Cost Benefit Analysis of Including Microsurfacing in Pavement Treatment Strategies & Cycle Maintenance

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16. Abstract

Preservation of the Pennsylvania state highway system has become more difficult with the development of funding shortages and placement of major emphasis on the bridge program. Therefore, it is appropriate to revisit the topic of timely, cost effective application of thin surface maintenance treatments to extend the life of existing pavements in the state highway system. While the benefit of previous approaches to maintaining pavements provides valuable experience, there are also available innovations for which experience is limited, or does not exist in Pennsylvania. This project was developed to address the need to re-evaluate thin surface treatments, review available new technologies with the objective of recommending potentially beneficial systems, and assess the cost effectiveness of these treatments for conditions in Pennsylvania.

For this study, thin surface treatments, i.e., "microsurfacing," has been defined as any treatment less than ¾-1" thick which can be applied to the surface of an existing pavement with the objective of improving the performance of the pavement and ultimately extending pavement life. Three distinct tasks were identified to achieve this objective; a review of existing related literature, a survey of experiences in other states with similar conditions, and a cost benefit analysis of the treatments identified. These tasks were conducted during the project study, with a summary report provided to PennDOT describing the findings from each. The details of these task results are subsequently presented in this report.

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I.0 INTRODUCTION

Preservation of the Pennsylvania state highway system has become more difficult with the development of funding shortages and placement of major emphasis on the bridge program. Therefore, it is appropriate to revisit the topic of timely, cost effective application of thin surface maintenance treatments to extend the life of existing pavements in the state highway system. While the benefit of previous approaches to maintaining pavements provides valuable experience, there are also available innovations for which experience is limited, or does not exist in Pennsylvania. This project was developed to address the need to re-evaluate thin surface treatments, review available new technologies with the objective of recommending potentially beneficial systems, and assessing the cost effectiveness of these treatments for conditions in Pennsylvania.

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II.0 LITERATURE REVIEW

II.1 Introduction

Determining the most cost-effective surface treatment strategy for a given project requires a thorough understanding of the benefits, limitations, performance, and associated costs of each viable treatment strategy. In this section, a thorough literature review of various microsurfacing treatments identified by PennDOT and other resources will be conducted. To be considered, treatments must not be thicker than 0.75 to 1.00 inch. The purpose of this literature review is to provide an overview of each microsurfacing treatment and identify proven information that could be valuable in the consideration of future life cycle cost-benefit analysis.

II.2 Treatment Types

According to the PennDOT Pavement Policy Manual, Publication 242, Appendix G, the allowable maintenance treatments on asphalt surfaced pavements on Federal Aid roadways are:

- Thin overlays
- Milling & Overlay
- Micro-surfacing or paver-laid seal/leveling course

Other surface treatments currently being used or investigated by PennDOT on non-Federal Aid roads consist of:

- Chip Seal
- Sand Seal
- Fog Seal
- Slurry Seal
- Cape Seal

Each of the above listed treatments will be investigated as well as some more recently developed surface treatments such as NovaChip® and E-Krete™ will be also included in this section.

II.2.1 Thin HMA Overlay

<u>Description and Purpose</u>

The thin HMA overlay treatment refers to the blend of plant-mixed asphalt binder and aggregate applied to the existing pavement as an overlay with thicknesses of 0.75 to 1.00 inch, or less. Based on the difference in the aggregate gradation, three different types of thin HMA overlays may be used[1]:

- Dense-graded overlays, consisting of a blend of asphalt cement and a well-graded (also called dense-graded) aggregate. A well-graded aggregate is uniformly distributed throughout the full range of sieve sizes.

- Open-graded friction courses (OGFC), consisting of a blend of asphalt cement and open-graded (also called uniformly graded) aggregate. An open-graded aggregate consists of particles of predominantly a single size.

- Stone matrix asphalt (SMA) overlays, consisting of a blend of asphalt, stabilizer material, and gap-graded aggregate. A gap-graded aggregate is similar to an open-graded material but is not quite as open. Significant coarse size fractions are present, as are the fine aggregate sizes, but there is a "gap" in the medium aggregate sizes.

The thin HMA Overlay is mainly used to correct surface irregularities that can not be adequately addressed by other maintenance surface treatments.[2] It helps to restore/ improve pavement ride quality and increase pavement surface friction. However, it can not be used to correct pavement distresses associated with structure failure for more than a very limited time.

A thin HMA Overlay can be placed with or without milling of the existing pavement. Studies by Hein and Croteau recommended milling the surface when segregation, raveling, or block cracking are present.[3] Milling also provides additional asphalt for recycling operations, maintains clearance at overhead structures, and provides high skid resistance for traffic before the overlay placement. If rutting is evident, the pavement can also receive a leveling course instead of milling.[4]

Advantages and Disadvantages

Some previous studies have summarized the advantages and disadvantages of using a thin overlay.[4,5, and 6] The advantages of using thin HMA overlays include: 1) thin overlays work well in all climate conditions; 2) provide effective treatment for almost all pavement conditions; 3) slightly enhance structure capacity; and 4) relatively long service life compared to other thin surface treatments.

The biggest disadvantage of using thin HMA overlays is the relative expense compared to other surface treatments. In addition, problems of surface debonding and reflective cracking are associated with this treatment, if it is not properly constructed.

States' Practices

In the past, most highway agencies used dense-graded thin HMA overlays as a common surface treatment. This has changed somewhat with the advent of Superpave. The Virginia Department of Transportation (VDOT) adopted a specialty mixture which they call thin hot mix asphalt overlay (THMACO). THMACO is a fine to medium (3/8 inch nominal maximum aggregate size) surface mix generally placed at 3/4 inch thickness. THMACO is a gap graded hot mix asphalt applied atop a polymer-modified emulsion membrane, known as Novabond®. Novabond® is mainly used to seal the existing roadway and provide a strong bond with the THMACO. THMACO is primarily for use in pavement preservation. The thin application of THMACO is placed as a SM-9.0 which is a fine to medium (3/8 inch nominal maximum aggregate size) surface mix generally placed at 1 inch thickness. It is generally used as a final riding surface in subdivisions and low volume pavements with little or no heavy vehicle traffic, including buses or trucks. It is generally placed on a minimum of 2 inch intermediate or base mix, and should never be placed directly on aggregate base material. Some guidelines about this material can be found in the VDOT special provision for THMACO (Appendix A).

The documented performance of thin HMA overlays, however, varies due to factors such as existing pavement condition, mix design methods, overlay construction quality, and climatic effects. Some highway agencies reported as little as 2 to 4 years of performance, while other agencies report as much as 9 to 10 years.[7] A similar conclusion was reached by Geoffroy, who did a survey which included the United States, District of Columbia, Puerto Rico, Canada, and 37 local agencies.[8] Labi and Sinha also conducted a survey in highway agency districts and sub-districts in Indiana and returned with a relatively high pavement extension life of 10-15 years.[9] Jahren *et al.* conducted field test sections to compare the performance of thin overlay, single and double chip seal, cape seal, slurry seal, microsurfacing and untreated sections for the Iowa Department of Transportation, and concluded that the thin overlay was the top performer with respect to surface condition index (SCI) and roughness index (RI) values.[10] In addition, Florida reports open graded friction courses (OGFC) service lives of 10-12 years on its interstate pavements and Oregon has found that OGFC are performing better than dense-graded HMA after up to 8 years of service and 2.5 million ESAL applications.[11] Overall, Cuelho estimated the average service life of the thin overlay treatment could be over 8 years.[4]

Cost

Costs for thin HMA overlays often vary, depending on thickness, aggregate properties, and whether the surface was milled. Typical costs are $14,600 per lane mile or $2.07/yd^2 based on the value of the US dollar several years ago.[6,4]

II.2.2 Microsurfacing

Description and Purpose

Microsurfacing has primarily been used as a term for a technologically improved version of the slurry seal treatment. The usual improvements include the use of a modified binder and set control agents which effectively reduce the required cure time and, thus, the opening to traffic time. The use of modified binders has resulted in better performance, particularly in freezing climates than achieved from slurry seals. Similar to a slurry seal, microsurfacing is placed as a thin lift of blended aggregate and emulsion which is typically a single aggregate thick. The application process and equipment are similar to those used for slurry seals. It is placed by the slurry/microsurfacing machine, and finished with a drag to produce the final surface. It is useful for sealing a pavement surface, and typically provides quality friction characteristics. Ralumac, as discussed later, was the earliest version of microsurfacing used in the United States. The process required very hard aggregate and the emulsion was modified using natural rubber.

Microsurfacing was first developed in Europe in the mid 1970s and then introduced in the United States in the early 1980s. It uses a polymer modified emulsion mixed with mineral aggregate, mineral filler (cement, lime, limestone dust, and fly ash), water, and additives. Microsurfacing is primarily used as a surface seal to address rutting and loss of friction. It also limits damage from water, oxidation, and ultraviolet rays (UV).[4] However, it can not overcome pavement distresses associated with structural failure. Therefore, pavements with fatigue cracking and/or significant linear cracking are not candidates for microsurfacing.[1]

Advantages and Disadvantages

Advantages of microsurfacing include: 1) quick opening to traffic[12]; 2) easily corrects wheel ruts and minor leveling problems; 3) works well for both high and low volume roads with minimum susceptibility to snowplow damage.[13]

The biggest disadvantage of microsurfacing is that it requires special equipment for application, which makes it more expensive than a slurry or chip seal treatment. In addition, its success is largely dependent on having an experienced contractor and the proper mix of ingredients.[14]

States' Practices

Since microsurfacing was first introduced in the United States in 1980 in Kansas, this treatment has been used by many other states and local agencies to address certain pavement conditions on their moderate to heavy volume roads. Major user states are Kansas, Ohio, Oklahoma, Pennsylvania, Tennessee, Texas, and Virginia. Microsurfacing has also been applied on several kilometers of heavily travelled turnpikes in New Jersey and Pennsylvania and other freeways in various other states.[15,16]

PennDOT conducted a series of studies regarding the use and performance of microsurfacing in the 1980s. The process used at that time was called Ralumac. The following conclusions regarding Ralumac are identified as follows:[17]

- Ralumac provides a rapid method of rut repair, and it provides a good wearing surface. Generally, roads can be opened to traffic within a few hours after its application.
- Compared to ID-2 and other wearing surfaces, Ralumac provides a significant (30% to 50%) cost saving, for comparable areas of road surfaces.
- Ralumac can be used in a variety of traffic and site conditions, and it can perform well on interstates and other major highways, under heavy traffic conditions.
- Ralumac surface provides an acceptable (SN-40 greater than 31) skid resistance, which generally improves in the first two years of its application.
- Ralumac can be placed consistently within specification limits with proper attention to details.
- Ralumac requires the services of experienced, specialty contractors and needs close construction control for both materials and construction practices. Construction should

be carefully planned to control traffic and temperature and should not be applied when rain is forecasted.

- Ralumac provides quick and economical improvements to pavement surfaces, but it must only be used on structurally sound pavements.

Performance

The performance of microsurfacing depends on many factors, including climatic conditions, traffic volumes, existing pavement condition, material quality, mixture design, and construction quality. Cuelho *et al.* summarized microsurfacing treatment life as reported by various studies in table 1, which indicated that a typical life of 4 to 7 years can be expected.[4] Wade *et al.* investigated the effect of microsurfacing as a surface treatment in correcting rutting and loss of friction in several states and those results are summarized in table 2.[1]

Table 1. Microsurfacing treatment life as reported by various sources[4]

Reference	Treatment Life (years)	Notes
Geoffroy, 1996	4 to 6	according to NCHRP
Geoffroy, 1996	5 to 7	according to FHWA
Johnson, 2000	7	for high volume roads
Johnson, 2000	>7	for low volume roads
Labi et al., 2006	5	based on roughness
Labi et al., 2006	7	based on pavement condition rating
Labi et al., 2006	24	based on rutting
Peshkin et al., 2004	4 to 7	from review of literature
Smith & Beatty, 1999	7 to 10	suggested expected life
Wade et al., 2001	4 to 7	generally reported range

Table 2. Effects of microsurfacing in various states[1]

State	Problem	Result
Kansas	0.6 inch ruts	Ruts returned in 5 years
Arkansas	Rutting	Ruts returned in 4 years
Pennsylvania	Rutting<0.8 inch	Returned to 0.1 inches in 3 years
Pennsylvania	Rutting 0.8-1.0 inches	Returned 0.24-0.51 inches in 3 years
Pennsylvania	Rutting 0.8-1.0 inches	Returned 0.63 inches in 5 years
Pennsylvania	Friction	Fn 40-50 in 5.5 years

Cost

Costs for microsurfacing are dependant upon several factors, including the availability of material and contractors. Table 3 summarizes costs for different states as reported by previous studies. The costs range from a low of $1,000 to a high of $34,100 per lane mile($0.14/yd^2 to $4.84/yd^2). Neglecting the effect of the time value of money, the average costs of microsurfacing, using the data contained in table 3, is approximately $12,600 per lane mile ($1.79/yd^2).[4]

II.2.3 Chip Seal

Description and Purpose

The chip seal treatment, sometimes referred to as a seal coat, is an application of asphalt (generally an asphalt emulsion) directly on the existing pavement followed by an aggregate cover, which is then seated into the asphalt by rolling. Chip seals can be single or multiple layers. Multiple layer chip seals are constructed by placing two or more applications of a chip seal operation over the same pavement; each subsequent layer being placed after the previous layer has cured.[1] Generally, the bottom layer has a higher asphalt application rate and a nominal aggregate size approximately twice that of the upper layer.

Chip seal is often used to correct pavement distresses associated with aging, raveling, bleeding, minor cracking, and polishing. It is used most often on low volume roads. Double chip seals have some performance advantages including that they generate less tire-pavement noise than single seals. They also provide additional waterproofing protection to the pavement, and are more robust. Consequently, they are used in high traffic stress situations such as high truck traffic locations or on steep grades.[18]

Table 3. Microsurfacing costs per lane mile as reported by various sources[4]

Cost per Lane Mile (12-ft width), $	Location	Year Data Taken	Reference
6,700 – 13,100	None specified	1999	Bolander, 2005
1,000 – 1,500	AR	1995	Geoffroy, 1996
5,000 – 7,000	TN, SUT(1)	1995	Geoffroy, 1996
7,000 – 10,000	MI, MS, MO, NC, OH	1995	Geoffroy, 1996
10,000 – 15,000	ID, TX, WI, IN	1995	Geoffroy, 1996
15,000 – 25,000	KS, VA, ON(2)	1995	Geoffroy 1996
9,100	IA	1996	Jahren & Bergeson, 1999
10,400	IA	1997	Jahren & Bergeson, 1999
10,600 – 14,100	None specified	1999	Johnson, 2000
21,600	IN	1995	Labi et al., 2006
26,800	IN	2006	Labi et al., 2006
12,000 – 34,100	LA	1995-1996	Temple et al., 2002
20,600	LA (average)	1995-1996	Temple et al., 2002
8,800	None specified	2000	Wade et al., 2001
8,800 – 14,100	OH	1997	Wade et al., 2001
6,000 – 14,200	OK	1983-1991	Wade et al., 2001

Notes: (1)Salt Lake County, Utah; (2)Ontario, Canada

The National Center for Pavement Preservation recommends the application of a fog seal to a chip seal surface within one to three days after placement of the chip seal. This application is relatively inexpensive, and helps to fill voids, lock any marginal aggregate in place, and provide a better surface for line paint adhesion. The Center recommends the use of a single size, cubical aggregate for chip seals. This results in a greater quantity of pavement treated per ton of aggregate, with better uniform coverage.

Advantages and Disadvantages

The advantages of using chip seals include: 1) relatively low cost; 2) the technology is well understood; and 3) quick open to the traffic.

Disadvantages include: 1) require constant attention and frequent adjustment of application rates of aggregate and asphalt binder[19]; 2) susceptible to snowplow damage[13]; and 3) loose chips can cause damage to vehicles, especially windshields.[20]

State Practices

The chip seal treatment is widely used throughout the world. According to a study conducted by Cuelho *et al.*, Australia and the United Kingdom reported using chip seals on about 273,000 and 213,000 lane miles, respectively – well above the 140,000 lane miles reported by the United States.[4] The United Kingdom commonly chip seals roads that have an ADT greater than 20,000, whereas only a few states (California, Colorado, and Montana) routinely chip seal such roads. Ohio limits chip sealing to low volume roads (less than 2,500 ADT) with rutting less than 1/8 inch.[21] However, some agencies reported using polymer-modified emulsions in the design of chip seals, particularly on high-volume roadways.[22] The polymer modification reduces temperature susceptibility, provides increased adhesion to the existing surface, and allows the road to be opened to traffic earlier.[22] Some states such as Texas and California use rubber modified asphalt chip seals to obtain similar performance benefits. While these states typically use a liquid rubber modification process, the use of crumb rubber with chip seal binders can mitigate reflective cracking, improve aggregate retention, and reduce tire-pavement noise.

Some agencies, such as Texas, Arizona, and Georgia also use hot asphalt in chip seals rather than emulsions. When hot asphalt is used as a chip seal binder it is possible to open the road to traffic sooner than when an emulsion is used. Typical asphalts used for hot applied chip seals include AC 10, AC 20, AC 15-P, and AC 15-5TR. However, the use of hot asphalt is sensitive to aggregate moisture, requires more rolling energy, and involves high application temperatures which are a safety concern.[18]

The performance of chip seals has been reported by several researchers. New York reports that chip seals with an asphalt emulsion have been observed to last 3 to 4 years.[9] Washington State reports that chip seals with a polymer-modified material have been observed to last 5 to 7 years under heavy traffic.[8] Texas reports an average life of 6 to 7 years.[7] Overall, an average performance life of 4 to 7 years can be expected.

Chip seal was also evaluated under LTPP Special Pavement Studies (SPS) program by Morian *et al.* and results indicated that the chip seal treatment in the no-freeze climate gave the best performance.[23] In addition, chip seals provided the most benefit across all climate regions and all pavement types. Outcalt conducted a chip seal study in Colorado and concluded that chip seals do "extend the life of the pavement by postponing environmentally induced cracking," and that lightweight chips offer the advantages of lower transportation costs and reduced windshield damage compared to the standard chips.[24] Jahren *et al.* carried out a study of chip seals in Iowa and found that chip seals performed better than the other treatments when used on pavements having a greater occurrence of cracking.[10]

Cost

Cuelho *et al.* summarized the cost for single and double chip seals based on various literature sources.[4] The results are given in tables 4 and 5, respectively.

Table 4. Single chip seal costs per lane mile[4]

Cost per Lane Mile (12-ft width), $	Location	Year Data Taken	Reference
8,400 – 10,600	None specified	1999	Bolander, 2005
5,500 – 7,500	OH	1997	Hicks et al., 2000
3,900	None specified	1999	Johnson, 2000
5,600 – 8,800	None specified	2004	Maher et al., 2005
7,000 – 12,300	OH	1999	Ohio DOT, 2001
8,000	SD	2000	Wade et al., 2001

Table 5. Double chip seal costs per lane mile[4]

Cost per Lane Mile (12-ft width), $	Location	Year Data Taken	Reference
13,000 – 17,600	None specified	1999	Bolander, 2005
8,500 – 12,000	OH	1997	Hicks et al., 2000
10,600	None specified	1999	Johnson, 2000
8,800 – 17,600	None specified	2004	Maher et al., 2005

II.2.4 Sand Seal

Description and Purpose

Sand seal is an application of asphalt emulsion followed by a covering of clean sand or fine aggregate. A pneumatic tired roller is often used after applying the sand and the excess sand is removed from the road surface after rolling.[19] It is mainly used to seal the pavement surface, rejuvenate oxidized HMA, provide delineation, and improve friction.

Advantages and Disadvantages

The advantage of a sand seal is that it generally provides a thicker coating on the pavement surface than the fog seal, which results in a longer life expectancy. It can also provide additional skid resistance when applied to a polished aggregate surface.

The disadvantage of the sand seal treatment is that it can only effectively fill fine cracks, while larger cracks tend to reappear within a year.[19]

Cost and Performance

The average cost of the sand seal treatment is about $4,900 per lane mile ($0.70/yd^2) .[19] An overall average performance life of 3 to 4 years can be expected.

II.2.5 Fog Seal

Description and Purpose

A fog seal is an application of diluted asphalt emulsion directly sprayed onto a pavement surface without an aggregate cover. A fog seal can be used to address pavement distresses associated with raveling, oxidation, and low-severity fatigue cracking. It can also be used on shoulders to provide delineation between the mainline pavement and shoulder.[7]

Advantages and Disadvantages

The biggest advantage of using the fog seal treatment is that it is inexpensive when compared with other surface treatment. In most cases, only a distributor truck is needed to apply the fog seal. A fog seal can also reduce aggregate loss when applied over a chip seal.[1]

The disadvantages of fog seals include short life and reduction in surface friction following application. It was reported that several accidents occurred as a result of the application of a fog seal on a section of I-90 in Erie County in the mid-1980s, so although it was technically a valid treatment selection, PennDOT subsequently severely limited the use of fog seals where the application might result in accident problems. This is less an issue in arid climates, as the fog seal emulsion breaks faster under these conditions. Also, the National Center for Pavement Preservation recommends that fog seal applications be preceded by surface preparation using a skid abrader to address portions of the pavement with bleeding. The Center reports this combined strategy can cost less than $1.00/SY, including appropriate traffic control. They recommend that fog seal be applied before cracks appear, once the new asphalt surface is gone and water will no longer bead on the surface. It is effective in treating surface oxidation and preventing top down cracking.

Cost and Performance

Estimated costs of the fog seal treatment are summarized in table 6 by Cuelho *et al.* based on several different literature resources.[4] As observed from the table, the cost ranges from less than \$1000 per lane mile (\$0.14/yd^2) to as much as \$3500 per lane mile (\$0.50/yd^2). The expected life of a fog seal is generally 1 to 3 years.

Table 6. Fog seal cost per lane mile[4]

Cost per Lane Mile (12-ft width), \$	Location	Year Data Taken	Reference
1,000 – 3,200	None specified	1999	Bolander, 2005
3,200	None specified	2000	Hicks et al., 2000
1,400 – 1,700	OH	1997	Hicks et al., 2000
700 – 1,400	None specified	1999	Johnson, 2000
1,400 – 3,500	None specified	2004	Maher et al., 2005
2,100 – 3,200	None specified	2001	Peshkin et al., 2004
3,200	None specified	2000	Wade et al., 2001

II.2.6 Slurry Seal

<u>Description and Purpose</u>

A slurry seal is a mixture of slow-setting asphalt emulsion, fine aggregate, mineral filler, additive, and water. There are three common sizes of slurry mixtures: Type I, Type II, and Type III, each with successively larger aggregate size. Generally, Type I slurry seal is used in parking lots while Type II and Type III seal are used on streets and higher traffic roads.[19]

Slurry seals are used to correct raveling and loss of surface matrix, and to improve surface.[25] They should not be used on highly deteriorated pavements. Slurry seals are appropriate when the primary deterioration is related to excessive oxidation and hardening of the existing asphalt .[7] It should be noted that slurry seals should not be used where sealing the pavement will cause a stripping problem or where the underlying pavement is cracked.[1]

<u>Advantages and Disadvantages</u>

The advantages of using slurry seal include: 1) minimize oxidation/aging; 2) fill small surface defects; 3) reduce water infiltration; 4) improve skid resistance; and 5) correct raveling and weathering.

One of the main disadvantages of slurry seals is that the emulsion requires a relatively long curing time, resulting in potential traffic delays.[6] This is more of an issue in the wet-freeze climate than in warmer and drier ones.

Cost and Performance

The performance lives of slurry seals are generally reported to be in the range of 3 to 5 years on roads with moderate to heavy traffic.[7] Specific findings from the 5-year evaluation of slurry seals under the LTPP SPS-3 study include the following:[23]

- Slurry seals are effective in reducing the development of pavement cracking and raveling.
- Slurry seals perform better in warmer climates.
- Slurry seals perform best when applied to pavements in relatively good condition (before extensive cracking developed).
- Slurry seals are marginally effective in preventing reflection cracking. Reflective cracking returns within 1 year under most conditions.

Estimated costs for slurry seal are summarized in table 7 based on different literature sources. The cost ranges from the lowest $4,900 per lane mile ($0.70/yd^2) to the highest $10,600 per lane mile ($1.51/yd^2).

Table 7. Slurry seal cost per lane mile[4]

Cost per Lane Mile (12-ft width), $	Location	Year Data Taken	Reference
5,300 – 10,600	None specified	1999	Bolander, 2005
4,900 – 7,000	None specified	2001	Peshkin et al., 2004
6,300	None specified	2000	Hicks et al., 2000
5,000 – 7,000	OH	1997	Hicks et al., 2000

II.2.7 Cape Seal

Cape seal is an application of a chip seal covered by a slurry seal. A cape seal is applied when the pavement deterioration is greater than a slurry seal can be expected to correct, but deterioration has not progressed to the point of requiring an expensive asphalt overlay.

A cape seal eliminates the problem of loose aggregate, holds the stones of the seal coat firmly in place, reduces traffic noise as compared with a seal coat surface, and prevents water penetration reducing subsequent damage to the road bed, along with providing a new wearing surface. The disadvantage of the cape seal treatment is that it requires equipment for both chip seal and slurry seal. In addition, the cape seal application process requires a much longer construction time than both chip seal treatment and slurry seal application, resulting in longer traffic delay.

The approximate treatment life of a cape seal ranges from about 6 to 15 years.[4] Reported cost estimates for cape seal application are shown in table 8.

Table 8. Cape seal cost per lane mile[4]

Cost per Lane Mile (12-ft width), $	Location	Year Data Taken	Reference
12,300 – 17,600	None specified	1999	Bolander, 2005
15,800 – 21,100	None specified	2004	Maher et al., 2005

II.2.8 Other Surface Treatments

Other surface treatments that are currently being used, or are under experimental evaluation are also discussed below.

<u>NovaChip®</u>

NovaChip® is an application of a layer of heavy polymer modified emulsion to the road surface followed by a thin layer of HMA. The NovaChip® Surface Treatment Process was developed by SCREG Routes STP in France in 1986 to increase skid resistance and to seal old pavement surfaces.[26,27,and 28] Since then, it has been used widely in Europe.[29,30] It is mainly used as a surfacing on high-speed, high-volume auto routes and the national route systems. It is also successfully used in curb and gutter sections to preserve curb reveal in urban areas. NovaChip® was first introduced in the United States in the 1990s, and several states, including Alabama, Louisiana, Mississippi, Texas, and Washington, immediately constructed experimental sections to evaluate its performance. A study conducted by Cooper *et al.* documented the performance of the NovaChip® Surface Treatment Process when compared to conventional mill and overlay systems with similar Average Daily Traffic (ADT) and age after six years.[28] They concluded that NovaChip® performed satisfactorily in regard to IRI, rutting, and longitudinal, random, and transverse cracking. With regard to cost, NovaChip® could save approximately $23,500 per lane mile or $3.34/yd^2.

Russell *et al.* conducted an experimental application of NovaChip® on a section of SR-17 through the city of Soap Lake, Washington.[31] NovaChip® was investigated as a possible substitute for HMA Class G normally specified through cities on routes that only warrant a bituminous surface treatment. The NovaChip® was placed in the summer of 2001. Pavement condition survey results and visual observations revealed that the NovaChip® was effective in reducing both the frequency and severity of cracking. Ride quality has remained constant throughout the six year evaluation period and wear/rutting has been minimal. Life cycle cost analysis showed that NovaChip® is comparable to HMA Class G when analyzed on a total project cost basis, but is not cost competitive when only the cost of the overlay is considered.

NovaChip® has also been used in Pennsylvania for over 10 years on many resurfacing projects throughout the state. In a report submitted to FHWA to validate the 7 to 9 year performance life of NovaChip®, PennDOT selected six projects, as shown in table 9, for performance evaluation including rutting, transverse cracking, smoothness, and skid resistance.[32] The result of performance evaluation indicated that NovaChip® placed on these selected projects have performed well over the service life of the overlay. The pavements have demonstrated good IRI (smoothness) characteristics. Typically, NovaChip® has significantly higher pavement surface friction numbers compared to HMA wearing courses. NovaChip® also demonstrated a tendency to only allow minimal transverse cracking and rutting. Overall, there was little to no raveling of NovaChip® on these projects. This indicates very good adhesion between the NovaChip® and the underlying surface.

Table 9. Selected NovaChip® projects for performance evaluation

NovaChip® Project List									
SR	County	From	To	Approx. Length Miles	Traffic		Pavement Type	Pre Overlay-Base Repair	NovaChip® Placement Year
		Seg/Off	Seg/Off		ADT	% Trucks			
0033	Northampton	16/0000	20/0000	0.487	**10000**	8	RCCP	Concrete patching, joint sealing	**2001**
		17/0000	21/0000	0.476	**10000**	8			
0222	Berks	242/0383	332/0607	4.306	**19399**	12	PCCP	Concrete patching, joint sealing	**1999**
		243/0383	333/0607	4.322	**19934**	13			
0476	Montgomery	155/1781 154/2522	185/2259 184/2045	2.92	**116000**	10	2.5" ID-2 on RCCP	BCBC patching, Ralumac scratch, ID-2/ID-3 leveling	**1999**
0309	Montgomery	70/2052	240/1129	9.13	**46800**	4	RCCP	BCBC patching, joint & crack sealing	**1997**
		71/1535	241/0834	9.13	**46800**	4			
0083	Cumberland	396/0000	416/1520	2.322	**49926**	12	RCCP	Concrete patching, joint sealing	**1999**
		397/0000	417/0655	2.152	**42200**	12			
0015	Adams	010/0000	191/2198	10.43	**10238**	12	RCCP	Concrete patching, joint sealing	**2001**
		201/0000	271/3493	4.508	**10238**	12			**1999**

The report also analyzed the cause of problems such as cracking, flushing, spalling, and delamination observed on the selected projects. Those problems were attributed to the properties of the substrate and the preliminary preparation work performed on it. A majority of the projects viewed in the field demonstrated failures due to improper patching preparation. The patches were not milled to the existing pavement depth, causing the NovaChip® to be raised at the patch locations. This in turn would cause NovaChip® to fail at these locations. Transverse cracking on some of the projects viewed in the field can be attributed to the fact that the underlying transverse joints were not cleaned and sealed prior to placement of the NovaChip®. Flushing that has occurred on several projects including SR 0322 in Dauphin County, which were limited to the wheel paths, is attributed to excess asphalt in the mix. Delamination, as observed along SR 0015 in Adams County and SR 0309 in Montgomery County, is a result of insufficient application thickness.

A present worth cost comparison of NovaChip®, Ralumac, and Superpave overlay applications was also performed to determine the most cost effective material on appropriate projects.[32] The result indicated that NovaChip® is a cost-effective alternative to a Superpave overlay when a 9-10 year service life and no increase in structural value is desired. Ralumac comes in at a much cheaper present worth, but its expected life is only 5-6 years.

Overall, PennDOT concluded that NovaChip® is a dependable and cost effective alternative to a Superpave overlay. These roadways will attain the anticipated performance life when the existing surface is correctly prepared, the NovaChip® material is properly placed, and PCC and RCC pavements are excellent candidates for placement of NovaChip®. A typical cost for NovaChip® ranges from $26,500 to $29,500 per lane mile ($3.76 to 4.18/yd^2).[33]

E-Krete™

E-Krete™ is a patented polymer composite micro-overlay (PCMO) that bonds to asphalt pavements, chip seals, polished stone, and other bituminous products, as well as concrete and primed metal. The thickness normally ranges from 0.0625 to 0.25 inch (1.5 to 6.0 mm) depending on aggregate size and the number of applications.[34] E-Krete™ is marketed by Polycon, Inc., Madison, MS. According to the company, E-Krete™ is unaffected by water, UV rays, ice, oxidation, automotive fluids, aircraft fluids, oil, diesel, and gasoline. The life expectancy is approximately 20 years with a10 year manufacturer's warranty. A 12 year life cycle cost analysis shows that the cost for E-Krete™ is about $59,500 per 21 ft wide lane mile ($4.83/yd^2) as compared with $160,000 ($12.99/yd^2) for chip seal or $200,000($16.23/yd^2) for asphalt overlay. The company stated it is the only cementitious pavement preservation material approved by the Federal Aviation Administration, the EPA, and The U.S. Army Corps of Engineers, and is currently in the approval process in several state DOTs including Mississippi, Louisiana, Alabama, Arkansas, Texas, Tennessee, and Florida. The product is authorized for distribution in Pennsylvania, but has not been used yet. This product could have a bright future in Pennsylvania if it provides the benefits and costs advertized.

Several studies have been carried to evaluate the performance of E-KreteTM. Newman et al. [35] conducted a laboratory study and field demonstrations regarding the application of E-KreteTM on airfields. The results indicated that the fuel and abrasion resistance of the E-KreteTM product exceed that of a typical unmodified coal tar emulsion. E-KreteTM was found to be resistant to hydraulic fluid, but shown to soften when in contact with synthetic jet turbine fluids. The use of a fuel resistant surface sealer will delay E-KreteTM from softening in areas where it is exposed to jet turbine fluid spills. Abrasion resistance is approximately 8 to 10 times greater for unsealed E-KreteTM than for coal tar emulsion, and relatively 2 times greater for sealed E-KreteTM.. E-KreteTM was not damaged by freeze-thaw with deicing fluid applied after seven freeze-thaw cycles. Both the laboratory data and field data suggest that the material is durable and resistant to weathering. The field demonstrations have been successful with performance meeting or exceeding expectations at all sites. However, the performance of the E-Krete was rated as excellent after 2 to 3 years in service.Several of the demonstrations were placed on severely cracked asphalt and many of those cracks have reflected through the E-KreteTM surface. No significant forms of distress directly related to the E-KreteTM product were observed as of November 2000. Although the initial cost is higher than coal tar, the estimated life cycle costs were considered to be substantially lower (based on the net present worth value) assuming an average functional life of a coal tar sealer to be 3 years and that of the E-KreteTM to be 10. For a 83,612 sq m (100,000 sq yd) parking area sealed with E-KreteTM that costs $6.67/m2 ($5.58/yd2) versus a coal tar sealer at $2.15/ m2 ($1.80/yd2), the cost savings realized over a 10 year period exceed $75,000 NPV assuming a 3 percent discount rate of. Overall, the study concluded that E-KreteTM would be an excellent alternative to conventional coal tar sealer for airfield use.

Another study was conducted by the National Center for Asphalt Technology (NCAT) [36] to compare the friction and surface texture characteristics of the E-Krete™ treated surface with those of a new HMA control surface. A dynamic friction tester (DFT) was used to evaluate the friction and a circular texture meter (CTM) was used to evaluate the surface texture characteristics. Based on the results of this study, the following observations and conclusions were offered:

- The DFT friction results of both slabs measured at speeds other than 0 km/h (0 mph) exhibited an initial spike in friction very soon after the onset of polishing associated with the removal of binder and mastic film from the surfaces, respectively.
- The DFT friction number of the E-Krete™ surface increased after the initial polishing and then stabilized throughout the laboratory testing.
- The E-Krete™ surface performed as well as the control surface in terms of friction under the laboratory testing conditions.
- The surfaces of the two slabs exhibited similar texture measurements after 64,000 polishing cycles.
- The E-Krete® treated surface showed little wear and seemed to be durable after 132,000 laboratory polishing cycles. This observation agreed with results from the Newman report discussed above in which the E-Krete® product exhibited good wear resistance (*35*).

The Center for Pavement Preservation also recommends the use of asphalt scarification/profile milling as a surface preparation technique. This process addresses only the upper 1/4 - 1/2 inch of the pavement surface, and is useful in eliminating surface bleeding or otherwise conditioning the existing surface to improve bonding of a thin surface treatment type.

II.3 Selection of Surface Treatments

The selection of a proper surface treatment for an existing pavement is a difficult challenge because of the number of variables which need to be considered. These include existing pavement conditions, environment, pavement geography or terrain, available material and equipments, available funding, and life expectancy. Basically, there are three steps in selecting a proper surface maintenance treatment. These steps include:[37]

- Assess the existing conditions.
- Determine the feasible treatment options.
- Analyze and compare the feasible options with each other.

Assessing the existing pavement conditions is the first step in the maintenance selection process. Pavement condition can be assessed in the following four steps:

- Review project information from a database or record
- In-situ inspection
- Test the existing pavement
- Indentify pavement distress mechanism

The Long Term Pavement Performance (LTPP) Distress Identification Manual can be used to identify pavement distress mechanism.[38]

Once the pavement condition is assessed, the next step is to determine the feasible treatment options based on pavement distress types. Table 10 provides possible surface maintenance treatments matched to different pavement distress types.[6] It should be noted that feasibility doesn't mean affordability, because at this stage of the selection process the primary purpose is to determine what treatments might work. Once the feasible options have been determined, factors such as climate, geography, and traffic need to be taken into account for analyzing their limitations. The final options should be those options that satisfy maintenance requirements within their limitations.

Table 10. Possible maintenance treatments for various distress types[6,19]

Pavement Distress		Thin Overlay	Milling & Overlay	Micro-surfacing	Chip Seal	Sand Seal	Fog Seal	Slurry Seal	Cape Seal
Roughness	Nonstability Related	X	X	X					X
	Stability Related	X							
Rutting		X	X	X					
Cracking		X	X	X	X	X	X	X	X
Flushing/Bleeding			X	X	X				
Raveling & Wear				X	X	X	X	X	X

Once the final feasible options are determined (it is very likely that more than one option is identified as feasible), a cost benefit analysis over the pavement life or other cost effective measurements should be performed to determine which maintenance option is the best suited for the application. The best treatment option is the one that provides the greatest benefit (whether that benefit is measured in terms of improvement in condition, extension of pavement life, or even, more simply, the life of the treatment) for the lowest life cycle costs. Table 11 summarizes typical unit costs and expected lives for various treatments taken from the literature. These values will vary depending on the project location, quantities placed, and environmental conditions. It should also be noted that the cost values shown in the table were obtained at least six years ago and did not consider time value of the money.

Table 11. Typical unit costs and expected life for various treatments[4,19]

Treatment Type	Cost per Lane Mile (12-ft width)	Expected Life of Treatment (Year)		
		Min.	Average	Max.
Crack Sealing	$5,300	2	4.4	10
Fog Seal	$2,200	2	2.2	4
Slurry Seal	$6,600	1	4.8	10
Micro-surfacing	$12,600	4	7.4	24
Chip Seal (Single/Double)	$7,800 / $12,600	1 / 4	5.9 / 7.3	12 / 15
Sand Seal	$3,300	2	3	5
Thin Hot-Mix Overlay	$14,600	2	8.4	12
NovaChip®	$26,500 – 40,000	4	8.5	12

II.4 Summary

This state of the art literature review is intended to provide a general picture of each surface treatment and provide a general understanding of their application, benefits, limitations, cost, and performance. The design and construction aspects of each technique were not specifically addressed here, except as they present an advantage or disadvantage. Factors such as existing pavement condition, environment, pavement geography, available material and equipment, available funding, and life expectancy would affect the selection of surface maintenance treatments.

The literature review will provide a firm basis for further benefit cost evaluation, with the objective of identifying treatments which could be cost effective for PennDOT pavement maintenance. It is clear that the cost of proprietary treatments such as NovaChip® is generally significantly more than that of generic treatments. A detailed breakdown of proprietary materials is generally not possible, since the owner of the rights to produce the product is unwilling to divulge ingredients and related costs. The cost benefit analysis to be carried out will help to quantify whether the additional cost can be justified on the basis of performance.

III.0 RESEARCH SURVEY

III.1 Introduction

Subsequent to the literature review of microsurfacing strategies, the research team undertook an investigation of practices in several states having similar climate, geographical features, or successful thin surfacing programs. A questionnaire was created to collect basic information about the practices in these states. To facilitate responses, the questionnaire was created in a one page format. The results from the state agency questionnaires are presented in this document.

Additionally, the research team undertook a survey of experiences in the individual PennDOT Districts. Contact information for both District Pavement Engineers and District Materials Engineers/Managers were provided by the Department. At least one of these individuals was contacted in each District. In some cases both individuals provided information, and in other cases the research team was referred to other individuals within the Districts for specific information.

Additional information about specific state practices was obtained when treatment performance seemed better than that generally experienced by other agencies. Additional information was also gathered about asphalt materials currently being used in Pennsylvania, and the opportunity to improve treatment performance by using other materials, and practices.

III.2 Summary of State Highway Agencies Surveyed

III.2.1 List of State Highway Agencies Surveyed

The research team sent out a total of 16 questionnaires and 13 state highway agencies provided responses, as shown in table 12. These agency responses were evaluated and the results summarized in figures 1 through 5 and tables 13 through 16. The questionnaire form is included in Appendix B.

III.2.2 Number of Treatments Used by Individual State Highway Agencies

As shown in figure 1, most of the agencies are using four to seven of the treatments, while Maryland reports the use of only one treatment (thin overlay). At the other extreme, Virginia and North Carolina both use seven treatments. Of the respondents, only Virginia, North Carolina, and New York use slurry seals while Michigan and North Carolina routinely use cape seals. None of these states report using sand seals.

III.2.3 Use of Specific Preservation Strategies

All of the responding agencies use some preventive maintenance techniques. As shown in table 13 and figure 2, the thin overlay microsurfacing, crack sealing and chip seal techniques are the most frequently used treatments, followed by NovaChip®. Fog seal, slurry seal and cape seal are the least used. Again, none of the states report the use of sand seals.

Table 12. List of state highway agencies surveyed

State	Highway Agency	Contacts		Response?
WV	DOT	David L. Maner	David.L.Maner@wv.gov	Y
VA	DOT	Tanveer Chowdhury	Tanveer.Chowdhury@vdot.virginia.gov	Y
TX	DOT	Magdy Mikhail	mmikhai@dot.state.tx.us	Y
CT	DOT	Edgardo Block	Edgardo.Block@po.state.ct.us	Y
OH	DOT	Adam Au	adam.au@dot.state.oh.us	Y
NH	DOT	Eric Thibodeau	ethibodeau@dot.state.nh.us	Y
MO	DOT	Tom Anna	Thomas.anna@modot.mo.gov	N
MI	DOT	Kevin Kennedy	kennedyk@michigan.gov	Y
VT	AOT	Mike Fowler	mike.fowler@state.vt.us	N
MD	SHA	Geoff Hall	ghall1@sha.state.md.us	Y
IN	DOT	Todd Shields	tshields@indot.in.gov	Y
NY	DOT	Russell Thielke	rthielke@dot.state.ny.us	Y
NC	DOT	Dennis Wofford	dawofford@ncdot.gov	Y
NJ	DOT	Robert Sauber	robert.sauber@dot.state.nj.us	N
MN	DOT	Roger Olsen	roger.olson@dot.state.mn.us	Y
KY	DOT	Jon Wilcoxson	jon.wilcoxson@ky.gov	Y

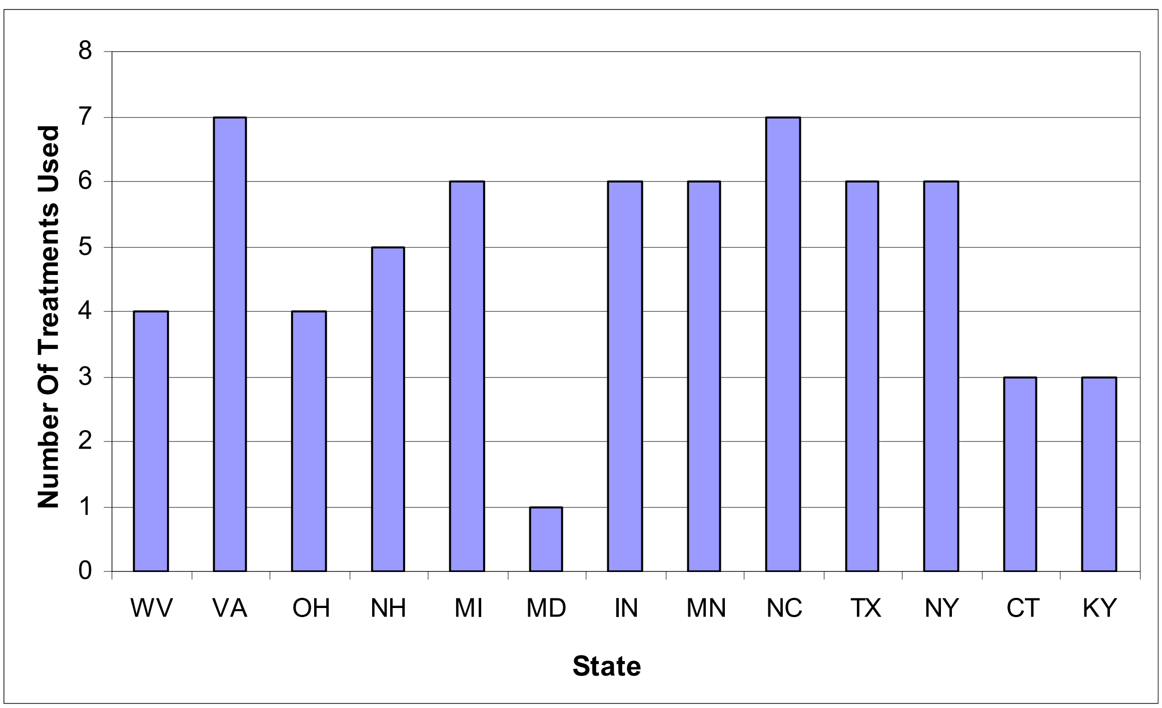


Figure 1. Number of treatments used by the individual state

Table 13. Number of agencies using pavement preservation strategies

Treatment Type	Number of Agency Used
Thin Overlay	12
Microsurfacing	12
Crack Sealing	12
Chip Seal	11
NovaChip®	9
Fog Seal	3
Cape Seal	3
Sand Seal	0
Slurry Seal	3

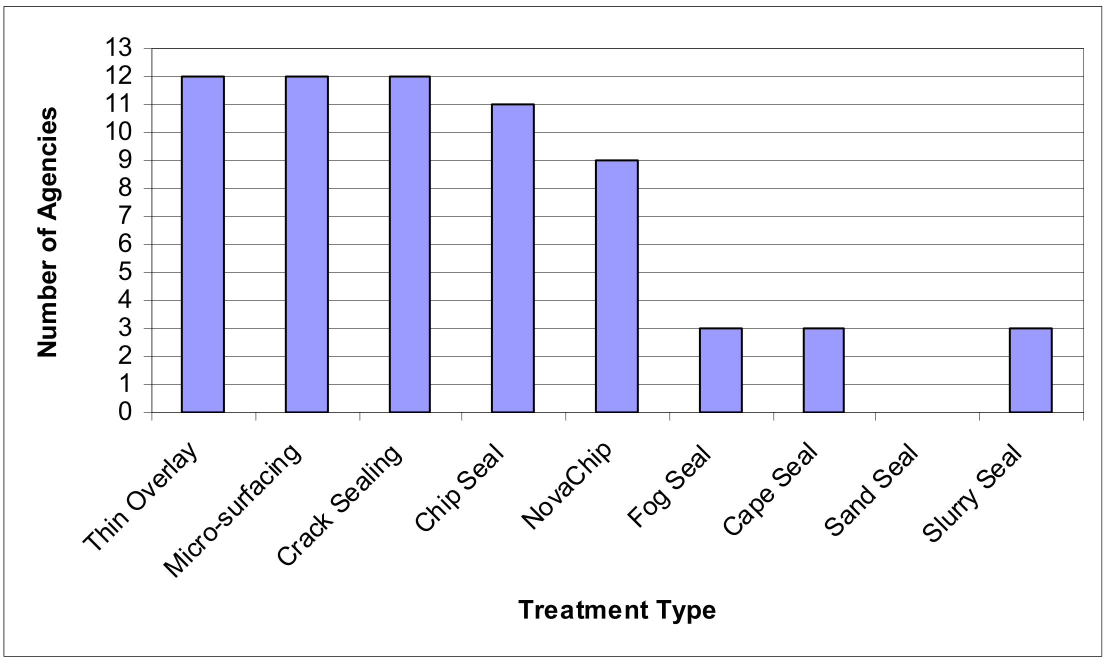


Figure 2. Number of agencies using pavement preservation strategies

III.2.4 Effect of Traffic Level on the Selection of Treatment Type

Traffic level is one of the most important factors that could potentially affect pavement durability. It is also a factor in user delay cost. A treatment with higher initial cost but earlier opening to traffic and longer performance life may provide a relatively less expensive alternative over the life of the pavement. As shown in figure 3, crack sealing, microsurfacing, NovaChip®, and thin overlays are the most commonly used treatments for the highest traffic level (> 10,000 ADT). Some state, such as New York, Texas, and Minnesota report using several of the treatments on much higher traffic volume roadways, as high as 50,000 ADT in some cases. Microsurfacing and crack sealing are the most frequently used treatments at the 5,000-10,000 ADT level. Chip seals and thin overlays are the most used treatments at the 2,000-5,000 ADT level. They are also the most used treatments on roads with less than 2,000 ADT. In this low traffic range, crack sealing is next most frequently used, with the other treatments being least used on low volume roads.

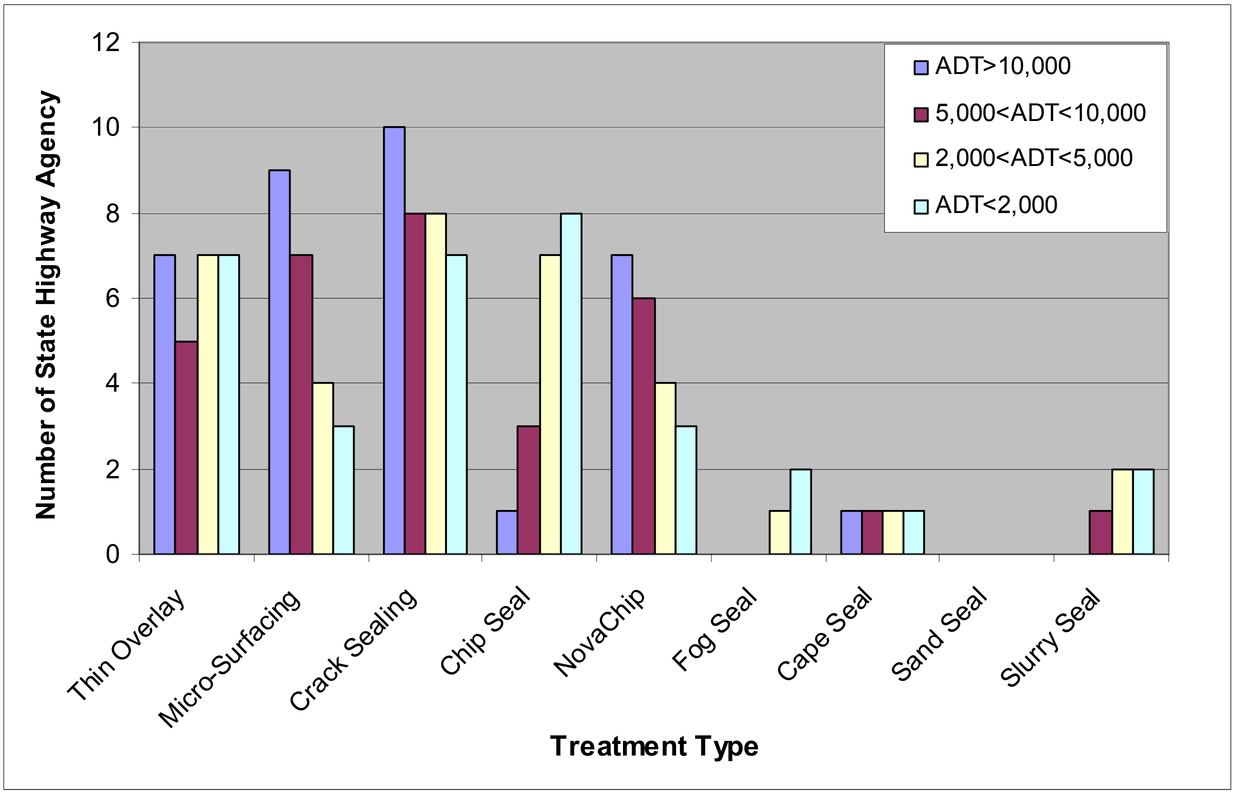


Figure 3. Effect of traffic level on the selection of treatment type

III.2.5 Effect of Pavement Condition on the Selection of Treatment Type

Surface treatments have proven to perform better when placed on a roadway with a specific level of pretreatment condition. The effectiveness of some treatments is limited when used on pavements in poor condition. As shown in figure 4, almost all treatments are applied to pavement in good and fair condition; with only thin overlay and NovaChip® being used on pavements in poor condition.

III.2.6 Factors in Determining Treatment Selection

As shown in figure 5, eight states consider a pavement condition index in the treatment selection process. Only Ohio uses just distress information. Five of the other responding states also consider other performance parameters including rutting, roughness, and friction in the decision making process. Four states also apply treatments according to an established cycle. Of these, only New Hampshire uses distress together with a frequency cycle to determine treatment type. Surface oxidation is another factor also considered by four other states. North Carolina, New York and Kentucky use a crack survey in their decision making process.

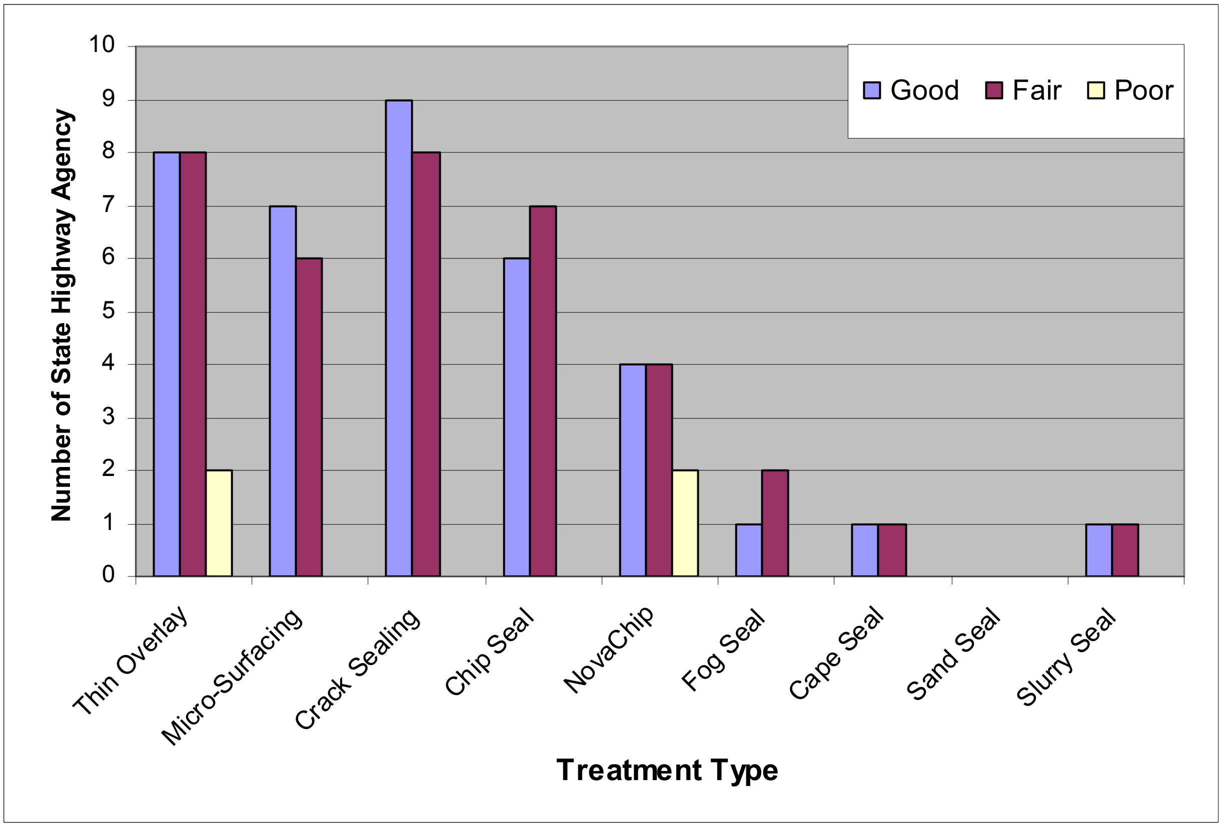


Figure 4. Effect of pavement condition on the selection of treatment type

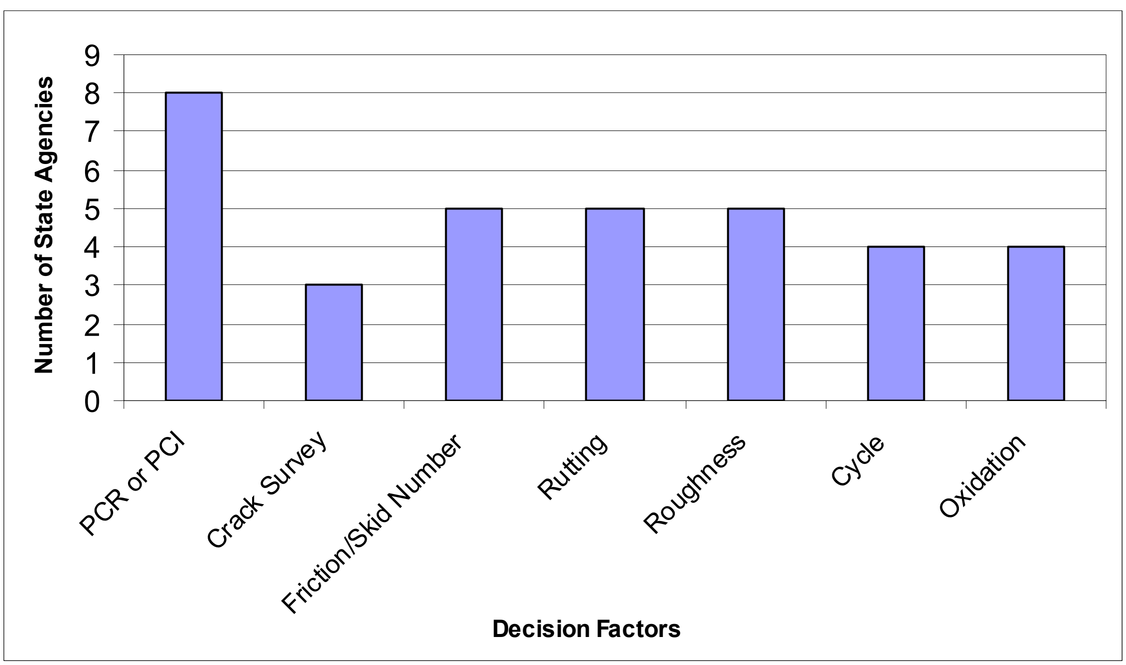


Figure 5. Factors considered in determining treatment selection

III.2.7 Factors in Selecting Asphalt Binder Type

Table 14 shows the factors considered by other states in selecting the asphalt binder type of specific treatments. The selection of asphalt binder type is most commonly influenced by traffic level, local climate, and past experience. Three of the states, New Hampshire, Maryland, and North Carolina, also consider geography in binder selection, while only Virginia and North Carolina indicated consideration of compatibility of aggregate and asphalt. Connecticut reported the use of only one PG grade throughout the state, and they have not used modified binders. Texas has had favorable experience in selecting asphalt emulsions. They consider traffic volume, temperature by season, and finally rely on past experience. Generally, Texas uses standard ASTM specifications to designate the emulsion used, and perform standard penetration and viscosity testing on the residue. They do not grade the base binder in the emulsion, and, therefore, do not specify performance graded binders. Although the study done by the Texas Transportation Institute (TTI) (Dr. Amy Epps) provided recommendations for the use of surface PG graded binders, the Texas Department of Transportation (TxDOT) is not yet prepared to implement those recommendations. They indicate that additional data collection and correlation with field performance is needed before findings from that research can be implemented.

Table 14. Factors in selecting asphalt binder type

Decision Factors	State Highway Agency												
	WV	VA	OH	NH	MI	MD	MN	IN	NC	TX	CT	KY	NY
Local Climate			x	x	x	x		x		x			x
Pavement Geography				x		x			x				
ESALs	x	x		x		x	x	x	x	x		x	
Past Experience	x	x	x		x	x	x		x	x			
Compatibility with Aggregate		x							x				
Other											x		

Two types of modified asphalt rubber chip seals have been used for the past several years by TxDOT. The first type, AC 20-15TR, contains 15% or more ground tire rubber. In this process the rubber is digested at a high temperature for a short period of time. This makes the rubber expand producing a texture sometimes described as appearing like oatmeal. This rubber modification method is reported to provide a well performing chip seal with good chip retention, although it is more expensive and requires contractors with the proper equipment and experience. The material is reported to be very effective when blended and constructed properly, although it is reported that extensive experience is required to become proficient in handling the tire rubber (TR) material.

The second type of asphalt rubber chip seal, AC 20-5TR, is TxDOT's commonly used binder for chip seal, and is currently used on about 40% of their projects (it was 60% in past years). This material contains 2 to 5% tire rubber cured at high temperature over a long period of time, such that the rubber fully dissolves into the base binder. The typical base binder is an AC 20 and the rubber mixture is specified as an AC20-5TR (AC 20 with 5% TR). This binder has proven to have very high chip retention and is used frequently.

III.2.8 Specific State Experience with Treatments

Minnesota uses a single size cubical aggregate for chip seals. Minnesota Department of Transportation (MnDOT) personnel indicate that this results in a reduction in the amount of aggregate needed per square yard, but increases the application rate of emulsion. They also apply a fog seal to the finished chip seal surface. These measures have been found to improve chip retention and chip seal performance. MnDOT has worked on their requirements for chip seals for some time, and during that process have developed a close relationship with their contractors. The liability for broken windshields resulting from loose chips has been passed on to the contractors in chip seal contracts. This requirement has not only resulted in fewer broken windshields, but also improvements in the mix designs and quality control furnished by the contractors. The commonly used binder for chip seals is CRS-2P, and testing is being carried out on CRS-2L (latex). The CRS-2P is reported to retain chips better than unmodified CRS-2.

MnDOT generally follows the International Slurry Seal Association (ISSA) guidelines for microsurfacing, but they do additionally require mixture testing. They report that this additional requirement assures good microsurface performance.

MnDOT is very pleased with the performance of NovaChip® for both preventive and corrective maintenance applications. Observations about the performance of NovaChip® are that it seems to stop top down cracking from developing when used as the surface course of a new pavement structure. They also observe fewer reflective cracks when NovaChip® is applied over jointed concrete pavement.

TxDOT uses a variety of thin surface treatments across their 13 engineering districts. They make use of several thin overlay mixtures including dense graded, open graded, and SMA types. Their use of these treatments is typically not constrained by traffic volume, although it is a factor in treatment selection.

TxDOT also uses chip seals extensively, including for high traffic volume roadways. Texas uses both single size and graded aggregate chip seal specifications, but has not compared the performance of the two. As chip seal binders they use hot asphalt, emulsions, polymer modified emulsions, asphalt rubber modified, and terminal blend materials.

TxDOT rarely uses fog seals or microsurfacing. Fog seals are typically applied to specific locations with surface raveling. Microsurfacing is used only to improve friction and preserve curb reveal. The cape seal treatment has not been used on TxDOT highways.

TxDOT makes extensive use of crack sealing on highways of all volumes. This is one of their most favored treatments.

The New York State Department of Transportation (NYSDOT) uses a quick set emulsion, CQS-1P to accelerate the opening to traffic time for chip seals.

New York also has a 6.3 mm polymer modified Superpave thin overlay mixture. The binder for this mix for Upstate is PG 64-22, and for the Downstate 76-22. Both binders are required to have a minimum 60% elastic recovery. The mix is designed on the basis of 75 gyrations.

PennDOT has placed one crumb rubber modified chip seal project as an evaluation project. The All States Materials Group (ASMG) placed the Asphalt Rubber Stress Absorbing Membrane (SAM) product in 2007 on SR-194 in York County. The project was approximately 10 miles in length including shoulders, for a total application of 179,650 square yards. PennDOT has designated this work as Rubberized Asphalt Seal Coat (RASC). The crumb rubber modification process of the PG 58-22 base binder followed ASTM D6114, Type II Asphalt Rubber (Wet Process). The binder material was applied hot at a rate of 0.25 gallons per square yard to a clean prepared surface and covered with 20-25 pounds of pre-coated chips, rolled, swept within approximately one hour, and opened to traffic. While the evaluation project will continue for two more years, a draft specification is being prepared for the use of the crumb rubber modified chip seal. While this experience represented one single evaluation project in the state, the cost of this project was reported as being more than that of a standard 1.5 inch Superpave overlay.

This product has been used in some of the New England states for several years. It is routinely placed in Rhode Island (which has a significant annual program) and New Hampshire, as well as by municipal customers throughout the New England states. New York has also placed evaluation projects under the Empire State Development program as an evaluation of alternative uses for processed tire rubber.

PennDOT District 1-0 is planning to try using Superpave RAP material as a precoated aggregate for chip seals. Preliminary trials have produced favorable results.

III.2.9 Expected Treatment Life

Table 15 summarizes treatment performance life as reported by the responding state highway agencies. As shown in the table, NovaChip®, thin overlays, and microsurfacing have the greatest expected life, followed by chip seal, crack seal, and cape seal. This ranking is generally consistent within individual states, except Michigan which indicated similar performance life for the thin overlay, microsurfacing, chip seal, NovaChip®, and cape seal treatments.

III.2.10 Treatment Cost

The responding states provided various levels of cost information. As shown in table 16, NovaChip® is the most costly of the treatments, followed by the thin overlay and microsurfacing. The cost of chip seal, slurry seal, and crack seal, follow in that order. Cost information was not provided for the other, less commonly used treatments. North Carolina did not provide any cost information about the treatments they use.

Table 15. Summary of state DOT treatment life reported in survey

Treatment Type	State Highway Agency												
	WV	VA	OH	NH	MI	MD	MN	IN	NC	TX	CT	KY	NY
Thin Overlay	8	10	10	7	3-6	5-10	8-12	9	10	10-12	NR	7	8-10
Micro-surfacing	8	6	8	6	3-6	NR	12	8	7	5-7	NR	8	8-10
Crack Sealing	4	N/A	2	5	1-3	NR	5	3	3	2-3	NR	4	2-5
Chip Seal	5	6	7	5	3-6	NR	10	4	7	7-8	4	NR	4-6
NovaChip®	NR	10	NR	10	3-6	NR	15	8	8	8-10	10	NR	8-10
Fog Seal	NR	5	NR	NR	NR	NR	3	2	NR	NR	NR	NR	NR
Cape Seal	NR	NR	NR	NR	NR	NR	NR	NR	8	NR	NR	NR	NR
Sand Seal	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
Slurry Seal	NR	6	NR	NR	NR	NR	NR	NR	3	NR	NR	NR	4-6

Note: NR: No Response

III.2.11 Summary of State Response Information

Many interesting state practices for several of the treatments were identified during the survey. Minnesota indicated accomplishing major improvement in the control, and by association, the performance of chip seals since they transferred the liability for loose chip damage to vehicles to the contractor. They did this after working closely with the industry over a period of time, during which they focused on refining the design and field control processes for chip seals. The transfer of loose chip liability to the contractor has sufficiently emphasized the importance of design and construction control to encourage contractors to make the necessary changes in their procedures.

Table 16. Summary of state DOT treatment cost reported in survey ($/yd^2)

Treatment Type	State Highway Agency												
	WV	VA	OH	NH	MI	MD	MN	IN	NC	TX	CT	KY	NY
Thin Overlay	2.59	4	3.52	3.00	2.55	5.00	4.25	5.50	NR	5.20	NR	NR	5.00
Micro-surfacing	NR	2.2	3.14	2.90	3.09	NR	2.00	3.50	NR	2.50	NR	NR	4.00
Crack Sealing	0.02	NR	0.41	0.35	NR	NR	0.4	<1	NR	0.32	0.95	NR	0.40
Chip Seal	1.65	0.9	1.70	2.15	1.38[1]/2.76[2]	NR	1.4	1.50	NR	1.78	2.10	NR	2.00
NovaChip	NR	5.5	NR	6.5	5.74	NR	4.5	6.50	NR	NR	8.50	NR	6.00
Fog Seal	NR	0.6	NR	NR	NR	NR	0.25	0.25	NR	0.24	NR	NR	NR
Cape Seal	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
Sand Seal	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
Slurry Seal	NR	1.5	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	3.00

Note: NR: No Response; 1: Single Chip Seal; 2: Double Chip Seals

TxDOT uses a variety of chip seal types with apparent success. They use single size and graded aggregates, rubber modified and polymer modified binders with hot asphalt and emulsions.

New York has an interesting 6.3mm polymer modified thin overlay material. The use of a rapid set emulsified tack coat is required with this thin overlay material.

State specifications with these rather unique treatment requirements from MnDOT, TxDOT and NYSDOT are shown for reference as Appendices C, D, and E, respectively.

The National Center for Pavement Preservation at Michigan State University has an extensive web site (http://www.pavementpreservation.org/) which provides a large amount of information related to pavement preservation and specific information about a number of the treatments. In addition, information obtained from the Center by telephone interview regarding specific treatments has been included in the current study, and incorporated into the discussion of individual treatments.

III.3 Survey of PennDOT Districts

The research team also contacted the PennDOT Districts to find out what the experience and practices of each has been in recent years with respect to thin surface treatments. Telephone contacts were initiated with the District Pavement Engineer, Materials Engineer, or both. In some cases, the research team was referred to other individuals within the District for specific information. Results of these interviews are summarized in table 17. Table 18 summarizes specific experiences of the PennDOT Districts with thin surface treatments.

From these interviews, it has been determined that the Districts use chip seals primarily for lower volume roads. The Districts have a range of experience with microsurfacing, some very good, and some poor. Most of the Districts have tried a limited number of NovaChip® projects with generally satisfactory results. The District representatives were specifically asked about any experience related to geographic features. The most frequent response was that in locations where tree canopy creates shadows on the road, problems are encountered with curing of some thin surface applications. This problem is related to construction conditions, primarily in the curing of emulsions. Differences in treatment performance were specifically identified for some of the treatments like NovaChip® and chip seals relative to geometric features such as curves and intersections.

Table 17. Survey summary of Pennsylvania districts

Maintenance Type	District										
	1-0	2-0	3-0	4-0	5-0	6-0	8-0	9-0	10-0	11-0	12-0
Thin Overlay	N	R	S	N	N	N	N	R	R	N	R
Microsurfacing	R	S	R	R	R	R	S	S	S	N	S
Chip Seals	R	R	R	R	S	R	R	R	R	N	R
NovaChip®	R	N	N	S	S	S	R	N	N	R	N
Note: S-Seldom; R-Regular; N-Not Used / Reported;											

Table 18. Summary of project experience of Pennsylvania districts

District	*Contacts*	*Project Experience*
1-0	Jeff Oswalt Steve Snyder	**Microsurfacing:** 1. Completed 3 projects in 2009 2. Used a centerline strip to seal longitudinal pavement joints. 3. It is being applied full width when performing a 19mm (Type 3) microsurfacing. 4. The aggregate used for microsurfacing was 100% passing the # 4 sieve. **Chip Seals:** 1. Applied to roads with less than 5,000 ADT. 2. Plan to use a modified asphalt binder. 3. Plan to use RAP as aggregate in future chip seals. **NovaChip:** 1. NovaChip has been used on five projects with relatively high traffic in the district in recent years. 2. Used only over concrete pavements to improve friction. 3. Overall it has performed well.
2-0	Steve Fantechi	**Thin Overlay:** 1. 95% or less of the maintenance completed is thin overlay (1 ½”). **Microsurfacing:** 1. Several microsurfacing projects have been done in the district. 2. Only used on surfaces in good condition with minimal distress. **Chip Seals:** 1. Chip seals are constructed on low volume roads only.
3-0	Tom Squires	**Microsurfacing:** 1. Microsurfacing has been used over a range of traffic volumes. It has been used on I-80 and I-180. 2. Only Type A (fine) gradation is used. 3. Microsurfacing can’t prevent reflective cracking, so they prefer to crack seal a year before surfacing. 4. Target life: 4-5 years, some could be 7 years. 5. Opening to traffic in one hour is advantageous. **Seal Coat (Chip Seals):** 1. Changed emulsion from CRS-2 to CRS-PM. **Thin SMA:** District 3-0 constructed a single ¾” SMA on SR. 15 3-4 years ago. The overlay is performing well. **Geography/Terrain:** 1. Problems with moisture in shaded areas. 2. Occasionally experience aggregate-asphalt compatibility

District	***Contacts***	***Project Experience***
		problems.
4-0	Joe Stroke	**NovaChip:** 1. They used it on one project in Luzerne County. 2. The project is now 12-13 years old and still looks good. **Seal Coat (Chip Seals):** 1. Mainly used in rural counties. 2. 80% or more of roads have ADT<7,000. **Microsurfacing:** 1. Microsurfacing has been used quite a bit in the past two years. 2. Type C (3/8”) aggregate in a single application. 3. Some problems with material slipping, particular in Hazelton. **Geography/Terrain:** 1. The District does see performance problems with emulsion applications where there is an overhead tree canopy.
5-0	Jeremy Mertz	**Microsurfacing:** 1. They have constructed a few projects over the past few years. 2. Overall, the performance is satisfactory. 3. Ideally, the life expectancy is about 5-7 years. 4. They are starting to use it on interstate and expressways. **NovaChip:** 1. One NovaChip project has been down for 10 years and is performing satisfactorily. 2. There are some issues with turning movements at intersections.
6-0	Lorraine Ryan	**NovaChip:** 1. They have constructed 4 projects since 1998, and all of them are still in service. **Microsurfacing:** 1. They have constructed two major projects and a dozen minor projects. 2. The performance life has varied, depending on conditions. **Seal Coat (Chip):** 1. Used on lower volume road projects with performance generally ranging from 4 to 6 years.
8-0	Doug Frank	**Microsurfacing:** 1. A single microsurfacing job was completed on a tangent section of roadway in the past 5 years, and performance remains satisfactory. 2. Past problems have been experienced with the microsurfacing on curves or hills.

District	*Contacts*	*Project Experience*
		Crumb Rubber Seal Coat: 1. A crumb rubber seal coat was built about 3 years ago on a large section of roadway, and the District thinks this is the best job they have completed. 2. Experienced some bleeding problems, primarily at intersections, but not able to determine the cause. **NovaChip:** 1. The District has experimented with NovaChip for the past 10 years. 2. They had issues with repairing failed areas, and with failure of the paver to allow for breakpoints and slopes in the early years. 3. They had problems in high shear stress areas, such as ramps with high truck traffic. 4. NovaChip is a satisfactory maintenance tool, based on the District experience.
9-0	Kevin Gnegy Larry Bilotto	**Thin Overlay:** 1. A 1 inch “fine” overlay was placed in Somerset County last year. 2. Aggregate is 9.5 mm. 3. Cost: $49.85/ton. **Seal Coat (Chip Seal):** 1. Chip seals are generally used on low volume roads with less than 5,000 ADT. 2. The most common emulsion type is E3M. **Microsurfacing:** 1. No microsurfacing project within the past 10 years, only a Ralumac surface may have been constructed years ago. **NovaChip:** 2. No NovaChip projects have been used in the District.
10-0	George McCauley	**Chip Seals:** 1. The majority of thin surface maintenance treatments are either single or double chip seals. 2. Generally placed on low volume roadways. **Thin Overlay:** 1. Many 1 ½” 12.5 mm mix thin overlays have exhibited performance problems, so the District now uses 9.5 mm mixes. **Microsurfacing:** 1. Several microsurfacing projects have been constructed on higher volume or heavy truck traffic routes. 2. The main purpose is to enhance skid resistance and maintain the existing surface. 3. Generally performs well, providing at least 4-5 years life extension.

District	Contacts	Project Experience
11-0	William Dipner	**NovaChip:** 1. They have a couple of NovaChip projects of 5/8" thickness. 2. The performance of NovaChip projects is generally satisfactory, except for some distress along the longitudinal and transverse joints. The majority of the distress at the joints has been attributed to inadequate concrete repairs prior to the overlay.
12-0	Tom Ryczek Tom Boyle	**NovaChip:** 1. NovaChip was tried several years ago over a concrete pavement but was immediately removed because of poor adherence. **Overlay:** 1. Overlay is their standard treatment, generally 2-4" in thickness **Chip Seal:** 1. The standard thin maintenance surface treatment is the seal coat with #8 aggregate. **Geography/Terrain:** 1. They use more pliable oil in the mountains and have begun using a PG 76-22 to prevent rutting on susceptible pavements.

III.3.1 Summary of District Experience

Chips seals are widely used by most districts, particularly the more rural counties. In general, chip seals are used on lower volume roads having less than 5,000 ADT. Chip seals are generally applied following a fixed cycle frequency of between four and seven years.

NovaChip® has been used by five Districts, and has performed reasonably well in four of them. District 12-0 placed one project which did not perform well. The other Districts generally have had limited problems in high surface stress locations such as high truck traffic entrances. There have also been some issues on curves, but the material seems to perform well on tangent sections. Performing repairs to NovaChip® has been noted as challenging at times.

Some of the districts have tried thin overlays. The 3/4"overlay placed by District 3-0 (Appendix F) seems to be performing well. The typical problem with thin overlays has been loss of bond to the underlying layer. The use of an improved bonding material for thin overlays, such as Novabond, has been successful in Virginia.

III.4 Climatic Zones

The climatic zone in which a pavement surface must perform can have a profound effect on the type of materials that should be used. Different binders or emulsions should be used in various surface treatments depending upon the temperature range and other climatic conditions in which the surface treatment is expected to perform. The use of traditional viscosity and penetration specifications for asphalt binders do not characterize the bituminous materials across the entire spectrum of temperatures experienced during production, construction, and in-service. The properties required under the penetration and viscosity systems are not directly related to the performance conditions of the pavement in the field. To address this issue, the Strategic Highway Research Program (SHRP) developed the performance-graded (PG) asphalt binder specifications in the 1990s. These specifications were developed to measure binder properties directly related to hot mix asphalt (HMA) concrete performance, and included material characterization at low, intermediate, and high performance temperatures. However, the HMA PG binder specification does not directly apply to surface treatments because of differences between surface treatments and HMA in terms of construction methods and environmental exposure. TxDOT supported research which developed a performance based specification system for surface treatment binders that maximize the use of existing tests required in the PG system for HMA binders. The proposed surface performance grading (SPG) specification assumes appropriate design and construction practices, and has considered only binder properties after construction. The Texas researchers developed the SPG system on the basis of physical property analysis of surface treatment binders at multiple temperatures, and corresponding performance in specific environmental conditions.

The final SPG recommendation includes suggested limiting values for high and low pavement surface design temperatures. The researchers recommended implementation of the new SPG after results from the suggested validation experiment are obtained. This work provides a good model for how surface treatment binders can be better characterized on the basis of the anticipated field performance temperatures. Efforts have been initiated to adapt this approach nation wide. However, it will be some time before this proposed system is ready for implementation.

This research has considered the feasibility of implementing the binder methodologies developed by TxDOT for Pennsylvania. To do this, the entire state must be subdivided into micro-climate zones based upon temperatures. Accordingly, a review of local climate data was undertaken. Results from this were assessed for usefulness in providing guidelines for binder selection statewide. The approach included in the FHWA's LTPPBind V3.1, of computing virtual weather station information for a given project site on the basis of five surrounding weather stations was also assessed. From this exercise, it was concluded that the use of the weather station information generated in the LTPPBind program is appropriate for the selection of thin surface treatment binders. Pavement surface conditions can be selected in the software by designating the depth within the pavement as zero. In this methodology, PG binder grades are selected on the basis of local air and pavement temperatures, triangulated from five adjacent weather stations. This approach was found to provide better reliability than other approaches considered. Based on the temperature information from LTPPBind V3.1 database, the high pavement surface temperature is determined by the SHRP model as follows:

$$T_{h\text{-}surf} - T_{air} = -0.00618\ Lat^2 + 0.2289\ Lat + 24.4 \qquad (1)$$

Where, $T_{h\text{-}surf}$ – high pavement surface temperature (°C);
T_{air} – air temperature (°C);
Lat – the latitude (°).

To consider the temperature factor at different levels of reliability, assuming a normal distribution for the temperatures in Pennsylvania, the pavement surface temperature at 50% and 98% reliability levels were calculated for all weather stations in Pennsylvania using the following equation:

$$T_{pav} = T_{h\text{-}surf} + Z \times S_{air} \qquad (2)$$

Where, Z – z-value of the standard normal distribution at reliability level
S_{air} – the standard deviation of the high 7-day mean air temperature (°C)

For the low temperature, the SHRP model assumes the pavement surface temperature is equal to the minimum air temperature as shown in the following equation:

$$T_{l\text{-}surf} = T_{air} \qquad (3)$$

The average low pavement temperature at both 50% and 98% reliability levels for all weather stations in Pennsylvania is determined by the following equation:

$$T_{pav} = T_{h\text{-}surf} - Z \times S_{air} \qquad (4)$$

All the calculated results for both high and low pavement temperature are given in table 19. Based on the results of this temperature analysis for Pennsylvania, binder performance grade for pavement surface maintenance treatments maintaining the 6°C temperature increments now incorporated in the LTPPBind program were computed, as shown in table 19.

It must be noted that several of the computed binder grades are not commercially available. In these cases, practical judgment must be used in selecting the best available binder. In general, the available binders indicated in the table provide 50% reliability at the low temperature and 98% reliability at the high temperature for most sites across Pennsylvania. The high temperature performance is important for the control of bleeding or raveling during the hot periods of the year. Since the low temperature criteria focus on low temperature thermal cracking for HMA materials, it is not clear how the low temperature grade affects the performance of thin surface applications, so for the present it is appropriate to focus on the high temperature requirements.

Table 19. Pavement surface temperature range and computed SPG Grade

County	Weather Station	Pavement Surface Temperature (ºC)				Computed PG Grade Selection for Surface Treatments	
		Low (ºC)		High (ºC)			
		Reliability		Reliability		Reliability	
		98%	50%	98%	50%	98%	50%
ADAMS	biglerville	-27	-20	60	56	PG64-28	PG58-22
ADAMS	eisenhower	-32	-21	61	57	PG64-34	PG58-22
ALLEGHENY	bakerstown	-30	-22	58	55	PG58-34	PG58-22
ALLEGHENY	mckeesport	-27	-18	60	56	PG64-28	PG58-22
ALLEGHENY	pittsburgh	-29	-22	59	55	PG64-34	PG58-22
ARMSTRONG	ford city	-33	-24	58	55	PG58-34	PG58-28
ARMSTRONG	putneyville	-31	-24	58	55	PG58-34	PG58-28
BEAVER	montgomery	-28	-21	59	56	PG64-28	PG58-22
BEDFORD	everett	-29	-21	60	56	PG64-34	PG58-22
BEDFORD	kegg	-30	-22	59	57	PG64-34	PG58-22
BERKS	blue marsh lake	-30	-21	59	56	PG64-34	PG58-22
BERKS	hamburg	-28	-19	60	56	PG64-28	PG58-22
BERKS	hopewell furnace	-28	-20	58	56	PG58-28	PG58-22
BERKS	morgantown	-25	-19	58	56	PG58-28	PG58-22
BERKS	reading	-27	-19	60	57	PG64-28	PG58-22
BERKS	rodale research ctr	-26	-21	59	56	PG64-28	PG58-22
BLAIR	altoona blair co ap	-30	-21	59	55	PG64-34	PG58-22
BLAIR	altoona	-28	-22	57	54	PG64-28	PG58-22
BRADFORD	canton	-32	-26	59	55	PG64-34	PG58-28
BRADFORD	towanda	-32	-25	58	55	PG58-34	PG58-28
BUCKS	bucksville	-30	-22	59	56	PG64-34	PG58-22
BUCKS	neshaminy falls	-26	-19	61	58	PG64-28	PG58-22
BUTLER	butler	-30	-23	58	55	PG58-34	PG58-28
BUTLER	slippery rock	-32	-25	58	55	PG58-34	PG58-28
CAMBRIA	ebensburg sewage	-32	-26	57	54	PG58-34	PG58-28
CAMBRIA	johnstown	-28	-21	60	57	PG64-28	PG58-22
CAMBRIA	prince gallitzin	-34	-24	58	55	PG58-34	PG58-28
CAMERON	emporium	-32	-25	57	54	PG58-34	PG58-28
CAMERON	stevenson dam	-30	-24	58	55	PG58-34	PG58-28
CARBON	palmerton	-28	-21	61	57	PG64-28	PG58-22
CENTRE	philipsburg mid-st	-33	-26	56	53	PG58-34	PG58-28
CENTRE	state college	-28	-21	58	55	PG58-28	PG58-22
CHESTER	coatesville	-26	-19	59	56	PG64-28	PG58-22
CHESTER	devault	-23	-18	59	56	PG64-28	PG58-22
CHESTER	phoenixville	-27	-20	60	57	PG64-28	PG58-22
CHESTER	west chester	-25	-18	60	57	PG64-28	PG58-22
CLARION	clarion	-33	-25	59	55	PG64-34	PG58-28
CLEARFIELD	madera	-32	-27	57	54	PG58-34	PG58-28
CLINTON	lock haven sewage	-29	-22	60	56	PG64-34	PG58-22

County	Weather Station	Pavement Surface Temperature (ºC)				Computed PG Grade Selection for Surface Treatments	
		Low (ºC)		High (ºC)			
		Reliability		Reliability		Reliability	
		98%	50%	98%	50%	98%	50%
CLINTON	renovo	-29	-22	59	56	PG64-34	PG58-22
COLUMBIA	millville	-28	-22	58	55	PG58-28	PG58-22
CRAWFORD	conneautville	-33	-27	58	54	PG58-34	PG58-28
CRAWFORD	jamestown	-32	-26	57	54	PG58-34	PG58-28
CRAWFORD	linesville	-33	-25	58	54	PG58-34	PG58-28
CRAWFORD	meadville	-30	-24	57	54	PG58-34	PG58-28
CRAWFORD	titusville wtr works	-34	-27	57	54	PG58-34	PG58-28
CUMBERLAND	bloserville	-25	-18	60	57	PG64-28	PG58-22
DELAWARE	marcus hook	-20	-14	62	58	PG64-22	PG58-16
ELK	ridgway	-34	-27	56	53	PG58-34	PG58-28
ERIE	corry	-32	-26	56	53	PG58-34	PG58-28
ERIE	erie intl arpt	-28	-21	55	53	PG58-28	PG58-22
FAYETTE	chalk hill	-33	-25	56	53	PG58-34	PG58-28
FAYETTE	uniontown	-30	-21	59	56	PG64-34	PG58-22
FOREST	tionesta	-33	-26	57	54	PG58-34	PG58-28
FRANKLIN	chambersburg	-27	-20	60	57	PG64-28	PG58-22
FRANKLIN	mercersburg	-29	-21	61	57	PG64-34	PG58-22
FRANKLIN	shippensburg	-25	-19	60	57	PG64-28	PG58-22
GREENE	waynesburg	-31	-23	59	56	PG64-34	PG58-28
HUNTINGDON	raystown lake	-28	-20	59	56	PG64-28	PG58-22
INDIANA	indiana	-32	-24	58	55	PG58-34	PG58-28
INDIANA	marion center	-30	-24	56	53	PG58-34	PG58-28
JEFFERSON	brookville swg	-33	-26	57	54	PG58-34	PG58-28
JEFFERSON	dubois faa ap	-30	-23	56	53	PG58-34	PG58-28
LANCASTER	ephrata	-24	-18	59	56	PG64-28	PG58-22
LANCASTER	holtwood	-23	-16	59	56	PG64-28	PG58-16
LANCASTER	lancaster	-28	-19	61	57	PG64-28	PG58-22
LANCASTER	landisville	-32	-22	60	57	PG64-34	PG58-22
LANCASTER	octoraro lake	-29	-21	61	57	PG64-34	PG58-22
LAWRENCE	new castle	-31	-23	59	56	PG64-34	PG58-28
LEBANON	lebanon	-28	-20	60	56	PG64-28	PG58-22
LEHIGH	allentown a-b-e Intl	-25	-19	59	56	PG64-28	PG58-22
LUZERNE	francis e walter dam	-33	-26	56	53	PG58-34	PG58-28
LUZERNE	freeland	-30	-23	56	52	PG58-34	PG58-28
LUZERNE	wilkes-barre scrantn	-27	-21	58	55	PG58-28	PG58-22
LYCOMING	english center	-32	-27	58	55	PG58-34	PG58-28
LYCOMING	williamsprt-lycoming	-29	-22	60	56	PG64-34	PG58-22
MCKEAN	bradford reqional ap	-33	-27	55	52	PG58-34	PG52-28
MCKEAN	bradford	-35	-28	55	52	PG58-40	PG52-28
MCKEAN	clermont	-39	-31	56	53	PG58-40	PG58-34
MCKEAN	kane	-36	-29	56	53	PG58-40	PG58-34
MERCER	greenville	-31	-24	59	55	PG64-34	PG58-28

County	Weather Station	Pavement Surface Temperature (ºC)				Computed PG Grade Selection for Surface Treatments	
		Low (ºC)		High (ºC)			
		Reliability		Reliability		Reliability	
		98%	50%	98%	50%	98%	50%
MERCER	mercer	-33	-25	57	54	PG58-34	PG58-28
MIFFLIN	lewistown	-27	-19	59	57	PG64-28	PG58-22
MONROE	stroudsburg	-30	-22	60	57	PG64-34	PG58-22
MONROE	tobyhanna	-32	-25	56	53	PG58-34	PG58-28
MONTGOMERY	graterford	-26	-19	59	57	PG64-28	PG58-22
MONTGOMERY	norristown	-23	-17	61	57	PG64-28	PG58-22
PERRY	newport river	-26	-20	60	57	PG64-28	PG58-22
PHILADELPHIA	philadelphia intl ap	-22	-16	60	57	PG64-22	PG58-16
PIKE	matamoras	-28	-22	60	56	PG64-28	PG58-22
POTTER	coudersport	-34	-27	54	52	PG64-34	PG52-28
SNYDER	selinsgrove	-30	-21	60	56	PG64-34	PG58-22
SOMERSET	confluence	-32	-24	60	56	PG64-34	PG58-28
SOMERSET	laurel mountain	-32	-24	54	50	PG58-34	PG52-28
SOMERSET	stoystown	-30	-23	56	53	PG58-34	PG58-28
SULLIVAN	eagles mere	-31	-24	54	51	PG58-34	PG52-28
SUSQUEHANNA	montrose	-31	-25	56	53	PG58-34	PG58-28
TIOGA	wellsboro	-29	-24	55	52	PG58-34	PG52-28
UNION	laurelton st village	-28	-21	61	57	PG64-28	PG58-22
VENANGO	franklin	-30	-23	58	55	PG58-34	PG58-28
WARREN	warren	-32	-24	58	55	PG58-34	PG58-28
WASHINGTON	burgettstown	-34	-27	59	55	PG64-34	PG58-28
WASHINGTON	donora	-28	-20	60	57	PG64-28	PG58-22
WASHINGTON	washington	-31	-22	59	55	PG64-34	PG58-22
WAYNE	hawley	-33	-25	57	53	PG58-34	PG58-28
WAYNE	pleasant mount	-31	-26	55	52	PG58-34	PG52-28
WESTMORELAND	derry	-32	-23	59	56	PG64-34	PG58-28
WESTMORELAND	donegal	-31	-23	57	54	PG58-34	PG58-28
WESTMORELAND	salina	-33	-24	58	56	PG58-34	PG58-28
YORK	hanover	-24	-18	62	58	PG64-28	PG58-22
YORK	harrisburg cap ctyap	-24	-17	61	57	PG64-28	PG58-22
YORK	york ssw pump stn	-29	-21	60	57	PG64-34	PG58-22

III.5 Current Binders Used in Emulsions in Pennsylvania

Information sought regarding the binders currently being supplied in Pennsylvania was obtained from the Materials and Testing Division, and also from several emulsion suppliers. This information was gathered by interviews with representatives of Ergon, Russell Standard, and Marathon Petroleum. The emulsion grades currently being supplied in Pennsylvania are primarily CMS-2, CRS-2, CRS-2P and CSS-1H, CSS-1HP, and asphalt emulsion tack coat. Ergon indicated they can supply Novabond in Pennsylvania if there is demand for the product.

The performance graded binders of the base asphalts currently being used are PG 64-22 and PG 58-22.

The base binders used to make the emulsions currently being used are typically PG 58-28 for CMS-2 and CRS-2 materials and PG 64-22 for CSS-1H materials. It appears that the high temperature grades being used are reasonably within the range identified above, at the 98% reliability level. These materials are being evaluated on the basis of penetration tests, with typical values for cationic emulsions ranging from 100-200, and for anionic emulsions from 160 to 190. The softer anionic grade can be expected to cure more slowly

A knowledgeable representative of Marathon Petroleum indicated that the emulsifier content is likely to have little effect on the grade of the base asphalt for cationic emulsions. However, for anionic emulsions the emulsifier content is approximately three times that used with cationic emulsions and there is a real chance that the quantity of solvents used may soften the base binder. This should be considered for projects that require an anionic binder.

Russell standard indicated that they typically provide CRS and CMS emulsions grades for use in Pennsylvania. They usually use PG 58-28 as the base binder in their asphalt emulsions. For modified emulsions they use a base binder of 64-22. They have performed limited testing of PG grades before and after emulsifying the asphalt, and found that for the cationic emulsions there is no effect on the binder grade.

Information was also obtained from the PennDOT Material and Testing Division regarding the binder evaluation system being used for emulsified asphalt materials. Current testing only checks for the penetration grade and residual asphalt content of emulsions. Specification criteria for these materials are contained in Bulletin 25, and approved suppliers are listed in Bulletin 15. Only the CSS-1H polymer modified material has a viscosity requirement on the base asphalt. Until further research and field validations are completed on the surface performance graded binders, the current penetration specifications used by PennDOT appear to be appropriate.

III.6 Treatment Type and Existing Pavement Condition

As stated earlier in the literature review the existing pavement condition must be evaluated to determine an appropriate treatment selection. The PennDOT Field Survey Manual (Pub 336) or LTPP Distress Identification Manual can be used to identify pavement distress types. Different surface treatments have proven to provide better performance when placed on roadways with specific distress types, and at a specific distress levels. Different treatments have been found to be effective when certain distresses at specific severity level are present, but not for others. For example, a pavement exhibiting fatigue cracking would require a different treatment than a pavement with bleeding, and while one treatment may be beneficial for low severity distress, it may not be at a high severity distress level. Other issues such as vehicle safety should also be included in the decision making process when considering treatment feasibility. For example, a fog seal was placed on a section of I-90 in Erie County in the mid 1980s. Several accidents occurred as a result of the application, so although it was technically a valid treatment selection, PennDOT subsequently severely limited the use of fog seals where the application might result in accident problems.

Considering a combination of the information reviewed during the literature review and research survey, a guideline summary has been drafted. This guideline can provide the basis for treatment selection in the future. The treatment selection process will be further refined by the addition of the cost benefit analysis. The draft guideline summary follows.

III.6.1 Draft Pavement Treatment Guidelines

Thin Overlay

The thin overlay can be used for all pavement conditions, all traffic levels, and all types of flexible pavement. It should be noted that in cases of severe rutting, rut filling is required prior to placement of the thin overlay. In cases of high severity fatigue cracking, and to a lesser degree any fatigue cracking, the expected additional performance obtained from the overlay should be limited.

Crack Seal

Crack sealing can be used for all pavement conditions, for all traffic levels and all types of flexible pavement. In certain urban conditions, and high traffic volumes, careful blotting of the fresh crack seal should be undertaken to prevent tracking. If the quantity of crack sealing will result in the initial cost of crack sealing being greater than applying another treatment, for example a chip seal, the alternative treatment will provide more cost effective results.

Chip Seal

Chip seals can be used on a wide variety of existing pavement surface conditions. The chip seal treatment can be placed on any traffic level roadway. However, for high volume roads specific techniques need to be followed including the use of hot asphalt binder and pre-coated chips. Without the use of pre-coated chips, chip seals should not be applied on roads with greater than 10,000 ADT. Chip seals are better used on rural roads than urban, and should be used selectively on urban roads where chip loss or delayed opening to traffic could be intolerable. Where severe ruts are present, ruts should be filled prior to applying the chip seal. Roads with areas of tree canopy should be considered carefully when emulsified asphalt is used, as the shade from trees will locally retard the curing process. When a roadway has high severity fatigue cracking, the expected increased performance resulting from the chip seal should be limited. Chip seals can be expected to provide limited ride quality improvement to very rough pavements.

Double seal coats can be used to achieve better performance than a single seal coat, and should be considered where appreciable truck traffic is present.

Polymer modified and rubber modified chip seals are reported by others to provide better aggregate retention than unmodified binders. Some of the Districts use polymer modified emulsions now, and the Department has drafted a specification for the use of crumb rubber modified emulsion. Experience to date has indicated that modified binders sufficiently improve the chip seal performance to justify the additional cost of the binder modification.

Microsurfacing

Microsurfacing can be used on roads with low to medium severity cracking and surface raveling. The treatment can be applied to all roadways at all traffic levels. However, if applied to badly distressed roads, such as in the case of high severity fatigue cracking, limited additional performance should be expected. When high severity cracking is present, crack sealing should be performed several months prior to the application of the microsurfacing. Different from the chip seal, microsurfacing provides an appearance similar to an HMA, and consequently may be more aesthetically pleasing to the travelling public in urban and high traffic volume situations. Minimal improvement in pavement roughness can be expected with this treatment.

Cape Seal

Cape seals can be applied to pavements with low to medium severity cracking and surface raveling. Cape seals provide better waterproofing protection and a smoother surface texture than a single chip seal. They can also address surface issues such as raveling and rough texture. The treatment is best used in locations with moderate traffic levels. Limited improvement in roughness can be achieved with this treatment. As with the slurry seal, the cape seal presents a surface texture and appearance similar to HMA.

Slurry Seal

Slurry seals can be used to address limited surface distress including cracking and raveling. The slurry seal treatment is best used in locations with limited freeze-thaw conditions. Since the cure time for slurry seals can be rather lengthy in the relatively humid conditions common in Pennsylvania, the affect of this climatic conditions on opening to traffic should be considered for this treatment. Slurry seal is best applied to low and moderate traffic level roadways.

NovaChip®

This treatment could be used for all highway traffic levels for both urban and rural roads. However, because of the cost, it is best used on medium and higher volume roads. Experience in Pennsylvania has largely been as a friction improvement overlay on structurally sound concrete pavements. This is a leading candidate for NovaChip® application. However, MnDOT reported success in limiting oxidation damage and preventing top down cracking when NovaChip® is installed as the original wearing surface of a new pavement structure.

Fog Seal

The fog seal treatment is intended to address surface oxidation of an existing pavement. By applying a fog seal early in the pavement life, within two years, the full benefit of resisting oxidation aging of the wearing course can be achieved. Fog seals have a record of producing slippery conditions for 24-36 hours after application. The National Center for Pavement Preservation recommends preparing a pavement surface, particularly one with excess asphalt, by shot blasting the surface prior to fog seal application. This preparation is reported to reduce the slippery surface usually associated with fog seals.

This document represents the findings from a survey of experience in other states with similar conditions, as well as the PennDOT Districts. The information gathered will be used to support the future analysis of cost benefit of the identified treatments during the remainder of the study.

IV. COST-BENEFIT ANALYSIS

IV.1 Introduction

It is well understood that cost-benefit analysis is a powerful tool to assist in the selection of construction, rehabilitation, and maintenance treatments by highway agencies. A proper and efficient cost-benefit analysis will provide the means for evaluating which surface treatment strategies are suitable for use in Pennsylvania. Based on the matrix of treatments and performance developed in task 2, a method that is very similar to the one contained in the performance analysis of SPS-3 treatments developed by Morian's team[39] was adopted in this task. Representative unit costs obtained from PennDOT districts, the ECMS database, or other industry sources were used in the analysis. The analysis was constructed so that each surface treatment is compared with conventional HMA surfacing. Additional commentary is provided about the performance of the various treatments relative to the performance of the initial hot mix asphalt pavement.

A summary of this task is provided in figure 6. First, cost information for the treatments used in Pennsylvania for both in-house maintenance and contract work was obtained from the Department. The performance life for different maintenance treatments was then determined based on the results of a research survey of other state experience developed in task 2. An equivalent annual cost (EAC) analysis was performed using this information to rank the cost effectiveness of the treatments. A life cycle cost analysis (LCCA) was also performed to provide a more in-depth analysis of treatment cost effectiveness.

As a next step, the effect of pavement condition at the time of treatment on benefit cost was evaluated using actual performance data. Pavement performance curves were developed for varying pavement conditions within each traffic network. The relationship between pavement life extension and pavement condition at the time of treatment was modeled using second order polynomial regression analysis; thus, the life benefit at any given pavement condition (OPI value) can be determined. Finally, the cost effectiveness was determined using both equivalent uniform cost and benefit cost ratio.

IV.2 Cost Benefit Analysis Methodologies

There are several approaches available for determining the cost effectiveness of various maintenance surface treatments[40,41], some of which can be very complex. Table 20 lists some common methods used by researchers and highway agencies. The EAC method was selected for use in this case because it is relatively straightforward and simple, which gives it utility for maintenance personnel. However, to look more in-depth into cost-benefit analysis of surface maintenance treatments, a LCCA is used as a supplement.

The equation for EAC is as follows:

$$\text{Equivalent Annual Cost (EAC)} = \frac{\text{Unit Cost}}{\text{Expected Life of Treatment, Years}} \quad (1)$$

As shown in the above equation, two input factors are critical to this method: representative unit costs and a meaningful representation of the performance life of individual treatments under the variety of climatic and geographic conditions encountered. Representative unit costs were obtained from several PennDOT districts, the ECMS database and, when necessary, supplemented by other industry sources.

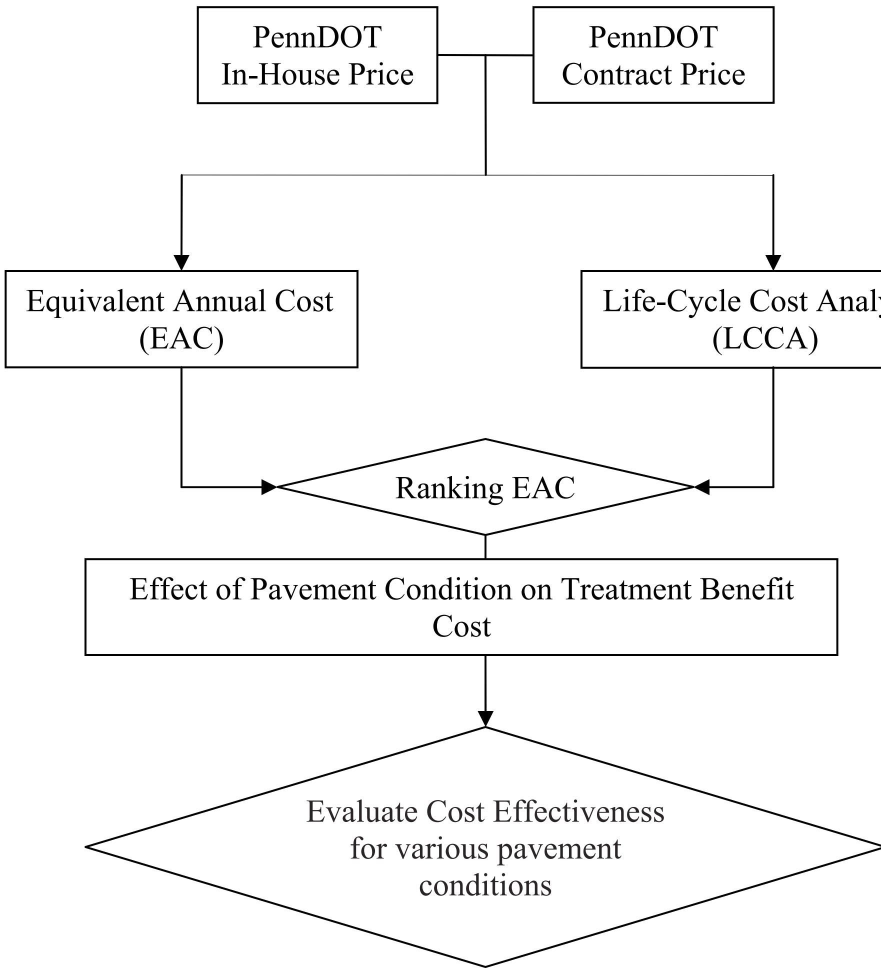


Figure 6. Road map for cost-benefit analysis

The performance life of individual treatments was based on performance data from the PennDOT Pavement Management database. When data was not available for a treatment, such as the thin hot mix overlay, average performance life information obtained from the survey of state highway agencies conducted in task 2 was used to fill the information gap.

To get a range of EAC to account for deviation of price and performance life under different conditions, minimum performance life and maximum costs were used, along with maximum performance life and minimum costs. Inordinately high/low treatment costs have not been used in this assessment. The performance life identified for the states selected on the basis of costs were then used to calculate an annual high and low cost for each treatment. This information was then expressed in terms of a ratio of equivalent costs relative to the thin overlay treatment.

The thin overlay treatment was selected as a reference value because of its widespread suitability and use.

Table 20. Common cost-benefit analysis methods[42]

Method	Input	Output
Life-Cycle Cost Analysis	• Interest rates • Inflation • Analysis period • Unit cost for treatment • Estimated life of treatment	Present Value (PV) or Equivalent Uniform Annual Cost (EUAC) for each proposed treatment
Equivalent Annual Cost	• Unit cost for treatment • Estimated life of treatment	Unit performance life of treatment per cost
Cost-Effectiveness Analysis	• Pavement performance curve	Area under the pavement performance curve is equivalent to effectiveness
Longevity Cost Index	• Treatment unit cost • Present value of unit cost over life of treatment • Traffic loading • Life of treatment	Relates present value of cost of treatment to life and traffic

As an example, the EAC of any treatment is divided by the EAC of the thin overlay to produce the thin overlay cost ratio:

$$Cost \quad Ratio = \frac{EAC \quad of \quad Crack \quad Sealing}{EAC \quad of \quad Thin \quad Overlay} \qquad (2)$$

IV.2.1 Equivalent Annual Cost Based Upon a Survey of State Highway Agencies

Table 21 gives EAC for various treatments based on the survey of state highway agencies developed in task 2. Accordingly, the cost ratio relative to thin overlay for each treatment was also calculated, as shown in table 21. As shown, NovaChip® is the only treatments whose average cost ratio are greater than 1, which indicates that NovaChip® could be less cost-effective than the thin overlay treatment. Crack sealing appears to be the most cost-effective treatment with an average EAC of 0.13 and benefit cost ratio of 0.26. Microsurfacing has only a slightly less cost ratio than the thin overlay, which means their cost effectiveness is similar to that of the thin overlay. The ranking of cost effectiveness for all treatments based on the average cost ratio relative to the thin overlay is provided in figure 7, showing that crack sealing has the lowest average cost ratio and NovaChip® has the highest.

Table 21. EAC based on the survey of state highway agencies

Treatment Type	Cost ($/yd^2)		Performance Life (year)		EAC ($/yd2/year)			Cost Ratio
	Low	High	Max.	Min.	Low	High	Ave.	
Thin Overlay	2.55	5.50	12	7	0.21	0.79	0.50	1.00
Micro-surfacing	2.00	4.00	12	5	0.17	0.80	0.48	0.97
Crack Sealing	0.32	0.40	5	2	0.06	0.20	0.13	0.26
Chip Seal	0.90	1.78	8	4	0.11	0.45	0.28	0.56
NovaChip®	4.50	6.50	15	8	0.30	0.81	0.56	1.11
Fog Seal	0.25	0.60	5	2	0.05	0.30	0.18	0.35
Slurry Seal	1.50	3.00	6	4	0.25	0.75	0.50	1.00

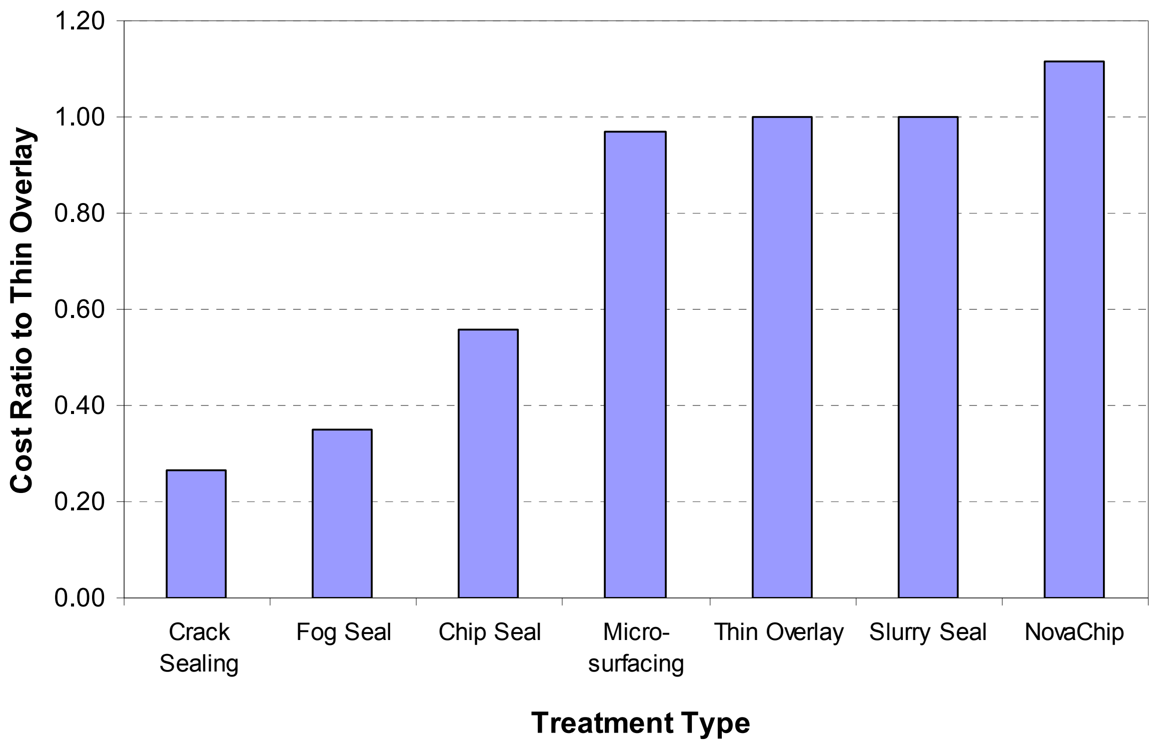


Figure 7. Ranking of surface treatment cost effectiveness based on state surveys

IV.2.2 EAC Based on PennDOT In-House Costs

Costs were obtained for three of the surface treatments from the PennDOT Districts for maintenance projects that are constructed using PennDOT maintenance crews; seal coat, 1" overlay, and crack sealing. The price for each treatment varies district by district. As is typical, a unit material price is greatly affected by the actual quantity purchased. For instance, the unit price for a 1" asphalt overlay was about $58 per ton for a quantity of 5,470 tons, while for 123 tons the price could be as high as $116 per ton. This illustrates the importance of selecting representative quantities for similar work when identifying unit material costs. Table 3 provides EAC for surface treatments based on PennDOT in-house prices. Again for this case cracking sealing provides the most cost effectiveness when evaluated in terms of the cost ratio compared with a 1” overlay. The seal coat treatment, with an average cost ratio of 0.58 is shown to be more cost effective than the overlay for in-house work.

Table 22. EAC based on PennDOT in-house costs

Treatment Type	Cost ($/yd^2)		Performance Life (year)		EAC ($/yd2/year)			Cost Ratio
	Low	High	Max.	Min.	Low	High	Ave.	
Seal Coat	1.50	2.20	8	4	0.19	0.55	0.37	0.66
1” Overlay	3.04	6.12	12	7	0.25	0.87	0.56	1.00
Crack Sealing	0.16	0.35	5	2	0.03	0.18	0.10	0.18

IV.2.3 EAC Based on PennDOT Contract (ECMS) Costs

This section of the report focuses on the analysis of the EAC based on PennDOT ECMS prices. The results of this analysis are shown in table 23. Again, the actual engineering quantity is the greatest factor affecting treatment price. However, another factor that affects the price of asphalt surface material is the aggregate type associated with different traffic levels to provide adequate skid resistance. For instance, for similar quantities of material the average price for microsurfacing with SRL-E coarse aggregate (two-way ADT: >20,000) has been about $\$3.15/yd^2$, but this decreases to $\$2.57/ yd^2$ for microsurfacing with SRL-G coarse aggregate (two-way ADT: 3,001-5,000). The ranking of treatment benefit cost effectiveness due to PennDOT ECMS prices is shown in figure 8. Again, crack sealing is found to be the most cost effective treatment in terms of cost ratio relative to the thin overlay. This is followed in the order of cost effectiveness by seal coat, microsurfacing, and NovaChip®. Both microsurfacing and seal coats are found to be between 2.5 and 3 times as cost effective as the thin overlay on the basis of contract unit prices.

Table 23. EAC based on PennDOT ECMS prices

Treatment Type	Cost ($/yd^2)		Performance Life (year)		EAC ($/yd2/year)			Cost Ratio
	Low	High	Max.	Min.	Low	High	Ave.	
Seal Coat	1.38	1.86	8.00	4.00	0.17	0.47	0.32	0.30
Thin Overlay	5.00	12.00	12.00	7.00	0.42	1.71	1.07	1.00
Crack Sealing	0.37	0.50	5.00	2.00	0.07	0.25	0.16	0.15
Micro-surfacing	1.53	5.32	12.00	5.00	0.13	1.06	0.60	0.56
NovaChip®*	5.00	10.00	15.00	8.00	0.33	1.25	0.79	0.74

*Note: Price was obtained from contractors.

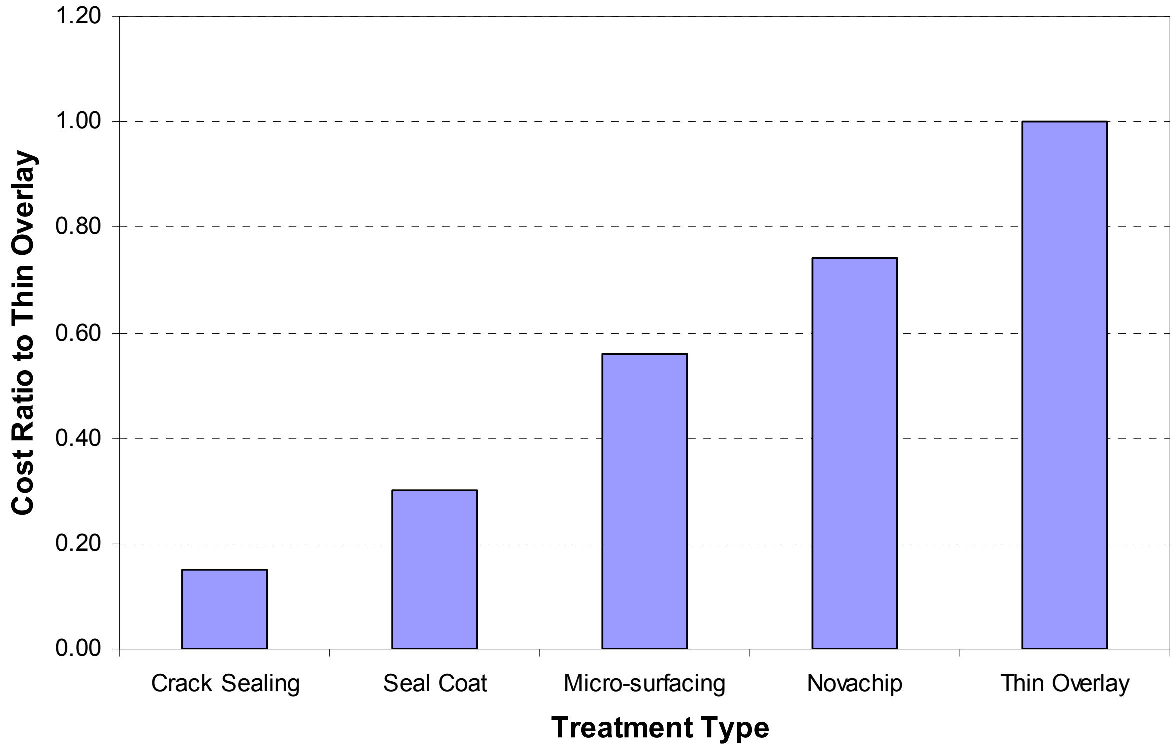


Figure 8. Ranking of treatment cost effectiveness based on PennDOT ECMS prices

IV.3 Life Cycle Cost Analysis (LCCA)

Life-cycle cost analysis (LCCA) is an engineering economic analysis tool used to compare the relative merit of competing project alternatives. LCCA provides an effective means of considering the total cost of an alternative to the agency, and user cost can also be considered in the investment decision. Performing LCCA is relatively complex when compared to the ECA evaluation method. A typical LCCA includes the following elements:

- Establish design alternatives
- Determine analysis period
- Discount rate
- Estimated costs (agency and user)
- Computation of life-cycle costs
- Analysis of the results

LCCA is typically used in two analytical forms: one is Net Present Value (NPV); the other is Equivalent Uniform Annual Costs (EUAC). These methods produce the same results, expressed differently, as discussed below.

IV.3.1 Net Present Value (NPV)

NPV is calculated by discounting all project costs to a base year, usually the present year. Thus, for purposes of comparison, all project costs throughout the analysis period are expressed in the form of a single cost in terms of the present (or other base year) year monetary value. The relative cost of alternatives can then be directly compared from this single representative value.

The calculation of NPV for pavement maintenance treatments can be expressed by the following equation:

$$NPV = IC + \sum_{k=1}^{n} PMC_k \frac{1}{(1+i)^k} \qquad (3)$$

Where:

IC= initial cost
i= discount rate
k= year of expenditure
PMC_k = maintenance treatment cost at year k
n= analysis period

IV.3.2 Equivalent Uniform Annual Costs (EUAC)

EUAC is another way to look at the results of a LCCA. In this case all alternative project costs are converted to the form of a uniform annual cost over the analysis period. Whereas NPV discounts all costs to a single base year which can then be compared, EUAC discounts all alternative activities to a yearly cost which is then compared. EUAC is particularly useful when budgets are established on an annual basis, and is, therefore, well suited to pavement maintenance treatment evaluation.

EUAC is determined by first calculating the NPV and then using the following formula to convert it to EUAC:

$$EUAC = NPV \left[\frac{(1+i)^n}{(1+i)^n - 1} \right] \qquad (4)$$

Figure 9 shows the relationship between NPV and EUAC based on a cash flow diagram.

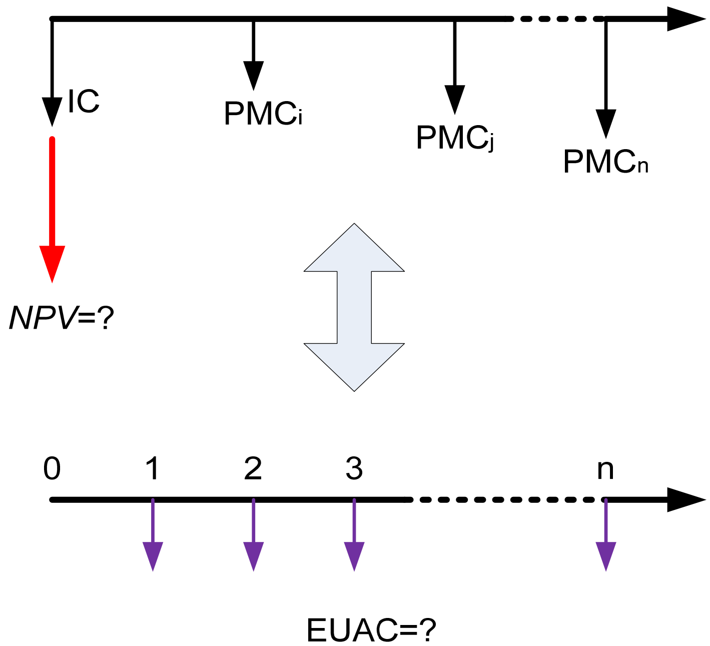


Figure 9. Relationship between NPV and EUAC based on a cash flow diagram

IV.3.3 Evaluation of Maintenance Treatment Cost Effectiveness

Previous investigations[39, 43, and 44] have shown that maintenance treatments in general are beneficial in extending the performance life of pavements. The goal is to determine which treatment is the most cost effective, and when in the life of a pavement the best benefit is realized. This evaluation includes not only the comparison of cost benefit between treatments, but also must consider the best time to apply the various treatments to realize the most benefit.

To evaluate the cost effectiveness of maintenance treatment activities at different times in the service life of a pavement structure it is necessary to assemble the range of activities, treatments cost information, and benefit realized at different application times during the pavement life. To illustrate this concept an exercise, using assumed values, was completed. The performance of the different treatments applied at various times was compared with the performance of the original pavement without any maintenance activity. The specific "maintenance treatment" scenario was then compared with the "do nothing" baseline performance model. For this exercise, an initial cost of $200,000 per lane mile was used for the baseline pavement with a 10 year service life in terms of net benefit (ΔEUAC) and benefit-cost (B/C) ratio (ΔEUAC divided by cost of annual preservation treatment).

The calculations of ΔEUAC and B/C are given by the following:

$$\Delta EUAC = EUAC_{do-nothing} - EUAC_{treatment} \qquad (5)$$

$$B/C = \frac{\Delta EUAC}{EUAC_{pvc}} \qquad (6)$$

Where, $EUAC_{do-nothing}$ is the computed equivalent uniform annual cost due to do nothing; $EUAC_{treatment}$ is the computed equivalent uniform annual cost with application of a treatment; and $EUAC_{pvc}$ is the computed equivalent uniform annual cost due to the cost of preservation.

Several scenarios were developed by varying the following:

- The maintenance treatment activity: crack sealing, chip seal, microsurfacing, thin overlay, and NovaChip®.
- The assumed year of maintenance treatment application: year 3, year 5, year 7, and year 10.
- The cost of a maintenance treatment: from $2,000 to $40,000 per lane mile, depending on treatment type.
- The additional year of pavement life resulting from maintenance treatment ranging from 0 to 10 years, depending on the scenario.

All the input information and output results based on the assumed treatment timing are provided in table 24 to illustrate the concept. As is evident in the table, all maintenance treatment scenarios produce a positive net benefit, which means the savings in EUAC were greater than the cost of the preservation treatment. Figure 10 shows a graphical comparison of the net benefit among different treatments. This indicates that the lower cost treatments such as crack sealing are most efficient when applied relatively early in the pavement life, while the higher cost treatments such as NovaChip® are more efficient when applied later in the pavement life. These results are consistent with the observed performance of the individual treatments, but they also serve to illustrate the importance of treatment application timing in obtaining the maximum treatment benefit for individual treatments.

Figure 11 provides a graphical comparison of cost effectiveness of different treatments expressed in terms of benefit-cost ratio. As expected, crack sealing has the highest benefit-cost ratio while NovaChip® has the lowest benefit-cost ratio, which agrees well with the EAC method. This also indicates that even though some of the treatments have a relatively low net benefit, they could have a very high benefit-cost efficiency. This information is useful in identifying treatments with a high benefit-cost ratio, which could be used when budget limitations may make it difficult to use a strategy with higher net benefit.

Table 24. Evaluation of the cost effectiveness of different maintenance treatments

Preservation Type	Preservation Cost ($ per lane mile)	Year Future Preservation Performed(year)	Life Value Added after Preservation (year)	Net Benefit (ΔEUAC) ($/year)	Benefit-Cost Ratio
Crack Sealing	2000	3	2	3118	15.57
Chip Seal	10000	3	2.5	3002	3.08
Microsurfacing	20000	3	3	2685	1.42
Thin Overlay	30000	3	4	2947	1.09
NovaChip®	40000	3	5	3123	0.90
Crack Sealing	2000	5	4	5496	34.18
Chip Seal	10000	5	5	5812	7.55
Microsurfacing	20000	5	6.2	6063	4.13
Thin Overlay	30000	5	7.5	6299	2.99
NovaChip®	40000	5	8.2	6074	2.21
Crack Sealing	2000	7	2	3160	19.91
Chip Seal	10000	7	3	3830	5.10
Microsurfacing	20000	7	4.5	4737	3.39
Thin Overlay	30000	7	8.5	7169	3.95
NovaChip®	40000	7	9.8	7312	3.14
Crack Sealing	2000	10	1	1673	11.82
Chip Seal	10000	10	2	2652	3.98
Microsurfacing	20000	10	3	3320	2.63
Thin Overlay	30000	10	7	6486	4.06
NovaChip®	40000	10	8	6639	3.22

IV.3.4 Effects of Pavement Condition on the Benefit Cost of the Treatment

It is well understood that the same treatment performs differently when applied to pavements in different condition levels (or at different times in the life of the pavement). Experience has shown that treatments applied too soon add little benefit, and treatments applied too late are relatively ineffective. For example, applying a seal coat to a 5-month old pavement in very good condition is not expected to significantly increase pavement life, since nearly all of the remaining performance of that pavement is still unused, and virtually no damage has taken place. Consequently, the seal coat applied with the objective of sealing cracks and preventing the egress of water, and possibly renewing the wearing surface adds little to the performance of the pavement. Similarly, applying the same treatment near the end of the pavement life when extensive structural deterioration has taken place is expected to have a limited effect in extending pavement performance, since the pavement is already in the advanced stages of failure. There may, however, be situations where it is necessary to make such a late application to keep a pavement in service until funding for more extensive repair or replacement are available.

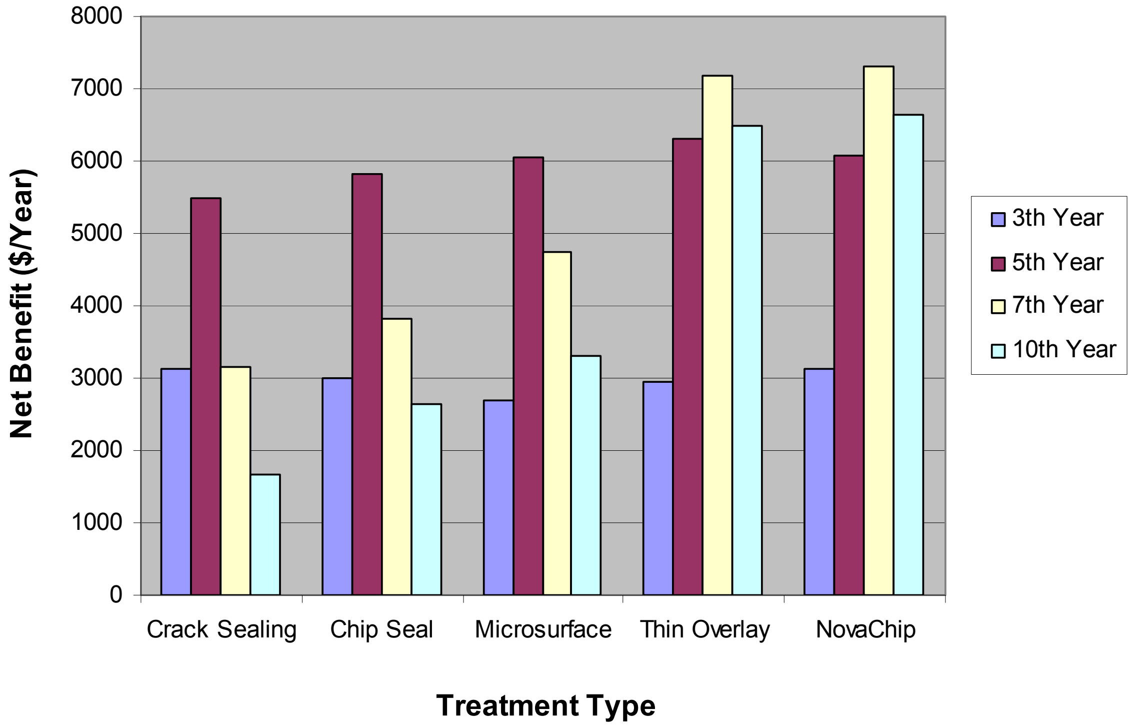


Figure 10. Net benefit based on the EUAC for different maintenance treatments

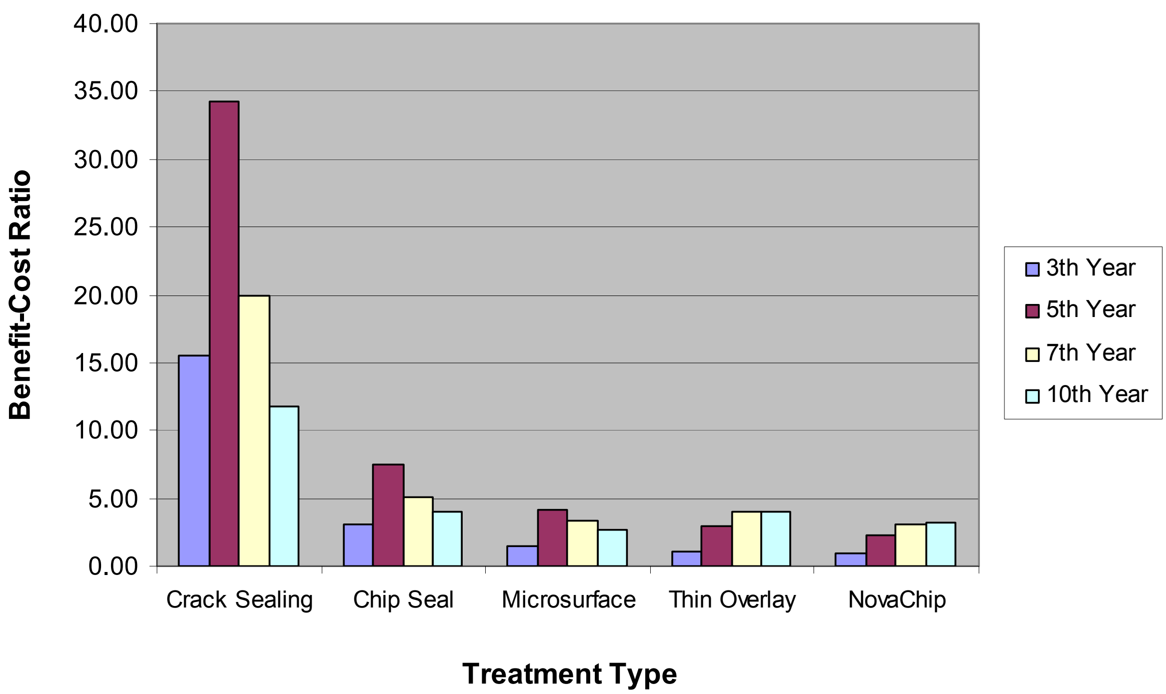


Figure 11. Benefit-cost ratio for different maintenance treatments

Between these two extreme application scenarios, there is an optimum pavement condition, and associated age (or a range of condition or age) when the benefit cost associated with a treatment is maximized. The analysis of how to identify when to "best" apply maintenance treatments has represented a challenge to maintenance professionals. The difficulty lies in establishing performance curves based on treatment application at different pavement conditions. Pavement management information in the form of the overall pavement index (OPI) from the PennDOT pavement management database has been used to make this evaluation.

The OPI was developed by PennDOT to measure overall pavement condition. It consists of a system of deductions for the presence of various distress and extent conditions. A 0-100 point scale is used as the basis for the OPI. In this scenario, 100 represents an undamaged pavement with no distress, and 0 represents the complete failure of the pavement. The OPI for asphalt concrete pavement (ACP) is computed as follows (PennDOT 2008; Morian and Cumberledge 1997):

$$OPI_{ACP} = 0.15FCI + 0.125TCI + 0.10MCI + 0.10EDI + 0.05BPI + 0.05RWI + 0.175RUT + 0.25RUF \quad (7)$$

Where, the fatigue cracking index (FCI), transverse cracking index (TCI), miscellaneous cracking index (MCI), edge deterioration index (EDI), bituminous patch index (BPI), raveling/weathering index (RWI), and rut depth index (RUT) are individual indexes ($INDEX_i$) computed as follows:

$$INDEX_i = 100 - D_{high} - (1 - D_{high}/100) \times D_{med} - (1 - D_{high}/100) \times (1 - D_{med}/100) \times D_{low} \quad (8)$$

Where, D_{high}, D_{med}, and D_{low} are the deduct values for each $INDEX_i$ and computed as functions of extent and severity (low, medium, and high) of the distress using the following equations:

$$D_{high} = 20 \times (extent)^{0.3495} \quad (9)$$

$$D_{med} = 10 \times (extent)^{0.3495} \quad (10)$$

$$D_{low} = 5 \times (extent)^{0.3495} \quad (11)$$

The roughness index (RUF) is computed as follows:

$$RUF = 100 - 0.27IRI + 11 \quad (12)$$

Where, *IRI* represents the international roughness index expression of pavement ride quality.

<u>Development of Pavement Performance Curves for Treatments</u>

The PennDOT pavement distress index is called the overall pavement index (OPI). This pavement performance data for flexible surfaced pavements was provided by PennDOT for the most recent historical 10-year period available (1998-2008). The OPI data was provided already grouped into the four traffic network levels defined by PennDOT:

- ADT less than 2000,
- ADT greater than 2000,
- National Highway System (NHS), and
- Interstate Highways.

Information from the pavement history providing maintenance activities for these four traffic network levels was also provided by PennDOT. Three maintenance treatments, seal coat, microsurfacing, and NovaChip®, were included in the maintenance history database provided. Based on the PennDOT pavement history, the seal coat treatment was applied most often to the network having ADT less than 2000 and microsurfacing was applied most often to roads in the network with ADT greater than 2000 and NHS. NovaChip® has only been applied to Interstate highways, typically as a thin overlay of sound concrete pavement with surface friction problems. Therefore, developed performance curves for NovaChip® were limited to the Interstate network. Performance curves were developed for the seal coats for both the low volume (the network with ADT less than 2000), and for the NHS. Microsurfacing performance curves were developed for the case of traffic volumes greater than 2000 and for the NHS.

Due to the overwhelming volume of pavement performance (OPI) data, the following procedures were developed for processing data:

- Sort OPI data based on the network level.
- Sort project maintenance history based on network level.
- Within each network level, sort project maintenance treatment history based on maintenance treatment type.
- Within each maintenance treatment history, sort by treatment application year.
- Based on maintenance treatment history and treatment application year, find corresponding project OPI information and process OPI data for that year.
- Select pavement segments with effective OPI data. The effective OPI data were defined as OPI would decrease with time after the application of treatments.
- Group effective OPI data based on pavement condition prior to maintenance treatment application.
- Perform linear regression analysis and develop OPI curves at different pavement conditions levels.

Using these procedures, pavement performance curves based on OPI were developed for the treatments for each traffic network, as shown in figures 12 through 16. The population data by network and treatment used to develop the OPI performance curves is summarized in table 25. As stated previously, not all of the performance data in the database were included in the analysis. The data for sections was screened by assessing whether the data for a section provided a reasonable trend over time. For example, for some segments, the OPI value increases with time which is not reasonable unless some work was performed on the section. Therefore, for this study only data showing a decreasing trend over time was included in the analysis. It can be observed that additional data quality could be beneficial to the use of the data, and that reasonable variation in the data can be identified by conducting more detailed analysis than time permitted here.

Table 25. Summary of population used to develop OPI curves for treatments

Preservation Type	Traffic Network	Population Used to Develop OPI Curves		Total Number of Routes in Maintenance History Database
		Number of Routes	Number of Segments	
Seal Coat	ADT<2000	233	2619	392
	NHS	6	39	10
Microsurfacing	ADT>2000	36	395	57
	NHS	4	104	7
NovaChip®	Interstate	10	60	16

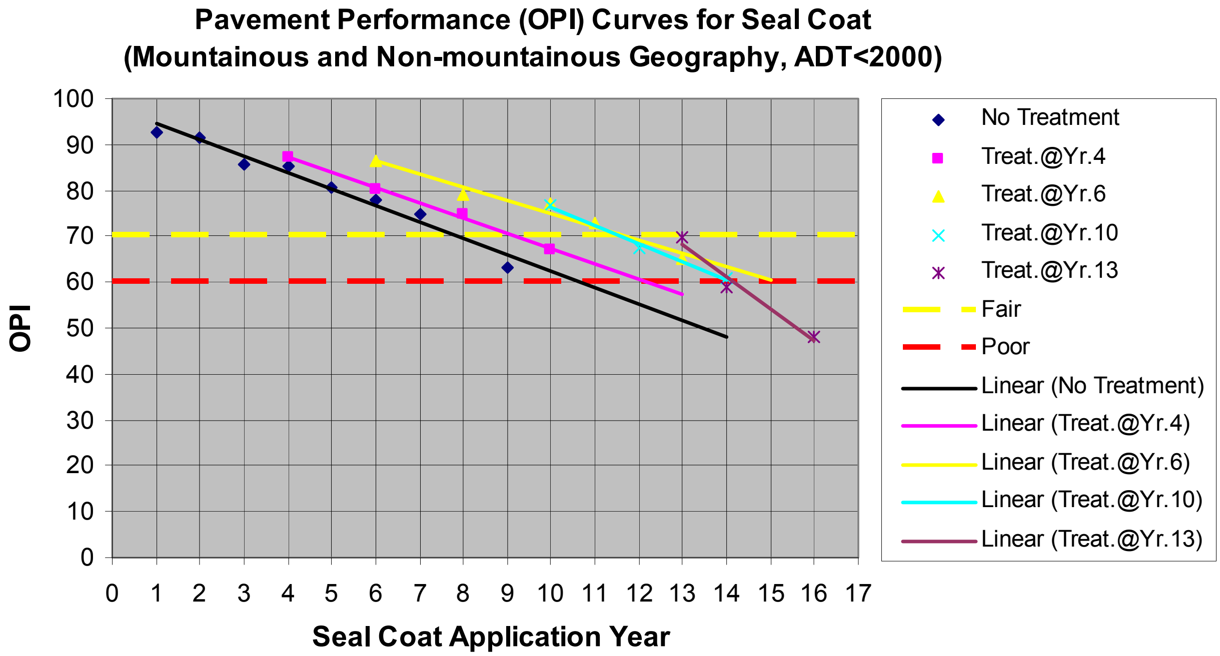


Figure 12. Developed OPI performance curves for seal coat including both non-mountainous and mountainous geography (ADT <2000)

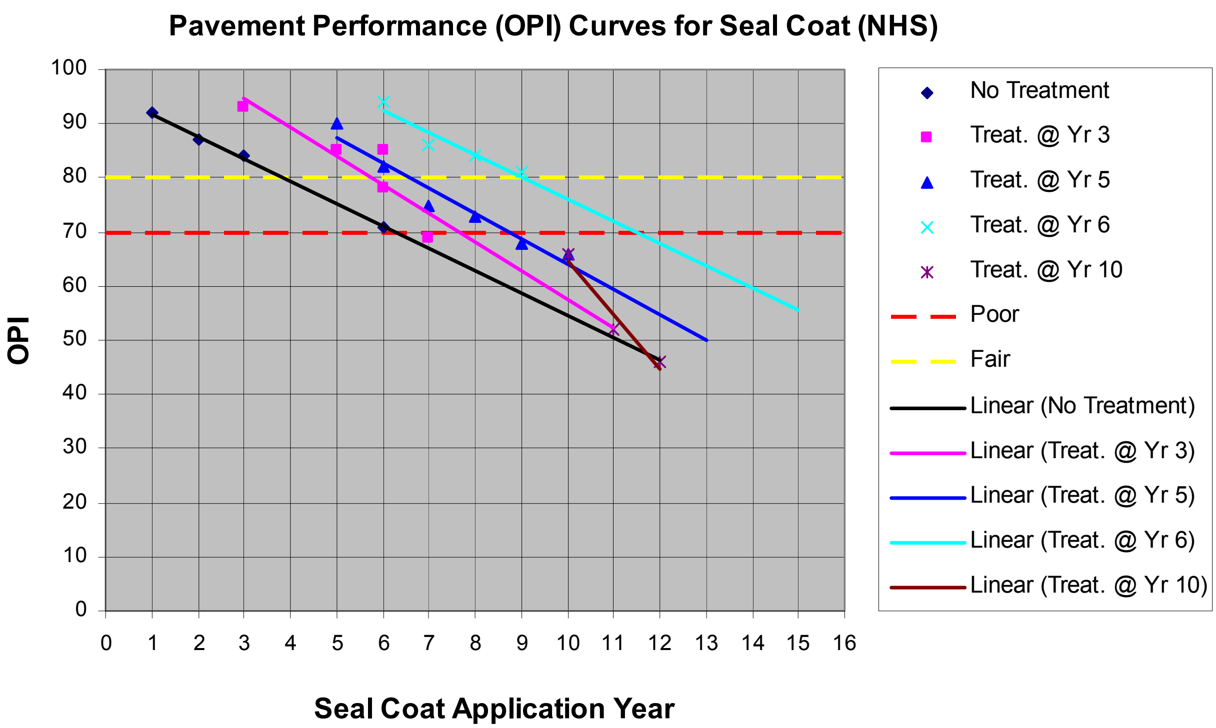


Figure 13. Developed OPI performance curves for seal coat (NHS)

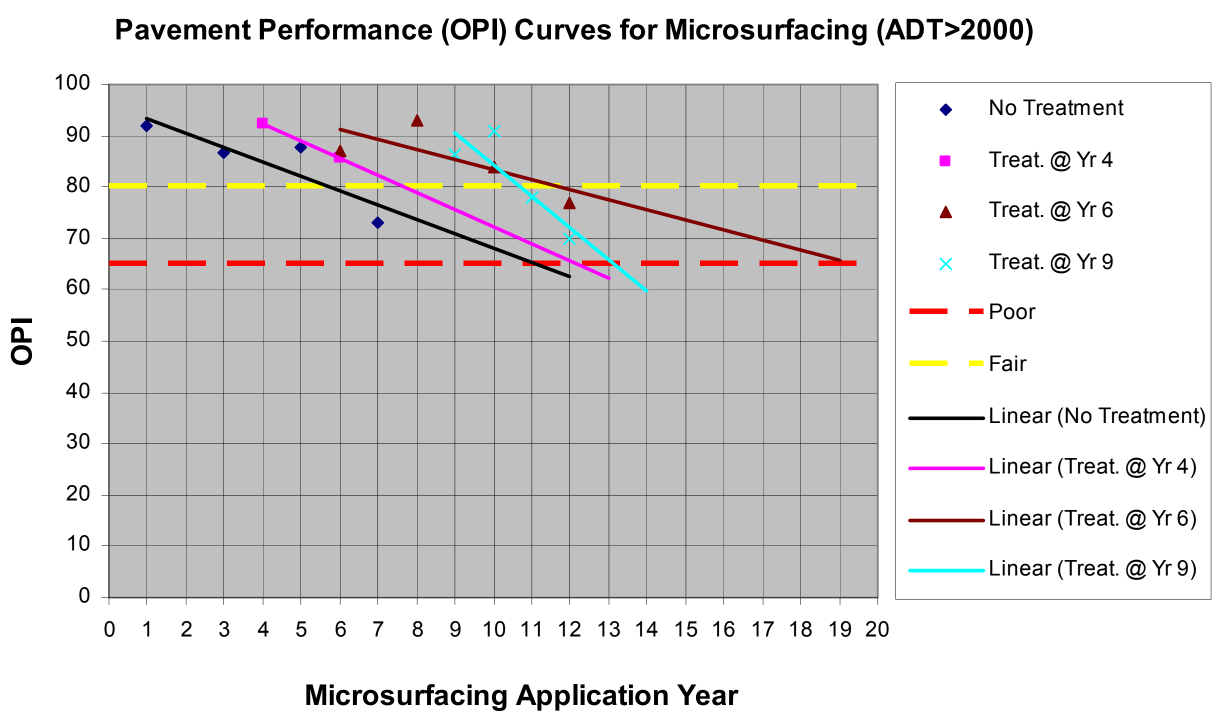


Figure 14. Developed OPI performance curves for microsurfacing (ADT>2000)

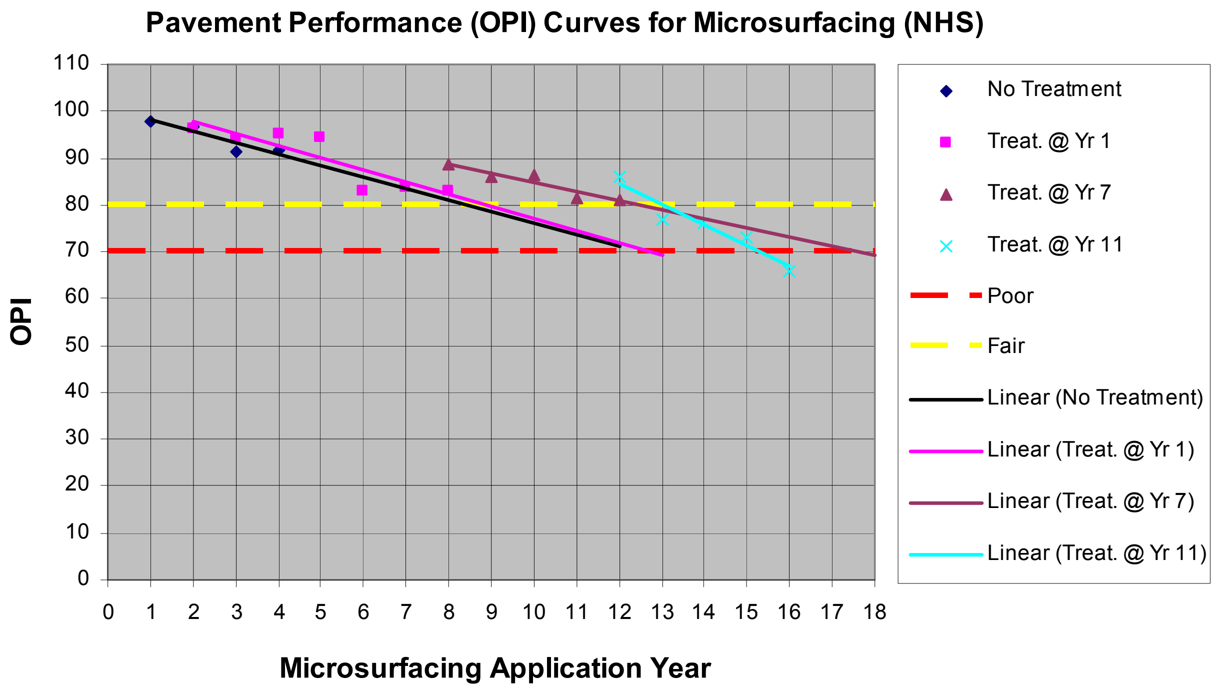


Figure 15. Developed OPI performance curves for microsurfacing (NHS)

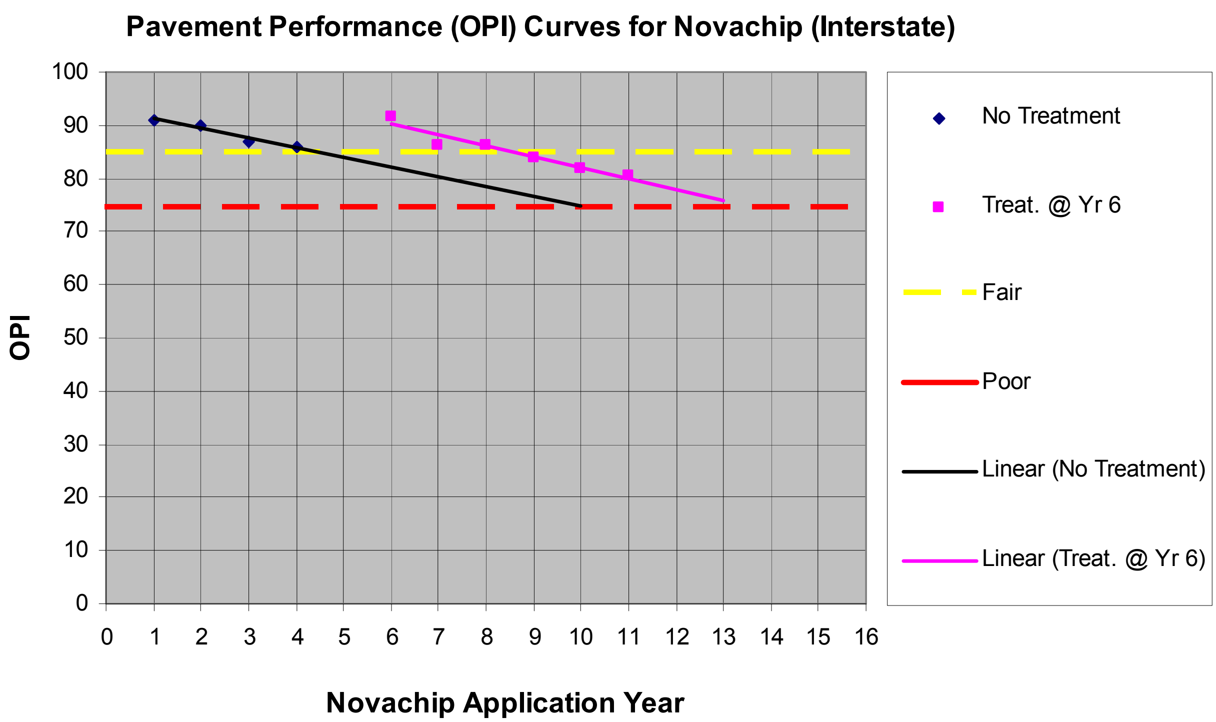


Figure 16. Developed OPI performance curves for NovaChip® (Interstate)

As observed from above figures, within each traffic network, the pavement condition before treatment application greatly affects OPI based performance curves with the exception of NovaChip® which is generally applied to good pavement sections with OPI greater than 80. From this information it can be seen that an optimum pavement condition or age exists (or a range of condition or age) where the pavement performance associated with a specific maintenance treatment is maximized. For example, the analysis shows that for the seal coat treatment for the network with less than 2000 ADT, the performance benefit can be maximized at an OPI of around 75 in this case. When the seal coat is applied to a pavement with OPI above 85, the increase in pavement life is limited to 1 year when the terminal index is defined as an OPI equal to 60. When the seal coat is applied to a pavement with OPI around 65, the increased pavement life is seen to be about 3 years. In this scenario the effect on pavement performance is less than the maximum value of 4.5 years for this treatment and this traffic level network. This analysis is consistent with the observation of many that treatments applied too soon or too late are not cost effective. The effects of traffic network on the pavement performance, expressed in terms of OPI, are also shown in the figures. In general, the condition of the pavement networks decrease as the traffic level decreases. For instance, the pavement deterioration rate, as shown by the slope of performance curves for the Interstate highway pavement network, is generally between -2 and -0.5. By comparison, for the NHS system pavements the slope is -2 to -4 and less than -4 for non-NHS pavement. For instance, the maximum life increase for the seal coat treatment applied to NHS system pavements is approximately 5.5 years, while for non-NHS system pavements with ADT less than 2000 the maximum increase in performance life is only 4 years.

To study whether local geography, i.e., mountainous vs. non-mountainous, has an effect on treatment performance, further analysis of the seal coat was conducted. The seal coat treatment was selected for this comparison because it had sufficient OPI data to perform the separate analysis of both geographical areas. To do this, counties were first separated on the basis of predominant geography. Then, pavement segments within each pavement geographic area were grouped to develop pavement performance curves for the seal coat treatment. The results are provided in figures 17 and 18. From these performance curves, a relationship between pavement life extension and pavement condition prior to the application of the seal coat was developed for the cases of terminal serviceability index (TSI) equal to 60 and 70, respectively. A single factorial ANOVA analysis was conducted to test whether the local geography surrounding the pavement has a significant effect on treatment performance expressed as pavement life extension. The results are shown in tables 26 and 27 for the two TSI values. It can be observed from these tables that the local geography surrounding a pavement is not a statistically significant factor in the performance of the seal coat treatment, as demonstrated by the p-value being much greater than the 5% test level. Therefore, a cumulative performance curve including both mountainous and non-mountainous geography was developed for the seal coat treatment, as shown in figure 12.

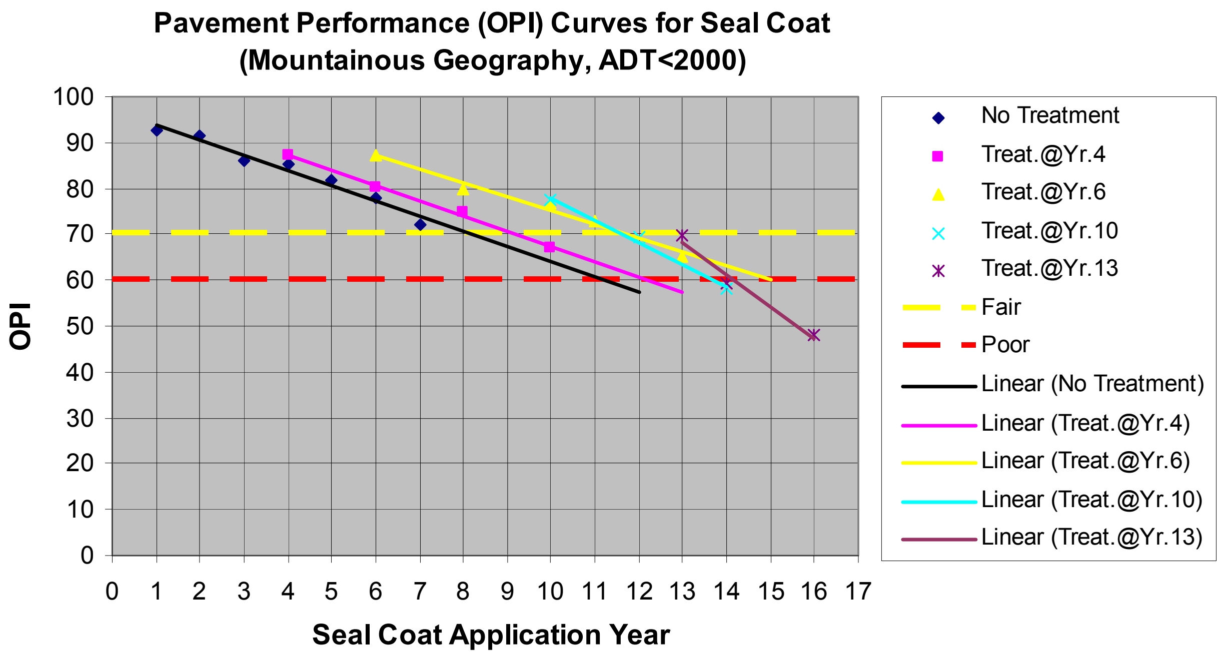


Figure 17. Developed OPI performance curves for seal coat in mountainous geography (ADT <2000)

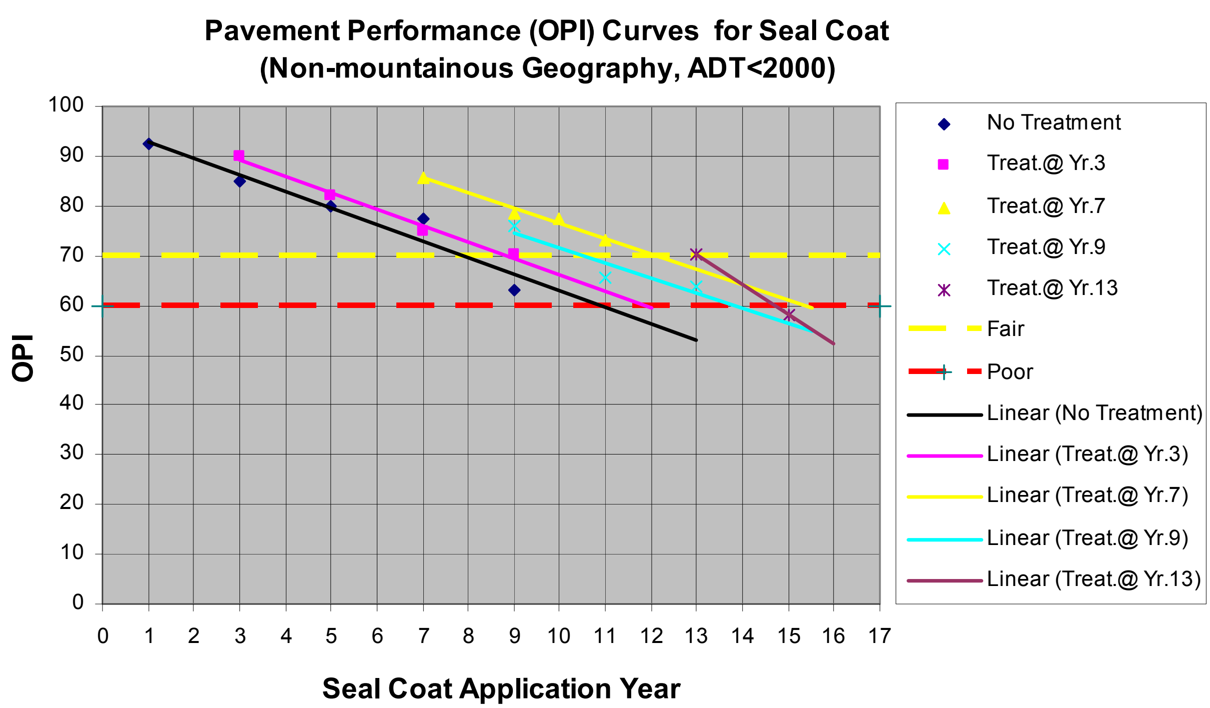


Figure 18. Developed OPI performance curves for seal coat in non-mountainous geography (ADT <2000)

Table 26. ANOVA for Geography Test (TSI: 60)

Groups	*Count*	*Sum*	*Average*	*Variance*
Non-mountainous	11	33.0363	3.0033	2.0712897
Mountain	11	32.978	2.998	1.4137762

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	$F_{crit@0.05}$
Between Groups	0.000154	1	0.000154	8.866E-05	0.992581	4.351243
Within Groups	34.85066	20	1.742533			
Total	34.85081	21				

Table 27. ANOVA for Geography Test (TSI: 70)

Groups	*Count*	*Sum*	*Average*	*Variance*
Non-mountainous	11	26.6662	2.4242	1.941315
Mountain	11	27.2063	2.4733	1.193328

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	$F_{crit@0.05}$
Between Groups	0.013259	1	0.013259	0.00846	0.927631	4.351243
Within Groups	31.34643	20	1.567321			
Total	31.35969	21				

Relationship between Pavement Life Extension and Pavement Condition Prior to Treatment

To further study how pavement condition affects the performance of maintenance treatments, a relationship between pavement life extension obtained after the application of the treatments and the condition level (expressed as OPI) at the time of treatment is expressed in the form of the pavement performance curves presented in section 3.4.1. Here, the pavement life extension is defined as how many additional years the pavement takes to reach the terminal serviceability value as a result of the treatment. For instance, if a pavement has 10-year life with no maintenance treatment, and a maintenance treatment is applied to this pavement at year 7 with the result that the pavement fails after year 15, then the increase pavement life due to the treatment is 5 years (15-10=5).

To calculate pavement performance, the increased pavement life from the OPI curves developed at an appropriate terminal serviceability index (TSI) must be defined for each network. The TSI is defined as the pavement condition level at which the treatment is considered to be failed, and extensive repair or replacement is required. PennDOT provided terminal serviceability index values for each network as shown in table 28. This table is also used to express general pavement condition based on OPI values in four categories: excellent, good, fair, and poor. The TSI values are shown as a red dashed line in figures 12 to 16. The yellow dashed line in these figures represents the boundary between good and poor condition, and are defined by PennDOT in table 28.

Table 28. PennDOT OPI reporting guidelines

<table>
<tr><th rowspan="2">OPI Value</th><th colspan="4">Network Category</th></tr>
<tr><th>Interstate</th><th>Other NHS</th><th>Non-NHS>=2000</th><th>Non-NHS<2000</th></tr>
<tr><td>>95</td><td>Excellent</td><td>Excellent</td><td rowspan="2">Excellent</td><td rowspan="3">Excellent</td></tr>
<tr><td>91-95</td><td rowspan="2">Good</td><td rowspan="3">Good</td></tr>
<tr><td>86-90</td><td rowspan="2">Good</td></tr>
<tr><td>81-85</td><td rowspan="2">Fair</td><td rowspan="3">Good</td></tr>
<tr><td>75-80</td><td rowspan="2">Fair</td><td rowspan="3">Fair</td></tr>
<tr><td>70-74</td><td rowspan="4">Poor</td></tr>
<tr><td>65-69</td><td rowspan="3">Poor</td><td rowspan="2">Fair</td></tr>
<tr><td>60-65</td><td rowspan="2">Poor</td></tr>
<tr><td><60</td><td>Poor</td></tr>
</table>

Using the pavement performance curves for the treatments in figures 12 to 16, a relationship between pavement performance life extension and pavement condition level at the time of treatment was developed for all treatments within each traffic network at the good/fair OPI values and at the network defined TSI value. To better illustrate how to develop this relationship, an example of microsurfacing for the network with ADT greater than 2000 is presented. As shown in figure 14, when microsurfacing is applied to a pavement with OPI around 87 (pink line), the pavement performance life increase is about 1.2 years using a TSI of 65. However, when microsurfacing is applied to a pavement with OPI around 78 (brown line), the pavement performance life extension is as much as 8 years. Further, when microsurfacing is applied to a pavement with OPI around 68 (blue line), the pavement performance life decreases to 2 years. With this information, a relationship between pavement performance life extension and pavement condition level (OPI) before treatment can be plotted and a regression analysis can be performed to determine pavement performance life extension at other pavement condition levels. Using this procedure, the relationship between pavement performance life extension and pavement condition at the time of treatment was developed for each treatment at the PennDOT designated TSI, as is shown in figures 19 through 23.

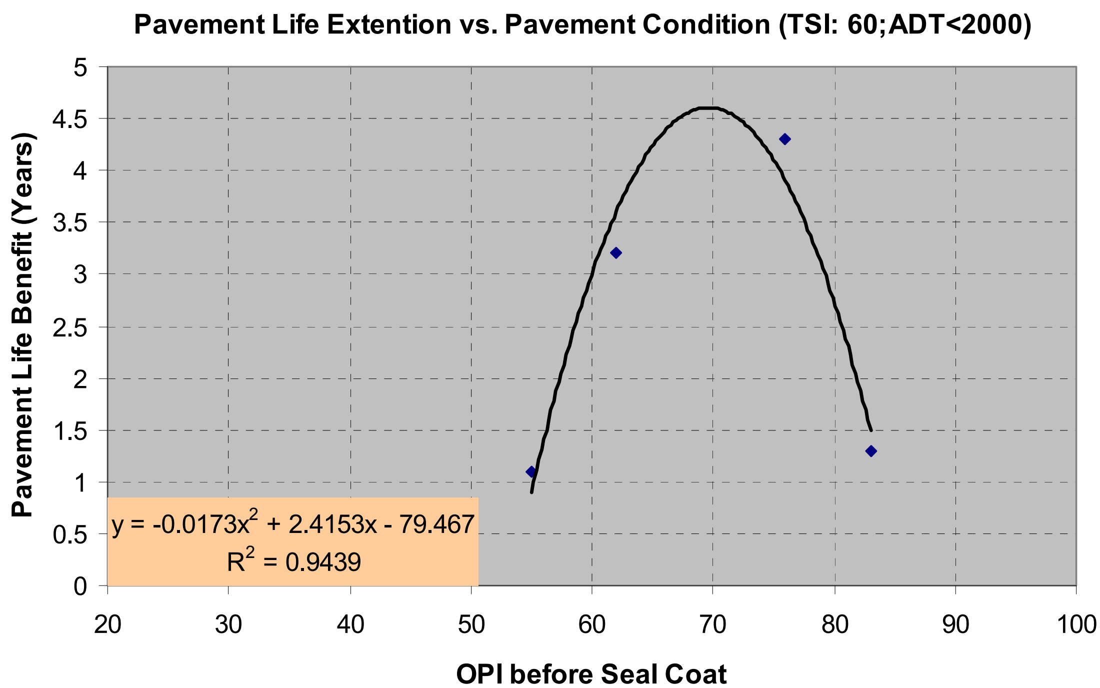


Figure 19. Pavement performance life extension vs. pavement condition at the time of seal coat application (TSI: 60; ADT<2000)

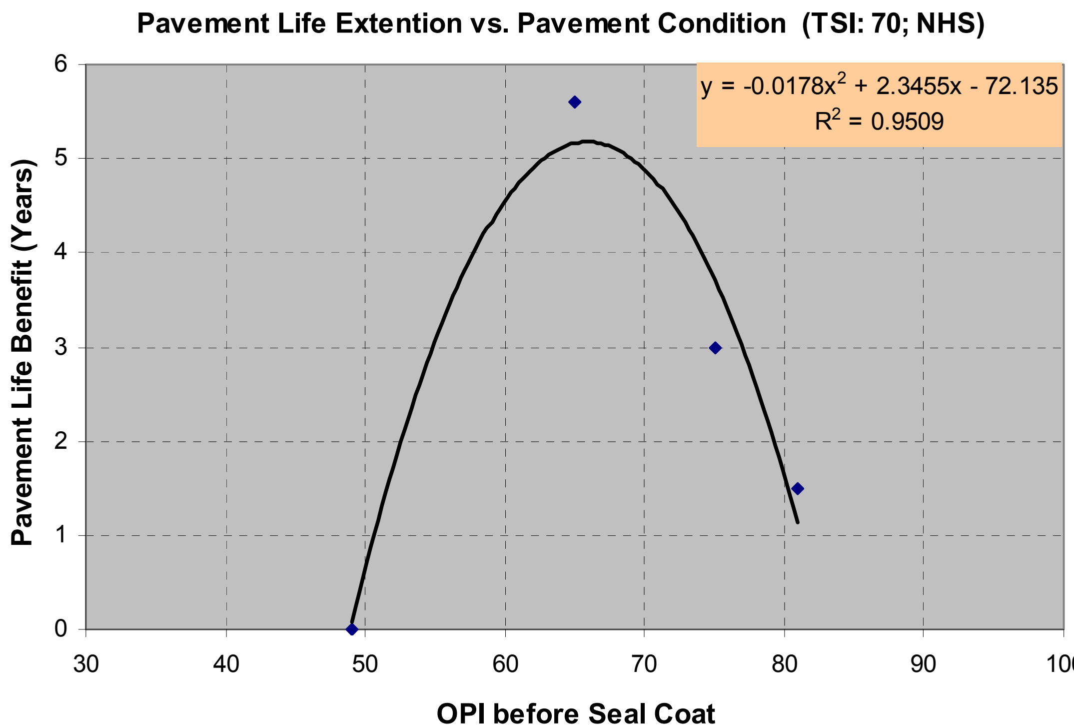


Figure 20. Pavement performance life extension vs. pavement condition before seal coat application (TSI: 70; NHS)

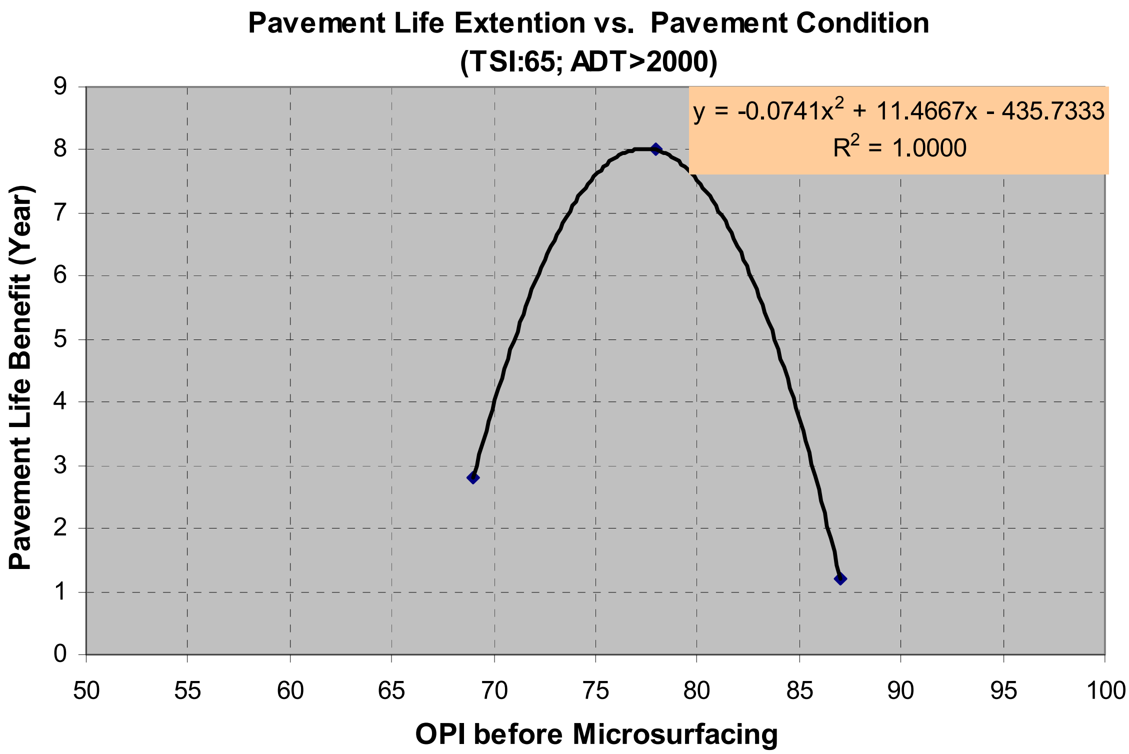


Figure 21. Pavement performance life extension vs. pavement condition before microsurfacing application (TSI: 65; ADT>2000)

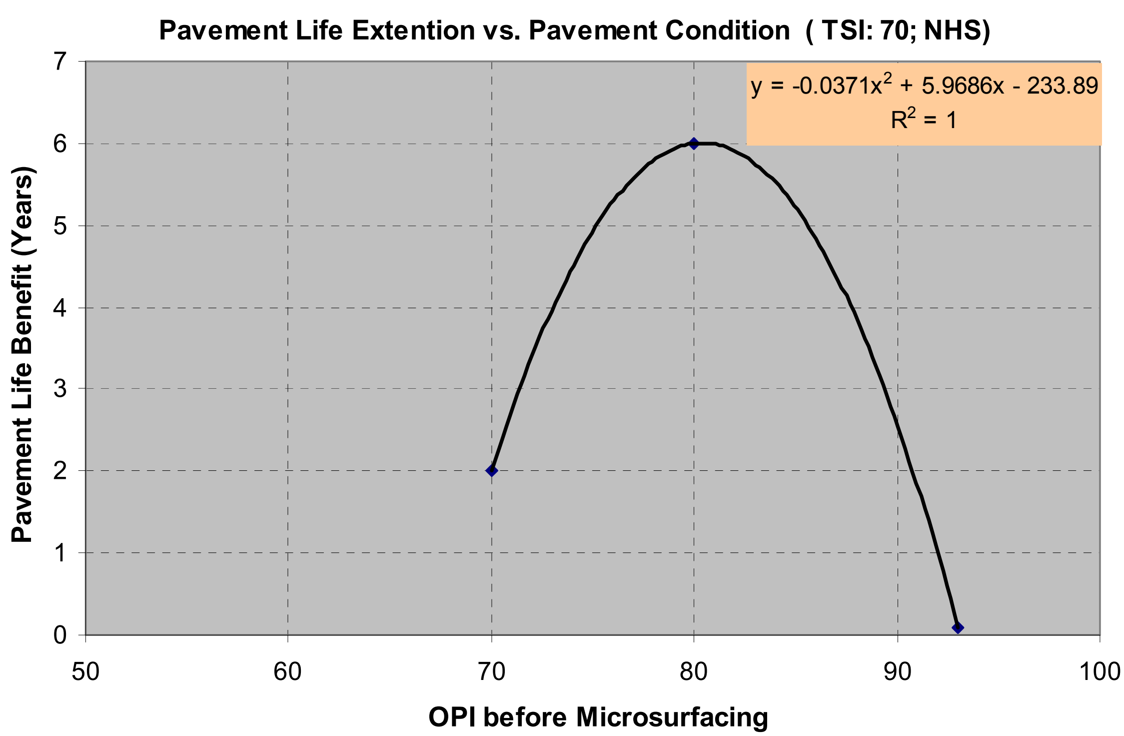


Figure 22. Pavement performance life extension vs. pavement condition before microsurfacing application (TSI: 70; NHS)

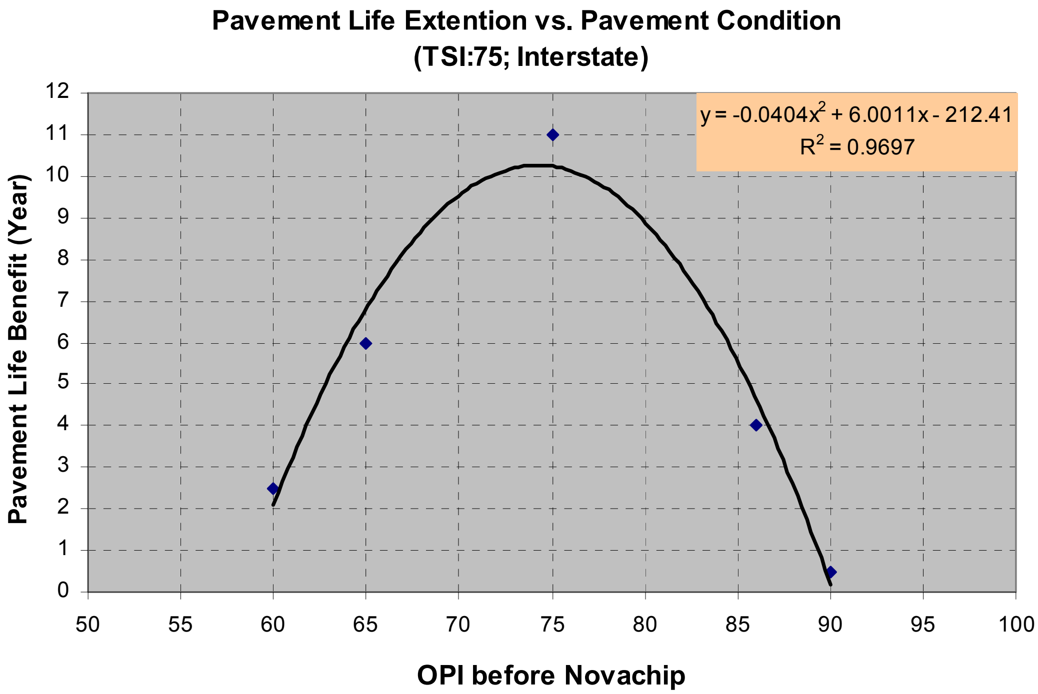


Figure 23. Pavement performance life extension vs. pavement condition before NovaChip® application (TSI: 75; Interstate)

To demonstrate the effect of selecting a different TSI, further analysis was conducted for each treatment and traffic network level at a second assumed TSI value. These results are provided in figures 24 through 28. A comparison of results for the same treatment and traffic level can be obtained from these two groups of figures.

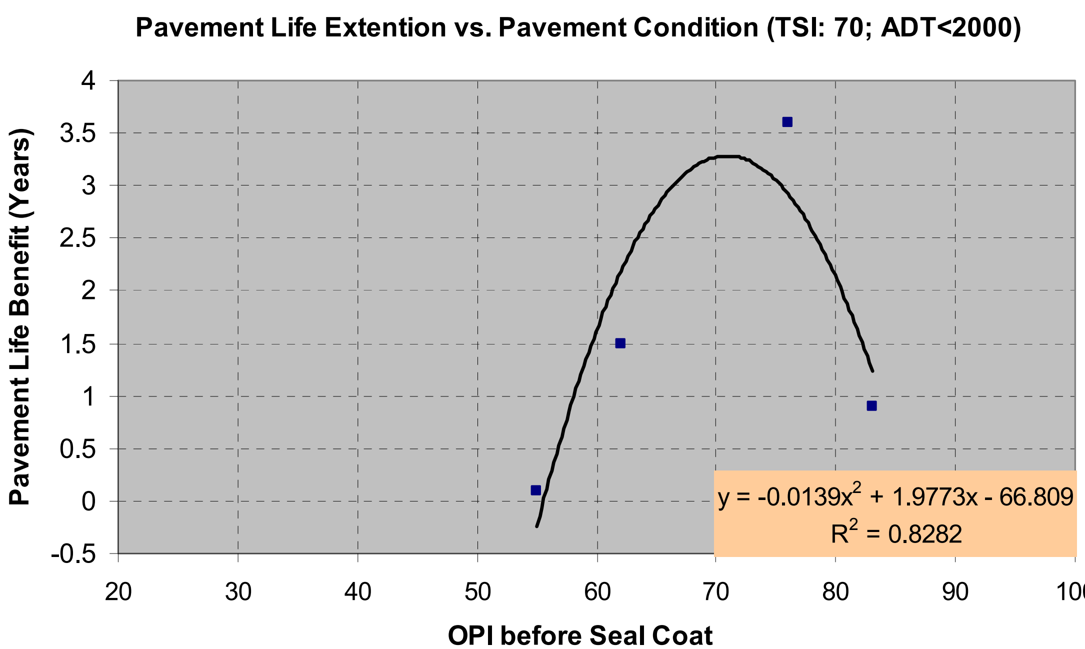


Figure 24. Pavement performance life extension vs. pavement condition before seal coat application (TSI: 70; ADT<2000)

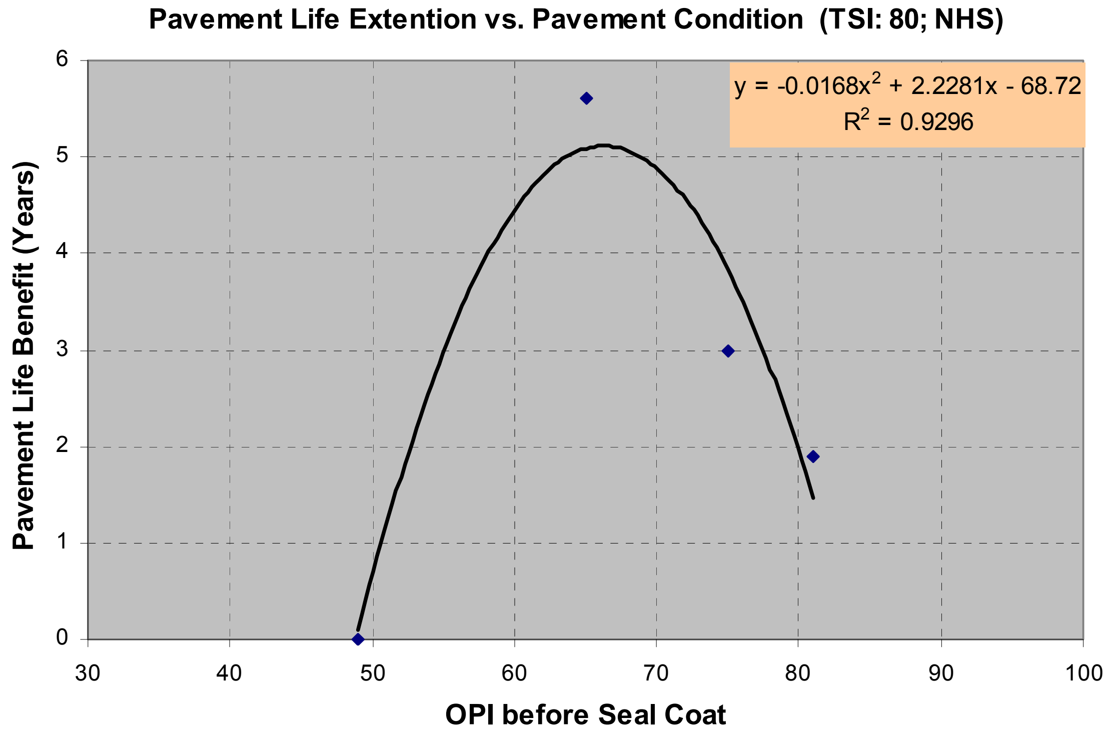


Figure 25. Pavement performance life extension vs. pavement condition before seal coat application (TSI: 80; NHS)

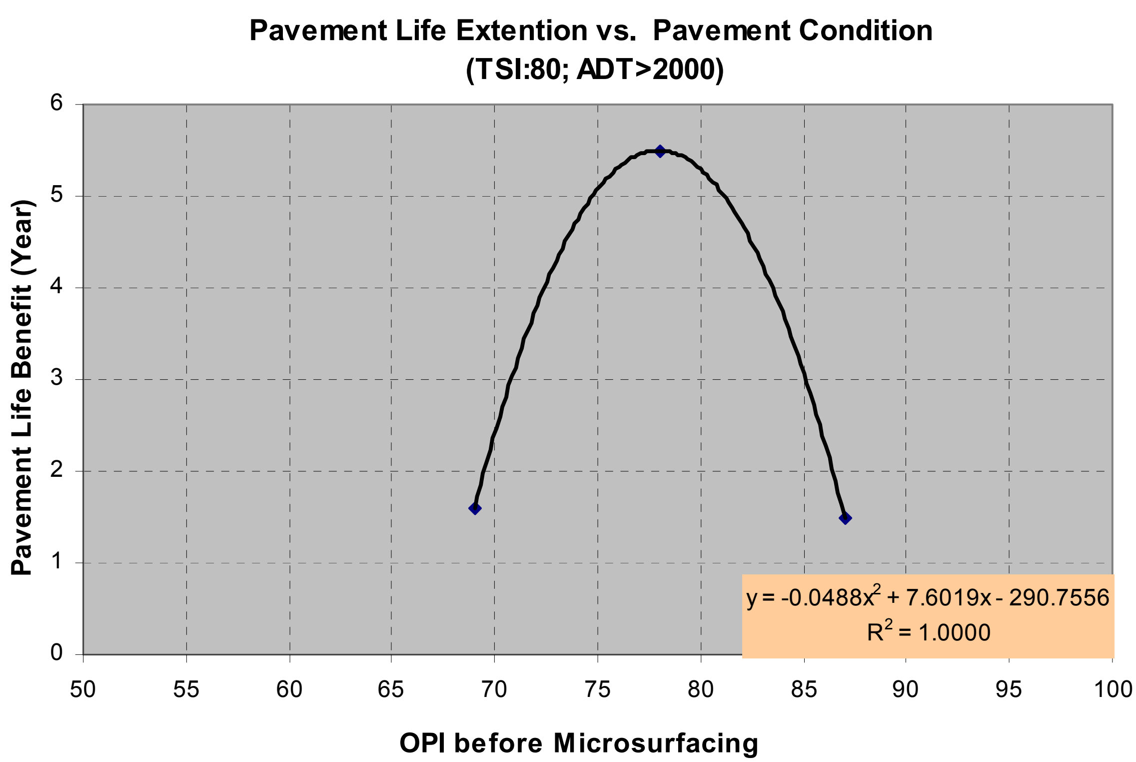


Figure 26. Pavement performance life extension vs. pavement condition before microsurfacing application (TSI: 80; ADT>2000)

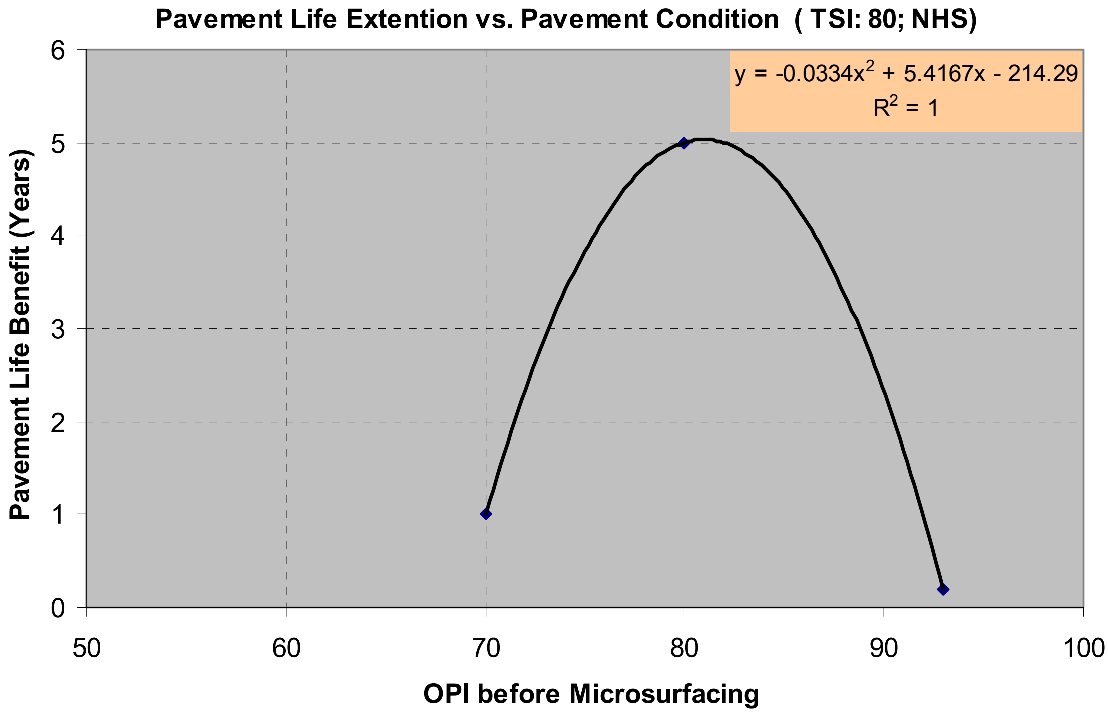


Figure 27. Pavement performance life extension vs. pavement condition before microsurfacing application (TSI: 80; NHS)

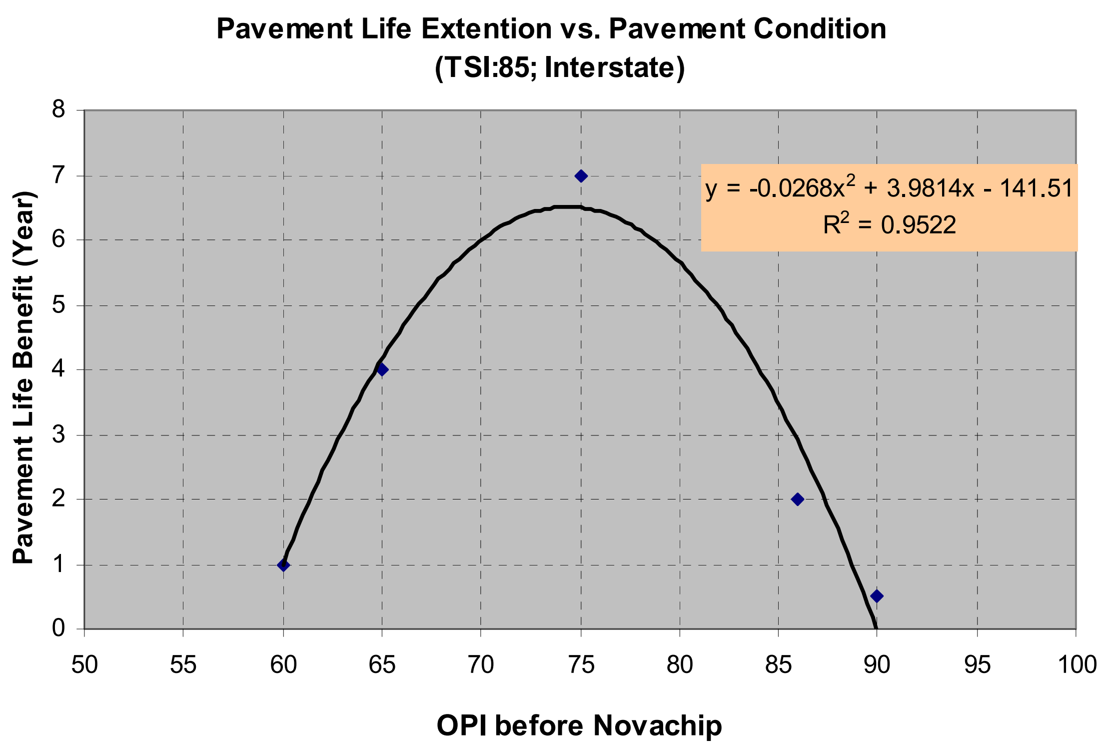


Figure 28. Pavement performance life extension vs. pavement condition before NovaChip® application (TSI: 85; Interstate)

A second order polynomial regression analysis was created for each curve using the following format:

$$y = ax^2 + bx + c \quad (13)$$

Where, y is the pavement performance life extension in years; *x* is the pavement condition level (OPI value) prior to treatment; and a, b, and c are regression coefficients. The regression results are summarized in table 29. Thus, the pavement performance life extension for a specific treatment can be easily computed for any condition level expressed as an OPI value using those regression equations in table 29. It should be noted that for NovaChip® there was not enough data to develop OPI performance curves for pavement condition less than an OPI of 80. Therefore, the pavement performance life extension for NovaChip® (about 8-12) was based on information from the research survey conducted in task 2.

Table 29. Summarized results of polynomial regression analysis

Preservation Type	Traffic Network	TSI	Polynomial Regression Equation	R^2
Seal Coat	ADT<2000	60	y = -0.0173x^2 + 2.4153 – 79.467	0.9439
		70	y = -0.0139x^2 + 1.9773x – 66.809	0.8282
	NHS	70	y = -0.0178x^2 + 2.3455x - 72.14	0.9509
		80	y = -0.0168x^2 + 2.2281x - 68.72	0.9296
Microsurfacing	ADT>2000	65	y = -0.0741x^2 + 11.4667x - 435.73	1
		80	y = -0.0488x^2 + 7.602x – 290.76	1
	NHS	70	y = -0.0371x^2 + 5.9686x - 233.89	1
		80	y = -0.0334x^2 + 5.4167x - 214.29	1
NovaChip®	Interstate	75	y= -0.0404x^2 + 6.0011x - 212.41	0.9677
		85	y = -0.0268x^2 + 3.9814x - 141.51	0.9522

Determine the Most Cost-Effective OPI Scenario

Once the life benefit is determined, the next step is to analyze the benefits and costs computed for each OPI value to determine the most cost effective OPI scenario that provides the largest B/C factor or net benefit ΔEUAC. A simple three-step LCCA is conducted to evaluate the cost effective of the preservation activities under different pavement conditions. First, the net present value (NPV) (at year zero) of each OPI scenario is determined using equation 3. Second, the computed NPV is converted into an equivalent uniform annual cost (EUAC) using equation 4. Third, ΔEUAC and B/C factor are calculated using equations 5 and 6, respectively. This process is best illustrated using an example.

Considering an original pavement in the network with ADT greater than 2000 has an initial cost of $ 200,000 per lane mile with 10 years service life, a microsurfacing will be applied to the pavement at various points in the pavement life, representing different pavement condition levels. The condition levels evaluated are represented as various OPI levels as follows:

- OPI scenarios: 87, 84, 81, 78, 75 and 70.
- Corresponding year of microsurfacing activity: year 2, year 3, year 5, year 7, year 8, and year 9.
- Cost of microsurfacing: $20,000 per lane mile.
- Discount rate: 6%.
- Terminal Service Index: 65.

Given the selected OPI values, the pavement life extension can be obtained using the regression equation from table 29, and then ΔEUAC and benefit-cost (B/C) can be calculated based on equations 3 to 6. The example results for microsurfacing are presented in table 30. As indicated in the table, except in the case of an OPI value of 87 and a TSI less than 65, all scenarios showed a positive net benefit. This implies that the savings in EUAC were greater than the cost of the treatment. The negative net benefit indicated occurs if the microsurfacing is applied to a pavement in very good condition, i.e., too early. The savings in EUAC won't offset the cost of microsurfacing. Figure 29 shows a graphical comparison of the net benefit at different OPI values. As indicated, the net benefit is maximized at an OPI value of 78. Figure 30 provides a graphical comparison of cost effectiveness for different OPI values in terms of B/C ratio. As indicated, the B/C ratio is greatest at an OPI value of 74. These two figures indicate the treatment having the maximum net life benefit does not necessarily have the greatest B/C ratio. It also indicates that even though the treatment has a relatively low net benefit, it could have a relatively high B/C efficiency. So, the treatment with high B/C ratio might be selected when budget limitations may not allow the strategy with highest net life benefit. In this case, the highway agency might not apply microsurfacing to the pavement at an OPI of 78 due to budget constraints; rather it might wait for the OPI value to decrease to 75 before applying the microsurfacing. The application of microsurfacing to the other traffic networks, with a range of TSI values used by PennDOT for each, is also presented in table 30. Tables 31 and 32 provide the analysis results for seal coat and NovaChip® treatments.

The analysis and information contained in this section is based on representative statewide data. This information can be used to provide guidance in the determination of when is the most cost effective time to apply treatments. From this information it can be determined if the benefit cost of a maintenance treatment can be maximized by applying the treatment sooner or later in the original pavement life than was done in the past. Also, by comparing the cost effectiveness between treatments, the selection of the most cost effective treatment can also be determined.

Table 30. Summary of cost effectiveness due to different OPI scenarios for microsurfacing

PV Type	Traffic Network	PVC ($ per lane mile)	Year Future Preservation Performed (year)	OPI	TSI	Life Benefit (year)	Net Benefit (ΔEUAC) ($/year)	B/C Factor
Micro-Surfacing	Non-NHS ADT>2000	20000	2	87	65	1.02	-414	-0.18
		20000	3	84	65	4.62	4492	2.56
		20000	5	81	65	6.90	6589	4.60
		20000	7	78	65	7.85	7379	5.98
		20000	8	75	65	7.46	7199	6.10
		20000	9	70	65	3.85	4222	3.29
		20000	2	87	80	1.55	493	0.23
		20000	3	84	80	3.78	3611	1.98
		20000	5	81	80	5.13	5158	3.37
		20000	7	78	80	5.58	5726	4.28
		20000	8	75	80	5.15	5429	4.23
		20000	9	70	80	2.47	2559	1.86
Micro-Surfacing	NHS	20000	1	90	70	2.61	1936	0.89
		20000	3	85	70	5.25	5077	2.97
		20000	6	80	70	6.03	6009	4.31
		20000	8	78	70	5.82	5996	4.80
		20000	9	74	70	4.51	4904	3.94
		20000	10	70	70	2.02	2017	1.52
		20000	1	90	80	2.67	2023	0.93
		20000	3	85	80	4.81	4677	2.68
		20000	6	80	80	5.29	5387	3.75
		20000	8	78	80	5.01	5295	4.10
		20000	9	74	80	3.65	4002	3.09
		20000	10	70	80	1.22	772	0.55

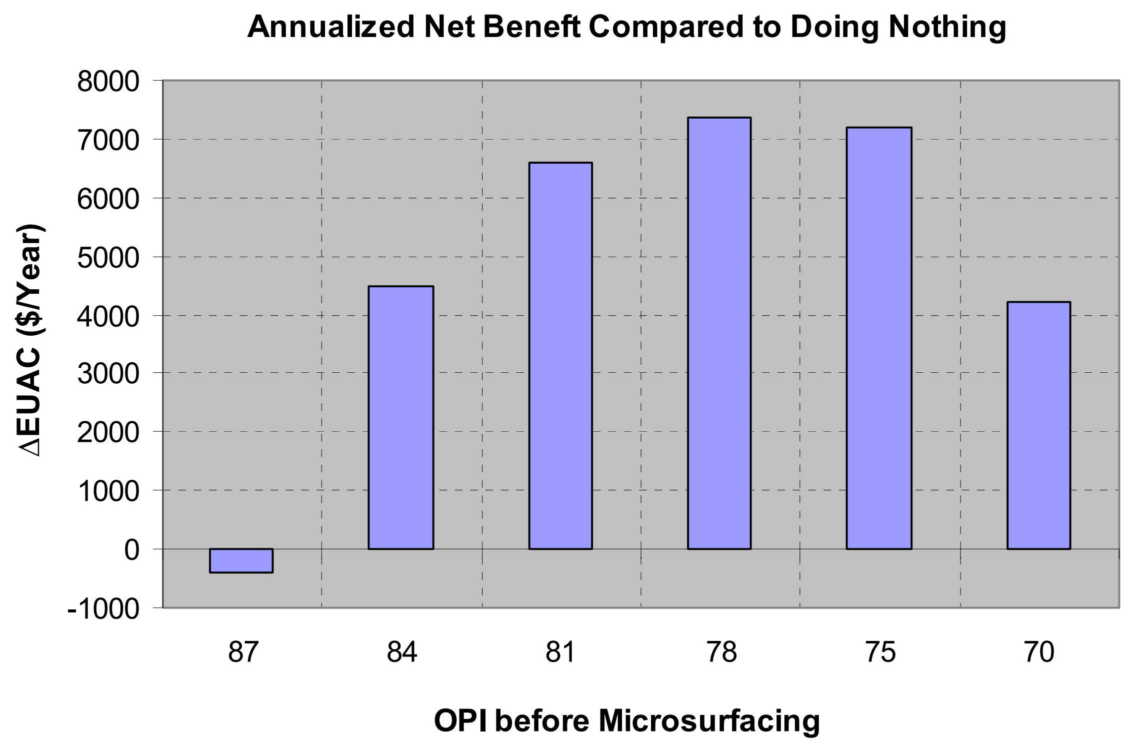


Figure 29. Net EUAC benefit as a function of OPI before treatment

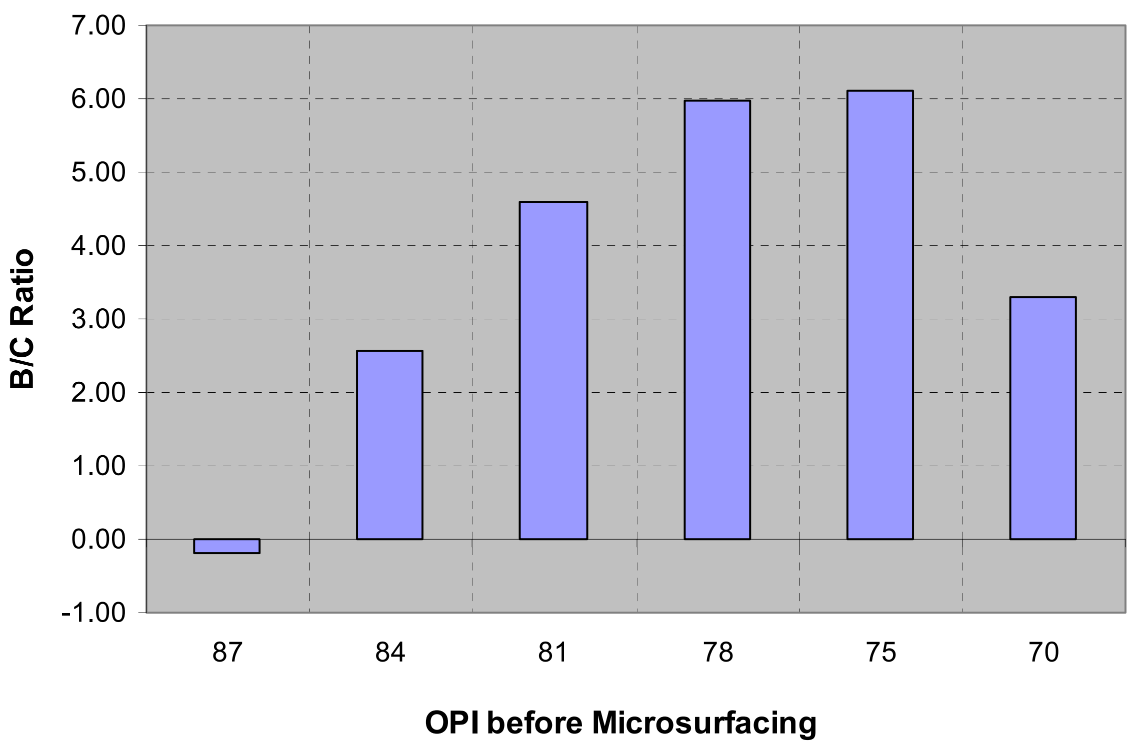


Figure 30. Benefit-cost ratio as a function of OPI before treatment

Table 31. Summary of cost effectiveness due to different OPI scenarios for seal coat

PV Type	Traffic Network	PVC ($ per lane mile)	Year Future Preservation Performed (year)	OPI	TSI	Life Benefit (year)	Net Benefit (ΔEUAC) ($/year)	B/C Ratio
Seal Coat	Non-NHS ADT<2000	10000	2	85	60	0.84	409	0.36
		10000	3	80	60	3.04	3678	3.89
		10000	4	75	60	4.31	5175	6.17
		10000	5	70	60	4.83	5662	7.31
		10000	7	65	60	4.43	5374	7.66
		10000	9	60	60	3.17	4115	6.21
		10000	2	85	70	0.83	397	0.35
		10000	3	80	70	2.42	2890	2.95
		10000	4	75	70	3.30	4042	4.59
		10000	5	70	70	3.49	4308	5.23
		10000	7	65	70	2.99	3816	5.08
		10000	9	60	70	1.79	2308	3.23
Seal Coat	NHS	10000	2	85	70	-1.36	-4525	-3.35
		10000	3	80	70	1.59	1713	1.67
		10000	4	75	70	3.66	4444	5.13
		10000	5	70	70	4.84	5665	7.31
		10000	7	65	70	5.12	6005	8.82
		10000	9	50	70	0.64	443	0.58
		10000	2	85	80	-0.71	-2814	-2.20
		10000	3	80	80	2.01	2328	2.33
		10000	4	75	80	3.89	4687	5.47
		10000	5	70	80	4.93	5746	7.45
		10000	7	65	80	5.13	6008	8.82
		10000	9	50	80	0.69	515	0.67

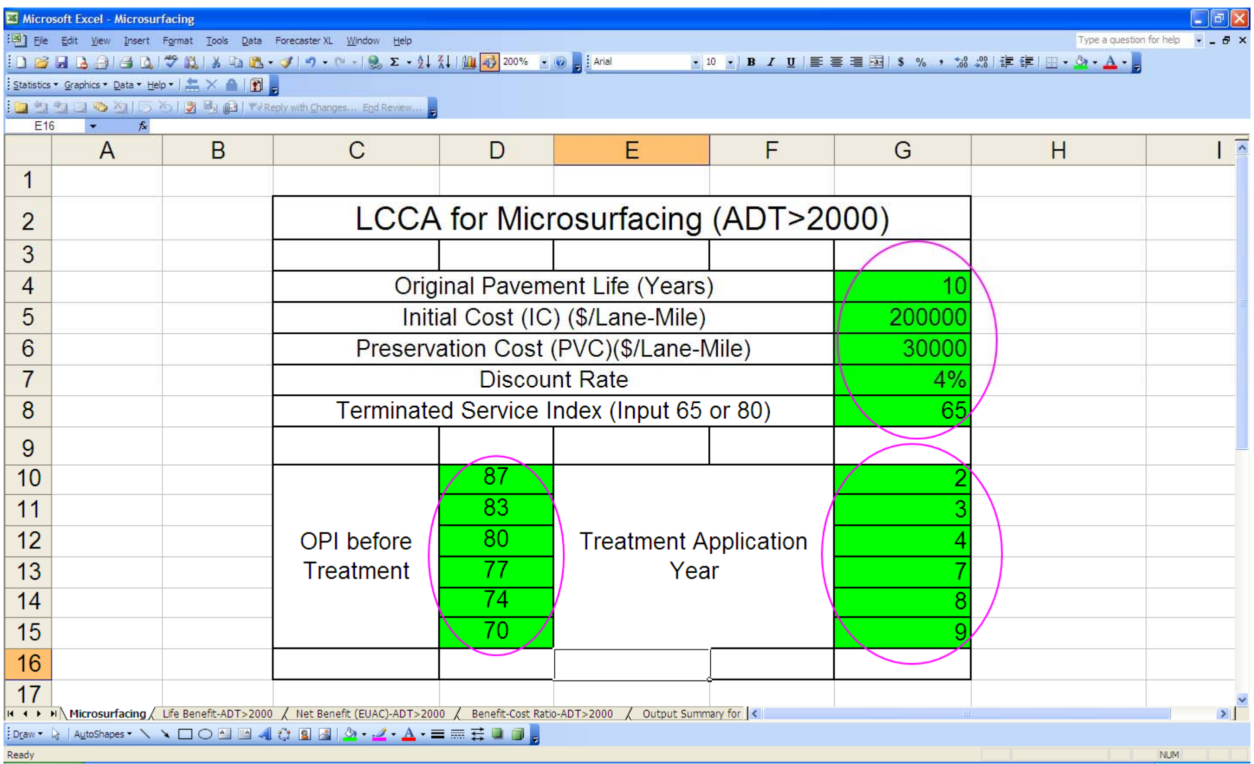
Table 32. Summary of cost effectiveness due to different OPI scenarios for NovaChip®

PV Type	Traffic Network	PVC ($ per lane mile)	Year Future Preservation Performed (year)	OPI	TSI	Life Benefit (year)	Net Benefit (ΔEUAC) ($/year)	B/C Ratio
Novachip	Interstate	50000	2	88	75	3.31	-11	0.00
		50000	3	85	75	6.11	3332	0.81
		50000	4	82	75	8.22	5193	1.43
		50000	7	78	75	9.93	6801	2.34
		50000	9	75	75	10.40	7365	2.88
		50000	10	71	75	9.94	7273	2.98
		50000	2	88	85	1.10	-3622	-0.65
		50000	3	85	85	2.72	-567	-0.12
		50000	4	82	85	3.93	1315	0.31
		50000	7	78	85	4.93	3087	0.90
		50000	9	75	85	5.21	3740	1.24
		50000	10	71	85	4.97	3674	1.28

IV.3.5 Specific Road Analysis

The information presented in the previous section can serve as a useful guideline for treatment selection and timing, based on current analysis conditions including; interest rate, unit treatment cost, current performance life information, etc. The discussion in this section will focus on how PennDOT can use the analysis methodology developed in the future when one or several of these input factors have changed.

A series of spreadsheets have been developed to perform the analysis, while allowing the user to change the input values, as appropriate at the time of analysis. An example for the microsurfacing treatment is shown in figures 31 thru 34 below. Figure 31 depicts the spreadsheet input, and figures 32 to 34 show the analysis results with those input values. Each of the variables in the spreadsheet can be changed by the user. Figure 35 shows the input sheet for a revised TSI, and the corresponding results are shown in figures 36 to 38.



LCCA for Microsurfacing (ADT>2000)			
Original Pavement Life (Years)			10
Initial Cost (IC) ($/Lane-Mile)			200000
Preservation Cost (PVC)($/Lane-Mile)			30000
Discount Rate			4%
Terminated Service Index (Input 65 or 80)			65
OPI before Treatment	87	Treatment Application Year	2
	83		3
	80		4
	77		7
	74		8
	70		9

Figure 31. Example of Excel spreadsheet input for microsurfacing (ADT>2000)

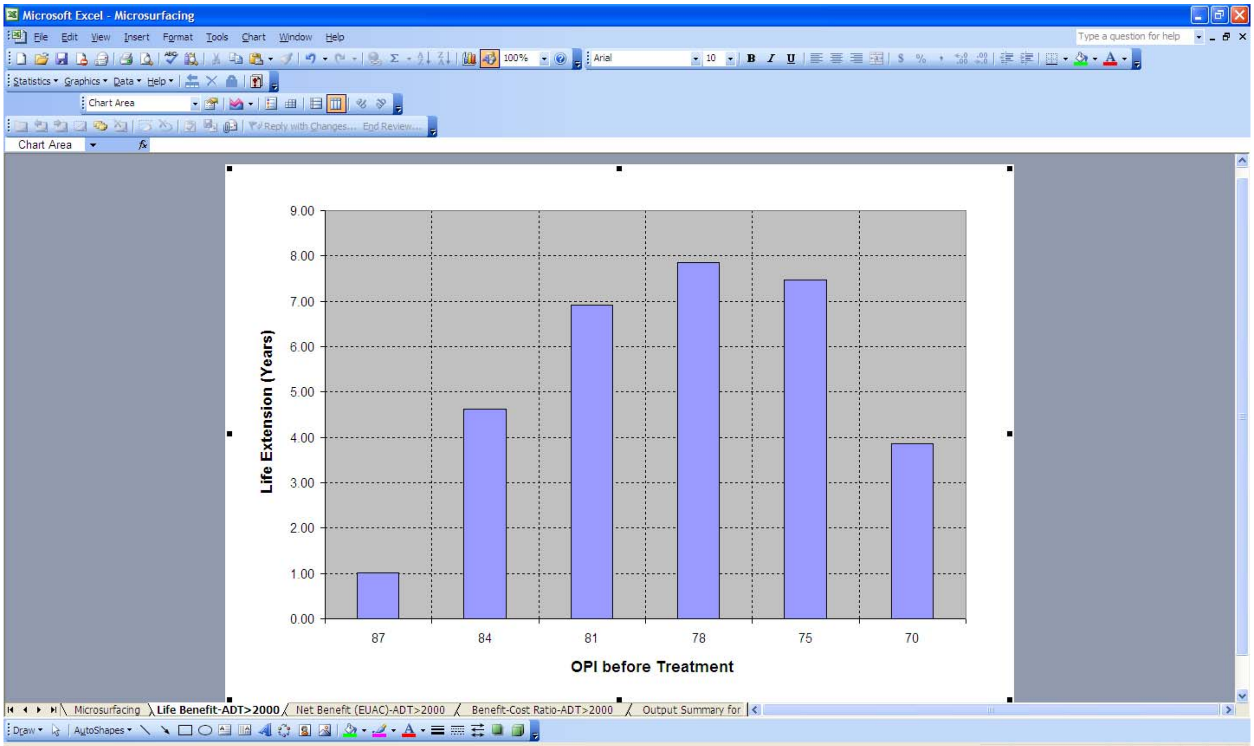


Figure 32. Example of output for life extension as function of OPI before microsurfacing

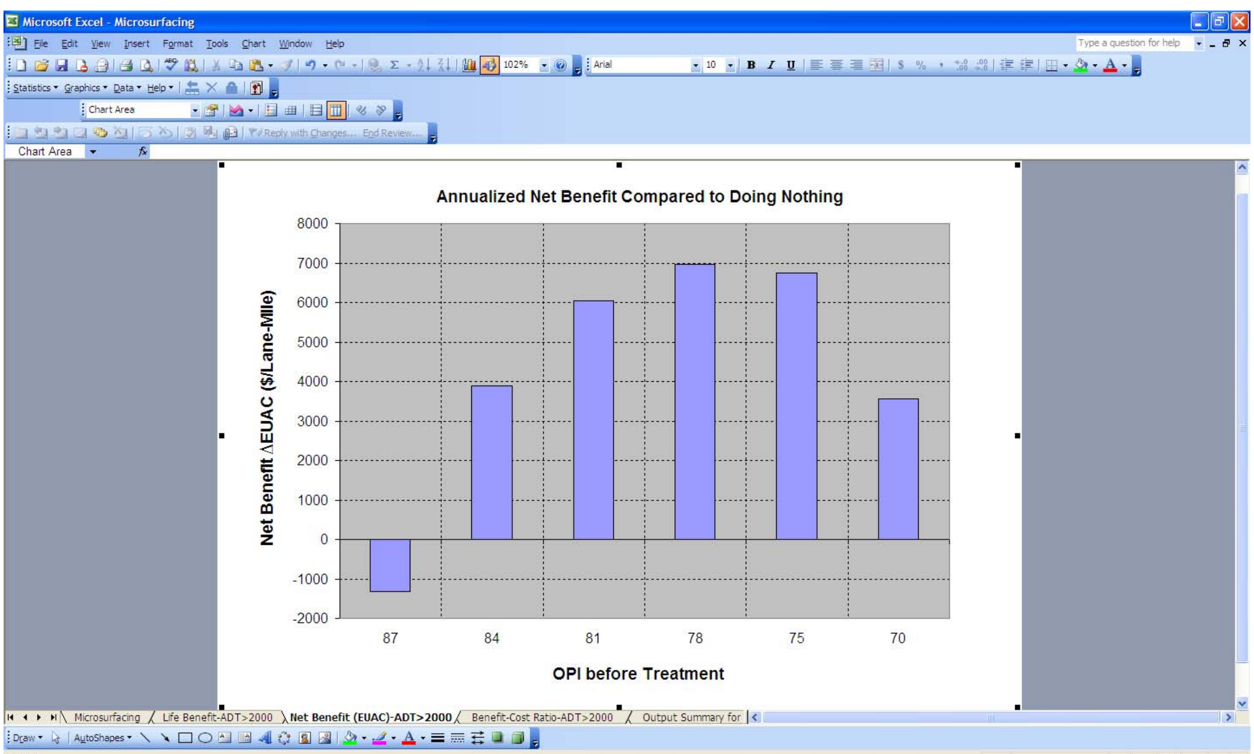


Figure 33. Example of output for net benefit as function of OPI before microsurfacing

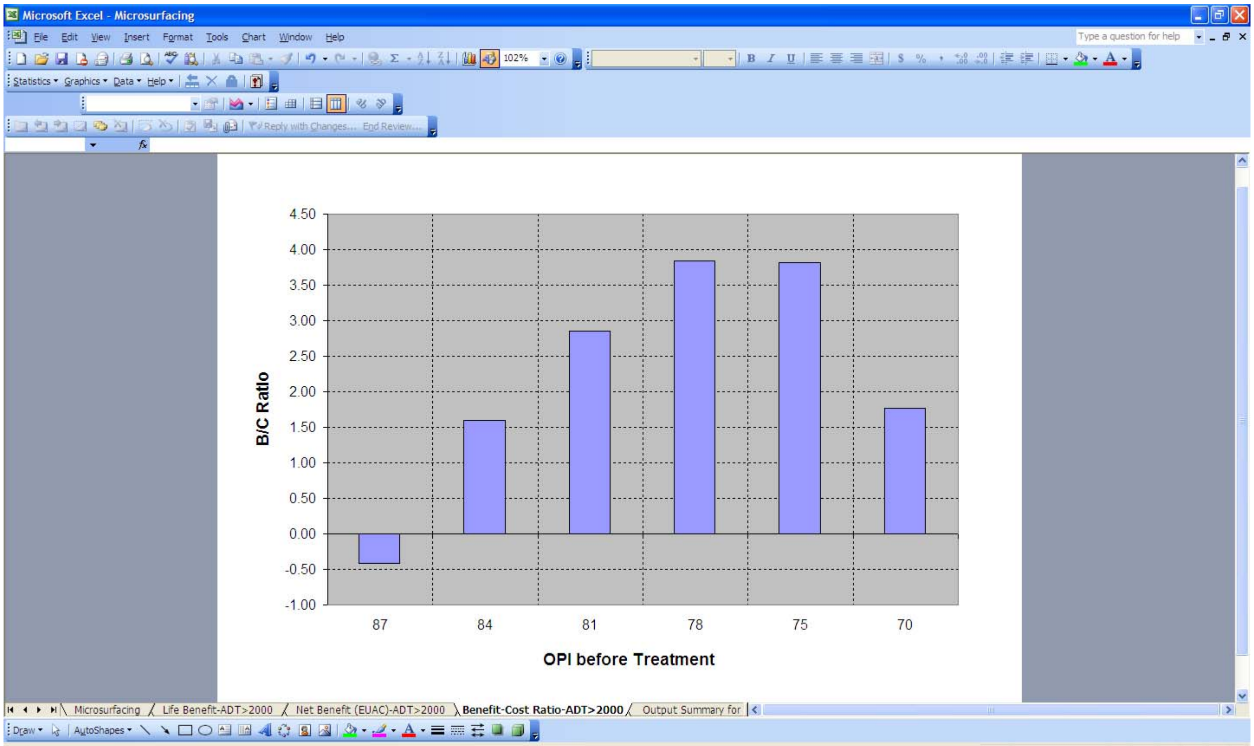


Figure 34. Example of output for benefit/cost ratio as function of OPI before microsurfacing

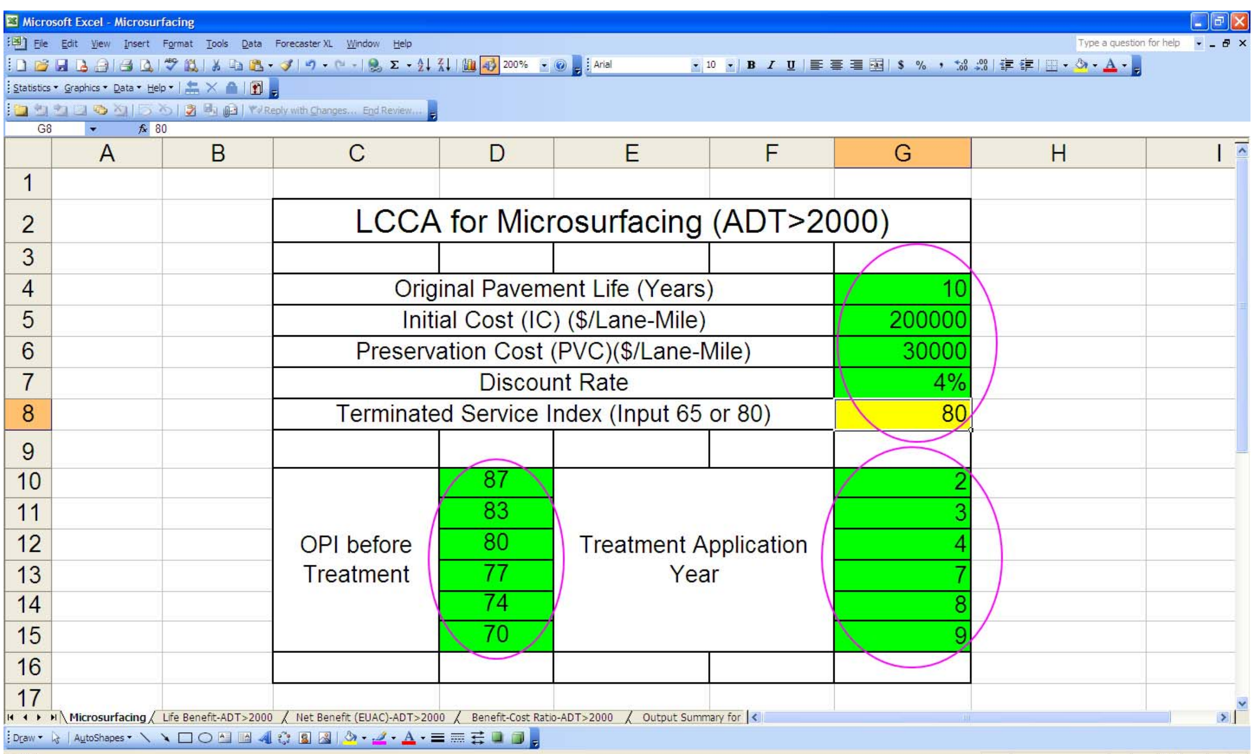


Figure 35. Example of revised Excel spreadsheet input for microsurfacing (ADT>2000)

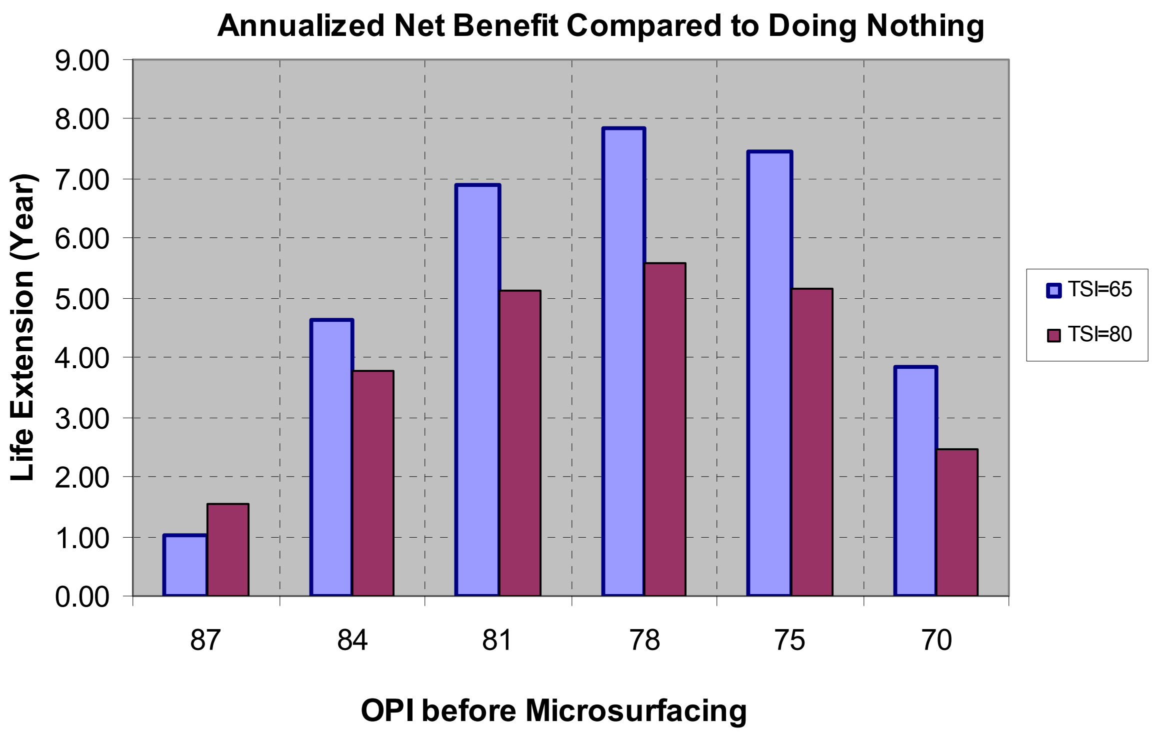


Figure 36. Example of output for life extension due to revised input

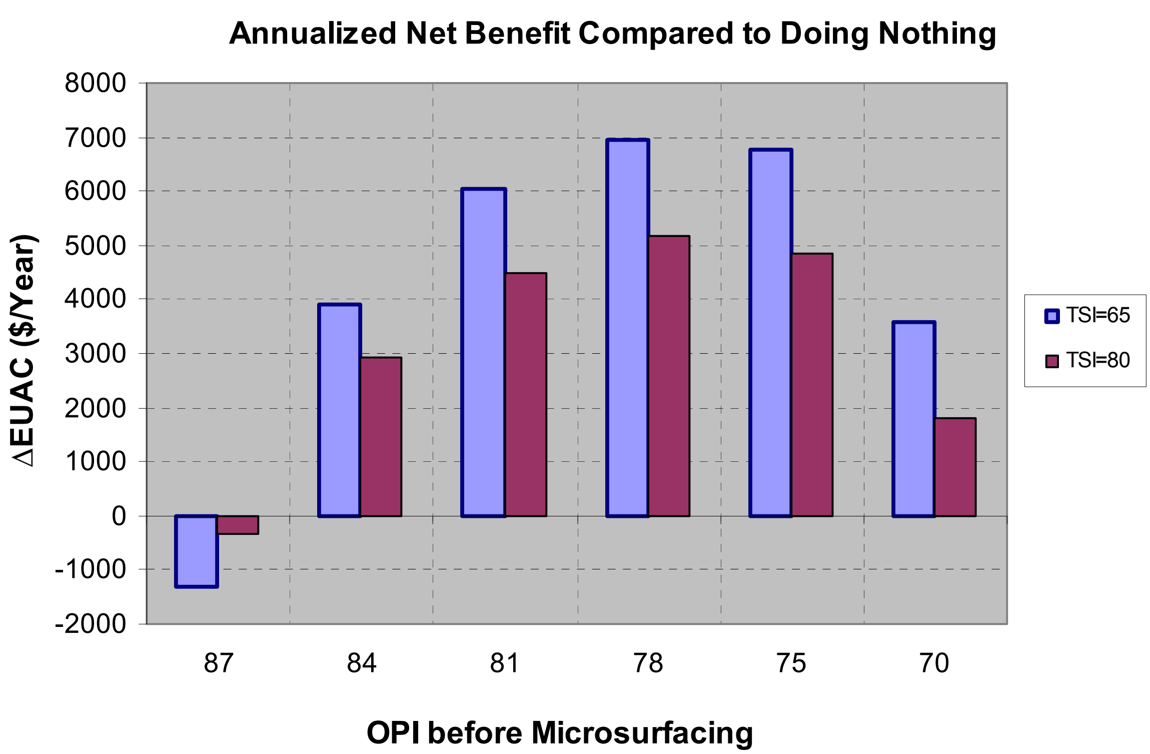


Figure 37. Example of output for net benefit due to revised input

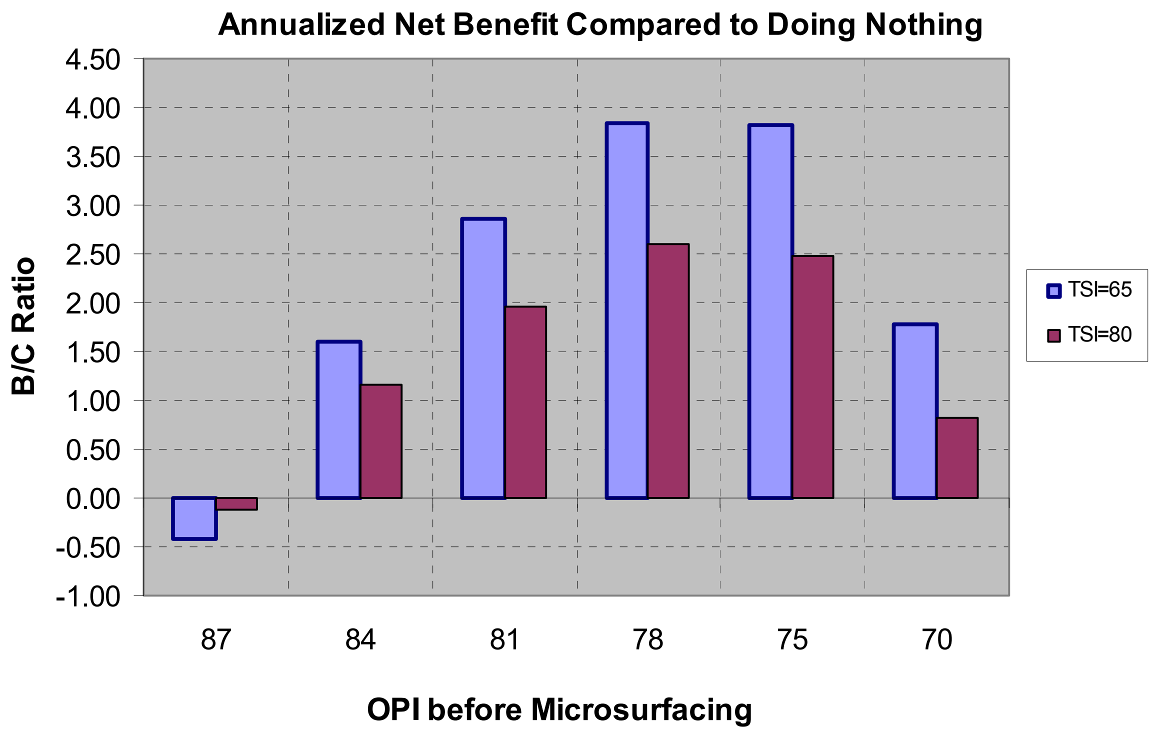


Figure 38. Example of output for benefit/cost ratio due to revised input

By using this tool, PennDOT personnel can perform a number of different situational analyses. Not only can analysis be performed to re-evaluate changed conditions, but other situations can be addressed as well. It is possible that even the performance trends developed in this project will change as the methodology is applied. The goal has been to help identify the optimum time to apply the treatments, and this should result in revised performance trends over time.

What if scenarios can be performed as well. Analyses can be performed with these spreadsheets to determine the consequences of these treatment decisions in the event certain input factors change.

The spreadsheet generates a pavement performance trend using the equations presented in table 29, for the specific networks. It then performs a life cycle cost analysis to determine the associated treatment cost effectiveness for the conditions described in the input sheet.

This tool is also useful for the evaluation of a specific road, which may be observed not to fit the average performance trends presented in the previous section. A customized evaluation of that specific road can be performed on the basis of the OPI value at the time. It can also be used to assess a group of roads in similar condition, for example within a County, for planning purposes. By using the average pavement condition (OPI value) of a group of similar pavements, a separate analysis can be performed for the entire group. Some assessment may be needed to determine a suitable range of OPI values for inclusion with the group for such an analysis.

It should also be remembered that at times there can be problems with the OPI data for many possible reasons. The database contains a large amount of data, and, although the goal is to have error free data, that is not likely for such a large amount of data. A reasonableness check should always be applied to any data which may not seem to be reliable. This can be done by comparing data over a period of years to determine whether the data is reasonably consistent, or shows unexplained deviations from a general performance trend, or by inspection of the road which reveals that the level of distress is not consistent with the OPI value.

IV.4 Conclusions

In this section, a cost-benefit analysis was performed using both the EAC method and LCCA analytical technology. As is illustrated in example calculations, the two methods may not recommend treatment at exactly the same pavement condition level, because of differences in the calculation methods used for each. However, consideration of the results from both methods appears to provide a reasonable range of condition level which provides the maximum treatment cost effectiveness.

The effect of the timing of treatment application expressed in terms of the OPI on treatment cost effectiveness was evaluated. Pavement performance curves based on OPI values for the various treatments applied at different pavement condition levels were developed within each of the four PennDOT traffic networks. The relationship between pavement performance life extension and OPI at the time of treatment was modeled using second order polynomial regression analysis. Some key observations are summarized as below:

- Given the cost information from the survey of state highway agencies, the ranking of cost effectiveness for all treatments based on average benefit cost ratio to thin overlay indicated that the NovaChip® treatment has the lowest average benefit cost ratio, while crack sealing has the highest. The slurry seal and microsurfacing treatments have benefit cost ratios similar to the thin overlay. Therefore, they can be expected to demonstrate comparable cost effectiveness.
- Based on the in-house PennDOT cost data, crack sealing is the most cost effective treatment, when evaluated relative to 1" hot mix overlay. The seal coat treatment is the second most cost effective in this evaluation.
- Based on the PennDOT contract price information from the ECMS system, crack sealing is again the most cost effective treatment when evaluated relative to the thin overlay. The other treatments for which contract price information is available rank in the following order in this analysis: seal coat, microsurfacing, and NovaChip®.
- Results from the LCCA analysis indicate an optimal pavement condition, or pavement age, when the benefit cost associated with a chosen treatment is maximized. Crack sealing has the highest benefit-cost ratio while NovaChip® has the lowest benefit-cost ratio, which agrees well with the EAC method.
- Investigating the effect of pavement condition, expressed as OPI value, on the benefit cost of the treatment indicated there is an optimal range of pavement condition, or age, at which the benefit cost ratio associated with a chosen treatment is maximized.

A methodology was also developed which PennDOT personnel can use in the future to refine these analyses. The spreadsheet developed allows the analysis to be repeated on the basis of changed input conditions, or to perform specific analysis of an individual road or group of roads which may appear to differ from the statewide average performance presented. This development is intended to provide PennDOT a means for adjusting to changing future conditions.

V. SUMMARY / RECOMMENDATIONS

V.1 Summary of Cost Benefit Analysis Study

The project has focused on identifying thin surface treatments which may be potentially cost effective in extending the performance life of flexible pavements. The work was conducted in the format of three specific tasks, as presented in the preceding chapters. A part of the effort consisted of evaluating the cost effectiveness of past surfacing treatments based on current treatment costs and performance within the recent ten year period from 1998-2008. This evaluation was conducted for both in-house and contract unit prices for the treatments used by the Department within that time period.

Task 1 consisted of a literature survey which identified not only conventionally used treatments, but also less common treatments of a similar nature. The most commonly identified treatments identified by the literature review are:

- Thin overlay
- Microsurfacing
- Chip seal

Other treatments identified included:

- Sand seal
- Cape seal
- Fog seal
- Slurry seal

The study also attempted to identify additional treatments which appear to have the potential to be cost effective. Two were specifically identified, NovaChip® and E-Krete™. NovaChip® is a proprietary thin overlay, and E-Krete™ is a patented polymer composite micro-overlay which bonds to asphalt and concrete surfaces. A number of researchers have evaluated the performance of NovaChip®, including a performance evaluation of several projects in Pennsylvania. A PennDOT evaluation concluded that NovaChip® is a dependable, cost effective alternative to Superpave when structural enhancement is not required and approximately ten years service is expected. E-Krete™ was identified as another potential treatment for which some field evaluation experience is available, but for which most of the limited performance information is from airfield pavements. An evaluation at NCAT produced similar results to those reported for airfield pavements, indicating that this is a potentially effective maintenance treatment. Although some highway agencies are evaluating the treatment, general experience with treatment is not available.

The Virginia DOT reported success with the use of a special thin hot mix asphalt material. The VDOT THMACO is a 9 mm surface mix placed at 80-85 lb/SY as a pavement preservation treatment on low volume pavement with little or no heavy vehicle traffic. It is placed using Novabond® as a tack coat material.

Under Task 2 the project team solicited information from a number of states regarding their use of thin surface maintenance treatments. The states selected had similar climatic or geographic conditions to Pennsylvania, or were known to have extensive experience with these maintenance treatments. A single page questionnaire was developed for this purpose, followed by additional contacts and phone calls for further information when indicated. Thirteen of 16 states responded to the questionnaire.

V.1.1 Survey Response from Other States

The general response indicated that thin overlays, microsurfacing, crack sealing, chip seals, and NovaChip® are commonly used thin maintenance surface treatments. Fog seals, cape seals, and slurry seals were rarely used and then only on low volume roads, while the sand seal treatment was never used by this group of states. Information was obtained about the use of treatments according to traffic volume. The thin overlay, microsurfacing, crack sealing and NovaChip® treatments were generally used on traffic volumes of 5,000 ADT or greater. Several states reported using many of the treatments on highways with volumes up to 50,000 ADT. The treatments are generally applied to pavements in good or fair condition, with only the thin overlay and NovaChip® being used on pavements in poor condition.

The states also reported the criteria used for selecting treatments. Past experience, traffic level, and local climate were the criteria used by most agencies. Pavement geography was considered by three states and compatibility with aggregate by only one.

The survey states also provided their estimated performance life for the individual treatments, along with unit price information. For the thin overlay and NovaChip® treatments the reported performance life ranged from 8-12 years. Microsurfacing and chip seals were generally reported to have a life of 6-10 years, while crack sealing was reported to be effective for 2-5 years. Typical thin overlay cost was on the order of $3-5/SY, while NovaChip® cost ranged from $5.50-8.50/SY. Crack sealing usually costs between $0.30-0.40/SY. Microsurfacing costs ranged from $2-4/SY, and chip seal from $1-2/SY. This information was included in the cost benefit analysis carried out in Task 3.

When states indicated inordinately good performance, or special materials, additional information was sought. As a part of this investigation it was identified that New York has also developed a special 6.3 mm thin polymer modified overlay material. Just as the VDOT THMACO, the New York 6.3 mm overlays were reported to be used successfully. Texas also reported the use of several forms of thin overlay on their highways.

Additional information was collected from Texas and Minnesota about the success of their chip seal programs, as well as the use of other treatments. Texas successfully uses a variety of asphalt materials for chip seals including hot asphalt, emulsified, asphalt, rubber modified asphalt, polymer modified asphalt, and terminal blend asphalt. They also successfully use both single size and graded aggregate chips seal specifications. Minnesota has significantly improved the application of chip seals by virtue of working closely with the contractors involved, and by transferring the liability for loose chip related windshield damage to the contractor.

V.1.2 PennDOT District Experience

Each of the 11 PennDOT Districts was contacted to learn which treatments in the thin surface category they have been using. The responses were generally similar, with minor exceptions. For the most part the Districts use chip seals (PennDOT seal coat) for the low volume (generally less than 7,000 ADT) portion of their road system. District 8 has constructed a crumb rubber seal coat as an evaluation project. This project generally performed well after three years, but was relatively costly.

Only District 3 has specifically constructed a thin, ¾" Stone Matrix Asphalt overlay, which is performing well after 3-4 years in service. District 10 reported adopting 9.5 mm material for 1.5" overlays as a result of problems with 12.5 mm mixes. The Districts generally have limited, but favorable experience with NovaChip®. District 12 reported the only bad construction experience with this treatment.

Five Districts reported using microsurfacing within the past ten years. Performance has generally been good, with some use on higher volume roads.

District 8 reported past problems with microsurfacing on hills and curves. District 12 reported adopting the use of PG 76-22 material on rut susceptible pavements, with softer asphalt in mountainous regions. The most commonly reported performance problem with emulsion applications was identified at locations where overhead tree canopy provided shade, resulting in slow emulsion cure. General performance problems with the thin surface treatments directly related to local road geography.

V.1.3 Current Emulsion Use in Pennsylvania

A review of the current emulsions used for thin surface treatments in Pennsylvania was also carried out. In addition to gathering information from Department representatives, emulsion suppliers were also contacted for specific information about materials supplied in Pennsylvania. It was determined that the anionic emulsion materials most frequently used in Pennsylvania are CMS-2, CRS-2, and CRS-2P. These are typically made using PG 58-22 base asphalt binders. The most commonly used cationic emulsions in Pennsylvania are CSS-1H and CSS-1HP using PG 64-22 base asphalt binders. Emulsion materials are currently evaluated using penetration grading criteria. Supplier's experience with performance grading of emulsions indicates that the preparation of cationic emulsions does not affect the performance grade of the asphalt. However, the emulsifiers used in anionic materials may affect the performance grade because much more emulsifier is required.

An evaluation of surface performance grade requirements was carried out using the LTPPVIND software. Based on this criteria it was determined that the binders currently being used in Pennsylvania provide 50% reliability at the low temperature, and 98% reliability at the high temperature for most sites across the state. The high temperature performance is important for the control of bleeding and raveling during hot weather periods. The low temperature criteria are focused on the development of thermal cracking. While this occurs in hot mix materials, because of the softening effect of the emulsifiers it has not been identified as a problem in thin surface treatments using emulsified asphalts. The materials currently being supplied in Pennsylvania appear to be suitable, until further advancement is made in a surface performance grading system. This work is being undertaken by NCHRP under project 9-50.

On the basis of this effort it is recommended that PennDOT further investigate the use of the specialized thin overlays in use in New York and Virginia. The results also imply that further improvement can be made in the installation of chip seals. The other states generally had successful experiences with microsurfacing and NovaChip®.

Task 3 provided the majority of work on this project. Cost-benefit analyses were considered for the maintenance treatments identified in the first two tasks. A cost-benefit comparison was developed on the basis of the performance and cost information provided by the other states surveyed.

Cost benefit analyses were performed using two appropriate methods, equivalent annual cost (EAC) and life cycle cost (LCCA). EAC results from the evaluation of performance based on the data from other states are provided in Table 21 and Figure 7. This summary of general cost benefit indicates that crack sealing is the most cost effective, followed respectively by fog seal, chip seal, and microsurfacing when compared to thin overlay. The cost benefit of slurry seal is equal to that of thin overlay, with NovaChip® being the only treatment identified as less cost effective than the thin overlay.

In addition, a more detailed analysis was performed for treatments used by PennDOT over the past several years. The analyses were divided into two categories on the basis of in-house costs and contract costs for treatments for which information exists in each. Results from these analyses indicated that crack sealing is very cost effective in both cases. Seal coats/chip seal has the next best ranking of cost-benefit in both categories. The thin overlay is the most costly of the standard treatments, again for both in-house and contract work. Cost information was also available for microsurfacing and NovaChip® treatments, for contract work only, since these treatments require special knowledge and equipment. They rank consecutively between the chip seal and thin overlay treatments in terms of cost-benefit. Results of these evaluations are shown in Table 22 using PennDOT in-house costs, and Table 23 and Figure 8 using ECMS costs.

V.1.4 Determination of Optimum Treatment Timing

Pavement performance data for flexible surfaced pavements in the form of PennDOT’s overall pavement index was also provided to the study team. Using this information together with the cost information, an additional analysis was conducted to determine the optimum timing for each treatment. Existing PennDOT pavement condition threshold values were used for the various traffic networks in this evaluation. From this analysis, it was determined that for current conditions the optimum treatment timing for the various treatments is:

Treatment	*Network*	*Optimum OPI*	*Estimated Years of Performance*
Crack seal			
Chip seal	<2000 ADT	68-72	4.5
	NHS	64-68	5-6
Microsurfacing	>2000 ADT	73-77	8
	NHS	78-82	6
NovaChip®	Interstate	73-78	10
Thin overlay			

An evaluation for the crack seal and thin overlay treatments was conducted in the conceptual evaluation for the treatments in Section IV.3.3, as well as on the basis of information collected from other states. However, since Department OPI data for crack seal and thin overlay treatments were not included in the data provided, it was not possible to develop those specific OPI performance curves for PennDOT.

Additional analysis of treatment effectiveness can be performed by using a spreadsheet developed under Task 3 to refine or repeat the cost benefit analysis work for specific roads, local networks, or changes which might occur in other parameter influencing the outcome of the analysis, such as interest rate, terminal serviceability, treatment costs, or treatment performance.

It must be remembered that the relatively poor cost effectiveness of the NovaChip® treatment is influenced by the fact that in Pennsylvania this treatment has only been used on Interstate highways in good or better conditions. The potential benefit of the treatment may consequently be limited. A different result is seen in the cost-benefit analysis based on information from other states is shown Figure 7.

Similarly, it is noted that the optimum treatment timing identified for the chip seal treatment is on the order of 4.5-5 years. This too is probably influenced by the fact that for decades this has been the treatment cycle for many of the roads on which the chip seal is used. The full potential performance of the treatment was never identified since the condition of those roads was never allowed to deteriorate prior to treatment, which might have increased the optimum application timing range. This is a consequence of applying maintenance cycles on the basis of time only, without pavement condition data. In contrast, the optimum application of the microsurfacing treatment has not been limited in this fashion, resulting in a higher identified optimum application timing.

V.2 Conclusions

It is well known that having water within a pavement structure is one of the most damaging factors in the performance of a pavement. The primary benefit of these thin surface treatments is the prevention of water from entering the pavement surface, since none of these treatments are applied to make structural improvement. All of these treatments are recognized as being beneficial in helping to keep surface water from entering a pavement structure. While this characteristic has not been directly evaluated, the pavement performance life extension discussed is an indirect measure of this performance related characteristic.

The functional performance of the surface is also of great importance to the success of the treatments. All these treatments have been recognized as providing acceptable functional surface characteristics, such as skid resistance and ride quality. However, no specific evaluation of that aspect of the treatments has been attempted in this study.

Several conclusions can be reached from the results of this study, as follow:

- While the study shows that cost-benefit results determined from the EAC method or LCCA method differ slightly, the ranking of treatments remains the same. For the treatments evaluated, cracking seal is the most cost-effective treatment in terms of cost ratio, followed by chip seal, microsurfacing, thin overlay / NovaChip®, in that order.

- Based on the information collected from other states, it appears that additional cost-benefit might be obtained from specialized thin overlays such as used by Virginia and New York. PennDOT should further investigate these specialized overlay materials for inclusion in future cost-benefit evaluations.

- A new product which appears to have the potential to provide good cost benefit is E-Krete™. The Department can evaluate E-Krete™ as a new product. To achieve good cost benefit E-Krete™ will need to perform successfully for several years. The evaluation of this product should also consider the feasibility of recycling it along with the underlying roadway paving materials.

- An evaluation of chip seal performance in mountainous and non-mountainous areas of the state resulted in no statistically significant difference between the two datasets.

- As a result of the relative treatment performance and associated costs identified, the lower cost treatments such as crack sealing are found to be most cost effective when applied relatively early in the pavement life, while the more costly treatments such as NovaChip® appear more cost effective when applied later in the pavement life.

- For each treatment there is an optimal pavement condition and corresponding pavement age which results in the maximum benefit cost associated with that treatment, based on recent prices and performance.

- To achieve the optimum return on investment, an agency should apply the treatments that provide the maximum cost benefit. There may be short term reasons for deviating from this approach, but the long term goal should be to follow this general plan.

- Based on the changes taking place in the industry which affect both treatment cost and performance, the analysis of treatment timing should be repeated periodically. Changes in the optimum timing for treatment application may affect the cost benefit analysis, but is not generally expected to change the ranking of treatments.

V.3 Recommendations

The Department should continue to practice preservation maintenance treatments, with the objective of improving the total life cycle cost of its pavement networks. The application of crack sealing as soon as practical after cracks develop has been shown to be a very cost effective means of extending pavement performance with minimum investment.

Based on experiences from other states, it is feasible for PennDOT to pursue improvements in the design and application of chip seals to achieve better performance and reduced related windshield damage. Improvements could come in the form of increased use of polymer and rubber modified emulsions, or hot asphalt to improve chip retention. Refinement of the chip seal design procedure for determining application rates for emulsions and aggregates based on the existing pavement surface condition could also result in improved performance, as demonstrated by the Minnesota DOT.

The use of specialized thin overlay materials such as the THMACO in Virginia and the polymer-modified 6.3 mm overlay in New York indicate that PennDOT could potentially benefit from the development/adoption of such materials. A key component of these thin overlays is the tack coat application used.

Based on past experience with microsurfacing, PennDOT can consider expanding the use of this treatment into additional Districts, and to higher traffic volume highways when appropriate.

Use of the NovaChip® treatment in Pennsylvania, while limited, has generally been successful. Problems associated with NovaChip® have usually been related to inadequate repair of the existing pavement prior to application. The Department could consider expanding the use of this treatment to additional situations. Based on the experience reported by the Minnesota DOT, NovaChip® is beneficial in resisting reflective cracking when placed over jointed concrete pavements, and in resisting top down cracking when used as the surface for a new pavement section. Such top down cracking is typically thermally induced by cold temperatures.

Over the recent past decades, Pennsylvania highways have benefitted greatly from the application of maintenance surface treatments. This study has endeavored to provide the basis for continued improvement in the use of these treatments by determining the cost effectiveness of the various treatments in use, and by identifying additional potential treatments which may prove to be beneficial in the cost effective preservation of Pennsylvania highways.

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