Front. Struct. Civ. Eng. 2017, 11(1): 17–26
DOI 10.1007/s11709-016-0369-3

RESEARCH ARTICLE

Life-cycle cost analysis of optimal timing of pavement preservation

Zilong WANG, Hao WANG*

Department of Civil and Environmental Engineering, Rutgers, The State University of New Jersey, Piscataway, NJ 08854, USA
**Corresponding author. E-mail: hwang.cee@rutgers.edu*

ABSTRACT Optimal application of pavement preservation or preventive maintenance is critical for highway agencies to allocate the limited budget for different treatments. This study developed an integrated life-cycle cost analysis (LCCA) model to quantify the impact of pavement preservation on agency cost and vehicle operation cost (VOC) and analyzed the optimal timing of preservation treatments. The international roughness index (IRI) data were extracted from the long-term pavement performance (LTPP) program specific pavement studies 3 (SPS-3) to determine the long-term effectiveness of preservation treatments on IRI deterioration. The traffic loading and the initial IRI value significantly affects life extension and the benefit of agency cost caused by pavement preservation. The benefit in VOC is one to two orders greater in magnitude as compared to the benefit in agency cost. The optimal timing calculated based on VOC is always earlier than the optimal timing calculated based on agency cost. There are considerable differences among the optimal timing of three preservation treatments.

KEYWORDS pavement preservation, life-cycle cost analysis, agency cost, vehicle operation cost

1 Introduction

Pavement preservation or preventive maintenance can be used to repair minor pavement distresses, retard pavement failures, and prolong pavement service life. A number of studies have been conducted to evaluate the effectiveness of pavement preservation considering the life extension brought by preservation treatments [1–3]. Quantification of the effectiveness of preservation has important implications for the selection of pavement maintenance strategies and decision making in pavement management system.

Due to the limitation of budget, state highway agencies are looking for guidance regarding the best time to apply preventive maintenance treatments. The use of economic analysis, such as life-cycle cost analysis (LCCA), has been mostly used to determine the optimal timing of maintenance treatments in terms of the cost-effectiveness and benefit-cost ratio of maintenance treatments. The benefit of preservation treatments is usually calculated as the reduction of agency cost due to maintenance treatments as compared to do-nothing scenario. The effectiveness of pavement preservation is usually defined as the life extension of pavement or the improved pavement condition in terms of surface distress, smoothness and skid resistance.

Peshkin et al. [4] considered weighting factors combining treatments, pavement conditions, costs, and expected benefits and developed an analysis tool called OPTime to calculate optimal timing of preventive maintenance treatments based on the benefit-cost ratio of agency cost, work zone-related user delay costs, and etc. Wei and Tighe [5] computed the optimal timing of application for each treatment based on cost-effectiveness analysis and applied it for a decision tree. Haider and Dwaikat [6] developed mathematical models to estimate the optimal timing on the basis of different treatment effectiveness evaluation criteria and the area-based effectiveness was used in the exemplary analysis. Wang et al. [7] analyzed the optimal timing of treatment application using benefit-cost analysis and found that the relationship between pavement life extension and the overall performance index at the time of treatment

Article history: Received Mar 20, 2016; Accepted Jun 2, 2016

could be modeled using second-order polynomial functions.

However, most previous studies focused either on the effectiveness of treatments on pavement life extension or the cost-effectiveness of treatments considering only the agency cost. Few studies have been conducted to quantify the effect of maintenance treatments on user cost, such as the vehicle operation cost (VOC). The VOC includes fuel consumption cost, tire wear cost, repair and maintenance (R&M) cost, which is dependent on vehicle type, pavement surface characteristics, roadway geometry, and environmental conditions.

It has been documented that preservation treatments provide significant benefit to the drop of International Roughness Index (IRI) [8–10]. Pavement roughness affects not only ride quality but also tire rolling resistance at the tire-pavement interface. Tire rolling resistance describes the vehicle energy loss associated with pavement-vehicle interaction due to hysteretic losses from deformations induced on the tire by the pavement. Increased road roughness can result in the increase of tire rolling resistance and reduction of fuel efficiency.

Therefore, further research is needed to consider the agency cost and VOC in the determination of the optimal timing for maintenance treatments. It is expected that the same treatment performs differently when applied to pavements at different roughness levels (or at different pavement ages). The optimal timing to apply maintenance treatments depends on the type of treatment, the existing condition before the treatment, and the effect of treatment on pavement performance deterioration.

2 Objective and scope

The objective of this study is to develop an integrated LCCA model to quantify the impact of pavement preservation on agency cost and VOC and determine the optimal timing of preservation treatments. The international roughness index (IRI) data were extracted from the long-term pavement performance (LTPP) program specific pavement studies 3 (SPS-3) to determine the long-term effectiveness of preservation treatments on IRI deterioration. The life extensions of pavement after were analyzed using the failure threshold of IRI. The LCCA model was used to analyze the influence of traffic volume and the initial IRI value on the optimal timing of preservation in particular considering both agency cost and VOC.

3 Development of LCCA model

3.1 Long-term pavement performance program (LTPP)

The long-term pavement performance (LTPP) program is a 20-year study of in-service pavements in the US and Canada. Its goal is to extend the life of pavements through various designs of pavement structures using different materials considering different factors such as precipitation, traffic, temperature, subgrade soil, or maintenance practices. The Specific Pavement Studies-3 (SPS-3) experiment in the LTPP program was designed in 1990 to evaluate the cost-effective methods for applying preservation treatments for flexible pavements [11].

There are totally 81 SPS-3 sites distributed in LTPP database. At each site, four preservation treatments (thin overlay, slurry seal, crack seal and chip seal) are implemented continuously on the pavement sections with the average length of 500ft in addition to the control section. Therefore, the pavement sections with preservation treatments and the control section have the same climate and traffic conditions.

In the LTPP database, pavement performance monitoring data are available in most SPS-3 sites. These data were used to develop the immediate performance jump at the timing of preservation treatments and the pre-treatment and post-treatment performance models, respectively. In this study, three preservation treatments were considered, namely thin overlay, chip seal, and crack seal. The slurry seal was not considered due to the incompleteness of data.

3.2 Short-term and long-term effectiveness of preservation

The effectiveness of preservation treatments can be measured in short- and long-term by using the attributes determined from the observed pavement performance with and without preservation treatments. Short-term effectiveness measures are the improvements in pavement condition (performance jump) and the reduction of deterioration rate due to the treatment [1]. The long-term effectiveness of preservation treatments can be evaluated by using the treatment service life and the area bounded by pavement performance curve [8,12].

Previous researchers have found that short-term effectiveness due to the treatment is mainly affected by the pre-treatment pavement condition, while the long-term effectiveness of pavement preservation treatment is affected by pavement type, traffic, and age factors [13]. In another word, the short-term effectiveness due to the treatment is significantly affected by the application timing of preservation. Although previous studies have considered the development of IRI as an exponential function of pavement age [14], traffic parameter was not considered. It has been proved that traffic have considerable influence on the deterioration of IRI and cannot be neglected in the analysis of long-term effectiveness of preservation [15,16].

3.3 IRI performance jump models

The effects of existing pavement roughness on the treatment performance have to be considered in the development of IRI model for maintenance treatments.

The ideal way to calculate the short-term effectiveness of treatments is to use the IRI values immediately before and after the treatments. However, it was found that the LTPP SPS-3 data set has no such data available for many sites. Instead, a linear interpolation method was used to project the short-term effectiveness of IRI values based on the closest IRI values before and after treatment [1]. The cut-off time lag before and after treatment was set to be 12 months.

In the study conducted by Lu and Tolliver [10], a polynomial function was selected to develop short-term performance jump models for IRI. The relationships between pretreatment IRI values and the IRI jumps are shown in in Eqs. (1)–(3), respectively, for thin overlay, chip seal, and crack seal [10]. In general, the average reductions in IRI for thin overlay, chip seal and crack seal were calculated to be 1.44 m/km, 0.72 m/km, and 0.27 m/km, respectively. These equations indicate that crack seal or chip seal will not affect pavement IRI condition if the pre-treatment IRI value is quite low (good condition) or if the pre-treatment IRI value is extremely high (poor condition). However, for thin overlay, significant benefits were obtained especially at the worse pre-treatment pavement condition or an older pavement age.

1) Thin Overlay

$$\text{IRI jump} = -0.008IRI_{existing}^{3} + 0.971IRI_{existing} - 0.726;$$

$$R^2 = 0.88. \tag{1}$$

2) Chip Seal

$$\text{IRI jump} = -0.008IRI_{existing}^{3} + 1.606IRI_{existing} - 1.637;$$

$$R^2 = 0.52. \tag{2}$$

3) Crack Seal

$$\text{IRI jump} = -0.052IRI_{existing}^{3} + 0.774IRI_{existing} - 0.749;$$

$$R^2 = 0.83. \tag{3}$$

The results indicate that a maximum effectiveness of IRI jumps for crack seal and chip seal, exists at the specific pre-treatment condition. As the pre-treatment pavement condition moves away from the specific condition, the treatment becomes less effective, which is consistent with the expectation and past research that identified the ceiling for treatment effectiveness [17]. However, for thin asphalt overlay, it shows that pavement with a worse pretreatment condition will demonstrate a more significant performance jump for most pre-treatment conditions.

3.4 Pre-treatment and post-treatment IRI models

The rationale for developing pre-treatment and post-treatment performance models stems from the fact that maintenance treatments will lower the deterioration rate of pavement performance. Due to the variation of IRI data in the LTPP database, some IRI data points may not represent natural development trend of IRI. The study set up several criteria for filtering IRI data points at each site. If the IRI difference between two data points that were recorded within one year was more than 1m/km, one of these data points was considered as an outlier considering that the traffic effect alone cannot contribute to such a big increase in IRI. Instead, the dramatic increase of IRI may be due to measurement error or other unknown factors. On the other hand, if the IRI values remain literally unchanged for over five years, the IRI values would not be used in the study. For those sections that have multiple treatment applications in the monitoring period, only the IRI data recorded between two consecutive treatments were selected for analysis.

In this study, an exponential model was used to describe the development of IRI subject to the influence of the initial pavement condition and traffic, as shown in Eq. (4)

$$IRT(t) = IRI_0 e^{R \cdot t}, \tag{4}$$

$$R = a + b \cdot AADTT, \tag{5}$$

where IRI_0 is the initial value of IRI ($t = 0$); R is deterioration rate of IRI; a and b are fitting parameters; $AADTT$ is average annual daily truck traffic in ESALs; and t is pavement age in year.

The initial IRI and the deterioration rate of IRI were determined through nonlinear regression of IRI data with pavement age. The analysis found that the average IRI deterioration rates (in m/km per year) were 0.0327, 0.0345, 0.0353, and 0.0289, respectively, for the pavement section with chip seal, crack seal, do-nothing, and thin overlay. Mann–Whitney U test was conducted for comparing the deterioration rates of IRI among different treatments. As a non-parametric test, it can be applied on unknown distributions contrary to t-test which has to be applied only on normal distributions, and it is nearly as efficient as the t-test on normal distributions. If the p-value of the result is smaller than 0.05, it suggests that the life of two rehabilitation activities have significant difference. The results indicate that that the deterioration rates of IRI for thin overlay is significantly lower than chip seal (p-value of 0.032), crack seal (p-value of 0.009), do-nothing (p-value of 0.002).

After the IRI deterioration rate at each site is determined, the traffic effect on the deterioration rates of IRI was analyzed. The fitting parameters a and b in Eq. (5) were computed through analysis of the deterioration rates of IRI and the ESALs, as shown in Fig. 1. The results show that the significance of traffic effect is depending on the treatment type. It can be seen that when $AADTT$ increases, the IRI deterioration rate increases slightly faster in control section as compared to other treatment sections. It is noted that the average annual daily truck traffic (AADTT) at most LTPP SPS-3 sites are less than 1000 equivalent single axle loads (ESALs).

3.5 Life extension of pavement preservation

To calculate the benefit of each preservation treatment on agency costs and VOC, the life extension of pavement brought by the treatment is needed. Treatment service life was determined from pavement performance curve by extrapolating the curve to the point at which the treated pavement reverts to an established threshold. Through the fitted IRI models, the life extension can be computed as the time when IRI reaches the terminal IRI threshold.

Figure 2 illustrates the life extension of preservation treatments. The pre-treatment IRI will develop following the original curve that starts from the initial IRI. If a treatment is applied, the IRI will reduce to a certain value (performance jump) and then develop following the new curve. For the post-treatment curve, the initial value and deterioration rate of IRI vary depending on the type of maintenance treatment. Finally, the pavement life before the IRI achieves the failure threshold can be calculated.

The initial values of IRI for pre-treatment performance curve typically ranged from 0.5 to 1.3 m/km [14]. This study selected 0.9 m/km as the base value for the initial IRI and considered the range of variation from 0.6 m/km to 1.4 m/km in the sensitivity analysis. The pavement life was determined when the IRI reached the terminal value of 2.6 m/km, which is the failure threshold defined in the new mechanistic-empirical pavement design guide (MEPDG) [18]. A wide range of AADTT from 500 to 6000 ESALs was considered in the analysis.

3.6 Life-cycle cost model

LCCA is an analytical technique for assessing potential economic impacts throughout a pavement's life and it is one of the most powerful tools available for evaluating the cost-effectiveness of preservation maintenance. An integrated LCCA model was developed to compute the benefit of preservation treatments in the category of agency cost and VOC.

Two economic indicators are typically used in the LCCA: net present value (NPV) and equivalent uniform annual costs (EUAC). NPV converts all costs occurred at different years to one single base year in order to conduct the comparison, while EUAC distributes NPV to a yearly cost within the whole life cycle, as shown in Eq. (6) and Eq. (7). The study selected EUAC as a major indicator since it is applicable to compare different preservation strategies when the budgets for pavement maintenance are usually established annually. Additionally, it is capable of comparing the effectiveness of pavement sections with various service lives. The benefit is defined as the difference between the EUAC for each treatment and the EUAC for do-nothing scenario.

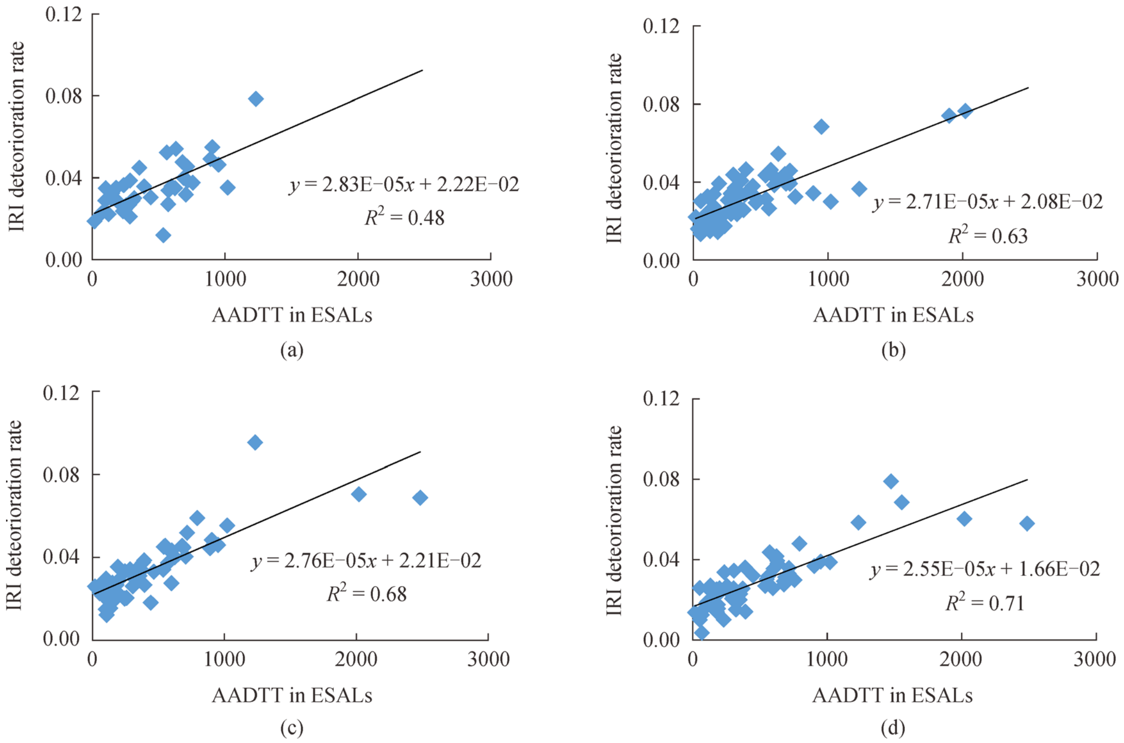


Fig. 1 Relationship between IRI deterioration rate and traffic for: (a) control group; (b) chip seals; (c) crack seals; (d) thin overlay

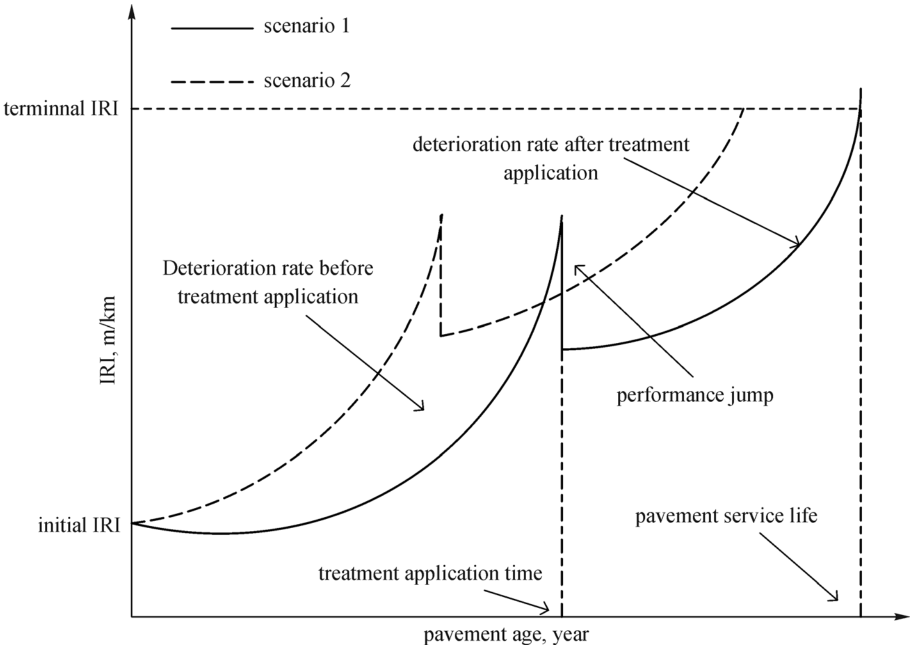


Fig. 2 Illustration of IRI developments before and after treatment

$$\mathrm{NPV} = \sum\nolimits_0^t \frac{C}{(1+i)^t}, \tag{6}$$

$$\mathrm{EUAC} = NPV\frac{i(1+i)^t}{(1+i)^t - 1}, \tag{7}$$

$$\mathrm{Benefit} = \mathrm{EUAC}_{\mathrm{control}} - \mathrm{EUAC}_{\mathrm{treatment}}, \tag{8}$$

where C is the agency cost of treatment or the VOC induced by the IRI; i is discount rate (assumed to be 4% in the study); t is the year when the treatment is applied.

The agency cost includes the initial pavement construction cost to achieve the initial IRI and the cost of preservation treatments. The initial pavement construction cost is assumed to be $200,000/mile for all scenarios. The costs of preservation treatments were extracted from the literature database and compared. The costs used in this study are $20,000/mile for thin overlay, $10,000/mile for chip seal, and $2,000/mile for crack seal, respectively [7,9].

There are a variety of models available for calculating vehicle operation costs. Among these models, the Highway Development and Management Tool (HDM-4) is the most comprehensive model. It quantifies the pavement roughness effect on VOC, including fuel consumption, vehicle repair and maintenance and tire wear costs [19]. Chatti and Zaabar [20] calibrated the HDM-4 model according to the US conditions by estimating the increase in fuel consumption considering pavement roughness effects for different vehicle types. This study selected the data form their work and conducted linear regressions to quantify the correlation between the IRI value and the VOC, as shown in Table 1. To consider the effect of vehicle type on VOC, it was assumed that medium car, sport utility vehicle (SUV), and light truck comprised 45%, 45%, and 10% of total traffic volume, respectively.

4 Results and analysis

4.1 Pavement life extension of preservation treatments

Based on the proposed IRI model, the life extension can be computed as difference between the years when the IRI reaches the terminal IRI threshold before and after preservation. It is expected that truck traffic volume, the initial IRI, the terminal IRI, and the application timing of preservation will affect life extension.

Figure 3 shows the life extensions of preservation treatments when traffic conditions have three different AADTT levels (1200, 2000 and 5000 ESALs) that represent low, medium, and high truck traffic volume. It is assumed that the application time is within the range of pavement life of control section, as it is reasonable to apply treatment before pavement reaches the end of service life. In this case, when AADTT is 1200 ESALs, the application time can vary from the 1st year to the 19th year; when when AADTT is 2000 ESALs, the application time can vary from the 1st year to the 13rd year. If AADTT increases to 5000 ESALs, the application time varies from the 1st year to the 6th year.

Generally, the life extension increases as the application time by year increases within the period of pavement service life for thin overlay. This is because significant

Table 1 Linear regression models calculating VOC [20]

	fuel consumption cost, \$/vehicle-mile	tire wear cost, \$/vehicle-mile	repair and maintenance cost, \$/vehicle-mile
medium car	0.0027IRI + 0.0867	0.00002IRI + 0.0021	0.024
SUV	0.0021IRI + 0.0983	0.00002IRI + 0.0017	0.032
light truck	0.0016IRI + 0.1568	0.00002IRI + 0.0017	0.034

*IRI in m/km.

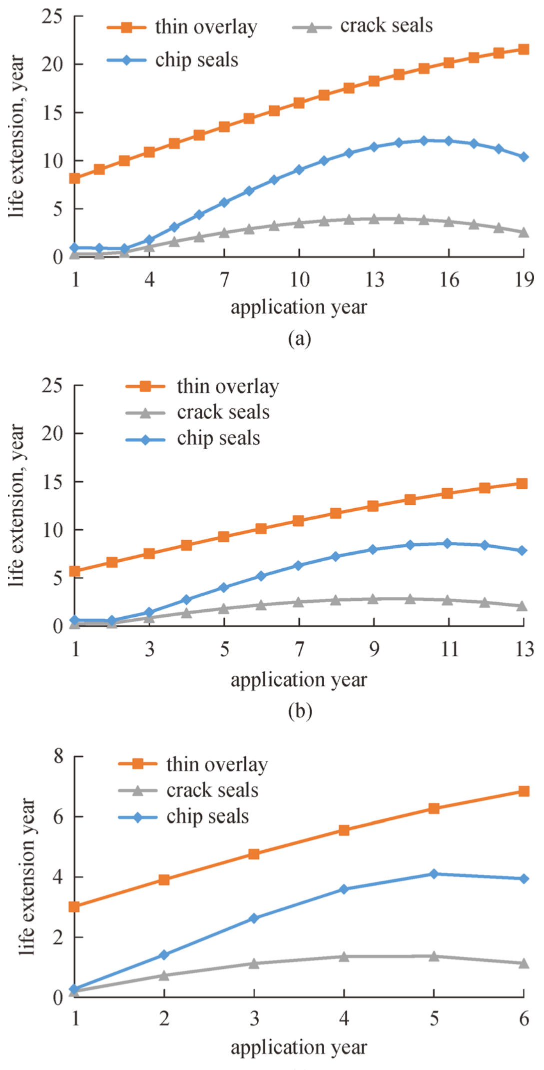


Fig. 3 Calculated life extension when (a) AADTT = 1200; (b) AADTT = 2000; (c) AADTT = 5000

benefits of IRI reduction were obtained after thin overlay, especially at the worse pre-treatment pavement condition or an older pavement age based on the performance jump model used in the analysis [10]. However, for chip seal and crack seal, the maximum life extension can be attained before the end of pavement life, which suggests the feasibility of optimization in LCCA.

The figures also demonstrate that the effect of truck traffic on life extensions of preservation treatments is dependent on the type of treatment. The life extension caused by thin overlay reduces significantly when the truck traffic volume increases, as compared to chip seal and crack seal. This can be explained by the combined effects of short-term and long-term changes of IRI after preservation treatments. Although the deterioration rates of IRI increase as traffic volume increases regardless of preservation treatments, the short-term changes of IRI after preservation treatments reach the maximum values at certain specific pre-treatment IRI values for crack seal and chip seal.

Figure 4 compares the life extensions of preservation treatments when the initial pavement condition has two different IRI values (0.7 and 1.4 m/km), which represent good and poor initial pavement condition, respectively. These results were obtained at the low traffic level so the life extension of thin overlay is relatively high. Another reason of causing the long service life of thin overlay is that pavement life is calculated based on the terminal IRI value of 170 inch/mile in the analysis. In the field sections, thin overlay could be regarded as failure due to other pavement distresses when the IRI is still smaller than 170 inch/mile.

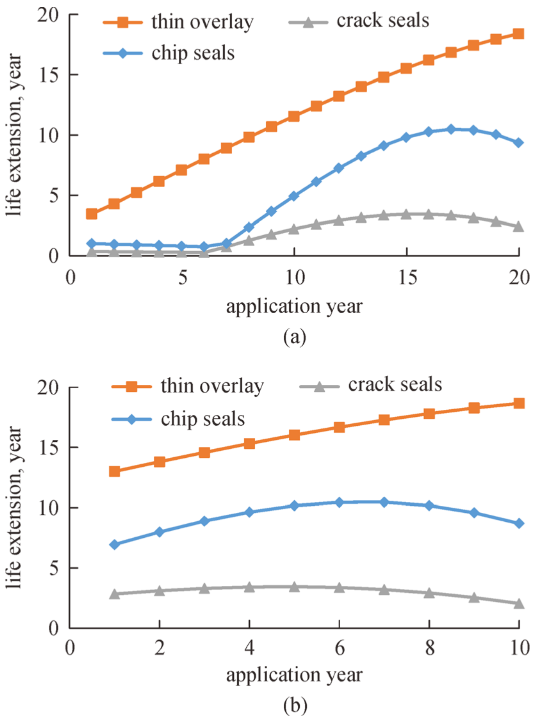


Fig. 4 Calculated life extension when (a) initial IRI = 0.7 m/km; (b) initial IRI = 1.4 m/km

It can be seen that the effect of initial IRI is similar to the effect of traffic level for the trend of life extension with the change of application year. If the preservation treatment is applied at a relatively earlier stage, the life extensions introduced by the applications of preservation treatments are much greater when the initial pavement has the greater initial IRI value. It is noted that when the pavement has the greater initial IRI value, the application timing of preservation treatment can barely affect the life extensions caused by crack seal.

4.2 Benefits of preservation in agency cost and vehicle operation cost

Figures 5 and 6 show the benefits of pavement preservation when traffic conditions have three different AADTT levels (1200, 2000, and 5000 ESALs), for agency cost and VOC, respectively. The results indicate that for chip seal and crack seal the benefits of pavement preservation reach the peak value when the preservation treatment is applied at a specific year, this implies the optimal timing of preservation treatment. This indicates that pavement preservation becomes more effective when the pavement condition deteriorates to a certain level. As compared to the agency cost, the optimal timing of preservation treatment is earlier for the VOC.

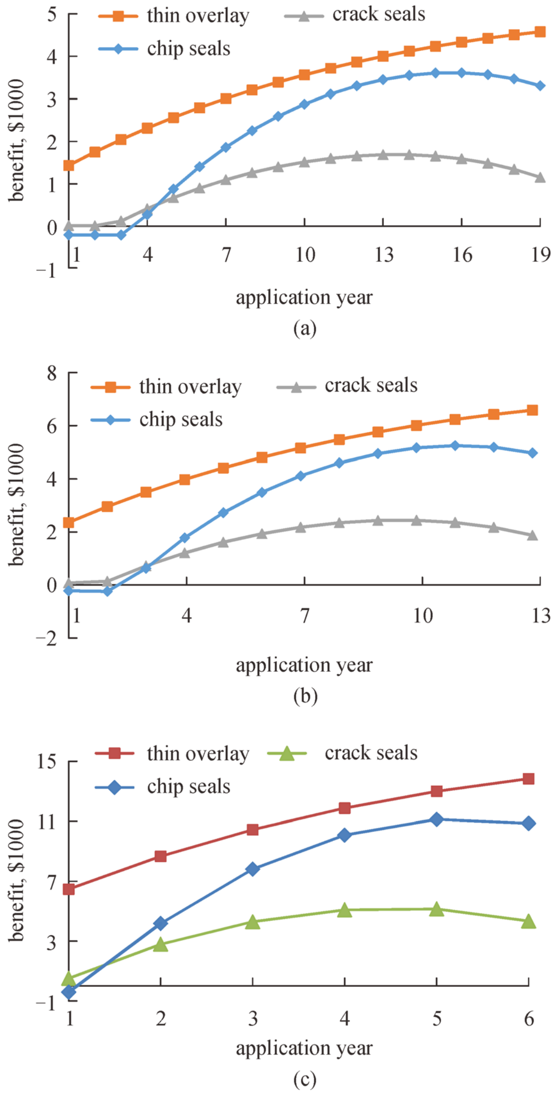


Fig. 5 Benefit of EUAC for agency cost when (a) *AADTT* = 1200; (b) *AADTT* = 2000; (c) *AADTT* = 5000

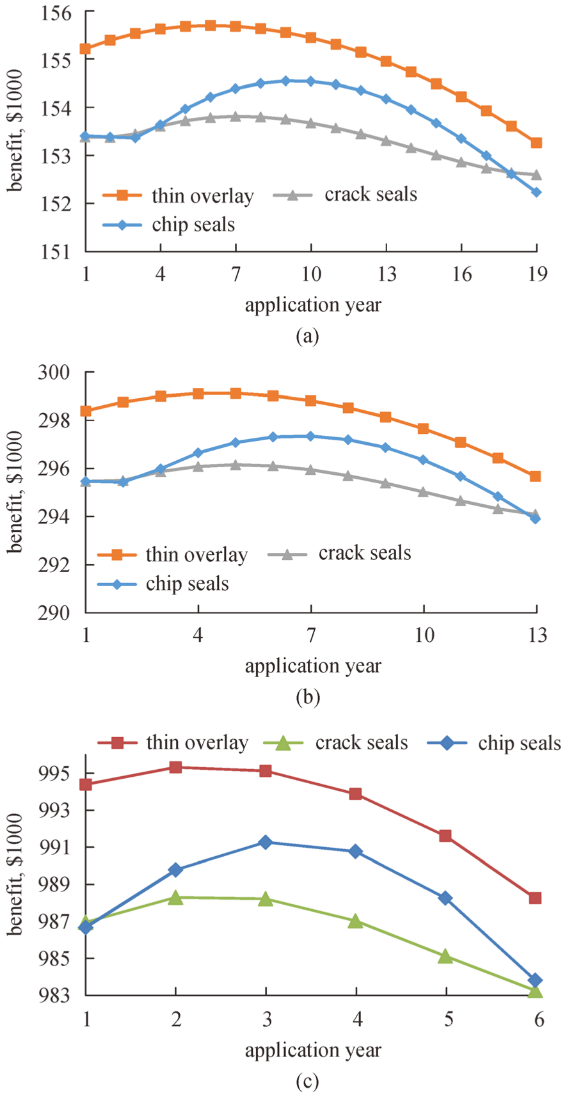
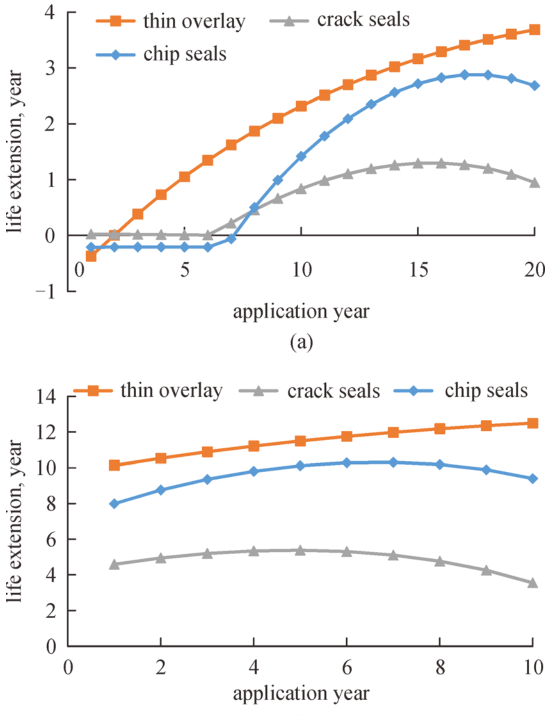


Fig. 6 Benefit of EUAC for VOC when (a) *AADTT* = 1200; (b) *AADTT* = 2000; (c) *AADTT* = 5000

The benefit in VOC is one to two orders greater in magnitude as compared to the benefit in agency cost. As expected, the benefit difference between agency cost and VOC become much greater as traffic volume increases. This is because when traffic volume increases, the benefit in VOC increases significantly while the increase of benefit in agency cost is relatively few. Overall, thin overlay has the highest benefit; while crack seal has the lowest benefit in most cases. It is noted that the crack seal may have the highest benefit-cost ratio due to its extremely low cost.

Figures 7 and 8 show the benefits of pavement preservation for agency cost and VOC, respectively, at two levels of initial IRI values (0.7 and 1.4 m/km). Likewise, the results indicate that for some cases the optimal timing of preservation treatment exists where the benefit reaches the maximum value when the treatment is applied at the specific year. The exceptional cases are that when the initial IRI value is very high, the benefit seems to be the highest if the preservation is applied as early as possible.

It is noticeable that when the initial IRI value is low, the benefits of preservation can become negative for agency cost if the treatment is applied early. Generally, the benefit for the pavement with poor condition is much greater than the benefit for the pavement with good condition. The benefit in VOC varies more distinctively than the benefit in agency cost when initial IRI value changes.



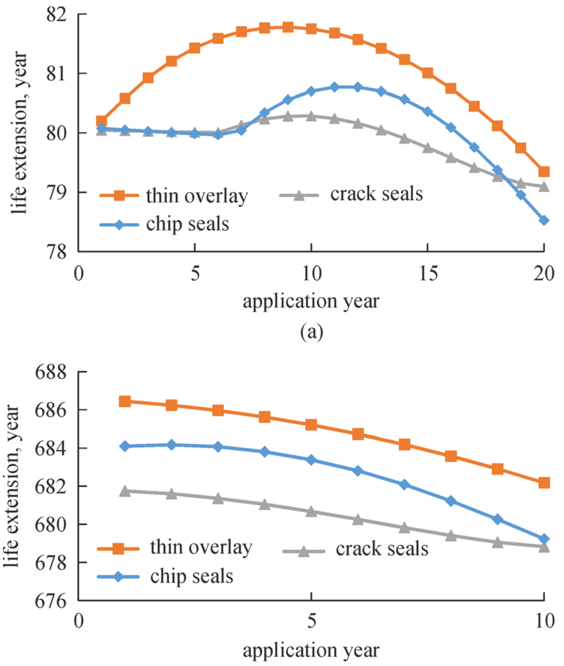
(a)

(b)

Fig. 7 EUAC for agency cost when (a) initial *IRI* = 0.7 m/km; (b) initial *IRI* = 1.4 m/km

4.3 Optimal timing of preservation treatments

Figure 9 summarizes the optimal timing for different AADTT levels for thin overlay, chip seal, and crack seal, respectively. For agency cost in thin overlay, it was found that due to the huge IRI jump after treatment and high IRI terminal threshold, the maximum benefits mostly occur at the end of pavement life (greater than 20 years for most combinations of traffic volume and the initial IRI value), which was not plotted.



(a)

(b)

Fig. 8 EUAC for VOC when (a) initial *IRI* = 0.7 m/km; (b) initial *IRI* = 1.4 m/km

In general, the results indicate that as AADTT increases, the optimal timing of preservation become earlier and the relationship can be described as an exponential function. The optimal timing of VOC is always earlier than the optimal timing of agency cost. The time gap between the optimal timings for these two costs becomes smaller as traffic volumes increase.

There are also considerable differences regarding the optimal timing between three preservation treatments. It can be seen that for VOC at the same traffic volume, the optimal timing of chip seal is the latest, followed by crack seal, and then thin overlay. As for agency cost, the optimal timing of thin overlay is always the latest, followed by chip seal and then crack seal.

As for the effect of initial IRI, it is found that different initial IRI values also affect optimal timing of preservation. Figure 10 illustrates the optimal timing with different initial IRI values for thin overlay, chip seal, and crack seal, respectively. The trend is similar to the effect of traffic except that the curves are more linear. According to the fitted linear functions, it can be roughly deduced that the increase of 0.1 m/km in the initial IRI value can contribute to the decrease of 1.5 years in optimal timing under medium traffic condition. This indicates that the initial pavement condition is vital for the appropriate time of preservation.

The study also conducted sensitivity analyses for the terminal IRI value, discount rate, and treatment cost. It was found that compared to the effect of traffic and initial IRI,

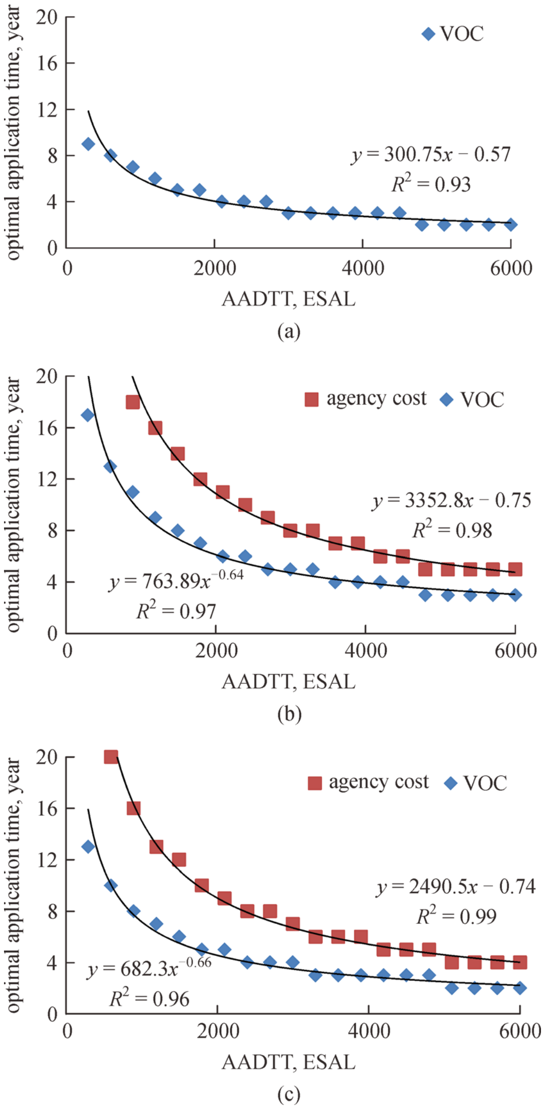


Fig. 9 Optimal timing under different AADTT for (a) thin overlay; (b) chip seals; (c) crack seals

these factors do not affect the optimal timing significantly. The variations of the optimal timing are within two years when these factors change in the reasonable ranges.

5 Conclusions

Pavement preservation brings the benefit in the reduced agency cost in the life-cycle of pavement and as well as the vehicle operation cost due to the improved pavement surface condition. The study determined the optimal timing of preservation treatments using life-cycle cost analysis. The following conclusions can be concluded from the analysis:

1) The analysis results of LTPP SPS-3 data indicate the traffic loading condition affects the deterioration rate of IRI for the control section and the sections with different preservation treatments.

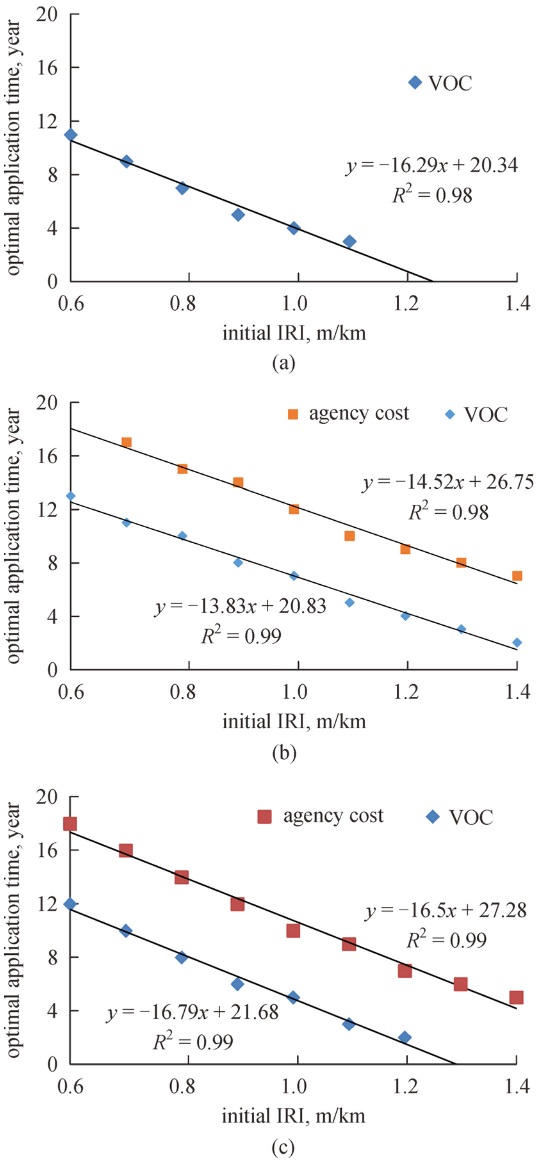


Fig. 10 Optimal timing with different initial IRI for (a) thin overlay; (b) chip seals; (c) crack seals

2) The traffic loading and the initial IRI value significantly affects life extension and the benefit of agency cost caused by pavement preservation. Overall, thin overlay has the highest benefit; while crack seal has the lowest benefit in most cases. The benefit in VOC is one to two orders greater in magnitude as compared to the benefit in agency cost.

3) The optimal timing calculated based on VOC is always earlier than the optimal timing calculated based on agency cost. There are considerable differences among the optimal timing of three preservation treatments.

4) The optimal timing becomes later as traffic volume decreases that can be described in an exponential relationship. On the other hand, the correlation between the initial IRI value and optimal timing can be represented by a linear function.

The optimal timing determined from LCCA considers only short- and long-term benefits or life extensions based on pavement serviceability (ride quality). By adopting the methodology developed in this study, similar models can be developed for other distress types such as fatigue cracking and rutting. The more complicated optimization analysis is recommended when multiple applications of preservation treatments are considered within the pavement life.

REFERENCES

1. Labi S, Sinha K C. Measures of short-term effectiveness of highway pavement maintenance. Journal of Transportation Engineering, 2003, 129(6): 673–683
2. Morian A D.Cost Benefit Analysis of Including Microsurfacing in Pavement Treatment Strategies & Cycle Maintenance. FHWA-PA-2011–001–080503, 2011
3. Wang H, Wang Z. Evaluation of pavement surface friction subject to various pavement preservation treatments. Construction and Building Materials, 2013, 48: 194–202
4. Peshkin D G, Hoerner T E, Zimmerman K A. Optimal Timing of Pavement Preventive Maintenance Treatment Measures. NCHRP Report 523, Transportation Research Board, 2004
5. Wei C, Tighe S. Development of preventive maintenance decision trees based on cost-effectiveness analysis an Ontario case study. Transportation Research Record, 2004, 1866: 9–19
6. Haider S W, Dwaikat M B. Estimating optimal timing for preventive maintenance treatments to mitigate pavement roughness. Transportation Record, the 89th Annual Meeting, 2010
7. Wang G, Morian D, Frith D. Cost-benefit analysis of thin surface treatments in pavement treatment strategies and cycle maintenance. Journal of Materials in Civil Engineering, 2013, 25(8): 1050–1058
8. Dong Q, Huang B. Evaluation of effectiveness and cost-effectiveness of asphalt pavement rehabilitations utilizing LTPP data. Journal of Transportation Engineering, 2012, 138(6): 681–689
9. Wang Y, Wang G, Mastin N. Costs and effectiveness of flexible pavement treatments: experience and evidence. Journal of Performance of Constructed Facilities, 2012, 26(4): 516–525
10. Lu P, Tolliver D. Pavement treatment short-term effectiveness in IRI change using long-term pavement program data. Journal of Transportation Engineering, 2012, 138(11): 1297–1302
11. Hall K T, Correa C E, Simpson A L.LTPP data analysis: effectiveness of maintenance and rehabilitation options. National Cooperative Highway Research Program, NCHRP Web Document 47 (Project 20-50[3/4]): Contractor's Final Report, 2002
12. Labi S, Mahmodi M I, Fang C, Nunoo C. Cost-effectiveness of microsurfacing and thin hot-mix asphalt overlays: comparative analysis. Transportation Research Board 86th Annual Meeting, 2007
13. Labi S, Lamptey G, Kong S H. Effectiveness of microsurfacing treatments. Journal of Transportation Engineering, 2007, 133(5): 298–307
14. Haider S W, Baladi G Y. Effect of pavement condition data collection frequency on performance prediction. Transportation Record, 89th Annual Meeting, 2010
15. Huang B, Dong Q. Optimizing pavement preventive maintenance treatment applications in tennessee (Phase 1). Final Report. Project#: RES1307, 2009
16. Ong G P, Nantung T, Sinha K C. Indiana Pavement Preservation Program. FHWA/IN/JTRP-2010/14, West Lafayette, IN, 2010
17. Markow, M J. Life-cycle costs evaluations of effects of pavement maintenance. Transportation Research Record, 1991, 1276: 37–47
18. ARA Inc. ERES Division. Development of the 2002 Guide for the Design of New and Rehabilitated Pavements. NCHRP 1-37A Report, Transportation Research Board, Washington, D C, 2004
19. Morosiuk G, Riley M, Toole T. HDM-4 Highway Development & Management. Volume Two, Application Guide. PIARC, World Road Association, 2002, 2–133.
20. Chatti K, Zaabar I. Estimating the Effects of Pavement Condition on Vehicle Operating Costs. NCHRP 720, Transportation Research Board, Washington, D C, 2012