Comparison of Methods for Evaluating Pavement Interventions

Evaluation and Case Study

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Decision makers are always faced with the challenge of selecting and implementing cost-effective pavement preservation alternatives, particularly when encountering shrinking budgets and increased competition for funds. Pavement intervention and investment evaluation criteria used in past research and practice are reviewed. The synthesis of pavement preservation effectiveness and efficiency evaluation techniques that is presented is unique from both benefit and cost perspectives. Criteria are of the following categories: effectiveness (benefit) only, cost only, cost-effectiveness, and economic efficiency. Computational details, past applications, merits, and demerits of various evaluation criteria are discussed for each criterion. Then selected criteria are computed with data from a national pavement study; they are used to evaluate alternative rigid pavement rehabilitation treatments. The case study results suggest that the superior short-term effectiveness exhibited by a treatment does not necessarily translate into superior long-term effectiveness. The evaluation results can vary widely for cost only, effectiveness only, and both cost and effectiveness criteria. Thus, evaluation based on cost-only or effectiveness-only criteria can yield biased evaluation results. To be a suitable candidate, a treatment or strategy must be not only effective but also cost-effective and economically efficient and the incorporation of user costs into evaluation can significantly influence the evaluation results. Such a synthesis can be a vital support for highway agencies in decision making for infrastructure management in general and pavement management in particular.

In the current transportation environment that is characterized by funding limitations and increased competition for funds, highway agencies grapple with how to identify cost-effective pavement preservation treatment. In a typical approach to pavement project evaluation, all potential alternatives capable of fulfilling the required function are analyzed and, the alternative associated with the least long-term cost is often selected (*1, 2*). Where evaluation factors are expressed monetarily, use of engineering economics has been done to select the alternative satisfying the needs for the lowest construction and maintenance costs over time (*3*).

Approaches involving benefits only have been used for evaluating capital investment projects, which typically involve a single large investment. In many such cases, it is difficult to measure the performance criteria for the evaluation, often due to the long duration of constructing and operating such assets and the spillover effects (*4*).

The cost-only approaches assume that all alternatives provide similar levels of service, and that the preferred option is one that minimizes costs (*4, 5*). These approaches seem to have been applied to most pavement preservation and maintenance (P&M) evaluation analysis. Compared with capital improvements, P&M are often smaller in value and take a relatively shorter period for completion.

In evaluating pavement investments, it has been recommended to use a combination of cost and benefit approaches. *NCHRP Synthesis of Highway Practice 223* suggests that benefits accrued to users and the cost incurred to provide those benefits both should be considered and that when monetization of benefits and costs is feasible, a benefit–cost analysis could be made (*6*).

This study presents a synthesis of criteria for evaluating pavement preservation interventions. Merits, demerits, and suitability of these criteria are discussed. The criteria are then computed and compared in a case study that uses data from the Long Term Pavement Performance Specific Pavement Studies Experiment-6 (LTPP SPS-6).

EVALUATION CRITERIA INVOLVING BENEFITS ONLY

Effectiveness, which represents the degree to which an alternative is expected to accomplish the objectives, typically involves nonmonetary benefits (*7*) and can be measured in the short or long term (*4, 8*). It may be useful to assess treatment effectiveness in the long term because a greater short-term effectiveness may not necessarily translate into greater long-term effectiveness. A summary of effectiveness measures including requirements for computation is given in Table 1.

Measures of Short-Term Effectiveness

At least two measures have been identified in the literature as possible measures of short-term effectiveness of pavement treatments. They are as follows.

Performance Jump

The concept of performance jump (PJ), the instantaneous elevation in performance on a treatment (Figure 1), has been discussed in the past (*9, 10*) but has seen relatively little application (*11, 12*). A mathematical form for an "immediate improvement model" for maintenance effectiveness was presented in a study (*13*). PJ may be considered as the best measure of short-term treatment effectiveness.

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TABLE 1 Summary of Common Pavement Evaluation Criteria

Evaluation Method	Performance Measure	Requirements	Output	Suggested Suitability
Effectiveness (Benefits) Only				
Effectiveness (benefits) (short-term)	Performance jump (PJ)	Pre- and posttreatment condition values	Instantaneous improvement in pavement condition	Highly recommended
	Deterioration rate reduction (DRR)	Pre- and posttreatment performance curves	Reduction in the rate of pavement condition deterioration due to a treatment	Recommended as supplementary performance measure
Effectiveness (benefits) (long-term)	Treatment service life (TSL)	Posttreatment condition data and performance model	Extended pavement life due to treatment	Highly recommended when posttreatment condition data are available to develop reliable performance model
	Increased average pavement condition over treatment life (effectiveness$_{APC}$)	Posttreatment condition data and/or performance model and SL	Estimate of the average improved pavement condition over treatment SL	Recommended as supplementary performance measure
	Area bounded by treatment performance curve	Post-treatment performance model and SL	Responsibility for the monetized user benefits	Highly recommended when user benefits are difficult to be monetized appropriately
Cost Only				
Cost analysis (initial and short-term cost impact)	Agency costs	Construction cost (labor, materials, equipment, contract engineering, etc.)	Costs incurred by the agency during intervention	Highly recommended Essential part of cost analysis
	User costs	Work zone user costs (delay costs, additional VOC including additional fuel consumption, and crash costs)	Costs incurred by the facility user during intervention	Recommended as a measure of motorist inconvenience during the intervention
Cost analysis (life cycle–long-term cost impact)	Agency costs and monetized benefits	Maintenance expenditure over the service life of a treatment or over the time span between two treatments	Life cycle costs incurred by the agency Reduced maintenance costs over life cycle	Highly recommended Essential part of cost analysis Estimation of agency benefits based on the condition of appropriate monetization
	User costs and monetized benefits	VOC, crash costs over the service life of a treatment or over the time span between two treatments	Life cycle costs incurred by the user User costs savings due to improved infrastructure condition over life cycle (reduced VOC, reduced crashes etc.)	Recommended as a measure of long-term benefits to public (user) due to an intervention Recommended when user benefits can be appropriately monetized
	Life-cycle costing (LCC)	Interest rate, initial construction and maintenance costs, salvage values, analysis period or estimated treatment SL	Life cycle costs (over the analysis period) either as EUAC or present worth of costs Identify the alternative with lowest life cycle costs	For long-term evaluation of treatments or strategies with different SLs, initial construction and maintenance costs, and salvage values but same levels of benefits
Cost and Benefits (Cost-Effectiveness)				
Short-term cost-effectiveness (CE)	PJ per total initial cost	PJ and total initial unit cost of treatment	PJ per total initial unit cost	Highly recommended as supplementary performance measure
	DRR per total initial cost	DRR and total initial unit cost of treatment	DRR per total initial unit cost	Recommended as supplementary performance measure
Long-term CE	Equivalent annual cost (EAC)	Unit cost of treatment, expected life of treatment (years)	Unit cost per expected life of treatment	For initial estimates Recommended as supplementary performance measure
	Longevity cost index (LCI)	Present value of unit cost over life of treatment, traffic loading, and life of the treatment	Present value of cost of treatment to life and traffic	Recommended as supplementary performance measure
	Benefit–cost ratio analysis (BCR or B × C product)	Nonmonetized benefits (e.g., AOC[a], SL) and LCC (e.g., EUAC[b])	Treatment benefit per unit life cycle cost Treatment benefit and cost product	Highly recommended when user benefits are difficult to monetize

(continued)

TABLE 1 *(continued)* **Summary of Common Pavement Evaluation Criteria**

Evaluation Method	Performance Measure	Requirements	Output	Suggested Suitability
Cost and Benefits (Economic Efficiency)				
Economic efficiency	Net present value (NPV)	Costs and monetized benefits, interest rate, analysis period, and estimated treatment SL	Present worth of all benefits after deducting all costs Highest NPV is the best	Highly recommended as providing the value of project at the base year (when benefits can be monetized explicitly)
	Present worth of costs (PWC)	Initial and maintenance costs, interest rate, analysis period, and estimated treatment SL	Present worth of all costs Least PWC is the best	Recommended when alternatives have different service lives but same levels of benefits
	BCR = PWB[c]/PWC or $\frac{\text{NPV (benefits)}}{\text{NPV (costs)}}$ or $\frac{\text{EUAC (benefits)}}{\text{EUAC (costs)}}$	EUAC or NPV or present worth of costs and monetized benefits	Monetized benefit per unit cost of investment	Recommended when benefits can be monetized explicitly

[a]AOC = area over the curve.
[b]EUAC = equivalent uniform annual cost.
[c]PWB = present worth of benefits.

Deterioration Rate Reduction

This measure involves the slowing down of pavement deterioration due to maintenance application; the slope of the deterioration curve becomes gentler after maintenance. Therefore, the deterioration rate reduction (DRR) is calculated as the difference in the slope before and after the treatment (*4, 9*). The DRR concept has been applied in past research (*9, 10, 14*), and a mathematical form for deterioration rate variation due to maintenance application was suggested in a national study (*13*).

Measures of Long-Term Effectiveness

In the literature, the long-term effectiveness of pavement treatments has been evaluated using following measures.

Treatment Service Life

Commonly used approaches for determining service life use pavement condition data to develop a treatment performance curve and to extrapolate the curve to the point at which the treated pavement reverts to an established threshold (Figure 1). The units of treatment service life (TSL) may be time (years), accumulated traffic loading, or climate effects. The TSL concept has been employed in numerous studies (*4, 8, 9, 15*).

Increased Average Pavement Condition over Treatment Life

The approach for estimating treatment service life can also be used to determine the average pavement condition over the life of a treatment. This criterion has been used in past studies (*8, 15*). The average pavement condition (APC) over the service life, perf_{avg}, can be determined as follows:

$$\text{perf}_{\text{avg}} = \frac{1}{t_c}\left(y_0 + y_1 + \cdots + y_c\right) \tag{1}$$

where

y_0 = condition just after treatment;
y_c = condition at the time when pavement condition reaches the threshold;
$y_1, y_2, \ldots, y_{c-1}$ = condition values at intervening years; and
t_c = service life.

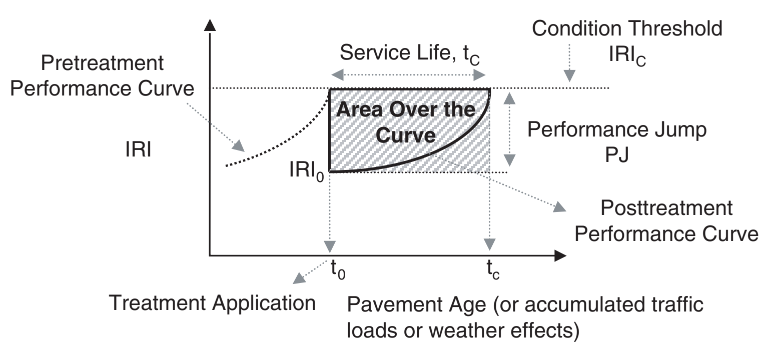


FIGURE 1 Graphical representations of AOC, SL, and PJ (IRI = international roughness index).

Increase in average pavement condition due to a treatment is the percentage change in average condition relative to the condition before treatment. It is determined as follows:

$$\text{effectiveness}_{\text{APC}} = 100 \times \left(\frac{\text{perf}_{\text{avg}} - \text{perf}_{\text{INI}}}{\text{perf}_{\text{ini}}} \right) \tag{2}$$

where $\text{effectiveness}_{\text{APC}}$ is treatment effectiveness, the percentage increase in APC, and perf_{INI} equals the initial (pretreatment) condition.

Area Bounded by Treatment Performance Curve

Probably the most conceptually superior of all measures of long-term effectiveness, the area bounded by the performance curve and the threshold line, embodies both concepts of average pavement condition and service life (*1, 4, 5*). For nonincreasing performance indicators such as pavement condition ratings, this effectiveness is the area under the curve; while for non-decreasing indicators such as international roughness index (IRI) and rutting, this is the area over the curve (AOC) (Figure 1) (*8*). The rationale for this approach is simple. First, a well-maintained pavement (thus gently sloping performance curve, and subsequently, larger area bounded by the curve) provides the user with benefits that are greater than a poorly maintained pavement (steep performance curve having a small bounded area). Second, because the benefits of a well-maintained pavement are numerous and may be difficult to quantify in monetary terms, AOC could be used as a surrogate for overall user benefits that generally include reduced accidents, travel time, vehicle operating and maintenance costs, and others (*4, 6, 16*). This concept of AOC has seen widespread application in the past (*6, 16, 17*).

EVALUATION CRITERIA INVOLVING COSTS ONLY

These approaches, where agencies seek to minimize cost, are useful where alternatives have different service lives but the same effectiveness or benefits. Costs can be classified as agency and user costs, short-term (incurred only at the time of initial pavement intervention), or long-term (incurred over the life cycle).

Agency Costs

Agency costs may comprise (*a*) initial construction cost, which may include the cost of labor, materials, equipment, contract engineering, and others; and (*b*) rehabilitation and maintenance expenditure over the service life of a treatment.

User Costs

User costs comprise (*a*) delay, safety costs, and vehicle operating costs (VOCs) incurred by facility users during work zone periods; and (*b*) user costs incurred during the normal use of the facility over the service life of a treatment, for example, VOC crash costs. Under forced-flow conditions, queuing delay costs can dominate work zone user costs (*2*).

Issues Associated with User Cost Computation

A certain school of thought contends that it is not appropriate to express user cost in dollars, and that there is no real "user cost" but rather a user benefit, which is the reduction in user cost relative to a do-nothing alternative. Also, it is argued that not all benefits can be monetized appropriately, and the effectiveness of pavement interventions (such as increased ride quality and service life and reduced crashes) can probably be best expressed only qualitatively. Indeed, only in relatively few studies are well-refined user cost estimation concepts and methodologies established (*4, 18–20*).

VOC, typically expressed in cents/veh mi, includes fuel, maintenance, repairs, and mileage-dependent depreciation. VOC savings simply refer to VOC reduction compared with a base case. Pavement roughness can affect maintenance and depreciation cost components of VOC. Therefore, reduction of roughness due to treatment consequently yields reduction in the condition component of VOC. The effect of pavement condition on user operating cost is not well documented (*2, 7, 21, 22*). A recent study stated that a unit increase in IRI (m/km) can generally lead to VOC increase of 1.67 cents/veh mi (*23*). Minor reduction in VOC rates caused by decreased roughness can yield significant VOC savings over the treatment life (*24*).

EVALUATION CRITERIA BASED ON COST-EFFECTIVENESS

Cost-effectiveness evaluation is a technique for comparing money spent to benefits gained (by the agency and the facility user) (*6*). Cost is often the long-term cost of a pavement treatment over a given evaluation period, and benefit is often the improvement in pavement serviceability over that period (*25*). Different cost-effectiveness concepts may be applied depending on whether the analysis is for the long term or for the short term. Long-term evaluation is typically characterized by multiple alternative strategies, each with its overall cost and effectiveness. In the short term, however, cost-effectiveness concepts may be appropriate in only a few cases, for example, where it is sought to compare two alternative treatments to address a given pavement distress, such as crack sealing with traditional sealant or with crumb rubber (*4, 25*). In this respect, the cost-effectiveness of a pavement intervention mainly depends on (*a*) how effectively the intervention addresses the existing condition and (*b*) how well a preservation strategy effectively delays the distress deterioration process, thereby extending pavement life (*2*). Several studies have evaluated and defined the various methods for evaluating the cost-effectiveness of pavement treatments (*1, 6, 15, 20, 25*). Since it is not always possible to monetize benefits appropriately, nonmonetized benefits such as the area bounded by the curve, service life, decrease in the structural index, and more, have been used successfully in the past for cost-effectiveness evaluation (*8, 15, 17, 20, 26*). A summary of various CE measures, their input requirements and suggested suitability is given in Table 1, and a selected few are discussed.

Product of Benefit and Cost

A particularly interesting application of cost-effectiveness as a product of treatment unit cost and decrease in structural index is seen in the literature (*26*). The product of area bounded by performance curve, annual average daily traffic (AADT), and pavement section length has also been observed in the literature as a cost-effectiveness criterion (*27*).

Equivalent Annual Cost

Equivalent annual cost (EAC) is the average of pavement treatment cost over the years until another treatment is required. Only few applications of this method are seen in the literature (*8, 25*). Pavement condition is not considered explicitly. EAC is determined as follows:

$$\mathrm{EAC} = \frac{\text{unit cost of treatment}}{\text{expected life of treatment (years)}} \tag{3}$$

Longevity Cost Index

Longevity cost index (LCI), which was developed by the Oregon Department of Transportation to evaluate the cost-effectiveness of thin-surface pavement treatments in different climates (*28*), relates the present value of treatment cost to the treatment life and traffic loading. Pavement condition is not considered explicitly. It has rarely been used in the literature. LCI is determined as follows:

$$\mathrm{LCI} = \frac{\begin{array}{c}\text{unit construction cost}\\ +\ \text{unit maintenance cost during treatment life}\end{array}}{\begin{array}{c}\text{treatment life}\\ \times\ \text{annual million equivalent single-axle loads}\end{array}} \tag{4}$$

EVALUATION CRITERIA BASED ON ECONOMIC EFFICIENCY

Efficiency indicates the relative monetary value of the return from a project with respect to the required investment. In a strict sense, economic efficiency is just another form of cost-effectiveness in which both cost and effectiveness are expressed in monetary terms. Efficiency evaluation aims to ascertain if the transportation project is yielding its money's worth. A summary of some commonly used economic-efficiency criteria is presented in Table 1, and a selected few are discussed.

Net Present Value

Net present value (NPV), the difference between the present worth of benefits and that of costs, reflects the project value at the analysis base year. NPV is often considered the most comprehensive of all economic-efficiency indicators because it provides a magnitude of net benefits in monetary terms. An alternative with the highest NPV is considered the most "economically efficient" (*7*).

Present Value of Costs

This method converts all costs into an equivalent single cost assumed to occur at the beginning of the analysis period. The alternative with the least present worth of costs (PWC) is considered the most economic option.

Benefit–Cost Ratio Method

The benefit–cost ratio (BCR) is a ratio of the equivalent uniform annual value NPV or present worth of all benefits to that of all costs incurred over the analysis period. The primary purpose is to ascertain whether the benefits to the public in dollars are greater than the cost of the project providing those benefits (*1, 4, 6*). Thus, an investment with a BCR exceeding 1 is considered to be economically feasible, and the alternative with the highest BCR value is considered the best alternative. Inconsistencies exist among agencies about what goes into the numerator as benefit or to the denominator as cost. BCR duly considers both benefits and costs but is susceptible to the problems of any ratio-based index: different values of BCR may be obtained depending on the definition, units, and dimensions of the benefits and costs. Most important, BCR does not provide any indication of the total extent of benefit. Thus, BCR is often viewed as being generally inappropriate for evaluation when monetized benefits are considered (*2, 7*).

CASE STUDY OF COMPARATIVE ANALYSIS OF ALTERNATIVE ASPHALTIC CONCRETE OVERLAYS OF RIGID PAVEMENTS USING LTPP SPS-6 DATA

Using data from a nationwide experiment in the United States, namely the aforementioned LTPP, this study evaluates the effectiveness of five rigid pavement rehabilitation treatments [asphaltic concrete (AC) overlays] under SPS-6.

Data Preparation

The primary source of data, including rehabilitation treatment type, pre- and post-treatment IRI values, is LTPP's DataPave Online. Other data from 12 states included annual average freeze index and AADT. Treatments are named after their test section codes. Details of rehabilitation treatments are as follows:

- 603 (MSP–4-in. AC)—minimal surface preparation with 102-mm (4-in.) AC overlay;
- 604 (S&S–4-in. AC)—minimal surface preparation with saw-and-seal, 102-mm (4-in.) AC overlay;
- 606 (ISP–4-in. AC)—intensive surface preparation with 102-mm (4-in.) AC overlay;
- 607 (CB&S–4-in. AC)—crack–break and seat section with 102-mm (4-in.) AC overlay; and
- 608 (CB&S–8-in. AC)—crack–break and seat section with 203-mm (8-in.) AC overlay.

Treatment Effectiveness Evaluation

Performance Jump

With the immediate pre- and posttreatment IRI values, the PJ was determined for each treatment (Table 2). Treatments 606 and 607 yielded the greatest and the lowest PJ, respectively.

Treatment Service Life

Treatment performance models were developed for each treatment on the basis of cumulative traffic loading and climate effects (Equation 5).

TABLE 2 Summary of Critical IRI Values and Treatment Effectiveness Measures

Treatment Type	IRI_{INI} (in./mi)	IRI_0 (in./mi)	IRI_{avg} (in./mi)	PJ (in./mi)	SL (years)	$Effectiveness_{APC}$ (%)	AOC (IRI-years)
603 (MSP–4-in. AC)	136.69	60.44	94.88	76.25	27	30.59	1,217.84
604 (S&S–4-in. AC)	140.01	60.82	96.59	79.18	25	31.01	1,134.07
606 (ISP–4-in. AC)	145.98	61.78	100.51	84.21	29	31.15	1,415.29
607 (CB&S–4-in. AC)	132.08	61.08	92.75	71.00	26	29.77	1,105.17
608 (CB&S–8-in. AC)	141.32	61.71	91.82	79.61	30	35.02	2,233.81

NOTE: IRI_{INI} = initial (pretreatment) IRI, IRI_{avg} = average (posttreatment) IRI, SL = service life, 1 in./mi = 0.015783 m/km.

TSL was estimated by incorporating pretreatment IRI as threshold in the performance models (Equation 6).

$$y = e^{(A+\beta_2 \times t \times \text{AATA} + \beta_3 \times t \times \text{ANDX})} \tag{5}$$

where

y = value of pavement condition indicator (IRI as in./mi) in a given year;
$\text{AATA} \times t$ = product of average annual truck traffic volume (millions) and time since the rehabilitation treatment, t (this product represents the accumulated average annual daily truck traffic experienced by the treated pavement section at a given year);
$\text{ANDX} \times t$ = product of average annual freeze index (thousands of Celsius days) and time since the rehabilitation treatment, t [this product represents the accumulated annual temperature loading (climatic severity) experienced by the treated pavement section in a given year];
A = constant term; and
β_i = estimated coefficients for model explanatory variables.

In Equation 5, freeze index represents the impact of freeze–thaw cycles (temperature loading) on pavement performance. Freeze–thaw cycles cause weakening of bonds in the pavement materials and volume changes in the pavement materials and any moisture that occupies the voids of such materials. The freeze index (climatic severity), as a significant predictor of pavement performance, has been used in past studies (*4, 8, 15, 29*).

Making t the subject of Equation 5 yields the following:

$$t = \frac{\ln y - A}{\beta_2 \times \text{AATA} + \beta_3 \times \text{ANDX}} \tag{6}$$

Table 2 presents the service lives for each rehabilitation treatment.

Increased Average Pavement Condition over Treatment Life

Developed performance models were used to determine the yearly IRI values over the treatment service life. These values were averaged to calculate IRI_{avg} (Table 1). $Effectiveness_{APC}$ was calculated by using Equation 2 (Table 2).

Area Bounded by Performance Curve Due to Treatment

The area-bounded-by-performance curve due to treatment was estimated using the developed performance models (Equation 5) in the following equation:

$$\text{AOC} = \text{IRI}_c + t_c - \int_{t_0}^{t_c} e^{(A+\beta_2 \times t \times \text{AATA} + \beta_3 \times t \times \text{ANDX})} \tag{7}$$

where

AOC = area over the performance curve in IRI years;
IRI_c = threshold IRI;
t_0 = year corresponding to pavement performance just after treatment; and
t_c = treatment service life (years).

Cost Analysis

Agency Costs

Cost analysis is composed of average initial construction cost (Table 3) and annual maintenance expenditure for each treatment, that is, \$/lane mile (Table 4) (*26*). Because of the absence of maintenance data of SPS-6 sections in LTPP database, annual maintenance expenditure (AMEXP) was estimated by using models from an Indiana study, giving due consideration to pavement type, treatment type, highway functional class, and pavement age (*5*). Since then, the current study is based on a versatile national database (LTPP), comprising a vast variety of regional, climatic, and traffic environments, so the performance models used in effectiveness analysis have adequate inherent spatial flexibility and adaptability. Therefore, AMEXP models from the Indiana study were deemed appropriate and applicable for a part of cost analysis vis-à-vis effectiveness analysis.

User Costs

Work Zone Delay Cost The following typical traffic conditions were considered: 65-mph speed limit for non–work zone sections, 45 mph for work zone sections, and closure of one lane in each direction during work zone operations. Travel time difference was estimated to be 0.0068 mph due to speed reduction from 65 mph to 45 mph in the work zone. Travel time costs (\$/vehicle hour) used

TABLE 3 Summary of Agency and Work Zone User Costs, 2008 \$ Value, $\$10^3$/LnM

Treatment Type	Agency Cost (\$) Initial Cost	Agency Cost (\$) AMEXP	Work Zone User Cost (\$) Delay Cost	Work Zone User Cost (\$) VOC (fuel + speed change)	Work Zone User Cost (\$) Total Cost (delay + VOC)	Total Initial Cost (agency + user)	Total Life-Cycle Cost (agency + user)	EUAC (agency + user)	EUAC (agency only)
603 (MSP–4-in. AC)	66.80	0.92	0.40	1.20	1.60	68.40	83.40	5.11	5.01
604 (S&S–4-in. AC)	67.10	0.92	0.40	1.20	1.60	68.60	83.00	5.31	5.21
606 (ISP–4-in. AC)	94.10	0.92	0.40	1.20	1.60	95.60	111.25	6.55	6.46
607 (CB&S–4-in. AC)	30.90	0.71	0.40	1.20	1.60	32.50	43.81	2.74	2.64
608 (CB&S–8-in. AC)	56.80	0.71	0.40	1.20	1.60	58.30	70.61	4.08	3.99

were \$33.30 for single unit trucks and combination trucks (*2*). Work zone duration of two days was considered. Costs were brought to constant dollars (Year 2008) using FHWA's construction price index. The section length is 154 m.

Work Zone VOC due to Speed Change Additional VOC (\$/veh mi) due to speed change in the work zone (from 65 to 45 mph) were estimated (Table 4) using Hepburn VOC models and look-up tables based on speed and vehicle class (*7, 30*).

Work Zone VOC due to Additional Fuel Consumption Fuel consumption (gals/min of delay) by vehicle type was estimated using AASHTO methodology (*19*) (Table 3). Average fuel price per gallon, p, is \$4.5. With the use of AASHTO fuel consumption tables, the change in fuel VOC was estimated as follows:

$$\text{Change in fuel VOC} = g \times D \times p \tag{8}$$

where g is fuel consumption in gal/min of delay and D is delay (min) due to the work zone.

VOC Savings due to Improved Pavement Roughness and Condition

VOC corresponding to pavement IRI was estimated (Table 3) using Equation 9, and developed by Barnes and Langworthy (*24*). This equation gives the adjustment factors for all VOC components combined (Tables 3 and 4), as a function of pavement condition.

$$m = 0.001\left[\left(\frac{\text{IRI}-80}{10}\right)\right]^2 + 0.018\left[\left(\frac{\text{IRI}-80}{10}\right)\right] + 0.9991 \tag{9}$$

Equivalent Uniform Annual Cost

To evaluate the effects of including or excluding the user costs from the total cost estimation, the equivalent uniform annual cost (EUAC) was determined for following two cases: using only agency cost, and using agency and user cost (Table 3). An interest rate of 4% was assumed. Figure 2*a* suggests that the calculation of EUACs with and without user cost makes a significant difference. The effect of including user cost and estimating CE ratios with different EUACs was the same for all treatments because of similar work zone conditions (i.e., section length and traffic). In reality, however, work zone conditions may differ by treatment type; therefore, work zone user costs may play a more critical role in identifying the best treatment.

Cost-Effectiveness Evaluation

Using a simple benefit (effectiveness) to cost ratio, the cost-effectiveness was determined for a number of criteria that use PJ, TSL, and AOC as benefits and EUAC as the cost. Details of cost-effectiveness analysis are given in Table 5 and Figure 2*b*. For comparison, cost-effectiveness ratios were weighted by a scale from 1 to 10, with 1 as most and 10 as least.

TABLE 4 Summary of VOC Savings

Treatment Type	Before Treatment m	Before Treatment VOC (\$/VM)	After Treatment m	After Treatment VOC (\$/VM)	VOC Change (\$/VM)	Truck AADT per Lane	VOC Saving $\$10^3$/LnM Per Day	VOC Saving $\$10^3$/LnM Per Year
VOC Savings (2008 \$ value)								
603 (MSP–4-in. AC)	1.133	0.399	1.028	0.362	0.037	882.575	0.033	11.922
604 (S&S–4-in. AC)	1.143	0.402	1.032	0.363	0.039	882.575	0.035	12.628
606 (ISP–4-in. AC)	1.161	0.409	1.040	0.366	0.043	882.575	0.038	13.735
607 (CB&S–4-in. AC)	1.120	0.394	1.024	0.360	0.034	882.575	0.030	10.912
608 (CB&S–8-in. AC)	1.147	0.404	1.022	0.360	0.044	882.575	0.039	14.200

NOTE: m = adjustment factor for VOC calculated using Equation (9), LnM = lane mile, \$/VM = dollars per veh mi.

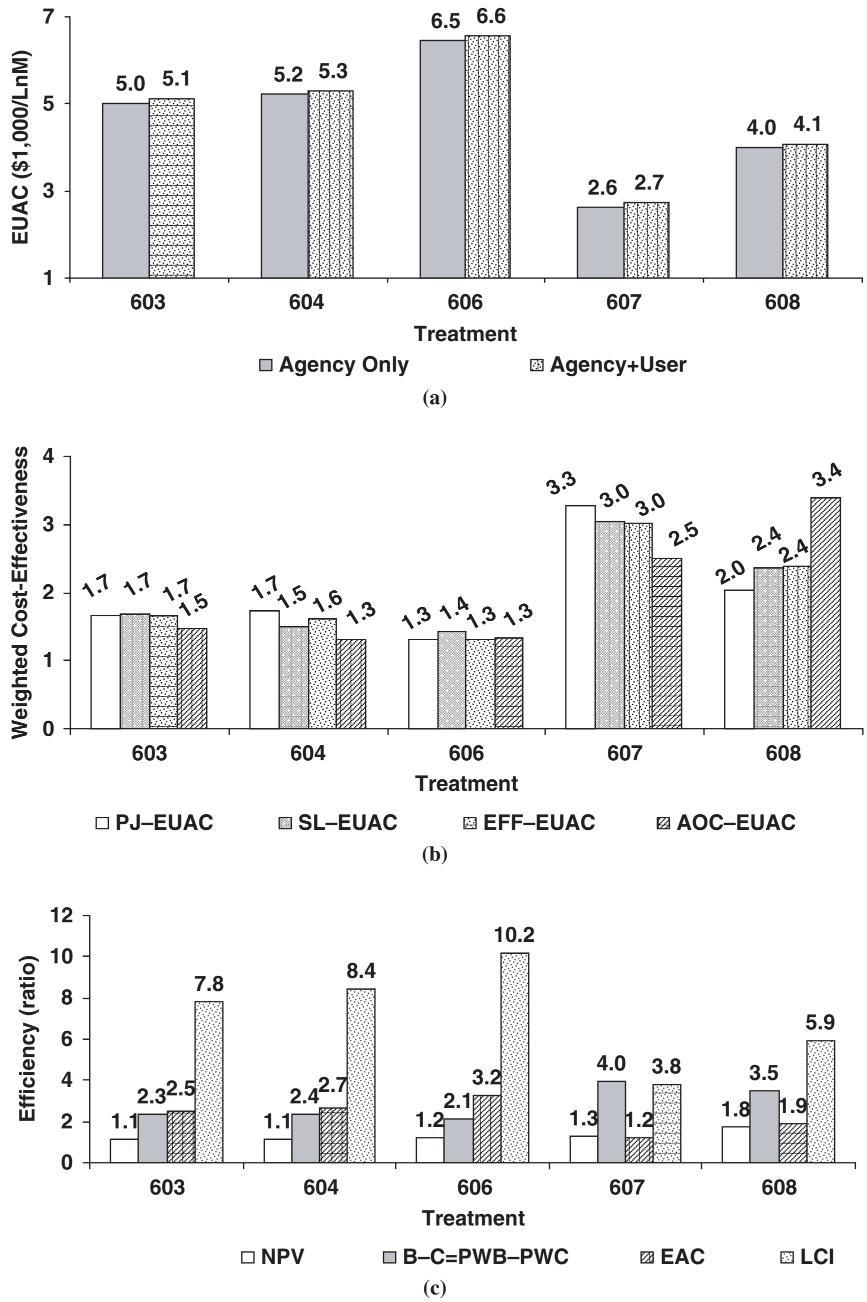


FIGURE 2 Comparisons of (*a*) EUACs, (*b*) cost-effectiveness measures, and (*c*) economic-efficiency measures.

TABLE 5 Summary of Cost-Effectiveness Evaluation

Treatment Type	PJ–Total Initial Cost IRI/10^3/LnM	SL–EUAC Years/10^3/LnM	Effectiveness$_{APC}$–EUAC %/10^3/LnM	AOC–EUAC IRI-Years/10^5/LnM
603 (MSP–4-in. AC)	1.12	5.29	5.99	2.38
604 (S&S–4-in. AC)	1.15	4.71	5.84	2.13
606 (ISP–4-in. C)	0.88	4.43	4.76	2.16
607 (CB&S–4-in. AC)	2.19	9.48	10.86	4.03
608 (CB&S–8-in. AC)	1.36	7.35	8.58	5.47

TABLE 6 Summary of Economic-Efficiency Evaluation, VOC Savings (2008 $ value)

Treatment Type	NPV $\$10^5$/LnM	PWB–PWC $\$10^3$/LnM	EAC $\$10^3$/LnM	LCI $\$10^3$/LnM
603 (MSP–4-in. AC)	1.11	2.33	2.47	7.79
604 (S&S–4-in. AC)	1.14	2.38	2.68	8.44
606 (ISP–4-in. AC)	1.23	2.10	3.24	10.17
607 (CB&S–4-in. AC)	1.30	3.98	1.19	3.77
608 (CB&S–8-in. AC)	1.76	3.48	1.89	5.95

NOTE: PWB = present worth of benefits, PWC = present worth of costs.

TABLE 7 Ranking Matrix for Overall Evaluation of Treatments

Evaluation Method and Number	Performance Measure	Performance Measure Number[a]	Treatment Rank 603	604	606	607	608	Best Criterion
Effectiveness (1)[b]	PJ	1	4	3	1	5	2	max value
	SL	2	3	5	2	4	1	max value
	AOC	4	3	4	2	5	1	max value
	$\text{Effectiveness}_{\text{APC}}$	3	4	3	2	5	1	max value
Cost (2)[b]	Total agency cost	5	4	3	5	1	2	min value
	Total user cost	6	1	1	1	1	1	min value
	EUAC (agency + user)	7	3	4	5	1	2	min value
Cost effectiveness (CE) (3)[b]	PJ–total initial cost	8	3	4	5	1	2	max value
	Eff–EUAC	9	3	4	5	1	2	max value
	SL–EUAC	10	3	4	5	1	2	max value
	AOC–EUAC	11	3	5	4	2	1	max value
Economic efficiency (4)[b]	EAC	12	3	4	5	1	2	min value
	LCI	13	3	4	5	1	2	min value
	PWB–PWC	14	4	3	5	1	2	max value
	NPV	15	5	4	3	2	1	max value

NOTE: max = maximum, min = minimum.
[a]Performance measure numbers used in Figures 3(b) to 3(f).
[b]Evaluation method number used in Figure 3(a).

Economic-Efficiency Evaluation

Economic-efficiency analysis of rehabilitation treatments was carried out using the methods discussed in this paper. VOC savings were considered as benefits and thus appear in the numerator of the PWB-PWC ratio. A summary of results is provided in Table 6 and Figure 2*c*.

Ranking Matrix

On the basis of the best value criterion for each performance measure, a ranking matrix was constructed to rank the pavement treatments (Table 7). This matrix helps compare the alternatives using various performance measures. Overall, Treatment 608 yielded the best results, considering all performance measures. Treatments 604 and 606 were generally ranked the lowest, particularly pertaining to performance measures involving cost (cost only, cost effectiveness, and economic efficiency)—obviously due to their higher initial agency costs relative to other treatments. With regard to effectiveness, Treatment 608 attained the overall highest rank. On the basis of cost-effectiveness and economic-efficiency measures, Treatment 607 was ranked higher than Treatment 608, and both treatments had higher ranks than other treatments did.

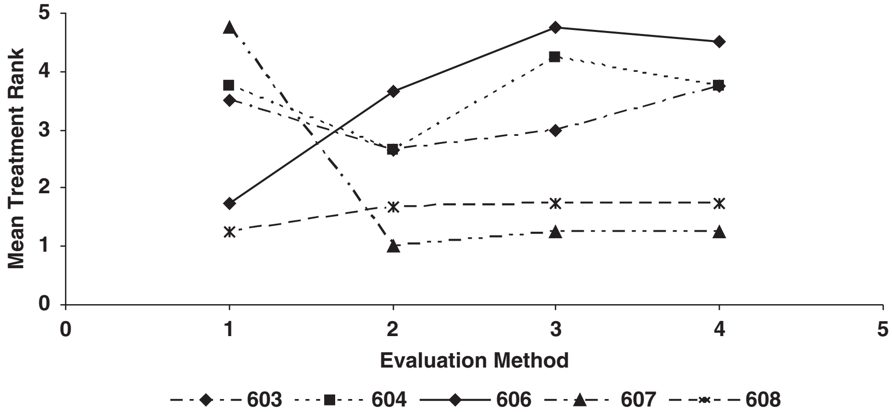
Consistency Analysis

In regard to treatment rankings among the performance measures for each evaluation method and also among the evaluation methods, a consistency analysis was carried out using statistical analysis software (SAS). Two-factor analysis, employing paired-test comparison and mean ranking values, was used (*31*). A summary of the results and the graphical representation are given in Table 8 and Figure 3, respectively.

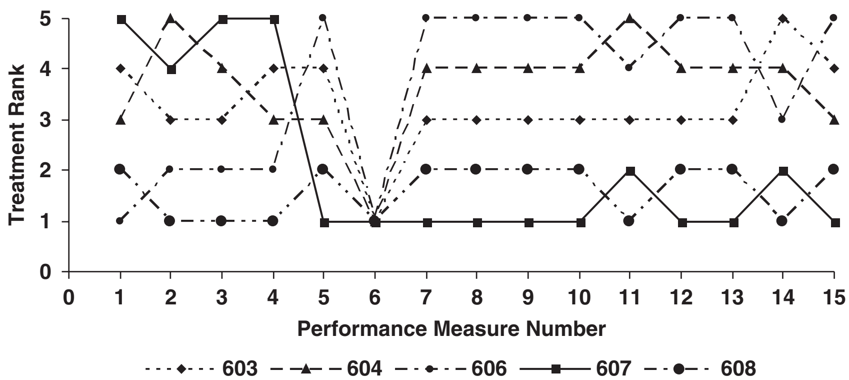
TABLE 8 SAS Results of Ranking Consistency Analysis

Evaluation Method and Number	Treatment Mean Ranking Value 603	604	606	607	608
Effectiveness (1)[a]	3.50	3.75	1.75	4.75	1.25
Cost (2)[a]	2.67	2.67	3.67	1.00	1.67
Cost-effectiveness (3)[a]	3.00	4.25	4.75	1.25	1.75
Economic efficiency (4)[a]	3.75	3.75	4.50	1.25	1.75
Overall treatment mean ranking value	3.23	3.60	3.67	2.06	1.60

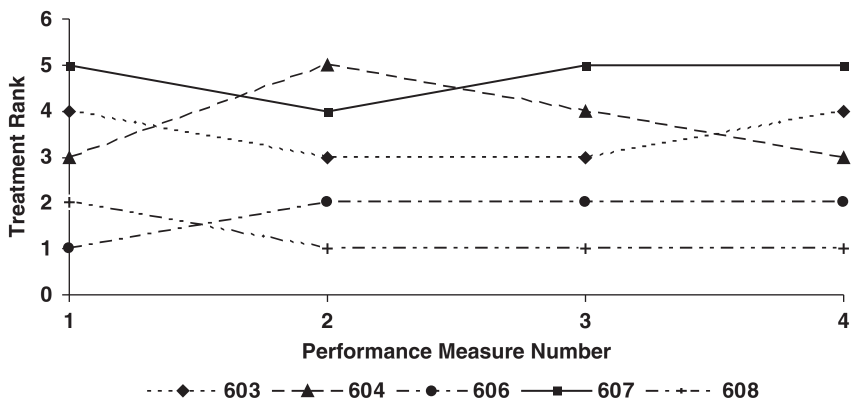
[a]Evaluation method number used in Figure 3*a*.



(a)



(b)



(c)

FIGURE 3 SAS results of ranking consistency analysis: (*a*) mean treatment ranking versus evaluation method, (*b*) treatment ranking versus performance measures, (*c*) treatment rankings versus performance measures of effectiveness analysis.

(continued)

Figure 3*a* represents the treatment ranking consistency among the evaluation methods. It is revealed that except for the effectiveness method, all other evaluation methods yielded reasonably consistent results. Hence, a treatment may be effective but may not yield a compatible cost-effectiveness and economic efficiency. But in the case of Treatment 608, even the effectiveness method showed consistency with all other methods. Figure 3*b* to 3*f* also represents the same facts about the consistency of results among the evaluation methods. Figure 3*b* and 3*c* shows fair consistency among the results of long-term effectiveness measures (i.e., SL, AOC, and effectiveness$_{APC}$), possibly because a lengthier service life corresponds to a less steep performance curve, which consequently yields larger area bounded by the curve and effectiveness$_{APC}$. The short-term effectiveness measure, PJ, did not show considerable consistency with long-term effectiveness measures in ranking. Therefore, when subjected to accumulated loading and weather effects in the long run, a treatment may not be able to sustain an initial high pavement performance. Similar findings have also been

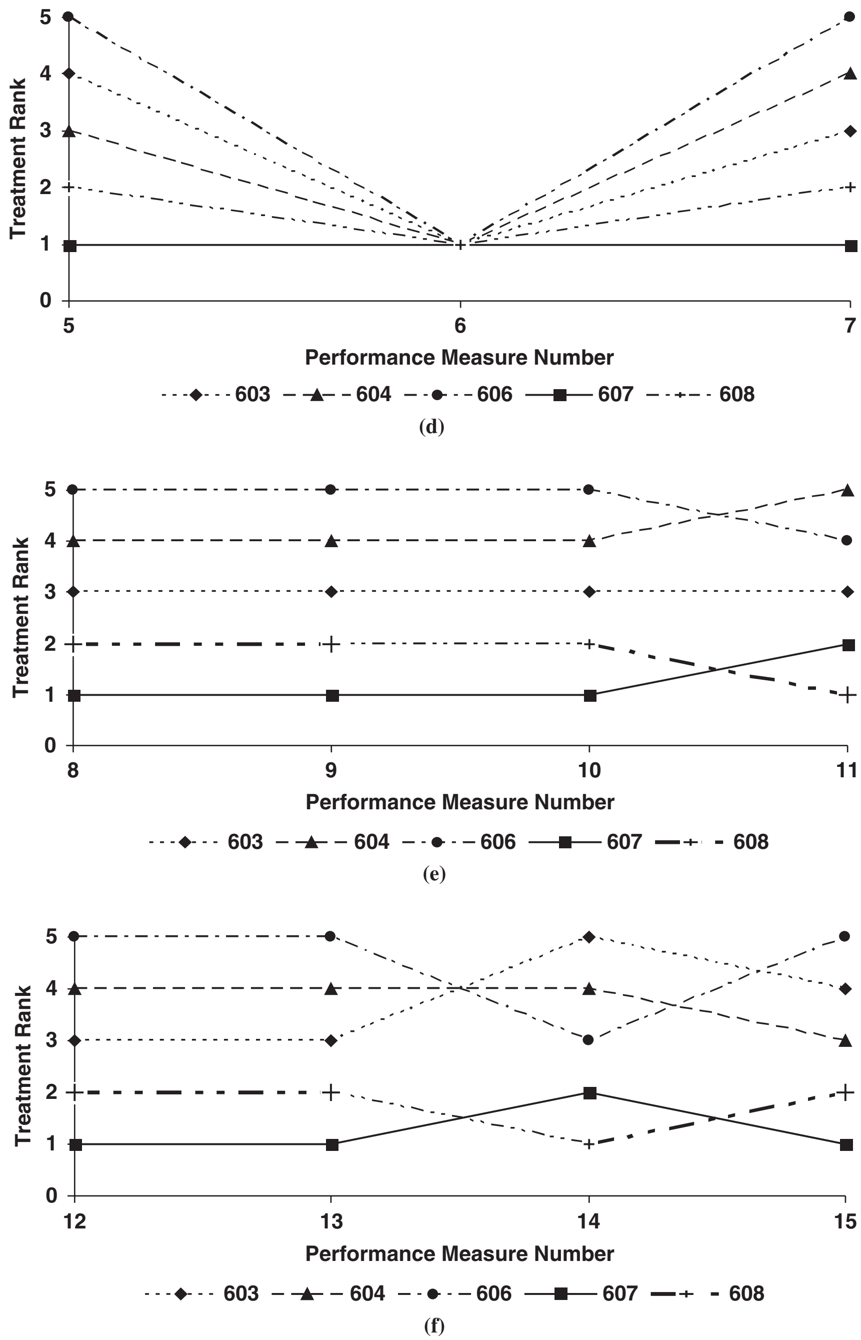


FIGURE 3 *(continued)* SAS results of ranking consistency analysis: (*d*) treatment rankings versus performance measures of cost analysis, (*e*) treatment rankings versus performance measures of cost-effectiveness analysis, and (*f*) treatment rankings versus performance measures of economic-efficiency analysis.

observed in past studies (*4, 8*). Figure 3*d* shows complete consistency among all the cost analysis measures. Figure 3*e* shows that all the CE measures yielded almost consistent results except in case of the AOC–EUAC ratio. Economic-efficiency measures also yielded almost consistent treatment ranking except in case of NPV and BCR with slight variations (Figure 3*f*). Hence, it can be concluded that different performance measures within a category (e.g., effectiveness, cost, cost-effectiveness, and economic efficiency) are likely to yield fairly consistent results.

CONCLUSIONS

This paper presented a synthesis of various criteria for evaluating pavement interventions including the computation methods, merits, and demerits. Using a case study that involved data from the LTPP SPS-6, this paper presents a methodology for identifying the most attractive preservation alternative. The case study results revealed that a treatment which seems to be most effective (or cost-effective) in the short term may not necessarily be the most effective (or cost-effective) in the long term, and that a treatment may be effective but may not yield a compatible cost-effectiveness and economic efficiency. This study suggests that a ranking matrix–based analysis of various treatment alternatives, involving various evaluation methods and performance measures, can greatly assist in identifying the best pavement investment option. To be a suitable candidate, a treatment must not only be effective but must also be cost-effective and economically efficient.

Relative weight between agency cost and user cost is also an important issue in pavement investment analysis. Direct addition of agency cost to user cost implicitly assumes that $1 of agency cost is equivalent to $1 of user cost. This approach has been used in the past (*1, 4, 17*). But there have been arguments that the value of each agency cost dollar is different from that of the user cost dollar, because agency costs are directly and physically borne by the agency, while the user costs are not so visible (*5, 20*). Therefore, sensitivity analysis–based decision on the use of these costs is one solution to this issue. A recent study, through a sensitivity analysis, found that the higher cost-effectiveness values were yielded when only agency costs were considered, compared with when both agency and user costs were considered (*21*).

Finally, even where all criteria are monetized, other nontechnical criteria may need to be considered. For example, FHWA cautions that the option with the lowest life-cycle cost may not necessarily be the best, and that other considerations such as risk, available budgets, and political and environmental concerns need to be taken into account. Also, traditional economic analysis provides critical information for the overall decision-making process, but not the final answer (*32*).

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