtexture measurements were roughly linear over time.

The Chip Seal (3/8″) test section, shown in Figure 5.1, shows a highly reliable deterioration model can be estimated as displayed on the graph, the R^2 value is 0.85. By extrapolating the deterioration model out and comparing that to a known failure criteria of 0.9mm, shown in Figure 5.2, the model estimates its service life to be 20 months (8). When compared to the actual data, on Figure 5.1, one can see that the deterioration model holds true because as the macrotexture approaches 0.9mm, the rate of change decreases until ultimate failure occurs at month 20. This validates the literature and the case that deterioration models can be used to estimate service life (9). Using this process, all three chip seal test sections, and both open graded friction course test sections produced highly reliable deterioration models.

The second possible outcome from this process is a deterioration model that doesn't show any failure criteria or improvement, which would be considered a "no model" scenario. This was seen in test sections that involved chemical treatments such as the standard fog seal, as shown in Figure 5.3, and the penetrating asphalt conditioner, as shown in Figure 5.4.

These treatments haven't exhibited deterioration but rather an increase in microtexture due to the chemical being worn off the surface by traffic. It is important to note in dealing with chemical treatments that there will be an initial decrease in microtexture followed by a gradual increase back to the original values or slightly lower than original values. By coupling the use of chemical treatments with other treatments that increase texture such as chip seals or shotblasting can prove to be a very effective pavement preservation technique (26). While discussing chemical treatments it is helpful to see the full picture as shown in Figure 5.5 and Figure 5.6, which show the application of a chemical only affects the microtexture while the macrotexture remains constant.

The last case is related to possible macrotexture or microtexture deterioration models where the texture was relatively constant and where the slopes of the texture trend lines are quite gentle. This occurred in a number of test sections during the research and can be explained by one of two possible scenarios. The first scenario is that the test section may be still at the beginning of its service life even with 3 years of data. Figure 5.7 shows the asphalt mill and inlay which should last around 10-12 years; therefore, any deterioration within the first 3 years would signal major problems (72). Because of the given material qualities, it's hypothesized that this section will fail due to microtexture loss rather than macrotexture loss, but currently as seen in Figure 8 the data remains fairly constant and texture loss is minimal. It is notable that mill and inlay section has markedly higher microtexture than the original surface and that texture appears to remain at that high level for a period longer than has been tested so far in this research project.

Figure 5.8 shows shotblasting (Blastrac), this section increased the macrotexture of the original surface and the macrotexture has remained constant for the length of the project. Both test sections have shown that constant levels of texture can be maintained over the length of the research project, as of May 2011 which was the analysis cutoff date for this research project, and these sections can also be used to increase and sustain higher texture levels.

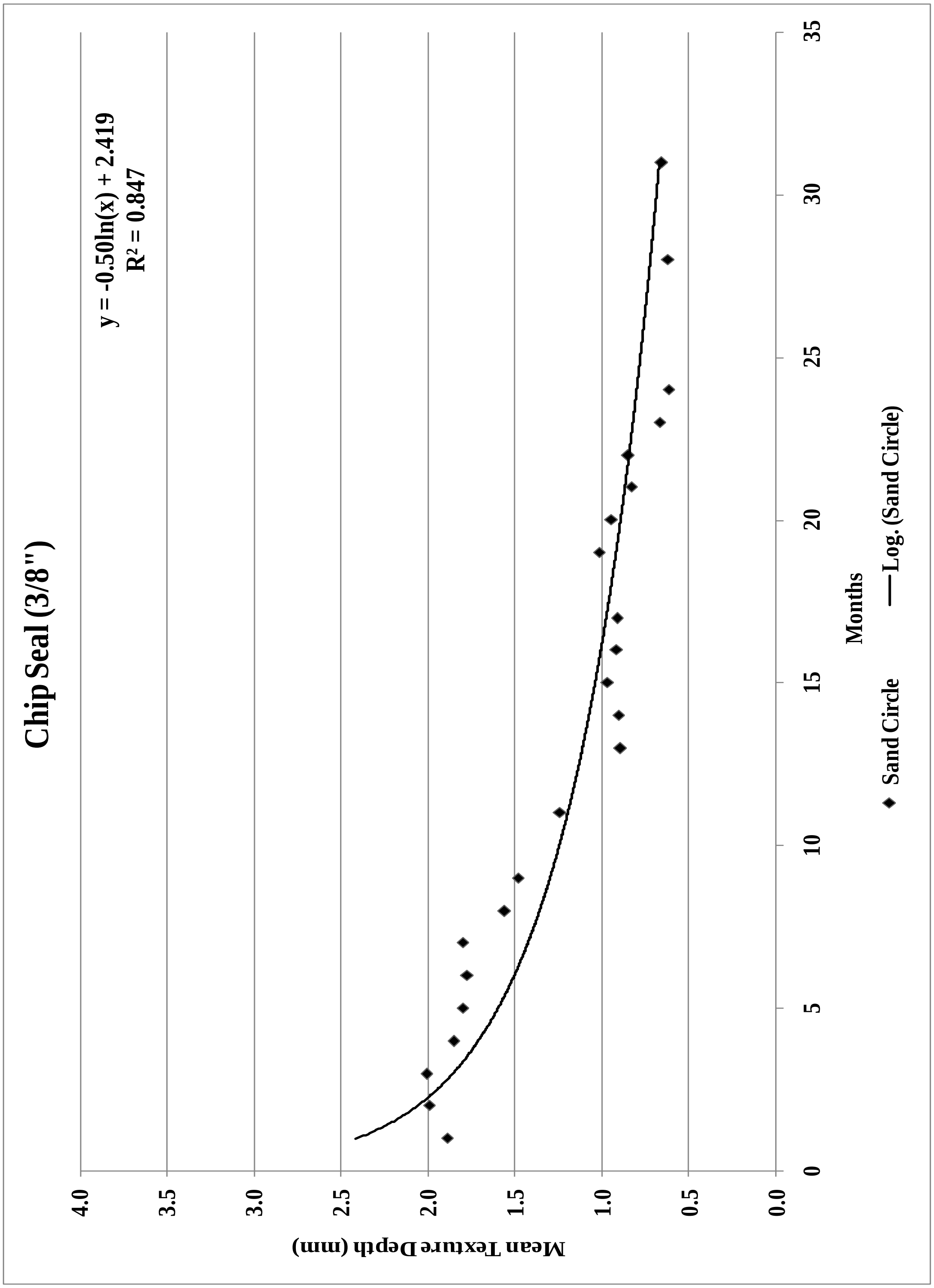

Figure 5.1 Chip Seal (3/8”) Actual Macrotexture Graph

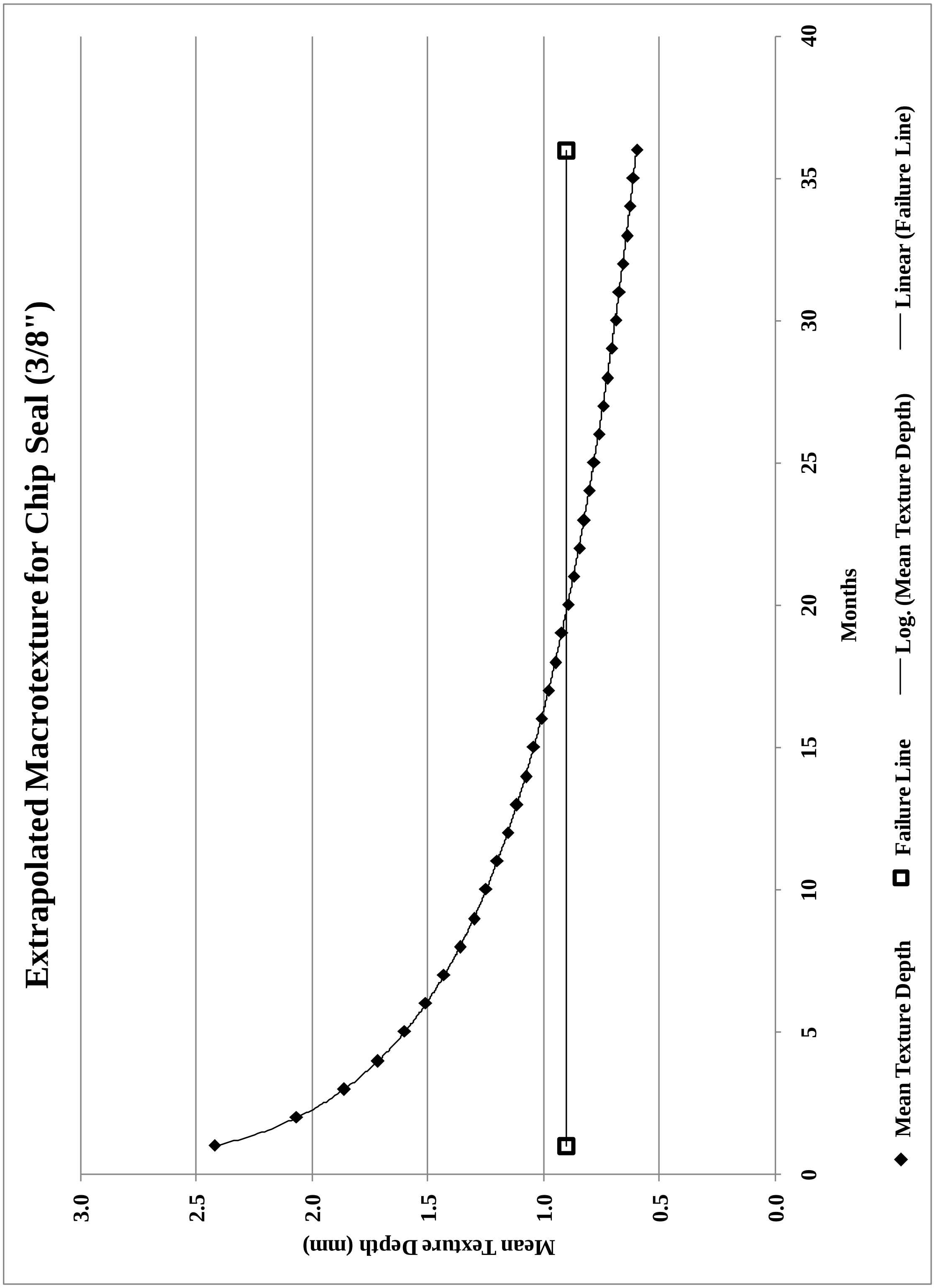

Figure 5.2 Chip Seal (3/8”) Extrapolated Macrotexture Graph

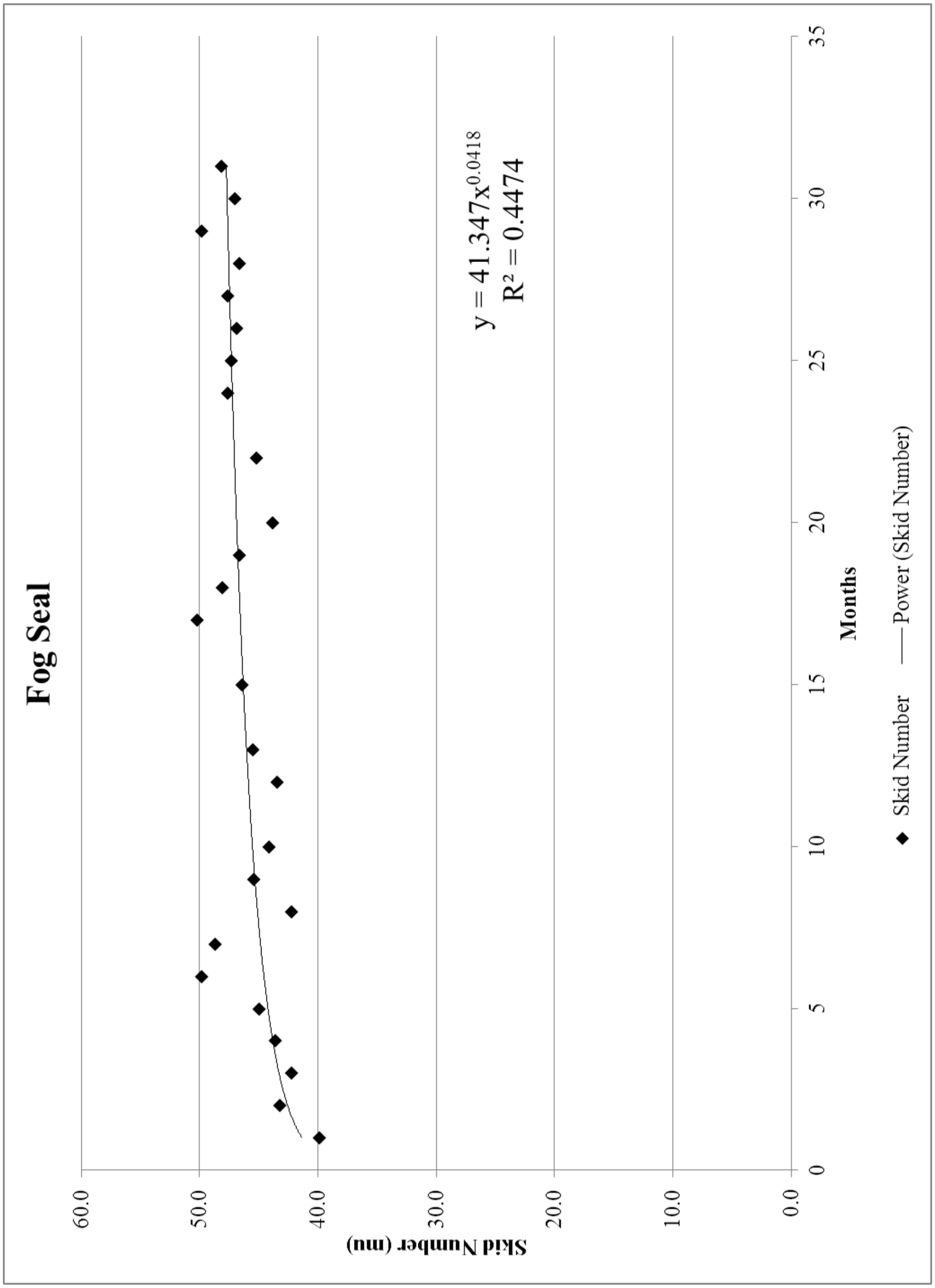

Figure 5.3 Fog Seal Microtexture Model

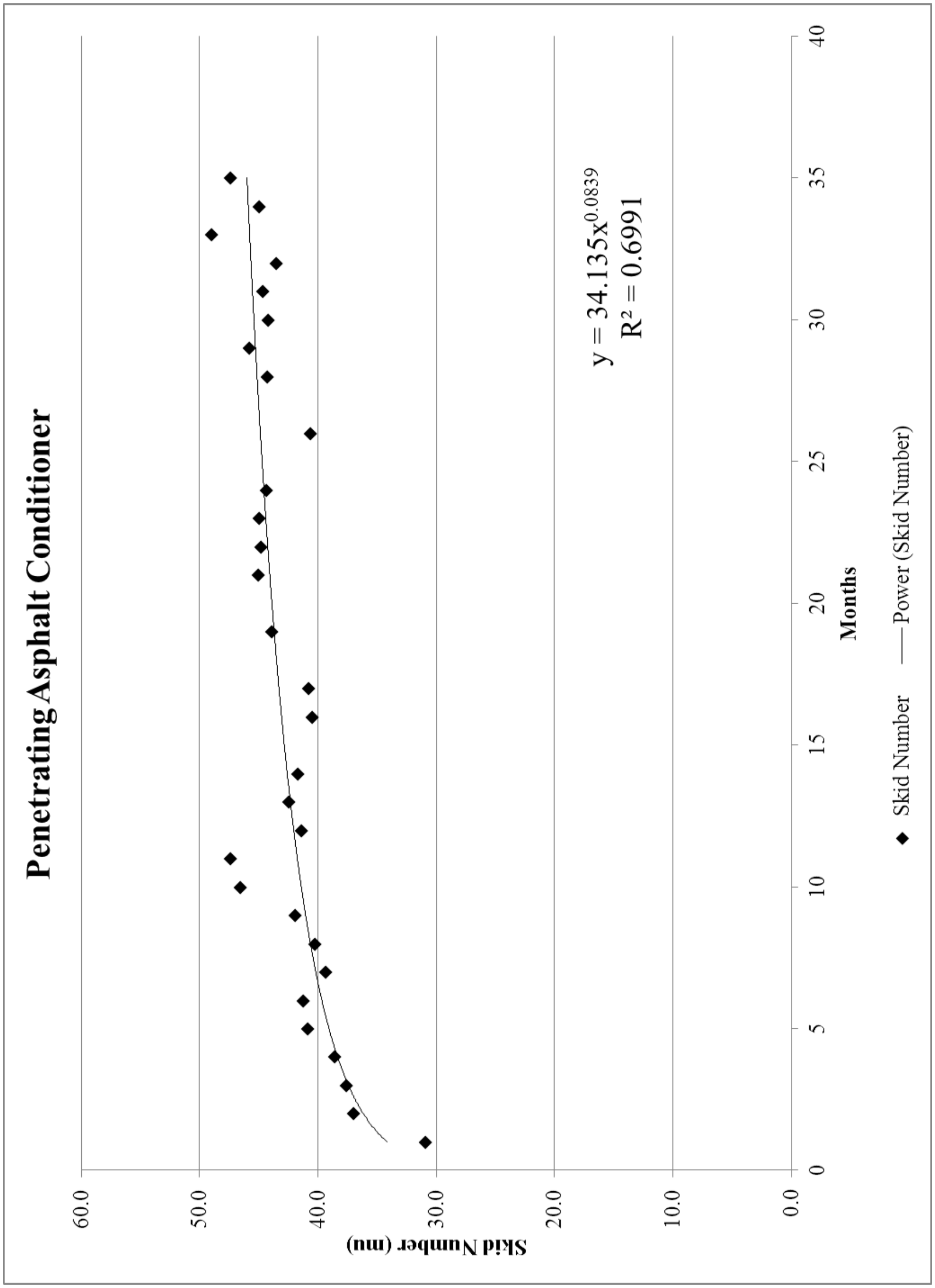

Figure 5.4 Penetrating Asphalt Conditioner Microtexture Model

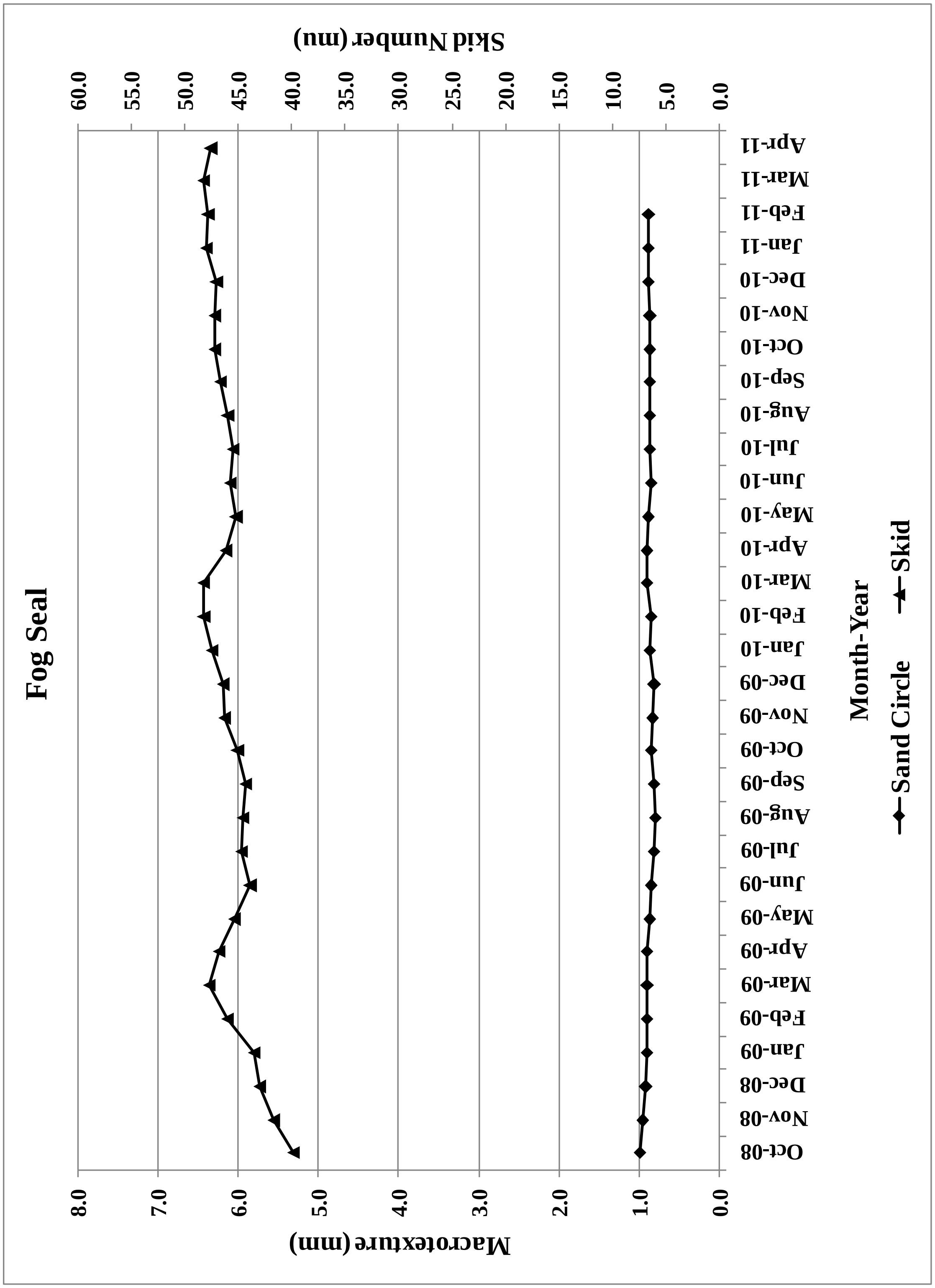

Figure 5.5 Fog Seal Texture Combination Graph

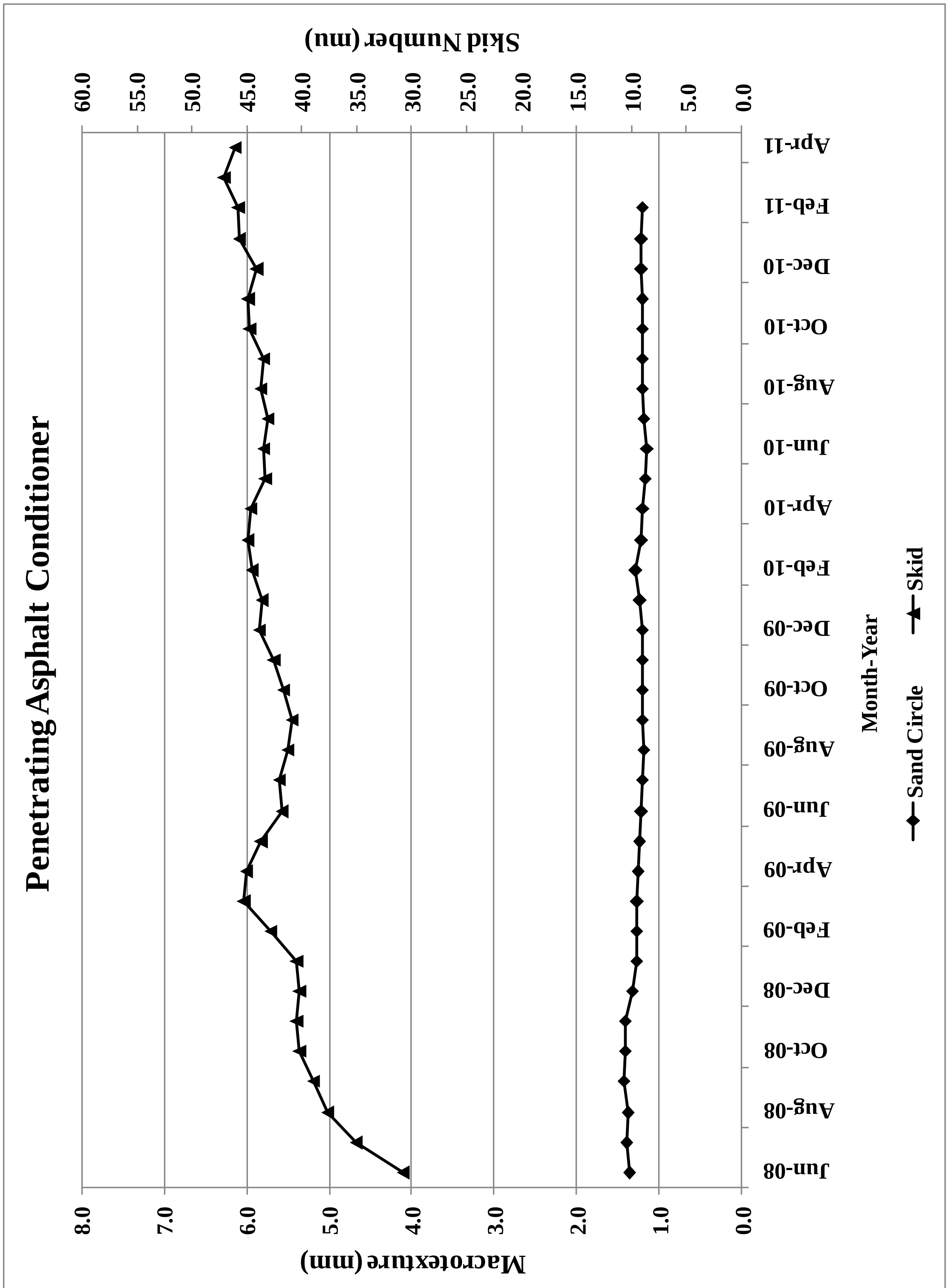

Figure 5.6 Penetrating Asphalt Conditioner Combination Graph

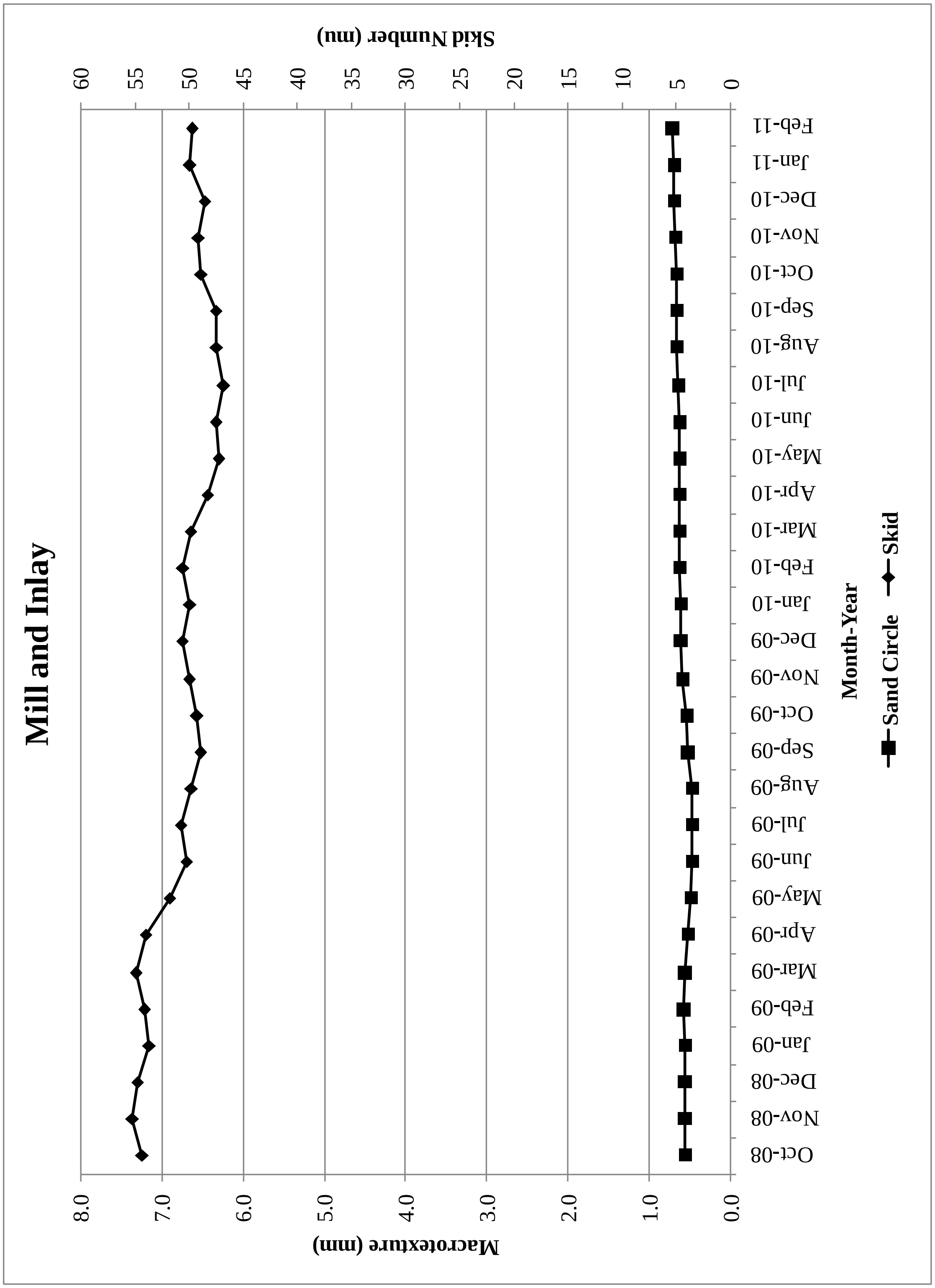

Figure 5.7 Mill and Inlay Texture Combination Graph

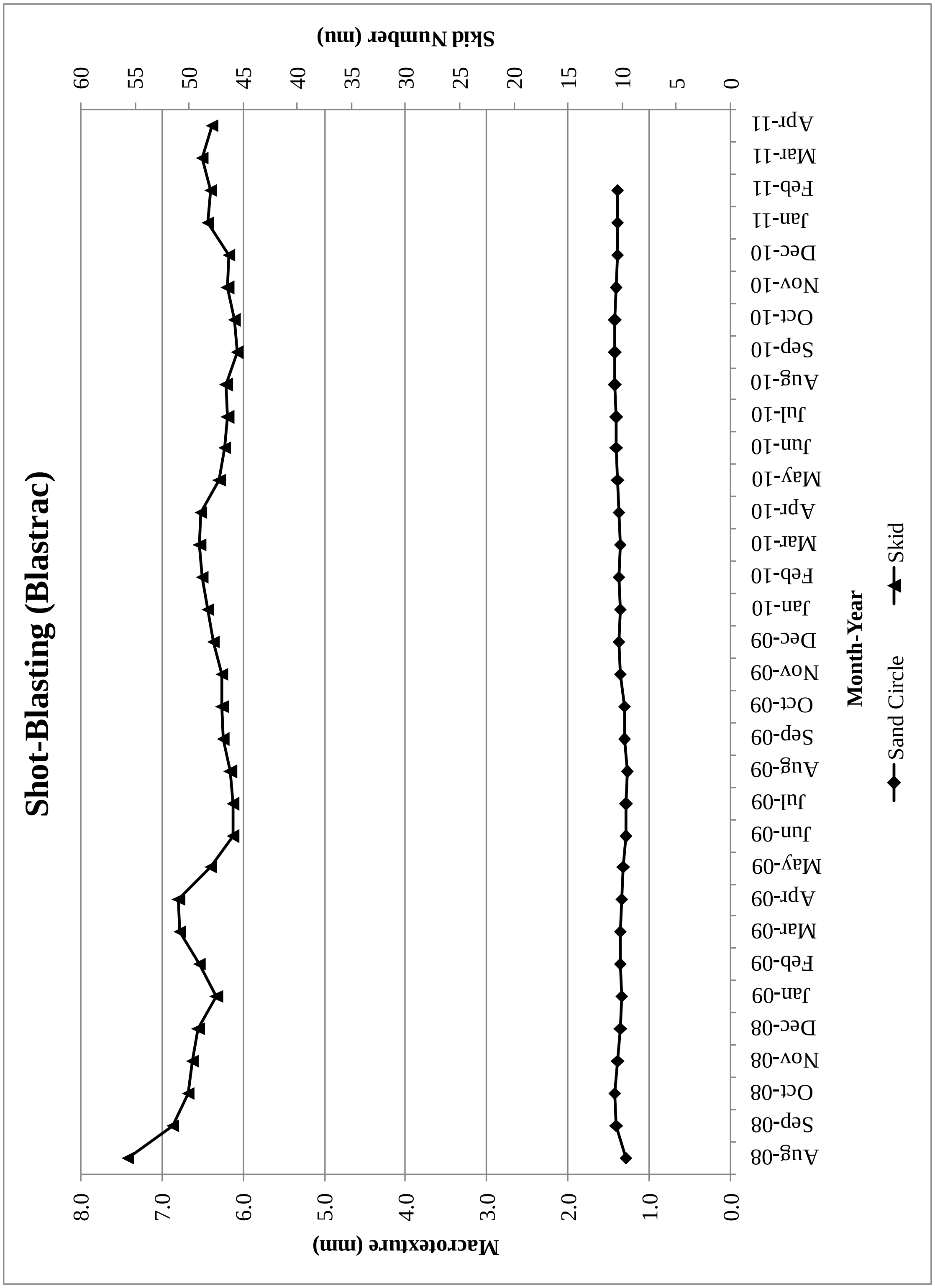

Figure 5.8 Shotblasting (Blastrac) Texture Combination Graph

5.4 Pavement Management System Implementation

This research lays the ground work to begin to associate safety data, the level of both types of texture, with the currently used surface characteristics and traffic data to develop a more holistic view of pavement management. An example of how this process could be implemented can be seen in Figure 5.9. In this scenario, the deterioration models, developed for a chip seal using 5/8″ aggregate, are used to determine trigger points that alert pavement management engineers that the project development process needs to begin in order to implement a pavement preservation project before the pavement fails. Recognizing that every state DOT's project development process is different and will take a different amount of time to go from a trigger point alert to the installation of a pavement preservation treatment. A hypothetical example with 12 months duration is used to illustrate the proposed process for integrating pavement texture into the pavement management process. The first step, of course, is to collect macro and microtexture data for the roads under management and develop the deterioration models as previously described in the paper. Next, failure criteria must be established to allow the computation of a rational trigger point. In this example, the macrotexture failure criterion of 0.9mm used in New Zealand is used (8). The pavement engineer then extrapolate the deterioration curve to the failure value and back up the required 12 months to initiate a project one can determine a macrotexture trigger value of 0.969mm. This is too precise to measure with the available test equipment. So a value of 1.0mm is chosen, which generates an alert 16 months prior to failure, giving the engineer a period greater than required project development and authorization period to initiate action to preserve this pavement. The same approach can be used with microtexture.

The example uses skid number criteria found in the literature to develop a skid number failure criterion. Minnesota, Wisconsin, Maine, and Washington have cutoff or acceptable value limits of 45, 38, 35, and 30, respectively (9). These values are the trigger points used by each DOT, and therefore this example will use 30, the lowest published trigger value and 25 as the failure criterion to illustrate the proposed process. Analyzing the test section used in this example, one can see that a trigger value for microtexture is reached early on in the life of the section, at month 29, yet this gives the pavement management engineer almost 9 years before ultimate failure to act and indicating that this particular treatment will likely fail due to macrotexture loss before it reaches the microtexture failure point. However, a chip seal in a different location that uses a less durable aggregate that is susceptible to polishing would have a deterioration model that predicted failure much earlier. If the failure occurred before the macrotexture trigger value the pavement manager would start the project development process upon reaching the microtexture trigger point. By using safety trigger values in this manner, the pavement management engineer should now be able to better prioritize which roads need to preserved first, and coupled with standard pavement management systems what treatments need to be placed, further ensuring that the “right treatment is placed on the right road at the right time” (4).

Testing apparatus have recently become available to maintain network wide data for both types of safety criteria; for microtexture, the ASTM E274 skid tester with ribbed tires serves as a texture index, and for macrotexture the ASTM E1845 can be used along with a high speed laser to determine mean profile depth at highway speed (77). Therefore, it appears the time-consuming macrotexture test procedure can be replaced with the high speed laser, making data collection both safer and more efficient since it can be collected without the need to establish traffic control. With high speed data collection and the above-described methodology for texture deterioration modeling, a pavement management engineer now has the tools to better incorporate surface texture safety criteria into the PMS system.

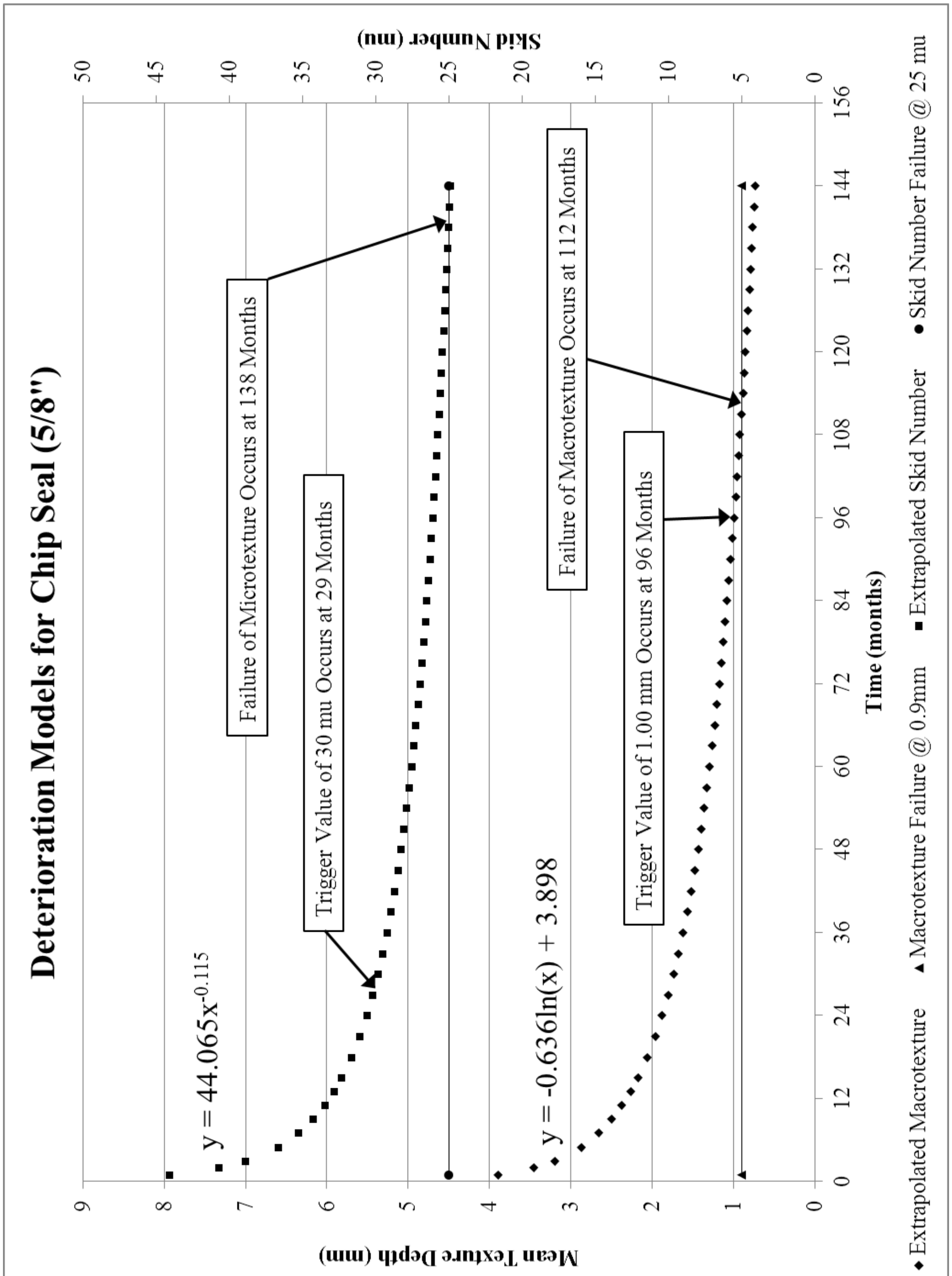

Figure 5.9 Deterioration Models for Chip Seal (5/8″)

5.5 Conclusions

This study has shown that not only can deterioration models be created using the safety criteria of various pavement preservation techniques, but that these models either show reliable deterioration models or can be shown to remain constant over the life of the treatment. Specific conclusions are as follows:

- Treatments with high coefficients of determination as shown in Table 5.1 have deterioration models that can used in determining their estimated service lives as defined by surface texture failure criteria
- Chemical treatments have a slight short term affect on the microtexture of the treatment but could prove a useful ally to other texture methods to be used in combination with these treatments
- Treatments like Shotblasting and Mill and Inlay exhibit constant texture over time and provide increased levels of texture when compared to the texture of the original surface.

6.0 PRESERVATION OF CONCRETE PAVEMENT USING A NANO-LITHIUM DENSIFIER AND SHOTBLASTING: A LIFE CYCLE COST ANALYSIS[5]

Riemer, C., D.M. Pittenger, and D.D. Gransberg, "Preservation of Concrete Pavement Using a Nano-Lithium Densifier and Shotblasting: A Life Cycle Cost Analysis," *2012 Transportation Research Record*, *Journal of the Transportation Research Board* National Academies, (Submitted for publication in August 2011).

6.1 Paper Synopsis

This paper explores the use of nano-lithium based concrete hardener applied over shotblasting as a concrete pavement preservation treatment for locations that are subject to wear due to studded tires, snow chains and snow plowing. Lithium-based concrete hardeners have long been used to preserve industrial concrete floors from wear due to forklift and other traffic in warehouses and parking lots. However, the concern with the treatment's effect on skid resistance has limited their use to slow speed areas only. This study combines field tests in California, Delaware, and Oklahoma and shows that when the concrete pavement surface is first retextured using shotblasting and then treated with the concrete hardener that not only does it reduce wear/rutting due to abrasion but it also maintains safe skid numbers for periods of up to 3 years. A life cycle cost analysis shows this treatment to be a cost effective

[5] A modified version of this paper has been submitted to the 2012 Transportation Research Board for publication in TR News, August 2011.

pavement preservation tool to extend the life of concrete pavements on roads prone to rutting caused by snow chains.

6.2 Literature Review

Pavement preservation involves keeping good roads good (17). There is a large body of literature describing asphalt pavement preservation tools and their benefits (27, 78). Unfortunately much less research has been completed regarding the preservation of concrete pavements and the research has largely been limited to topics crack sealing, joint filling, grinding, etc. (58, 79, 80). Much fundamental research in this area remains to be accomplished (80). This paper reports the results of three geographically separated studies that focused on the use of a concrete surface treatment to harden the surface against abrasion. Two common types of abrasion found in mountain highways are surface wear due to snow plowing and rutting due to snow chains and studded tires. Since these distresses are unavoidable due to the need to allow safe passage of traffic during winter periods, developing a pavement preservation tool to reduce the long-term impact on pavement service life is important for major northern highways.

6.2.1 Concrete Densification

The term “densify” refers to a chemical process where a reaction between a hardening agent and the concrete creates a surface texture that is denser and hence harder than plain concrete. Lithium silicate has proven itself to be a reliable agent to harden the surface of Portland cement concrete (81). It has been used successfully to extend the service lives of concrete floors in industrial setting where low speed vehicular traffic is present. It works by reacting with the calcium hydroxide produced by cement hydration. The reaction produces calcium silicate hydrate. This is the same product that is produced by adding water to Portland cement, which develops the strength and hardness in Portland cement concrete. During hydration, the calcium hydroxide is dissolved in the water; migrates to the surface where the lithium silicate reaction occurs; and the newly formed calcium silicate hydrate is deposits itself in the pores and voids on the concrete’s surface. The lithium part’s function of the silicate is "to stabilize and solubilize the silicate so it can remain in solution until it penetrates the concrete and then can react with the abundant calcium hydroxide found in the concrete" (81).

Lithium silicate has two main advantages over other, less expensive hardening agents. First, when it dries, it forms a dust rather than a crust. Secondly, after the lithium silicate penetrates the concrete's pores, it reacts with calcium hydroxide to create the chemical hardening and densifying, which increases the concrete's surface strength and resistance to wear from abrasion due to wheeled traffic. In the Portland cement concrete pavement (PCCP) scenario, it makes the pavement more rut resistant. It also makes it more resistant to wear from snow plow abrasion. The reaction works best when applied to a porous concrete surface because the porosity promotes penetration of the hardening agent, which in turn results in a deeper hardened surface (81).

The major concern with many concrete surface treatments is the impact of the treatment on skid resistance. For example, the use of curing compounds and sealants on bridge decks often requires the agency to specify shotblasting after the curing is completed to restore surface microtexture that is filled by the treatments themselves in order to perform the intended function (82). Additionally, concrete floor hardeners were originally developed with a secondary purpose of producing a “shiny” surface for aesthetics (81). This reduces surface friction and resulted in their use only in areas with low speed traffic. Therefore, while the preservation of PCCPs by hardening their surface to make them rut and wear resistant certainly makes sense, this quality cannot be achieved while sacrificing safety.

6.3 Methodology

This study combines the results of three research projects that involved the use of the same nano-lithium concrete densifier and shotblasting on highway projects to harden the concrete pavement’s surface and make it resistant to abrasion. The first is a study that looked at lithium penetration in the concrete pavement of Route 113 in Delaware (83). Its purpose was to compare concrete pavement surfaces that had been shotblasted before being treated with the concrete hardener and those that were treated in situ. The second study was sponsored by the California Department of Transportation (Caltrans) and measured concrete pavement wear over 12 months on a test section on in Donner Pass which was subjected to both frequent snow plowing and over which traffic was required to use snow chains or studded tires (84). This project also measured skid numbers on the test sections. Finally, a 3-year pavement preservation study in Oklahoma included a concrete test section that had been shotblasted and treated with nano-lithium concrete densifier as well as shotblasted sections with no treatment. Monthly macrotexture and skid numbers tests were conducted to construct deterioration models for use in estimating pavement preservation treatment service lives (58). While the Oklahoma test sections did not experience abrasion from snow chains, the sections did receive two to three periods where snow was plowed.

The Delaware DOT study sought to determine the efficacy of diamond grinding and shotblasting for enhancing the penetration of the lithium silicate densifier (83). The field test site had 7 different surface conditions .Two sections were designated as “typical” and since they were only treated with the densifier, they formed the baseline against which the shotblasting and diamond grinding were compared. The next two were shotblasted with densifier; another set of two consisted of a shotblasted, diamond ground surface with densifier and the last was an unblasted, but diamond ground surface treated with densifier. The amount of penetration was determined by the percentage of the initial amount of lithium silicate that was present in core samples taken approximately 6 months after the application of the densifier. Figure 6.1 illustrates the results of that study and clearly shows that shotblasting the pavement’s surface before applying the densifier greatly enhances penetration, which should result in a thicker surface layer of hardened concrete.

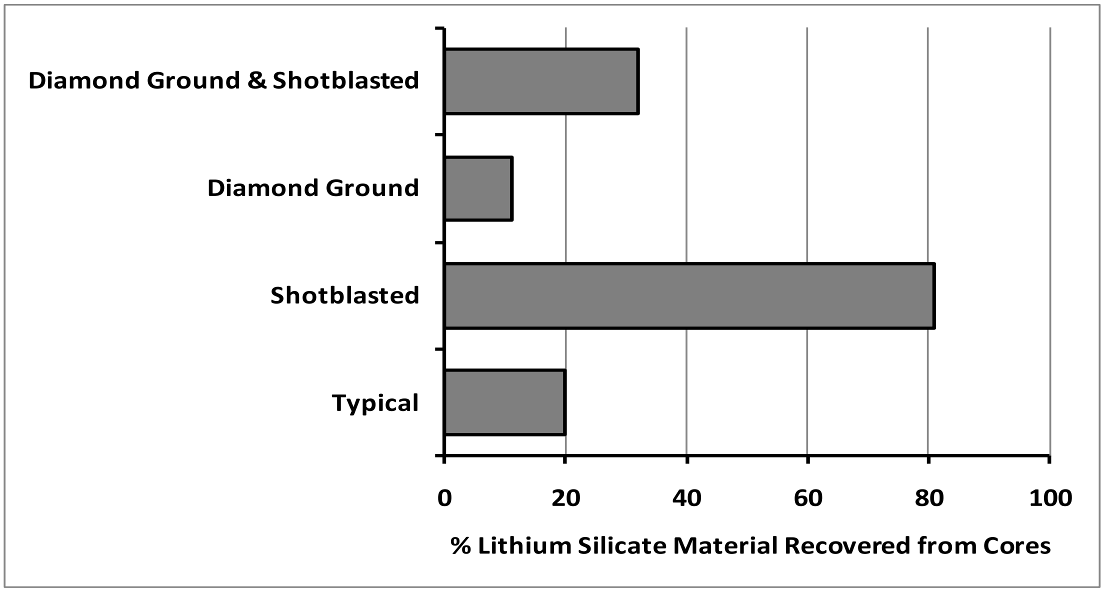

Figure 6.1 Results of Delaware DOT Surface Texture/Densifier Penetration Study (adapted from *(*83*))*.

The Caltrans study built a test site on Interstate 80 on Donner Summit. The site was selected because it "sees some of the worst conditions in the country in terms of deicing salts, chain traffic, and snow removal" (84). The test site was three lanes wide and one mile long and included three different test sections. The first acted as the control and was not shotblasted nor treated with densifier. The second section was only treated with densifier and the last was shotblasted and treated with densifier. Measurements of rut depth were taken before constructing the test sections and after 12 months. Table 1 contains the outcome of the test. The Caltrans research oversight engineer commented that "in general the [lithium silicate densifier] treated areas appeared to have about half the wear of untreated section." Skid numbers were also checked in this experiment and found to be an average of 45 across the three lane test site.

Table 6.1 Results of Caltrans Donner Pass Study on the Effectiveness of Lithium Silicate Densfier on Enhancing Resistance to Abrasion Loss (84)

Core ID	C1	C3	C4	C6	C10	C12	D1	D3	D5	D6	D7	D8
Wear (inches)	3/16	1/4	1/4	1/4	1/8	3/16	1/16	1/8	1/16	1/16+	0	1/16

The final study was sponsored by the Oklahoma DOT and consisted of a total of 23 different pavement preservation treatments installed on US Highway 77 near Oklahoma City (58). Two of the sections are related to this specific topic and consisted of a section of concrete pavement that had been shotblasted and another that had shotblasting and a densifier treatment. This study took monthly measurements of macrotexture and skid numbers for 33 months. One of the study's objectives was to track skid number change over time and directly addresses the potential safety issue of applying a chemical treatment that might reduce skid resistance. Figure 6.2 shows the findings of that study for the test sections that were shotblasted with and without the densifier. One can see that after an initial loss of skid number as the microtexture is initially abraded by traffic, the addition of the densifier surface treatment results in a marginally lower skid number, but one that is above safe limits. Additionally, Figure 6.2 shows that the skid resistance of the shotblasted, densifier-treated section retained its skid resistance for 26 months at a skid number of roughly 44.

To summarize the three studies, it seems that the application of a lithium silicate densifier on a PCCP whose surface has been prepared by shotblasting as a pavement preservation tool is technically viable. The Delaware DOT study showed that shotblasting enhances the penetration of the densifier. This leads to increased resistance to wear and rut due studded tires/snow plow abrasion has shown in the

Caltrans study, and the process can be used on a high speed highway without compromising safety has shown in the Oklahoma study.

6.4 Life Cycle Cost Analysis

The Federal Highway Administration's (FHWA) *Life-Cycle Cost Analysis in Pavement Design —Interim Technical Bulletin* defines life cycle cost analysis (LCCA) for highway projects as: "…an analysis technique … to evaluate the overall long-term economic efficiency between competing alternative investment options" (85). This study uses the FHWA LCCA model complete the LCCA for two alternatives that best describe the potential for concrete pavement preservation using lithium densifier over shotblasting. The following list describes the scenario used in the calculations of net present worth.

- The selected road is a lane mile of Interstate 80 in Donner's Pass, California, which has an average daily traffic of 20,000. Both alternatives begin with an initial cost for completing a 12″ full-depth replacement
- The engineer has the following pavement preservation options with regard to rutting due to snow chain and studded tire wear
- Whitetop the pavement when ruts reach a failure depth of 10 millimeters (86)
- Finish the new pavement by shotblasting it and applying nanolithium densifer (84).

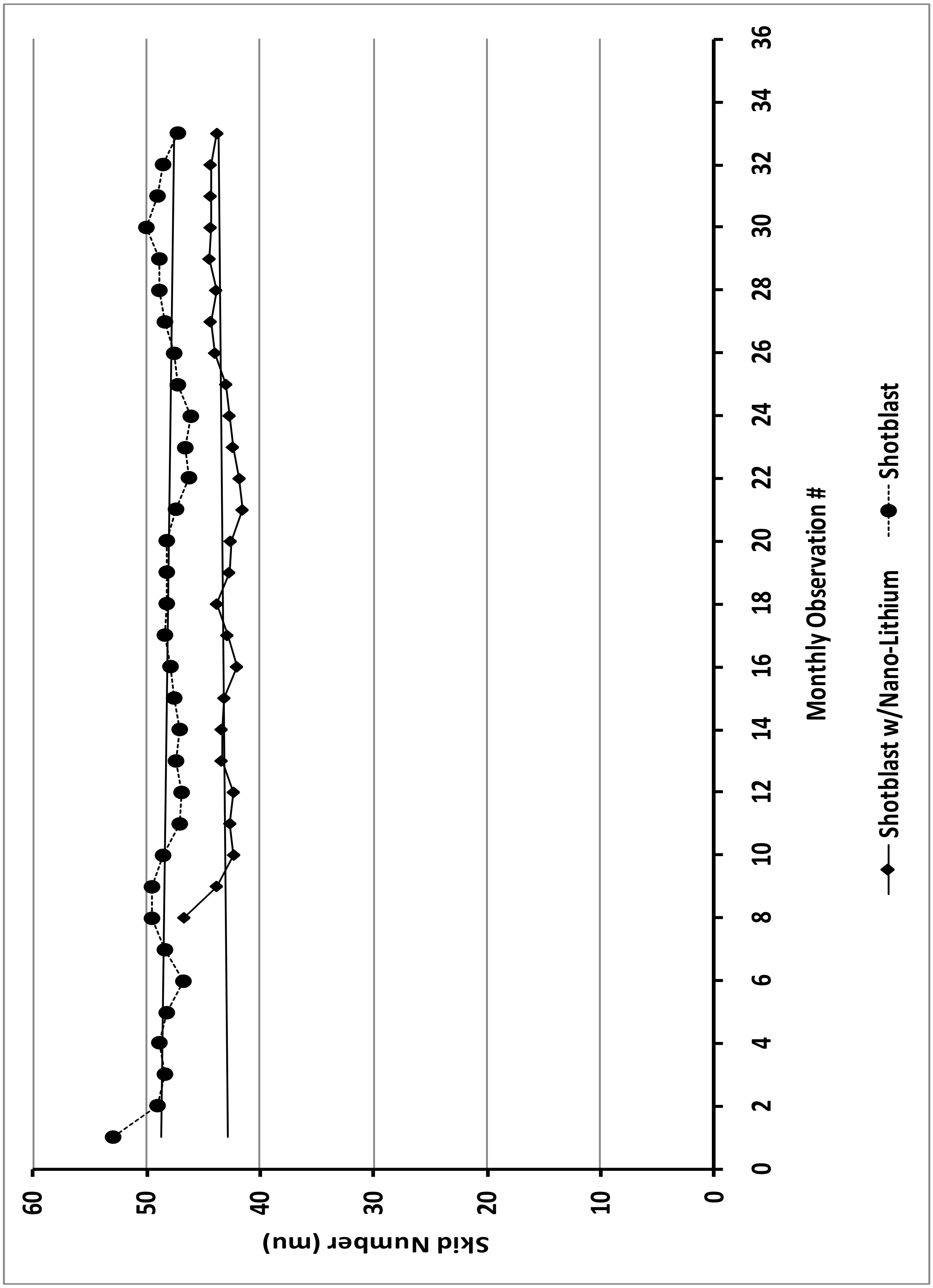

Figure 6.2 Oklahoma DOT Results of Skid Number Change Over Time (58).

Research completed by the Washington State DOT (86) has shown that it takes from 6 to 9 years for a PCCP to develop ruts 10mm deep. The same report shows the predicted service life for a Thin Whitetopping (TWT) of 6.3 to 7.1 years. The Caltrans study found that shotblasting and coating a PCCP with densifier reduced wear by 50%. Based on these and other facts found in the literature, the following assumptions are made to support the calculation:

- The service life of a new PCCP subjected to snow chain/studded tire wear will be 7 years
- The service life of the same new PCCP will be 14 years if densifier over shotblasting is applied before opening it to traffic
- Every 7 years a TWT alone or a TWT finished with densifier over shotblasting (DOS) will be installed as a pavement preservation measure
- All alternatives will be analyzed over a period of 28 years and the patterns for each alternative described above will repeat throughout the period of analysis
- All other maintenance costs associated with the road are equal in all the alternatives
- A discount rate of 3% will be used in accordance with the FHWA technical bulletin (85)
- Work zone user costs during the installation of the TWT and the TWT with DOS are computed using the Florida DOT method for a rural freeway with an ADT of 20,000 (87)

- The Net Present Value (NPV) of the life cycle costs for a single lane-mile of roadway will be calculated.

The FHWA Technical Bulletin LCCA is done two ways (85). First a deterministic life cycle cost analysis is conducted using the minimum, mean, and maximum possible values for each option, providing life cycle costs for each of three possible scenarios. Next, a stochastic version of the FHWA life cycle cost analysis model is run using the possible range in values as a probability density function to associate the probability of achieving a lower life cycle cost for each of the alternatives and to quantify the differences between each using a Monte Carlo simulation.

6.4.1 Deterministic Life Cycle Cost Analysis

Deterministic LCCA uses “minimize estimated life cycle costs” as the decision criterion to compare alternatives. Thus, the economic dynamics of each alternative must be fully understood. Unit prices for each alternative were taken from 2010 bid tabulations from across the nation. The unit prices were then extended to calculate a cost per lane-mile assuming a standard 12-foot (3.7 meter) lane. Table 1 shows the values used for the various cost components to the LCCA model. One can see that the adding the densifier over shotblasting adds to the cost of each treatment. Thus, the LCCA is warranted to determine if the service life extension gained by this method is cost effective.

Table 6.2 shows the results of the deterministic life cycle cost analysis. One can see that while the TWT with densifier over shotblasting has a lower estimated lane-mile cost than the other options at each possible value. This leads to the conclusion that using densifier over shotblasting as a pavement preservation treatment is at very least a competitive alternative to thin whitetopping overlays.

Table 6.1 Life Cycle Cost Analysis Input Values

Alternative	Minimum $/lane-mile	Mean $/lane-mile	Maximum $/lane-mile
12″ Full-depth Replacement	$1,056,000	$1,056,000	$1,056,000
12″ Full-depth Replacement with Densifier over Shotblasting	$1,069,939	$1,079,126	$1,090,214
Thin Whitetopping	$221,769	$400,340	$633,600
Thin Whitetopping with Densifier over Shotblasting	$242,011	$436,106	$643,864

However, the highest possible value of the DOS option is greater than the lowest possible value of the TWT option alone, making it is theoretically possible that prices associated with the TWT could put them at the low end of their possible ranges at the same time that the actual cost of DOS is at the high end of its range. Thus, it is impossible to conclude without further analysis that the DOS option is the preferred alternative.

Table 6.2 Deterministic Life Cycle Cost Analysis Output

Alternative	Minimum $/lane-mile	Mean $/lane-mile	Maximum $/lane-mile
Thin Whitetopping	$1,599,054	$2,607,582	$2,607,582
Thin Whitetopping with Densifier over Shotblasting	$1,335,715	$1,558,056	$1,792,816

6.4.2 Stochastic Life Cycle Cost Analysis

A spreadsheet was developed using the FHWA life cycle cost model and a commercial simulation software package was used to perform the Monte Carlo simulation necessary to conduct the stochastic LCCA. The input variables shown in Table 6.1 were modeled as having stochastic values, and each was assigned a triangular probability distribution using the minimum, maximum and mean values shown in Table 6.1. 100,000 iterations of the simulation were run, and the resulting LCC are shown in Table 6.3. The probability distributions for the two alternatives are shown in Figure 6.3. Taking Table 3 and Figure 6.3 together, one can see that there is only about a 7% the minimum probable value for the TWT option’s LCC will be less than the maximum probable value of the DOS option’s LCC.

Table 6.3 Deterministic Life Cycle Cost Analysis Output

Alternative	Minimum $/lane-mile	Mean $/lane-mile	Maximum $/lane-mile
Thin Whitetopping	$1,599,054	$2,607,582	$2,607,582
Thin Whitetopping with Densifier over Shotblasting	$1,343,194	$1,563,690	$1,790,942

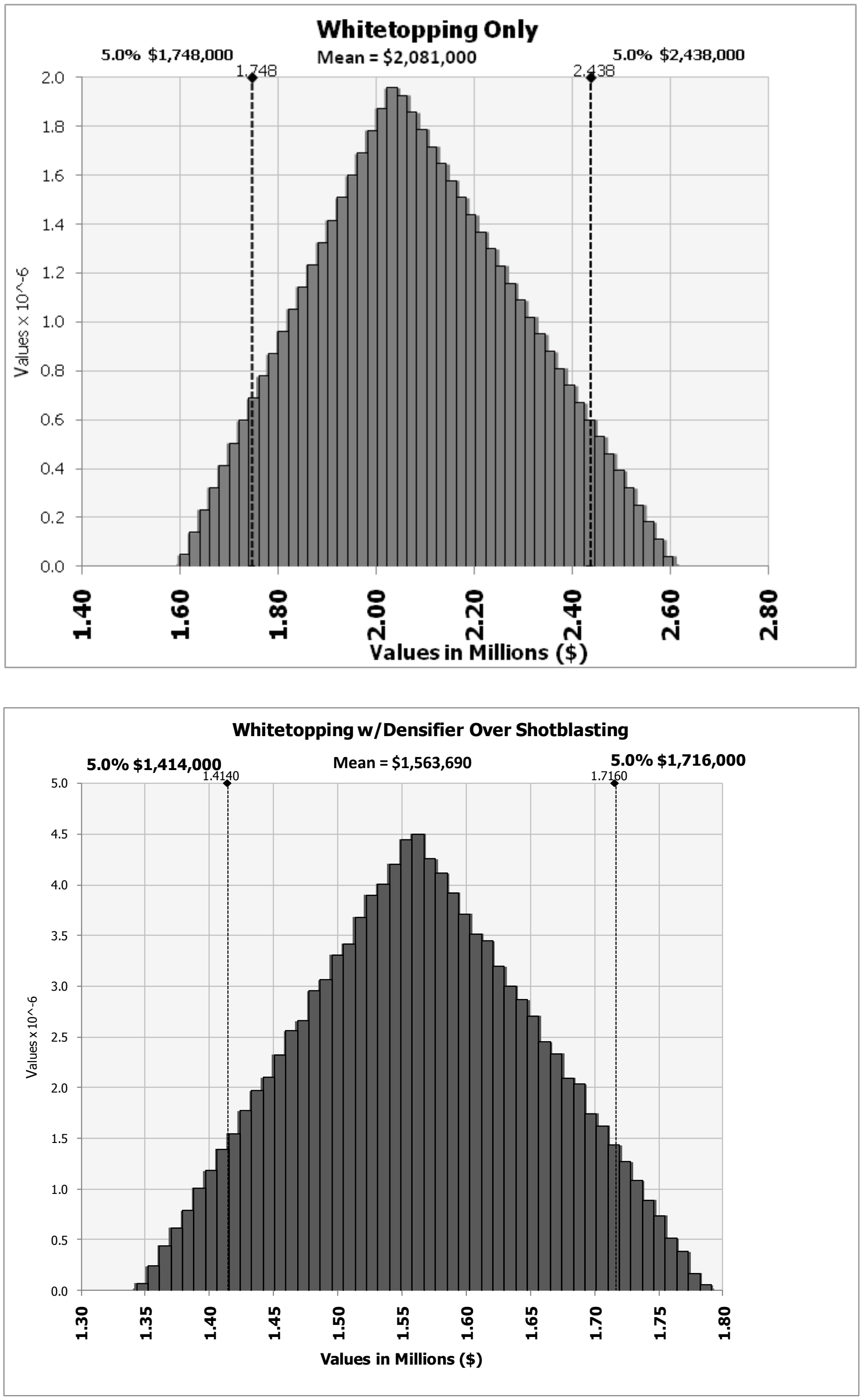

Figure 6.3 Probability Density Functions for the LCCA Comparison of Two Alternatives

6.5 Conclusions

This study has shown that the use of nanolithium densifier over shotblasting to extend the life of concrete pavements by making them more wear resistant is both technical and financially viable. Specific conclusions are as follows:

- Shotblasting the surface of a PCCP creates a condition where the nanolithium densifier is able to penetrate deeper, making the depth of the hardened surface greater and enhancing the wear-resistance of the pavement.
- Treating a new concrete surface such as a new pavement or a thin whitetopping overlay by with nanolithium densifer applied over shotblasting can be done without compromising the skid resistance of the pavement. The Oklahoma study shows that the surface maintains its skid numbers for at least 33 months.
- Treating a new concrete surface such as a new pavement or a thin whitetopping overlay by with nanolithium densifer applied over shotblasting is more cost effective than merely whitetopping due to the increased service life extension.

7.0 CONCLUSIONS AND RECOMMENDATIONS

This study focuses on the importance of pavement preservation as a tool to manage infrastructure at a time in our nation's history where appropriate stewardship of governmental resources is critical and can be applied at all levels of government.

7.1 Conclusions

This research demonstrated the cooperation that can take place within the industry and state agency for the betterment of travelling public. This is evident in the amount of support received from both parties to do this research. In this project the researchers were able to establish like comparisons for 23 different pavement preservation treatments. This comparison included both, microtexture and macrotexture measurements. Along the way a number of discoveries were made that can be attributed original contributions to the field of study within pavement preservation. These include the following:

- This research produced a clear guideline as to testing procedures for measuring macrotexture using two different testing apparatuses, as discussed in Chapter 3. The value of the research is validated by the fact that in response to the limitations chronicled in this project's journal paper, the production company for the outflow meter altered the design of new flowmeters to include a more accurate timer.
- This research produced a previously unpublished EUAC-based model for LCCA that specifically addresses the nature of pavement preservation

treatments and develops LCCA-based pavement preservation treatment design. The model's fixed flexibility offered via continuous and terminal scenario allow it to adhere to engineering economic principles and provide the pavement manager project-level evaluation within a wider spectrum of pavement manager expertise.

- This research demonstrated how deterioration models could be utilized by a pavement manager in selecting the most cost effective pavement preservation treatment on a case by case basis. It also provides a rational method to determining the timing of treatment application by using the deterioration model for each treatment to identify trigger points.
- This research validated the use of these procedures by applying the deterioration models to each Phase 1 test section and determining viable candidates for deterioration models using the chosen failure criteria.
- Lastly, this research combined external data with data produced by this project to analyze the effects of densifiers on the life cycle of concrete pavements exposed to abrasion from studded tires and snow chains.

7.2 Limitations

The objective of the research is to focus on the change in microtexture and macrotexture measurements over time and develop rational deterioration models for a suite of pavement preservation treatments. All treatments were applied to the same highway (SH77) and as a result, experienced the same traffic loads, the same environmental conditions, and the same frequency of testing. Hence, the major limitation of the research is that the deterioration models developed in this project can only be applied to the local region, Oklahoma City, Oklahoma, in which the testing was conducted. Researchers and maintenance engineers from other parts of the nation can replicate this project's methodology but must collect their own data and develop pavement preservation treatment models that are appropriate for the materials and conditions in the region in which the testing is conducted.

The second limitation deals with the skid testing procedures. The initial experimental plan depended on the locked wheel skid test using a ribbed tire skid testing. Consultation with Dr. Tom Yeager, a NASA scientist and author of much of the seminal research on pavement surface friction, indicated that a bald tire might furnish a more consistent measurement of microtexture. As a result, the research team purchased bald tires for the ODOT skid test trailer and began collecting both data using both methods. Because the bald tire was not used during the first year of the research, no conclusions can be drawn by comparing the two methods. This leads to the final limitation which is the time period over which the research was conducted. Even though this research has been active over a 3.5 year period, a number of the preservation treatments have not yet begun to fail. This forced the researchers to utilize failure criteria found in the literature to develop proposed trigger points for treatments that had not reached the end of their service lives. Therefore, testing needs to continue beyond the time allotted in the scope of the funded research project to follow each treatment to failure and furnish ODOT with validated deterioration models for every pavement preservation treatment in the project.

7.3 Recommendations for Future Research

The following are recommendations for future research based on to the findings of this research project. These include the following:

- Continue testing each test section for both microtexture and macrotexture to the point of failure. This will validate the deterioration models as well as help determine the actual service life of each test section as it relates to the metrics chosen in this project.
- Expansion of the research data to include a set of national test sections would allow this research to cover various climatic and traffic conditions. This would further make this a national research project rather than just a regional project. The AASHTO pooled fund model would be an ideal mechanism to fund this research.
- Create and analyze a comparison of the ribbed tire with the smooth tire skid measurements on each treatment in order to better define testing protocols as they relate to microtexture and macrotexture.
- Develop a protocol for the routine measurement of macrotexture on those treatments found in this project to have macrotexture as the critical failure criterion.
- Investigate the pavement noise of each treatment and compare it to each treatment's deterioration model.

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