Optimum Time for Application of Slurry Seal to Asphalt Concrete Pavements

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This study evaluated the field performance of asphalt pavements with and without slurry seal applications, developed performance models for asphalt pavements without slurry seals and asphalt pavements receiving slurry seals at various times following construction, and identified the optimum time for applying slurry seals on asphalt pavements in the Washoe County, Nevada, region. This determination was achieved by evaluating the long-term pavement performance data collected with the MicroPAVER system for the past 15 years and the cost-effectiveness of slurry seals applied to new and existing flexible pavements at Years 0, 1, 3, 5, 7, and 9 after construction. This study found that applying slurry seal immediately after or 1 year after construction of the asphalt layer is not effective in regard to the benefit to users and the benefit–cost ratio for the agency. The optimum time of applying slurry seal depended on the type of construction activity. For newly constructed pavements, the optimum time to apply slurry seal was 3 years after construction. For pavements subjected to overlays, the optimum time to apply slurry seal was between 3 and 5 years after construction. However, for uniformity purposes, it was recommended that the agency apply slurry seal 3 years after construction of the asphalt layer for both new and overlay constructions.

In light of shrinking agency budgets, pressure is being placed on agencies to become more cost-effective in their delivery of services to the public. Unfortunately, transportation infrastructure, by nature, begins to deteriorate as soon as it is placed. Roadway preventive maintenance provides users with safer and more comfortable rides and has been shown to reduce overall transportation costs when maintenance treatments are properly selected and timed. As such, infrastructure agencies have expressed an increasing interest in the selection and timing of maintenance activities for their existing transportation infrastructure.

The long-term performance of an existing roadway is highly dependent on the conditions of an existing roadway, traffic, pavement material properties, environmental conditions, and maintenance history. Depending on the roadway deterioration experienced and other factors, agencies select an appropriate maintenance treatment to slow and retard further roadway deterioration. Agencies have the opportunity to save money when they know the optimal time in which a roadway would most benefit from a preventive maintenance treatment. Agencies can then start to look forward for opportunities to apply maintenance treatments before more costly rehabilitation treatments are required to maintain user satisfaction.

Even though the selection of appropriate maintenance treatments is critical for a long-lasting pavement, this study focuses on determining the optimal time for applying a proven maintenance treatment: the slurry seal. A slurry seal is a mixture of slow-setting emulsified asphalt, well-graded fine aggregate, mineral filler, and water. It is used to fill cracks and seal areas of old pavements, to restore a uniform surface texture, to seal the surface to prevent moisture and air intrusion into the pavement, and to improve skid resistance (*1*).

This report summarizes the findings of a study conducted by the Pavements/Materials Program at the University of Nevada, Reno, for the Washoe Regional Transportation Commission (RTC) to evaluate the field performance of slurry seals on asphalt pavements.

OBJECTIVE

The overall objectives of this study are (*a*) to evaluate the field performance of asphalt pavements with and without slurry seal applications, (*b*) to develop performance models for asphalt pavements without slurry seals and asphalt pavements receiving slurry seals at various times following construction, and (*c*) to identify the optimum time for applying slurry seals on asphalt pavements in the RTC region. This objective was achieved by evaluating the long-term pavement performance and the cost-effectiveness of slurry seals applied to new and existing flexible pavements in the Washoe County, Nevada, region with respect to the time of slurry seal application.

BACKGROUND

Pavement performance is defined as the serviceability trend of the pavement over a design period; serviceability indicates the ability of the pavement to serve the demand of the traffic in the existing condition (*2*). A pavement performance model is defined as an equation that relates a pavement performance index, such as the pavement serviceability index, with time and can be used to predict the future pavement condition of the pavement on the basis of the current pavement condition data. In that regard, pavement performance models are critical to the pavement management process because the scheduling of maintenance and rehabilitation activities is based on the present pavement serviceability conditions measured in the field and future pavement service conditions predicted with pavement perfomance models (*3*).

In 2004 Hein and Watt indicated that one method municipalities have been using to prioritize and justify transportation infrastructure

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expenditures is regular road surface condition ratings that are summarized by using an index value such as the pavement condition index (PCI) (*4*). By using road surface ratings in conjunction with construction and maintenance histories, pavement condition prediction models can be developed that are imperative for the development of a complete pavement management system. In 1994 Shahin presented different aspects of pavement condition prediction modeling, emphasizing the focus on sound, cost-effective management rather than the identification of emergency repairs (*5*).

Research by Rohde et al. used the World Bank's highway design and maintenance model (HDM-IV) to calibrate the performance models for slurry seals by using field data from specific test sections at Gauteng, South Africa, and long-term pavement performance data (*6, 7*). HDM-IV uses the following distresses to calibrate its condition index: crack initiation, crack progression, ravel initiation, pothole progression, rut progression, rut standard deviation progression, and riding quality. The HDM-IV condition index is a composite index calculated from the HDM prediction models for cracking, rut depth, potholes, and roughness. Unfortunately, the research focused only on calibrating the slurry seal performance models and did not include conclusions concerning the field performance of slurry seals (*6, 7*).

In 2010 Liu et al. determined the cost-effectiveness of ultrathin bonded bituminous surface and modified slurry seals. The research used information from the Pavement Management Information System from the Kansas Department of Transportation. The performance was assessed by using the following distresses: roughness, rutting, fatigue, and transverse cracking. The research concluded that a modified slurry seal increases the service life of a Kansas state highway by 4.7 years (*8*).

The pavement modeling for this study is used for identifying the effectiveness of a slurry seal application to a flexible pavement in the Washoe County region with respect to time. To document pavement performance, the Washoe County Engineering Department uses the MicroPAVER pavement management software system, which is supported, maintained, and periodically updated by the Construction Engineering Research Laboratory of the U.S. Army Engineer Research and Development Center (*9*).

The MicroPAVER system works in conjunction with the ASTM D6433 inspection standard to determine and monitor the PCI of a given roadway section. The PCI rating of a roadway is based on the observed surface distresses. The PCI rating is not a direct measure of structural capacity, skid resistance, or road roughness; however, it is an objective tool for assessing the maintenance and rehabilitation needs of a roadway section with respect to an entire pavement system.

The environmental conditions of the Washoe County region can be characterized as a high desert, which generally indicates a relatively low annual precipitation rate, generally about 10 in., but nearly all locations in the county are below 20 in., except for the mountainous regions surrounding Lake Tahoe (*10*). Being a high desert, the area is subject to relatively high summer temperatures, periodically higher than 100°F, and generally mild winters, usually not below 0°F. However, the region is subject to significant daily temperature fluctuations varying by 30°F to 40°F, but may exceed fluctuations of 45°F, between consecutive day and night temperatures throughout the year (*11*).

EVALUATED PAVEMENT SECTIONS

To achieve the objectives of this study, asphalt pavement sections were identified in the jurisdictions of Washoe County, the city of Reno, and the city of Sparks. The evaluation covered pavements that were newly constructed and pavements that received overlays. Asphalt mixtures were generally dense-graded hot-mix asphalt with a 0.50- or 0.75-in. nominal maximum aggregate size with AC-20, AR4000, or PG64-22 unmodified asphalt binders. Slurry seals were designed in accordance with guidelines contained in the International Slurry Surfacing Association Publication A105 (*12*). In general, emulsion asphalts consisted of latex modified cationic quick set with a minimum of 3% latex rubber by weight of the binder, following agency requirements. The majority of the roadways under the county's direction are classified as minor arterials, collectors, and residential streets. The Washoe County regional functional classifications for the various road categories are defined as follows:

- Arterial:
  - Approximate average daily traffic (ADT) of 10,000 and above;
  - Principal arterial roads that serve major centers of activity of urbanized areas and in rural areas function primarily to provide service to through travel, such as on rural highways; minor arterial roads interconnect with and augment principal arterials; and
  - Roads that do not penetrate identifiable neighborhoods and provide connection to urban and rural collector roads;
- Collector:
  - Approximate ADT of less than 10,000,
  - Roads that provide both land access service and traffic circulation in residential neighborhoods and commercial areas, and
  - Roads that collect traffic from residential streets and channel traffic into arterial roads; and
- Residential:
  - Approximate ADT of less than 6,000 with a high percentage of trucks (>4%) and
  - Lower-volume roads that provide direct access to commercial and industrial lands.

A total of 2,700 pavement sections were evaluated in this study. Residential streets are by far the highest number of pavement sections included in the study because of the high availability of such pavements in the urban area. The pavement sections were grouped into the three categories listed below:

- Do-nothing—slurry seal not applied to the pavement,
- Slurry seal applied immediately after construction, and
- Slurry seal applied at 1, 3, 5, 7, and 9 years after construction.

Only pavement sections that were slurry sealed once during their intended performance life were included in this study. Analysis of pavement sections that received multiple applications of slurry seals was outside the scope of this study. The majority of the evaluated slurry sealed pavement sections received the surface treatment between June and September, which is the construction season in northern Nevada.

The performance of the various pavement sections was measured in relation to the PCI that agencies collect with the MicroPAVER system. All three local agencies use the same pavement evaluation procedures and score their pavements on the same cycle (i.e., every other year). A joint refresher meeting is held every year to ensure that all pavement survey teams are conducting similar surveys. In addition, a portion of the network is periodically cross-scored by an independent rating source to make sure that ratings are comparable between each agency (*13*).

MicroPAVER divides the road network into sections on the basis of uniform properties of the pavement and traffic conditions. Each pavement section is further divided into units, and the units to be surveyed in a given section are identified randomly. The average PCI value of the surveyed units in each section is used to represent the condition of the entire section for the specific survey date.

PERFORMANCE MODELS

The PCI data collected by the owner agencies were used to develop the performance prediction models for the various pavement categories as shown in Tables 1 and 2. The number of sections reported in Tables 1 and 2 represents the number of sections identified by the MicroPAVER system. This indicates that multiple sections may have been located on the same road. The R^2 value indicates the goodness of fit between the model and the actual data. An R^2 value of 1.00 indicates a perfect fit between the model and the data, and an R^2 value of .00 indicates an extremely poor fit.

The data indicate that all models have a very good fit with the observed data. When multiple models for the same data set are compared, the relative quality of the models can be assessed by looking at the sum of squared residuals divided by the number of sections (SSR/N) and the mean square error (MSE). The lower the SSR/N and MSE, the higher the quality of the model. For this study, the best model for each category was determined to be the model with the lowest SSR/N and MSE.

Figure 1 shows the performance models for pavements that have not received slurry seals in the new construction and overlay categories. The performance data show different shapes of the performance models for the various categories of pavements. In general, pavements

TABLE 1 Do-Nothing and Slurry Seal Performance Prediction Models and Statistics for New Construction

Road Classification	Year of Slurry Seal Application	Equation	Age	R^2	N	SSR	MSE	SSR/N
Do-Nothing Performance Prediction Model								
Arterial	—	$PCI = -0.0058\ age^4 + 0.1863\ age^3 - 1\ 7141\ age^2 - 0.6472\ age + 99.752$	≥0	.978	36	402.9	100.7	11.2
Collector	—	$PCI = 0.001\ age^4 - 0.0312\ age^3 + 0.2715\ age^2 - 4.4837\ age + 100.77$	≥0	.979	33	2,45.3	245.3	7.4
Residential	—	$PCI = -0.0026\ age^4 + 0.0891\ age^3 - 0.9833\ age^2 - 0.8446\ age + 99.24$	≥0	.911	525	43,872.9	528.6	83.6
Slurry Seal Performance Prediction Model								
Arterial	0	$PCI = -0.01\ age^4 + 0.2956\ age^3 - 2.6491\ age^2 + 2.318\ age + 99.864$	≥0	.984	5	511.9	255.9	102.4
	1	$PCI = -0.0063\ age^4 + 0.2053\ age^3 - 1.9753\ age^2 + 0.5229\ age + 101.04$	≥1	.993	6	262.4	131.2	43.7
	3	$PCI = 0.0062\ age^4 - 0.263\ age^3 + 3.9034\ age^2 - 27.769\ age + 154.81$	≥3	.902	9	150.9	150.9	16.8
	5	$PCI = -0.0291\ age^4 + 1.1522\ age^3 - 16.164\ age^2 + 89.136\ Age - 82\ 919$	≥5	.942	4	1,249.1	1,249.1	312.3
	7	$PCI = -0.0267\ age^4 + 1.1819\ age^3 - 18.513\ age^2 + 114.5\ age - 148.19$	≥7	.910	8	1,478.3	1,478.3	184.8
	9	$PCI = -0.0119\ age^4 + 0.6523\ age^3 - 13.036\ age^2 + 105.1\ age - 204.78$	≥9	.931	9	1,115.4	1,115.4	123.9
Collector	0	$PCI = -0.0001\ age^4 + 0.0117\ age^3 - 0.2608\ age^2 - 2.2817\ age + 100.0$	≥0	.979	5	1,391.6	231.9	278.3
	1	$PCI = -0.0039\ age^4 + 0.1344\ age^3 - 1.5335\ age^2 + 2.052\ age + 98\ 616$	≥1	.980	6	907.5	453.7	151.2
	3	$PCI = -0.0087\ age^4 + 0.3024\ age^3 - 3.5674\ age^2 + 11.332\ age + 90.658$	≥3	.969	9	1,066.3	533.1	118 5
	5	$PCI = -0.0084\ age^4 + 0.3646\ age^3 - 5.5033\ age^2 + 27.831\ age + 58.078$	≥5	.971	9	1,065.2	532.6	118.4
	7	$PCI = -0.0195\ age^4 + 0.878\ age^3 - 14.307\ age^2 + 93.745\ age - 123.33$	≥7	.897	7	2,616.7	2,616.7	373.8
	9	$PCI = -0.0397\ age^4 + 2.0316\ age^3 - 37.849\ age^2 + 296.55\ age - 738.93$	≥9	.888	6	1,963.9	1,963.9	327.3
Residential	0	$PCI = -0.0023\ age^4 + 0.0805\ age^3 - 0.8721\ age^2 - 1.4712\ age + 99.924$	≥0	.977	85	3,933.6	87.4	46 3
	1	$PCI = 0.0044\ age^4 - 0.123\ age^3 + 0.9508\ age^2 - 6.0974\ age + 105.24$	≥1	.983	103	5,264.4	181.5	51.1
	3	$PCI = 0.0026\ age^4 - 0.123\ age^3 + 1.5781\ age^2 - 10.1x + 119.2$	≥3	.988	105	3,322.0	75.5	31.6
	5	$PCI = 0.0069\ age^4 - 0.0838\ age^3 - 0.5742\ age^2 + 1.7814\ age + 111.34$	≥5	.977	139	5,911.9	1,182.4	42.5
	7	$PCI = -0.038\ age^4 + 1.6358\ age^3 - 25.47\ age^2 + 162.66\ age - 276.58$	≥7	.952	123	13,571.5	1,233.8	110.3
	9	$PCI = -0.1157\ age^4 + 5.7882\ age^3 - 107.39\ age^2 + 867.71\ age - 2{,}493.6$	≥9	.825	48	9,158.3	286.2	190.8

TABLE 2 Do-Nothing and Slurry Seal Performance Prediction Models and Statistics for Overlay

Road Classification	Year of Slurry Seal Application	Equation	Age	R^2	N	SSR	MSE	SSR/N
Do-Nothing Performance Prediction Model								
Arterial	—	$PCI = -0.0185\ age^4 + 0.5036\ age^3 - 4.0695\ age^2 + 3.6796\ age + 98.809$	≥0	.973	34	457.4	457.4	13.5
Collector	—	$PCI = -0.0004\ age^4 + 0.0099\ age^3 - 0.2232\ age^2 - 3.7809\ age + 99.192$	≥0	.959	226	1,882.6	1,882.6	8.3
Residential	—	$PCI = -0.0048\ age^4 + 0.1177\ age^3 - 0.9078\ age^2 - 1.9824\ age + 98.666$	≥0	907	1,848	49,069.7	9,813.9	26.6
Slurry Seal Performance Prediction Model								
Arterial	0	$PCI = -0.0181\ age^4 + 0.4951\ age^3 - 4.0048\ age^2 + 3.5562 age + 99.899$	≥0	986	7	786.8	393.4	112.4
	1	$PCI = -0.0128\ age^4 + 0.3481\ age^3 - 2.7262\ age^2 - 0.4666\ age + 102.81$	≥1	.981	9	907.9	454.0	100.9
	3	$PCI = -0.0162\ age^4 + 0.5902\ age^3 - 7.7303\ age^2 + 35.778\ age + 46.482$	≥3	977	8	1,328.0	332.0	166.0
	5	$PCI = -0.0594\ age^4 + 2.3389\ age^3 - 33.321\ age^2 + 194.57 age - 295.9$	≥5	.984	9	547.6	547.6	60.8
	7	$PCI = -0.0348\ age^4 + 1.4056\ age^3 - 20.539\ age^2 + 120.78\ age - 153.72$	≥7	.939	6	948.6	948.6	158.1
	9	$PCI = 0.0356\ age^4 - 1.4926\ age^3 + 22.796\ age^2 - 159.65\ age + 526.72$	≥9	.925	8	1,291.6	1,291.6	161.5
Collector	0	$PCI = -0.0009\ age^4 + 0.0387\ age^3 - 0.5779\ age^2 - 2.6513\ age + 99.98$	≥0	.979	10	2,051.8	410.4	13.2
	1	$PCI = -0.0006\ age^4 + 0.0379\ age^3 - 0.5773\ age^2 - 3.1878\ age + 103.21$	≥1	.982	12	1,213.5	606.8	10.6
	3	$PCI = -0.0024\ age^4 + 0.1387\ age^3 - 2.4837\ age^2 + 9.179\ age + 91.239$	≥3	.980	15	1,463.2	731.6	12.6
	5	$PCI = 0.0044\ age^4 - 0.2179\ age^3 + 4.0245\ age^2 - 40.362\ age + 225.73$	≥5	.973	19	1,185.7	592.9	15.6
	7	$PCI = -0.0481\ age^4 + 2.0665\ age^3 - 33.252\ age^2 + 228.1\ age - 482.91$	≥7	.958	12	1,159.0	579.5	18.7
	9	$PCI = 0.0537\ age^4 - 2.9244\ age^3 + 58.057\ age^2 - 509.19\ age + 1{,}736.2$	≥9	927	13	1,056.6	528.3	24.0
Residential	0	$PCI = -0.0041\ age^4 + 0.1056\ age^3 - 0.8448\ age^2 - 2.2707\ age + 99.849$	≥0	.973	236	1,973.1	1,973.1	8.4
	1	$PCI = -0.0049\ age^4 + 0.1159\ age^3 - 0.7594\ age^2 - 3.6479\ age + 104.28$	≥1	965	242	2,784.0	2,784.0	11.5
	3	$PCI = -0.0194\ age^4 + 0.6336\ age^3 - 7.2921\ age^2 + 28.83\ age + 63.294$	≥3	.958	291	2,307.6	329.7	7.9
	5	$PCI = -0.0076\ age^4 + 0.2747\ age^3 - 3.41\ age^2 + 9.8706\ age + 106.29$	≥5	.936	295	6,130.1	1,226.0	20.8
	7	$PCI = -0.0052\ age^4 + 0.076\ age^3 + 1.2761\ age^2 - 33.311\ age + 241.73$	≥7	934	159	2,455.0	2,455.0	15.4
	9	$PCI = -0.4638\ age^4 + 21.490\ age^3 - 369.690\ age^2 + 2787.3\ age - 7{,}682.4$	≥9	.986	7	786.8	393.4	112.4

in the new construction category tend to perform 2 to 3 years longer than pavements in the overlay category, except for residential streets that did not show significant difference in the performance of the two categories. In general, regardless of the pavement type, fatigue and block cracking were the two major types of distresses that were observed on the evaluated pavement sections before the application of slurry seal 7 or more years after construction.

Figures 2 through 7 superimpose the performance models for pavements without slurry seals and pavements that received slurry seals at 0, 1, 3, 5, 7, and 9 years after construction for the new construction and overlay categories and for all three classes of roads. In addition, Figure 8 shows the increase in the initial PCI value at the time of slurry seal application. The following general trends can be observed from the presented data:

- Applications of the slurry seal at Years 0 and 1 did not show a significant change in the shape of the performance curve or in the initial PCI value.
- Applications of the slurry seal at Years 3 and 5 showed significant jumps in the PCI value at the time of application and in the shape of the performance curve for future years. On average, the initial PCI value increased by 12 points when slurry seal was applied 3 years after construction. However, an increase in the initial PCI value of between 11 and 24 points was observed for the newly constructed pavements when slurry seal was applied 5 years after construction. The increase in PCI value was more significant for the residential roads, followed by the collector and arterial roads. In the case of overlay asphalt pavements, the increase in initial PCI value when slurry seal was applied 5 years after constuction ranged

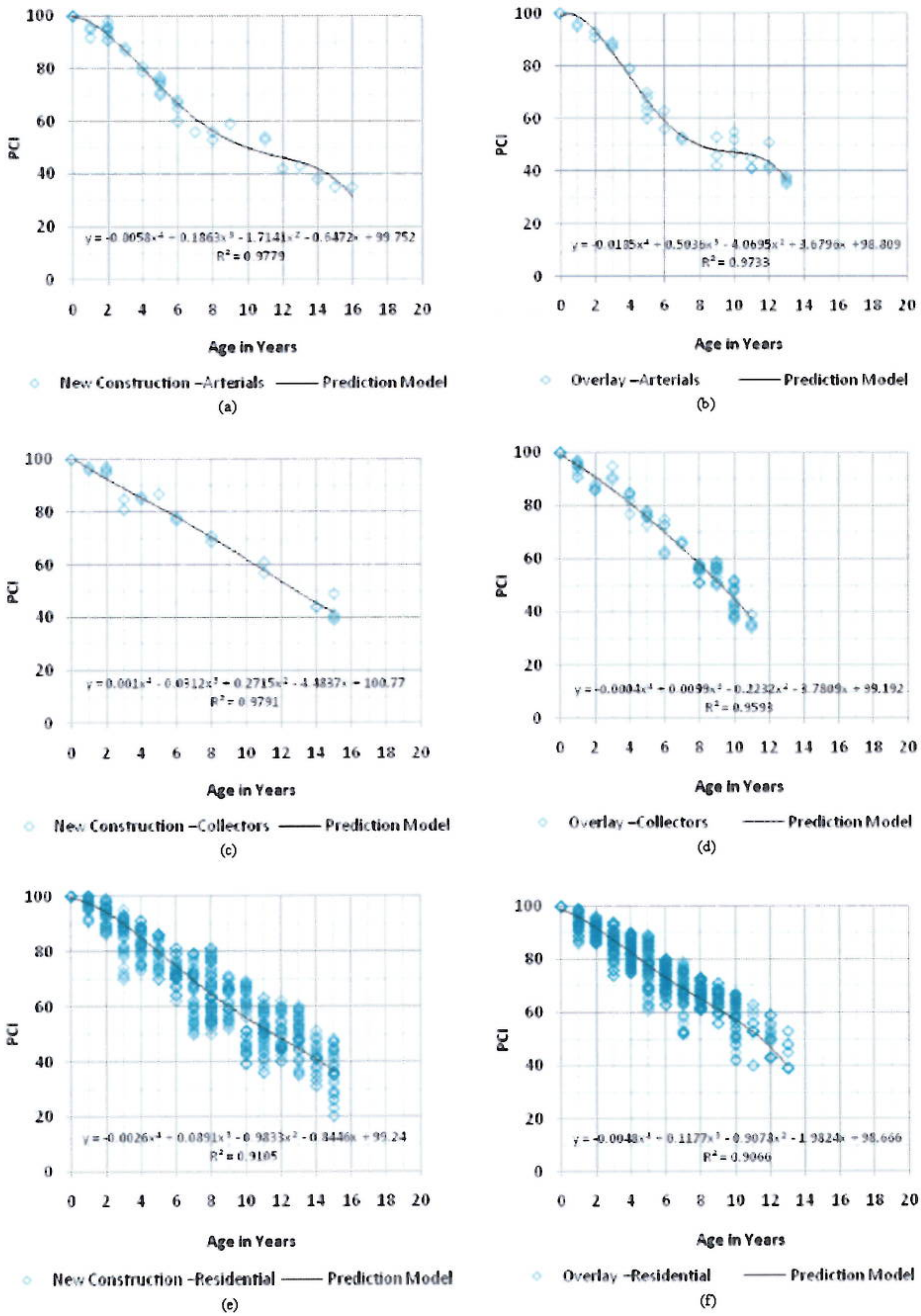

FIGURE 1 Do-nothing performance models for (a) new construction on arterials, (b) overlay on arterials, (c) new construction on collectors, (d) overlay on collectors, (e) new construction on residential, and (f) overlay on residential streets.

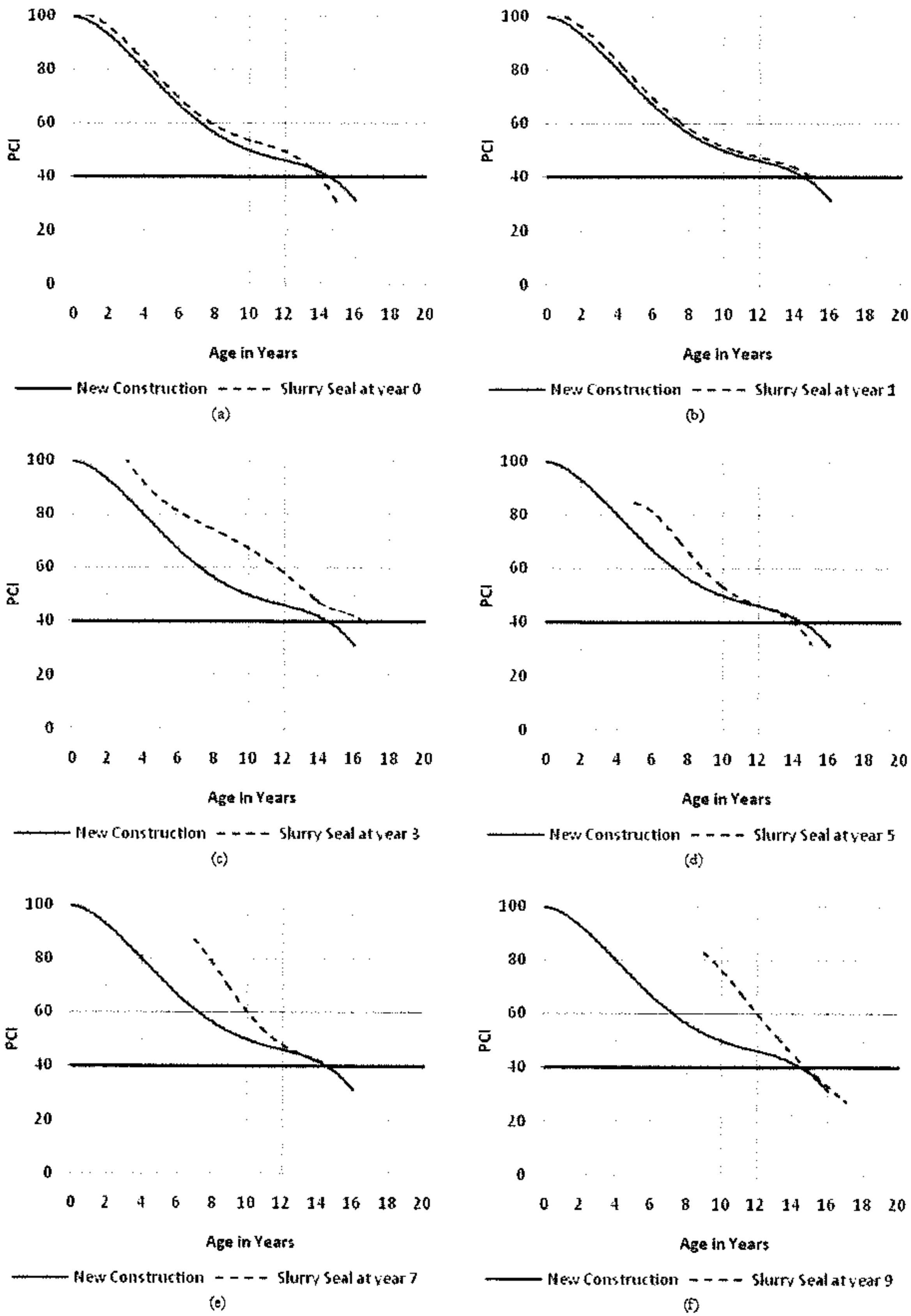

FIGURE 2 New construction on arterials: do-nothing and slurry seal performance models at (a) Year 0, (b) Year 1, (c) Year 3, (d) Year 5, (e) Year 7, and (f) Year 9

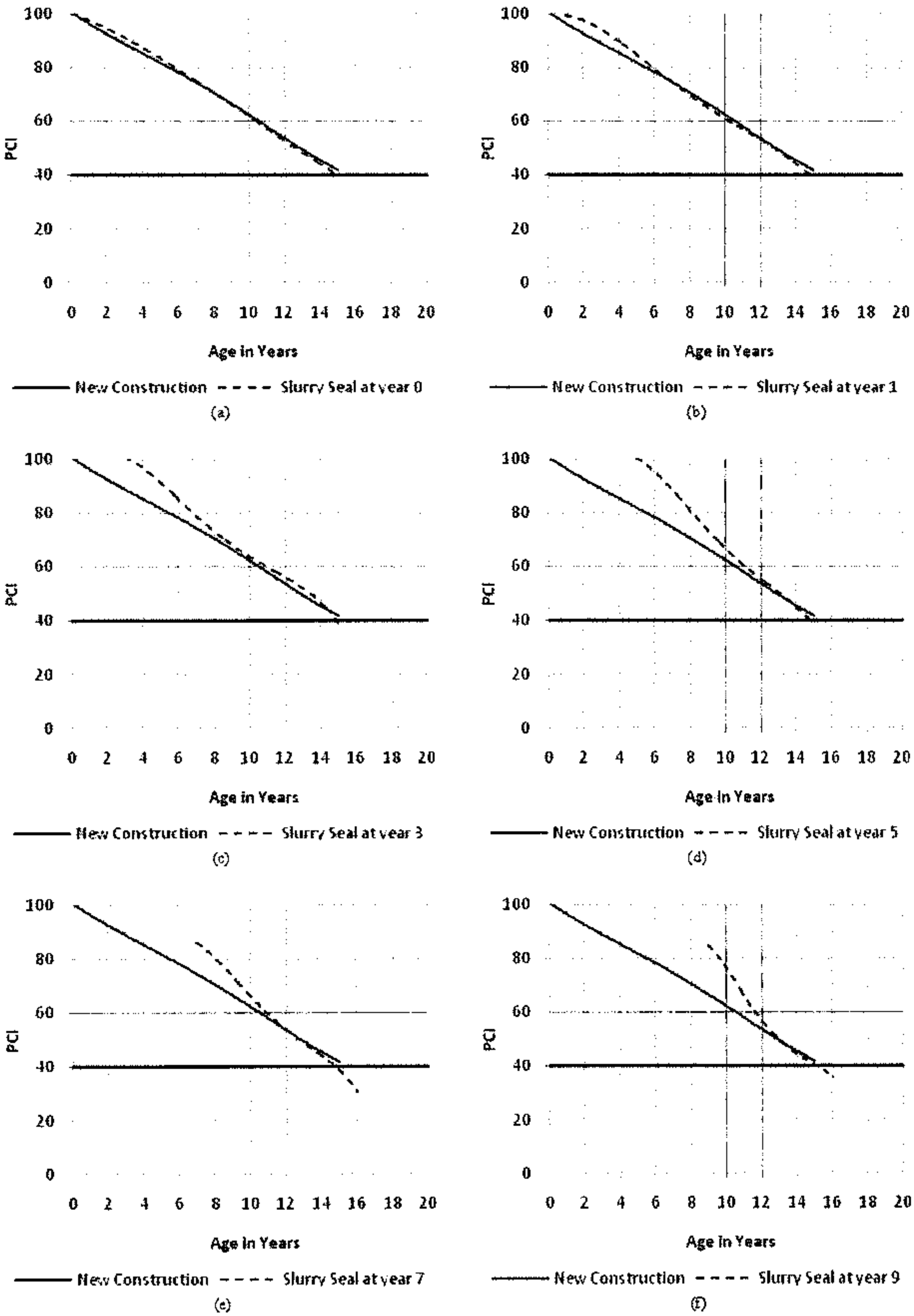

FIGURE 3 New construction on collectors: do-nothing and slurry seal performance models at (a) Year 0, (b) Year 1, (c) Year 3, (d) Year 5, (e) Year 7, and (f) Year 9.

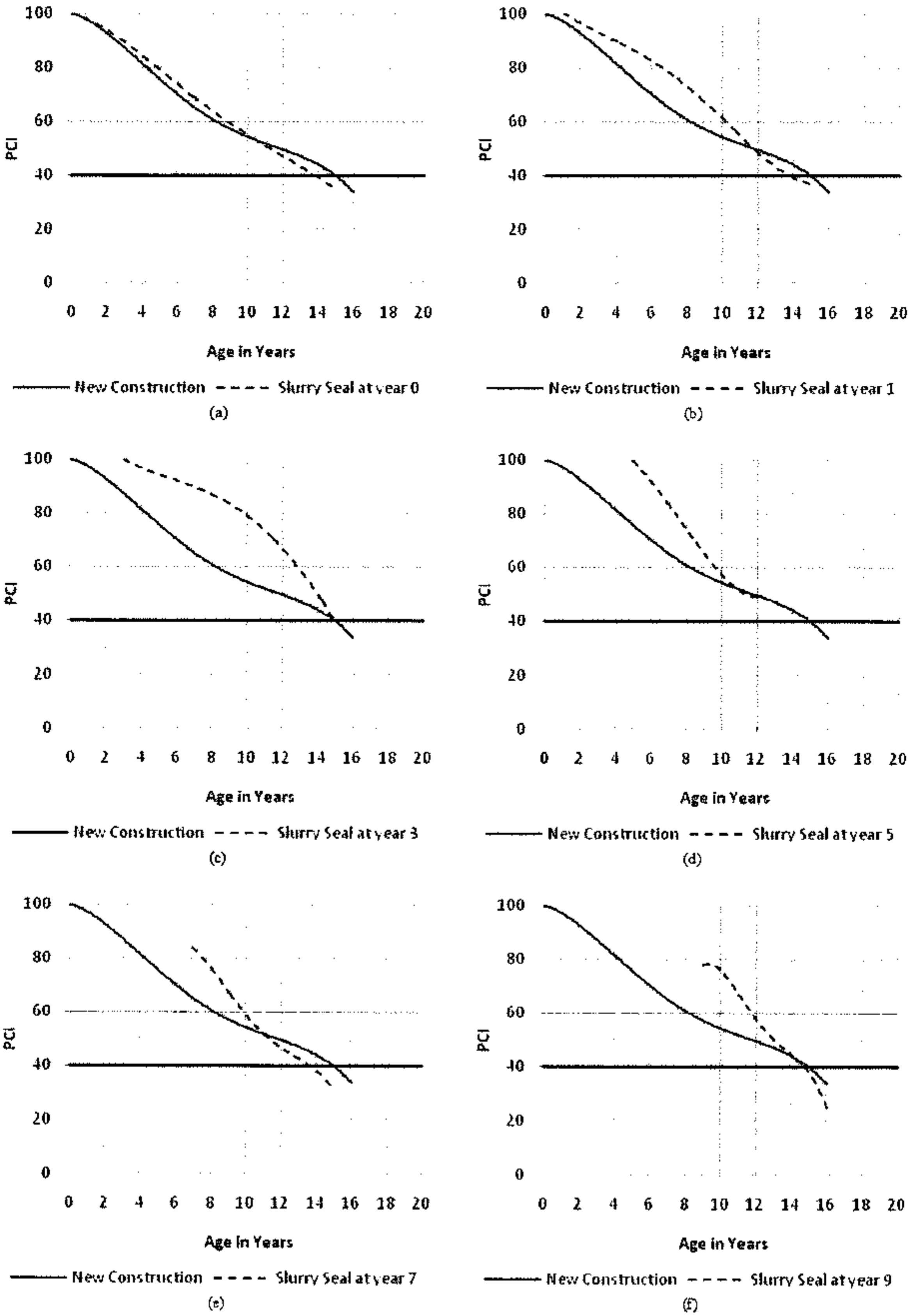

FIGURE 4 New construction on residential: do-nothing and slurry seal performance models at (a) Year 0, (b) Year 1, (c) Year 3, (d) Year 5, (e) Year 7, and (f) Year 9.

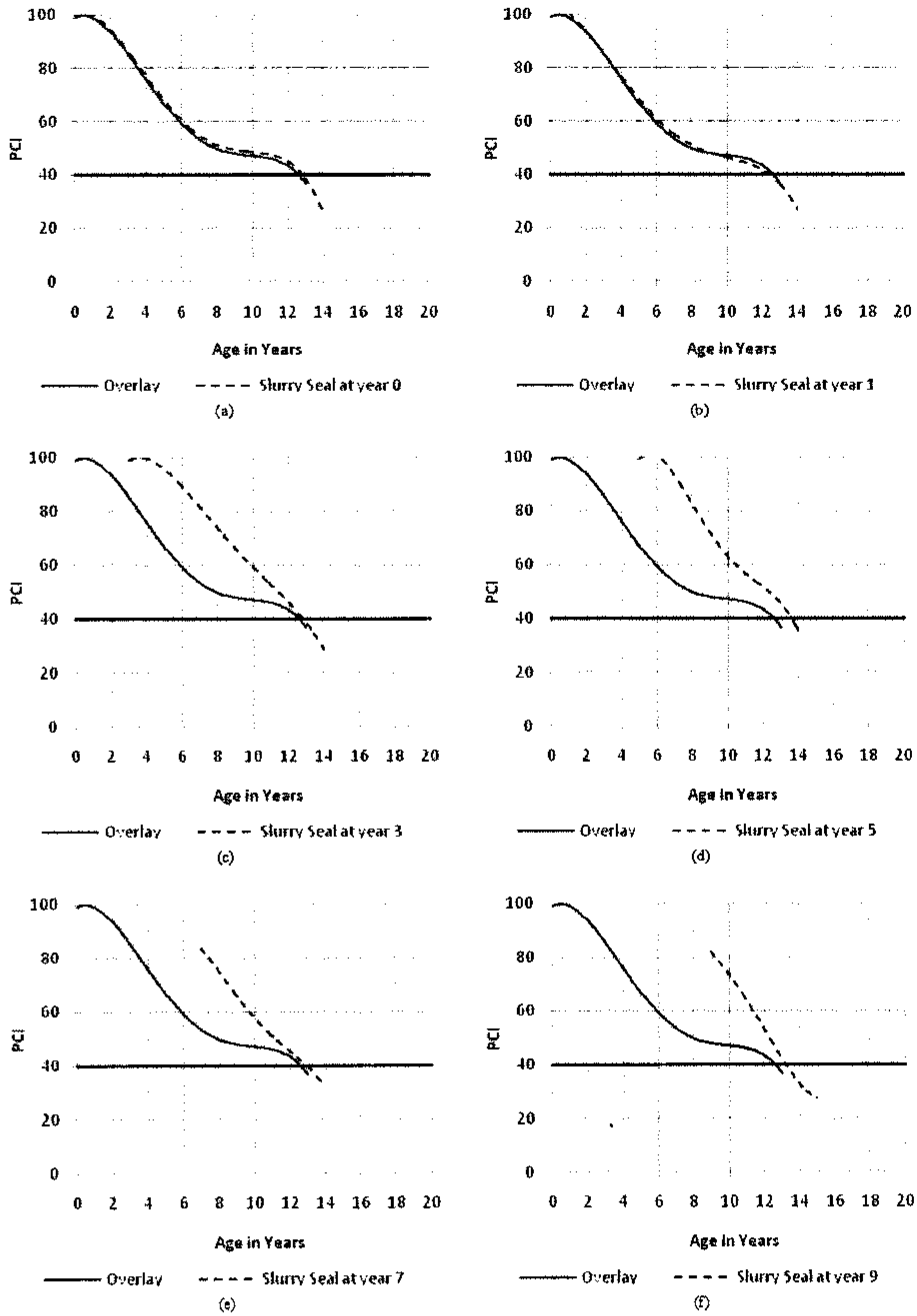

FIGURE 5 Overlay on arterials: do-nothing and slurry seal performance models at (a) Year 0, (b) Year 1, (c) Year 3, (d) Year 5, (e) Year 7, and (f) Year 9.

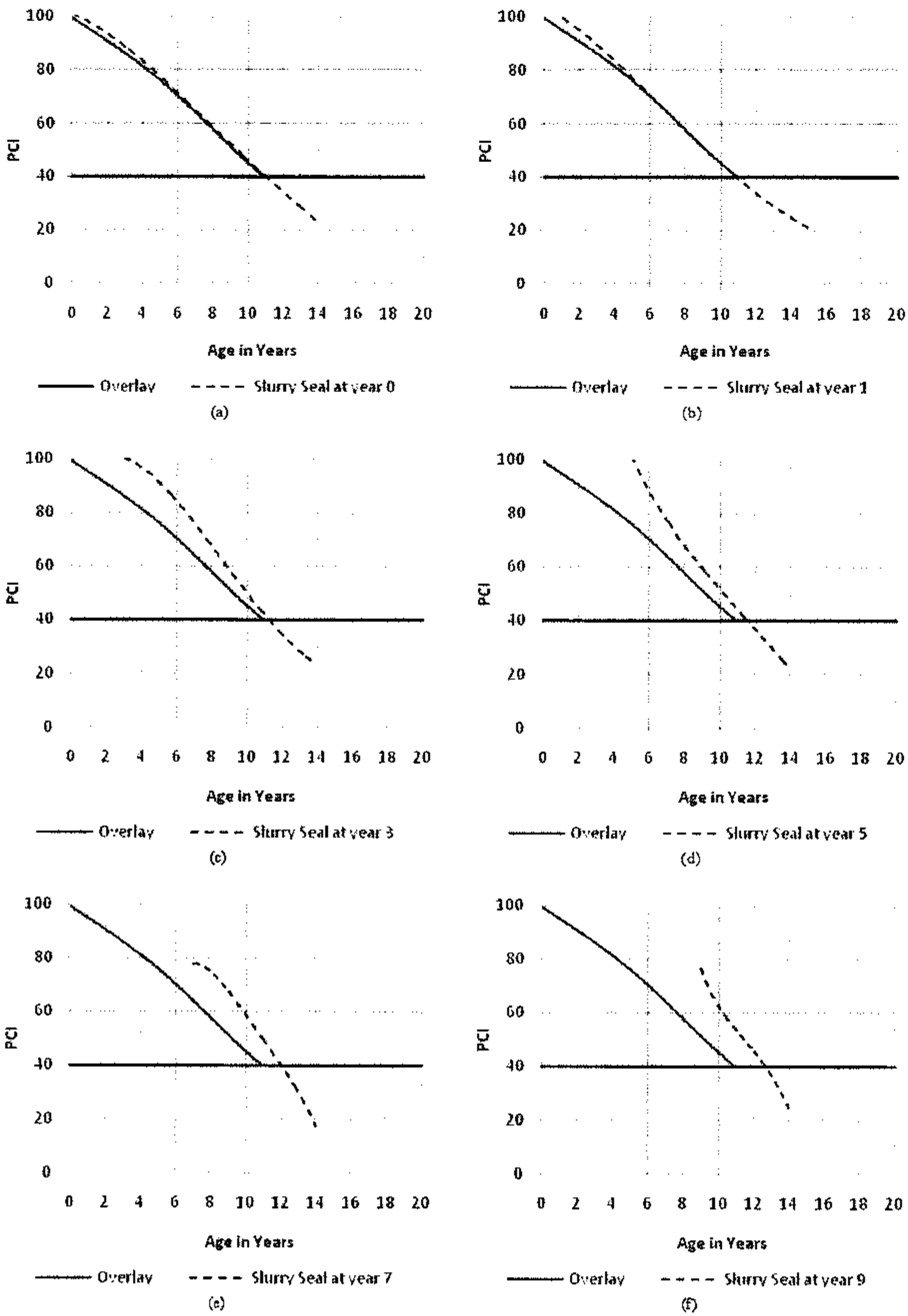

FIGURE 6 Overlay on collectors: do-nothing and slurry seal performance models at (a) Year 0, (b) Year 1, (c) Year 3, (d) Year 5, (e) Year 7, and (f) Year 9.

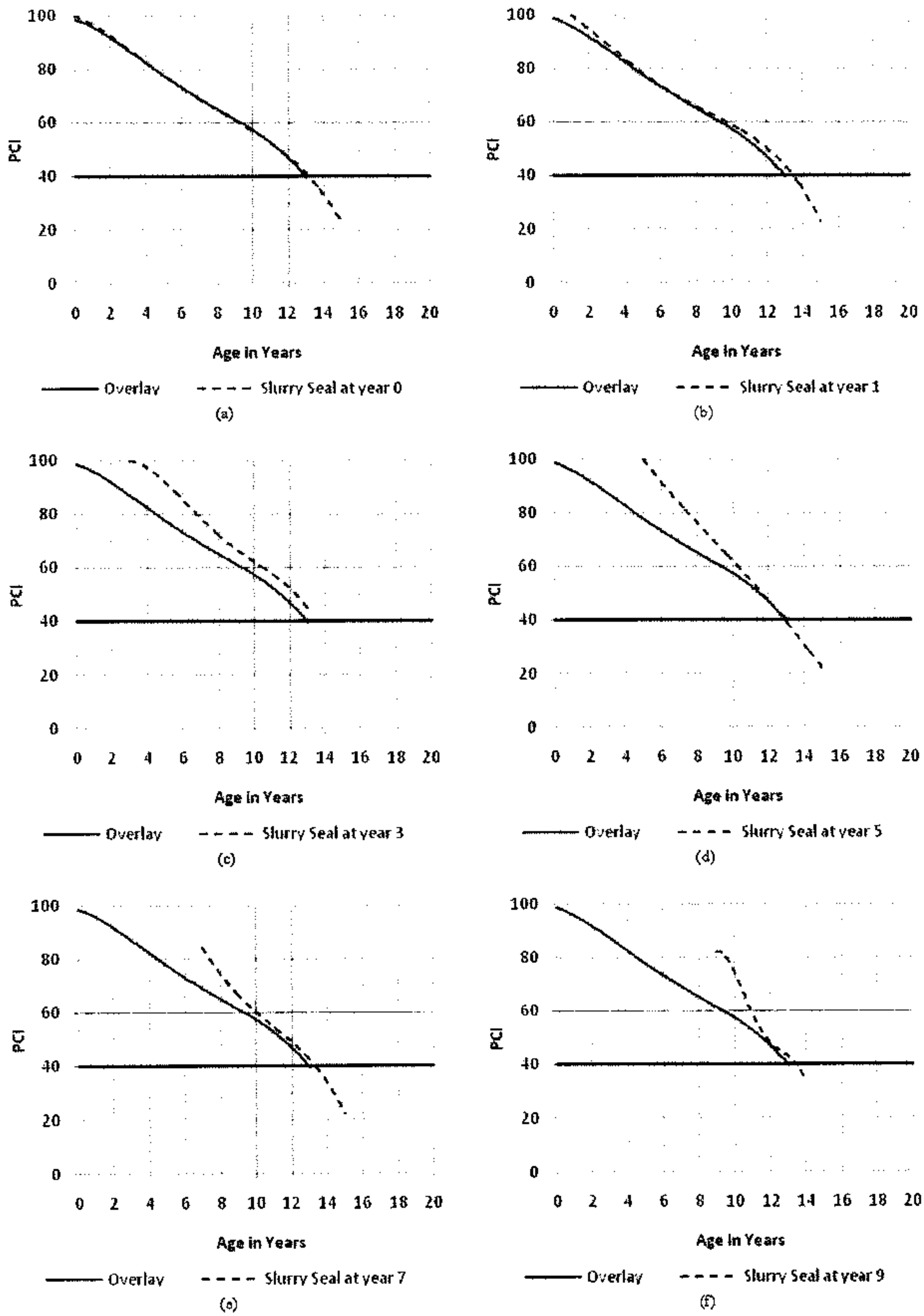

FIGURE 7 Overlay on residential: do-nothing and slurry seal performance models at (a) Year 0, (b) Year 1, (c) Year 3, (d) Year 5, (e) Year 7, and (f) Year 9.

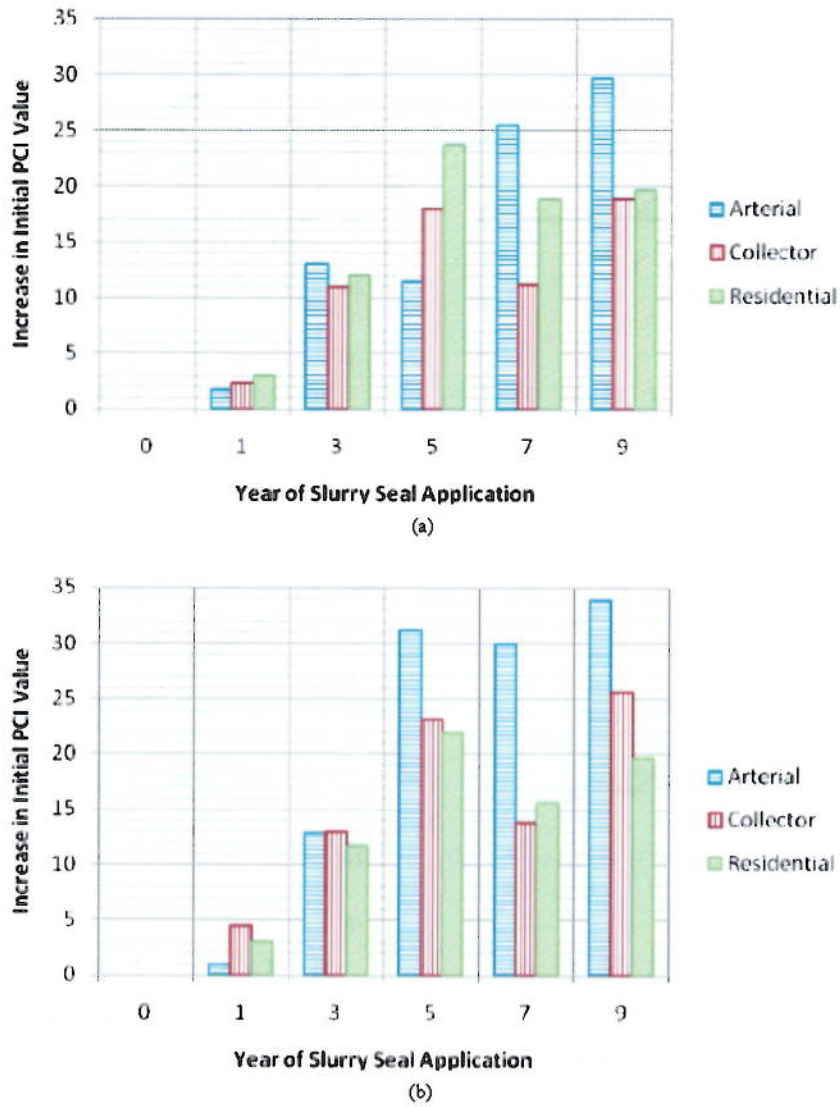

FIGURE 8 Increase in initial PCI value for (a) newly constructed pavements and (b) overlay asphalt pavements.

between 22 and 31 points, with the highest increase being observed on arterial roads.

- Applications of the slurry seal at Years 7 and 9 showed significant jumps in the PCI value at the time of application coupled with a steeper decay in the performance curve for future years. An increase in the initial PCI value between 11 and 30 points was observed for the newly constructed pavements when slurry seal was applied 7 or 9 years after construction. However, an increase in the initial PCI value of between 14 and 34 points was observed for the overlay asphalt pavements when slurry seal was applied 7 or 9 years after construction. For both new construction and overlay categories, the highest increase in initial PCI was observed on arterial roads.

From the performance models in Figures 2 through 7, the slurry seal performance life and extensions in pavement service life can be determined for the various slurry seal applications. The slurry seal performance life is defined as the number of years for the slurry seal performance curve to reach the PCI of the existing pavement before treatment application. In other words, the slurry seal performance life is the number of years for the treated pavement section that provides a higher user satisfaction before the pavement returns to the serviceability condition before treatment. The extension in pavement service life is the number of additional years the pavement will have at the end of its service life (i.e., PCI = 40) as a result of the application of the slurry seal. In other words, the extension in pavement service life is the number of years a pavement reconstruction is delayed. For example, it took 2.0 years for the slurry seals applied in Year 3 of service to the newly constructed arterials to deteriorate from a PCI of 100 right after treatment to the pretreatment PCI of 87 (Figure 2*c*). For the same example, the treatment extended the pavement service life and delayed the time until a PCI of 40 was reached by 2.0 years (Figure 2*c*). However, it took 3.0 years for the slurry seals applied in Year 7 of service to the newly constructed arterials to deteriorate from a PCI of 87 right after treatment to the pretreatment

PCI of 62 (Figure 2e). However, for the same example, the treatment did not extend the pavement service life; both performance curves reached the PCI of 40 after 14.5 years (Figure 2e).

Typically, the slurry seal performance life ranged from 2.0 to 4.0 years, except when applied in Years 0 and 1. When the slurry seal was applied at Years 0 and 1, the slurry seal performance life ranged from 0.0 to 1.0 year. In addition, the pavement service life was not extended by application of the slurry seal except in a few cases. The service life was extended (*a*) by 2.0 years for newly constructed arterials with slurry seal at Year 3; (*b*) by 0.5 to 1.5 years for overlaid collectors with slurry seal at Years 5, 7, and 9; (*c*) by 0.5 to 1.0 year for overlaid residential streets with slurry seal at Years 1 and 3; and (*d*) by 1.0 and 0.5 years for overlaid residential streets with slurry seal at Years 5 and 9, respectively.

The aforementioned performance lives and extensions in pavement service life are for single applications of slurry seal. For multiple applications of slurry, the behavior, especially the extensions in pavement service life, is expected to be different. The focus of this study was only on a single application of slurry seal at different times of the pavement life.

BENEFIT–COST ANALYSIS

The next step of the analysis consisted of calculating the pavement performance benefit of applying slurry seals at various years following construction activities. The slurry seal performance benefit (*B*) is defined as the area between the performance curves of the pavement without slurry seal and the pavement with slurry seal up to the terminal PCI of 40 as shown in Figure 9. The PCI value of 40 is the threshold value used by the Washoe County Engineering Department for reconstruction. The pavement performance benefit represents the increase in a pavement's level of service in regard to the safety and comfort of the public caused by the application of the slurry seal, as measured by PCI.

The relative benefit is defined as the ratio of the slurry seal performance benefit (*B*) over the area under the performance curve of the pavement without slurry seal (*A*) up to the terminal PCI of 40 (i.e., $B/A \times 100$). The relative benefit differs from the pavement performance benefit in that relative benefit scales the increase in pavement serviceability from a slurry seal application to be relative to the pavement serviceability of the existing roadway. The relative benefit can thus be viewed as the percent improvement in the serviceability of the pavement, which is directly related to users' satisfaction.

In the example shown in Figure 9, the application of the slurry seal on a newly constructed arterial after 3 years of construction created an 8-point jump in the PCI, a noticeable upward shift in the performance curve leading to a benefit value of 160, and 2 years extension in the pavement life at the terminal PCI of 40. Looking at these data in relative terms, one can conclude that applying the slurry seal 3 years after construction achieved the following:

- Brought the pavement up to its original serviceability (i.e., PCI = 100),
- Created a noticeable improvement in the serviceability of the pavement and therefore improved users' satisfaction by 43% (Table 3, newly constructed arterial pavements), and
- Extended the service life of the pavement by 15% (i.e., from 14 to 16 years).

The cost of the slurry seal (*C*) was estimated on the basis of the cost figures of 2009 (i.e., 0 years after construction) at $11,070/lane mile. A discount rate of 3% was determined on the basis of historical 15-year records (1991–2005) for the region and that rate was used to estimate the cost figures for the various years of slurry seal applications. For example, the cost of slurry seal applied at Year 3 after construction will be $\$11{,}070(1 + 0.03)^4 = \$12{,}459$/lane mile. In general, the longer a slurry seal is postponed, the higher the present cost of the slurry seal will become as shown in Table 3.

The benefit–cost ratio is defined as the ratio of the benefit (*B*) divided by the cost (*C*) of the application of the slurry seal. The benefit–cost ratio was used to determine the relative cost-effectiveness of the slurry seal treatment with respect to various times of application. Table 3 summarizes the benefit and cost figures for the application of slurry seals at various years after construction for the new construction and overlay. Figure 10 shows the distributions of the benefit, relative benefit, and benefit–cost ratios of slurry seals as a function of the year of application for the new construction and overlay.

For new construction, the highest benefit, relative benefit, and benefit–cost ratio from a slurry seal application occur in Year 3 for arterials and residential streets and in Years 3 and 5 for collectors as shown in Figure 10. For overlays, the highest benefit, relative benefit, and benefit–cost ratio from a slurry seal application occur in Years 3

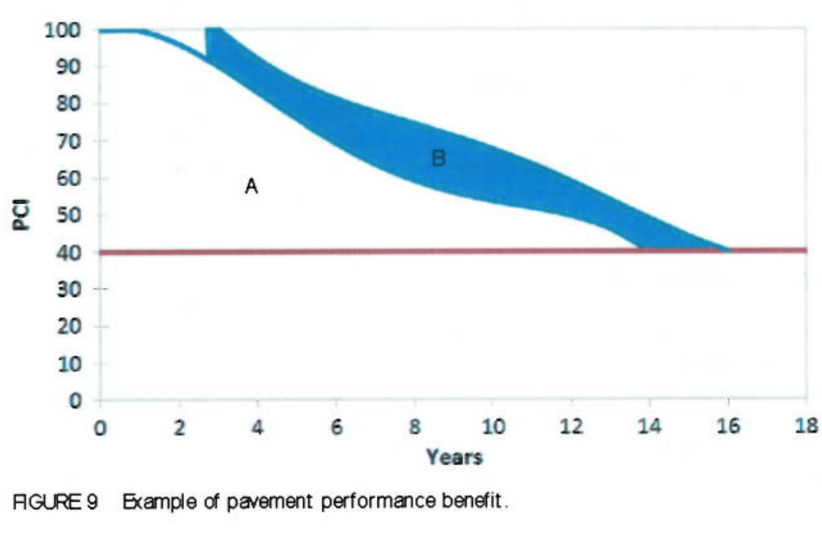

FIGURE 9 Example of pavement performance benefit.

TABLE 3 Effectiveness of Slurry Seal for Newly Constructed and Overlay Asphalt Pavements

Traffic	Year of Slurry Seal Application	Benefit, *B* (Area)	Relative Benefit × 100	Cost, *C* ($/lane mile)	Benefit–Cost Ratio (*B/C* × 1,000)
Newly Constructed Pavement					
Arterial	0	32.8	9	11,070	3.0
	1	19.2	5	11,402	1.8
	3	160.2	43	12,459	12.9
	5	45.5	12	14,444	3.1
	7	70.5	19	17,764	4.0
	9	80.1	22	23,178	3.5
Collector	0	19.5	4	11,070	1.5
	1	15.4	3	11,402	2.1
	3	54.9	12	12,459	4.6
	5	75.0	16	14,444	5.6
	7	34.8	8	17,764	1.9
	9	41.3	9	23,178	1.6
Residential	0	0.0	0	11,070	0.0
	1	58.4	14	11,402	5.1
	3	204.6	48	12,459	16.4
	5	57.3	14	14,444	4.0
	7	34.7	8	17,764	2.0
	9	65.4	15	23,178	2.8
Overlay Asphalt Pavement					
Arterial	0	26.7	8	11,070	2.4
	1	1.8	1	11,402	0.2
	3	183.4	58	12,459	14.7
	5	189.2	60	14,444	13.2
	7	75.6	24	17,764	4.3
	9	70.2	22	23,178	3.0
Collector	0	17.4	5	11,070	1.6
	1	14.5	4	11,402	1.3
	3	86.3	25	12,459	6.9
	5	71.8	21	14,444	5.0
	7	62.9	18	17,764	3.5
	9	49.2	14	23,178	2.1
Residential	0	3.1	1	11,070	0.3
	1	16.4	4	11,402	1.4
	3	83.6	20	12,459	6.7
	5	78.0	19	14,444	5.4
	7	27.7	7	17,764	1.6
	9	30.6	7	23,178	1.3

and 5 for arterials, collectors, and residential streets as also shown in Figure 10. On the basis of the relative benefit and benefit–cost ratio observations, user satisfaction and agency cost-effectiveness are maximized when slurry seals are applied as follows:

- Year 3 for newly constructed arterials and newly constructed residential streets,
- Years 3 and 5 for newly constructed collectors, and
- Years 3 and 5 for arterials, collectors, and residential streets with overlays.

CONCLUSIONS AND RECOMMENDATIONS

Review of the pavement performance data and benefit–cost ratio of the slurry seals as a function of the year of application leads to the following conclusions and recommendations:

- The performance data of slurry seals analyzed for this study supported the basic engineering principles of preventive maintenance of asphalt pavements as discussed below:

  – Asphalt pavements should be allowed to cure for the first 3 years before the application of any surface treatment. This is shown by the low benefits of applying slurry seal immediately after and 1 year after construction.

  – A 3-year curing period of asphalt pavements will allow the asphalt mix to gain strength and build up its resistance to early rutting and shoving. This gain is shown by the noticeable upward shifting of the performance curve for the pavements that received slurry seals 3 years after construction.

  – Application of surface treatments on asphalt pavements 3 years after construction will protect the asphalt mix from excessive aging and improve its resistance to cracking, for example, fatigue, thermal, and block. This improvement is shown by the noticeable upward shifting of the performance curve for the pavements that received slurry seals 3 years after construction and the extension of the pavement life at the terminal PCI level of 40.

- Application of the slurry seal immediately after or 1 year after construction of the asphalt layer is not effective for either the benefit to users or the benefit–cost ratio for the agency.
- The optimum time to apply slurry seal depends on the type of construction activity. For newly constructed pavements, the optimum

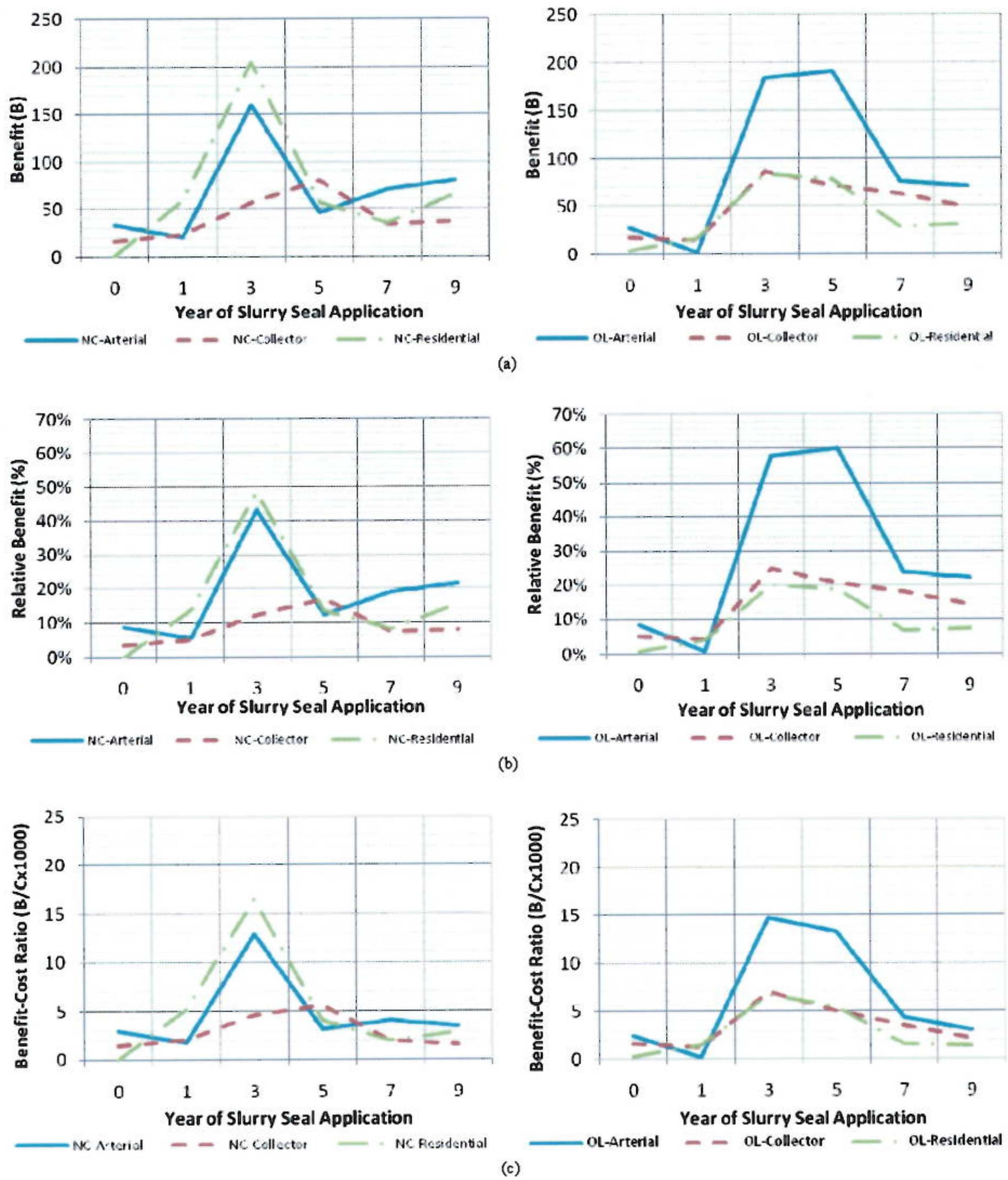

FIGURE 10 Effectiveness of slurry seal (NC 5 new construction; OL 5 overlay): (a) benefit, (b) relative benefit, and (c) benefit cost ratio.

time to apply slurry seal is 3 years after construction. For pavements subjected to overlays, the optimum time to apply slurry seal is between 3 and 5 years after construction. However, for uniformity purposes, it is recommended that the agency apply slurry seal 3 years after the construction of the asphalt layer for both new and overlay constructions.

The conclusions and recommendations above were based on the analysis of asphalt pavement sections that received a single application of slurry seal during their intended performance life. It is expected that multiple applications of slurry seals at different times of pavement life may result in a behavior different from the one observed in this study.

REFERENCES

1. Peshkin, D. G., T. E. Hoerner, and K. A. Zimmerman. *NCHRP Report 523: Optimal Timing of Pavement Preventive Maintenance Treatment Applications.* Transportation Research Board of the National Academies, Washington, D.C., 2004.
2. *Special Report 61E: The AASHO Road Test Report 5, Pavement Research.* HRB, National Research Council, Washington, D.C., 1962.
3. Li, Z., and Z. Zhang. Using Ordered Probit Model to Predict Pavement Performance from Experimental Data. In *Pavement Management, Design, & Testing* (CD-ROM). Transportation Research Board of the National Academies, Washington, D.C., 2004.
4. Hein, D., and D. Watt. *Municipal Pavement Performance Prediction Based on Pavement Condition Data.* Presented at Very Long-Term Life-Cycle Analysis of Pavements—Determining the True Value of Our Investment Session at the Annual Conference of the Transportation Association of Canada, Calgary, Alberta, 2005
5. Shahin, M. Y. *Pavement Management for Airports, Roads, and Parking Lots.* Springer Science+Business Media, LLC, New York, 2005.
6. Rohde, G. T., F. Jooste, E. Sadzik, and T. Henning. *The Calibration and Use of HDM-IV Performance Models in a Pavement Management System.* Presented at 4th International Conference on Managing Pavements, Durban, South Africa, 1998.
7. Rohde, G. T., I. Wolmarans, and E. Sadzik. *The Calibration of HDM Performance Models in the Gauteng PMS.* Presented at 21st Annual South African Transport Conference, South Africa, 2002.
8. Liu, L., V. S. Manepalli, D. S. Gedafa, and M. Hossain. Cost-Effectiveness of Ultrathin Bonded Bituminous Surface and Slurry Seal. In *Compendium of Papers from the First International Conference on Pavement Preservation*, Newport Beach, Calif., 2010, pp. 317–329.
9. Shahin, M. Y. *MicroPAVER Homepage.* U.S. Army Engineer, Research and Development Center, Construction Engineering Research Laboratory, Department of Defense. http://www.cecer.army.mil/paver. Accessed July 29, 2010.
10. *Washoe County Quality of Life Webpage.* Economic Development, NV Energy, Las Vegas, Nev. http://www.nvenergy.com/economicdevelopment/county/washoe/quality.cfm. Accessed July 29, 2010.
11. *Climate Description Webpage.* Reno Weather Forecast Office, National Weather Service, National Oceanic & Atmospheric Administration, U.S. Department of Commerce, Reno, Nev. http://www.wrh.noaa.gov/rev/climate/description_reno.php. Accessed July 29, 2010.
12. *Recommended Performance Guidelines for Emulsified Asphalt Slurry Seal.* Publication A105. International Slurry Surfacing Association, Annapolis, Md., Jan. 2001
13. *Washoe RTC's Regional Preventive Maintenance Program Manual.* April 2004. Revised June 2004. http://www.rtcwashoe.com/streets-highways-32. Accessed Nov. 12, 2010.

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