Idea Point Method for Multi-Objective Optimization Model of Pavement Maintenance Treatments

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ABSTRACT

A specific pavement maintenance treatment can deal with many pavement distresses, while a specific pavement condition can be improved by many different pavement maintenance treatments. This makes it difficult to develop a generalized method for treatment selection. In this paper, the problem is approached as a multi-objective optimization problem and the Ideal Point Method (IPM), mathematics technique is applied to address these concerns. The indicators, including a performance jump of present serviceability index, treatment service life, and equivalent annual cost are used in the multi-objective optimization model to determine the adequate treatment. A case study focusing on the optimization of three pavement preventative treatments is presented. A benefit-cost ratio model is presented for comparison. A comparison between the two methods suggests that the ideal point method is more objective. The proposed model provides a new way to optimize the selection of pavement maintenance treatments and can lead to profound implications for maintenance and rehabilitation decision-making.

INTRODUCTION

Determining the optimal treatment is the core of maintenance and rehabilitation (M&R). Pavement management systems (PMS) generally include a subsystem for pavement maintenance which may contain models to determine the most cost effective treatment (Hicks 2000). These are generally based on pavement type, condition, and other important factors. Selecting the right treatment at the right time can effectively extend the pavement service life and save a lot of maintenance costs. A specific pavement maintenance treatment can deal with many pavement distresses, while a specific pavement condition can be improved by many pavement maintenance treatments. Affected by numerous factors, such as pavement performance and economics, the selection of maintenance and rehabilitation treatments is a complicated decision-making problem that is both multi-level and multi-objective. Highway agencies are always faced with the challenge of determining optimal treatment for maintenance.

As an evaluation method, the benefit-cost ratio method is extensively used in the treatment selecting. However, it is a simple computation of benefit and cost, which does not reflect the objective relationship between the treatment and numerous evaluation indicators. In fact, as a complicated multi-objective optimization problem, the treatment selection includes many technological and economic indicators, some of which are dependent on each other. Additionally, the dimensions and units of the indicators may be different. These factors limit the use of the benefit-cost ratio method. An effective method is essential for developing a reliable treatment that performs effectively in the right conditions. Some new models may also help highway agencies to solve this problem. Decision support systems are used in treatment selection (Herabat 2003), and the Pareto optimal solution is also applied on the multi-objective optimization model in pavement maintenance and rehabilitation programming (Wei 2007). An innovative model featuring multi-hierarchy fuzzy decision is established based on analyzing factors which affect treatment selection for highway asphalt pavement (Ling 2008). Genetic algorithms are also proposed for the maintenance model (Okasha 2010).

The idea point method, which indicates the complicated relationship between evaluation indicators and numerous factors, is one of the effective methods for solving multi-objective optimization problem. It has been applied on the dividing of maintenance and rehabilitation section and its validity and usability is confirmed (Wang 2006).

In this paper, the ideal point method (IPM) is introduced in the maintenance treatment selection. The multi-objective optimization model, including three evaluation indicators, such as a performance jump, treatment service life and equivalent annual cost, is established. The computing result is then presented and compared with benefit-cost ratio (BCR) model in a case study.

METHODOLOGY

This section presents the proposed method that is based on the idea point method. The central idea is to define a model based on the evaluation indicator system. That is to say, a point in the m dimensional Euclidean space is found to close to the ideal point to acquire the minimum distance from evaluation function. Closeness is then introduced: the greater the better.

Evaluation Indicators Standardization

For the evaluation object R, it is assumed that there are n indicators, recording as $f_1(x)$, $f_2(x)$,…,. Which is the objective function of the evaluation object R. So the vector function is $F(X)$ =[$f_1(x)$, $f_2(x)$,…, $f_n(x)$]^T. $f_i(x)$ in the object R is suppose to be x_i. For different dimensions of the indicators, data standardization is needed. It is presented as follows.

$$y_i = \frac{x_i}{\sum_{i=1}^{n} x_i} \qquad i = 1,2,...,n \tag{1}$$

Where x_i is the data of each indicator, y_i is the standardized data.

Ideal Point Determination

Commonly, indicators and targets can be divided into two major categories, such as positive indicators and negative indicators. The value of a positive indicator is better if it is greater, while the value of negative indicator is better if it is smaller. It is assumed that the change of the indicator is monotonous and then the positive and negative ideal point is defined.

When the indicator is a positive indicator

$$\begin{cases} f_i^*(+) = \max_{x \in R} f_i(x) & i = 1,2,...,n \\ f_i^*(-) = \min_{x \in R} f_i(x) & i = 1,2,...,n \end{cases} \tag{2}$$

When the indicator is a negative indicator

$$\begin{cases} f_i^*(+) = \min_{x \in R} f_i(x) & i = 1,2,...,n \\ f_i^*(-) = \max_{x \in R} f_i(x) & i = 1,2,...,n \end{cases} \tag{3}$$

Where $f_i^*(\pm)$ is the positive and negative ideal point vector for the indicator i, $f_i(x)$ is the actual value of the indicator.

Ideal Point Evaluation Function

A Hutchison vector function F^*=[f_1^*, f_2^*,…, f_n^*]^T is the ideal point of the object R. $\overline{X}$ is found in the R point to make the smallest deviation between $f(\overline{X})$ and f^*. When the optimal value is closer to the ideal points, the solution is better. Therefore, the model in the n-dimensional space can be defined as $\left\|F(x) - F^*(+)\right\| \to \min$, $\left\|F(x) - F^*(-)\right\| \to \max$. The Minkowski distance method is used to evaluate as follows:

Distance from the positive ideal point:

$$D_1 = \left\|F(x) - F^*(+)\right\| = \left\{ \sum_{i=1}^{m} \lambda_i \left[f_i(x) - f_i^*(+) \right]^p \right\}^{\frac{1}{p}} \tag{4}$$

Distance from the negative ideal point:

$$D_2 = \left\| F(x) - F^*(-) \right\| = \left\{ \sum_{i=1}^{m} \lambda_i \left[f_i(x) - f_i^*(-) \right]^p \right\}^{\frac{1}{p}} \quad (5)$$

Where λ_i is the weight, P is the coefficient.

The value of P is selected to define a different distance space: P = 1, it is Hamming distance or absolute distance; P = 2, it is Euclidean distance; and P =∞ is Chebyshev distance. No matter what value of P is selected, the law of results is the same (Lin, J. 2003).

Computing Closeness to Ideal Point

The closeness to the ideal point is defined as follows:

$$T = \frac{D_2}{D_1 + D_2} \quad (6)$$

T is taken to evaluate the object, which is at the range of [0,1]. A larger T indicates that it is closer to the positive ideal point and further away from the negative ideal point.

CASE STUDY

In this section, based on the established methodology and evaluation indicators, both the IPM model and the traditional BCR model are estimated using the data from the INDOT of the USA. The results obtained from the two modeling approaches are presented and compared.

Evaluation Indicator

Establishing an evaluation system for pavement maintenance can help highway agencies to find a cost effective treatment is extremely important. Three indicators, including short-term and long-term performance effectiveness, and cost, are presented in this section.

Performance Jump of Present Serviceability Index

A performance jump (PJ) may be considered the best measure of short-term treatment effectiveness (Khurshid 2009). The concept of PJ is defined as the instantaneous increase in performance upon maintenance, which aims at one special indicator: the present serviceability index (PSI), which reflects efficacy was established after the AASHO Road Test and has been widely used to express pavement performance (Labi 2004). The PSI is selected to evaluate the pavement performance in this paper.

Treatment Service Life

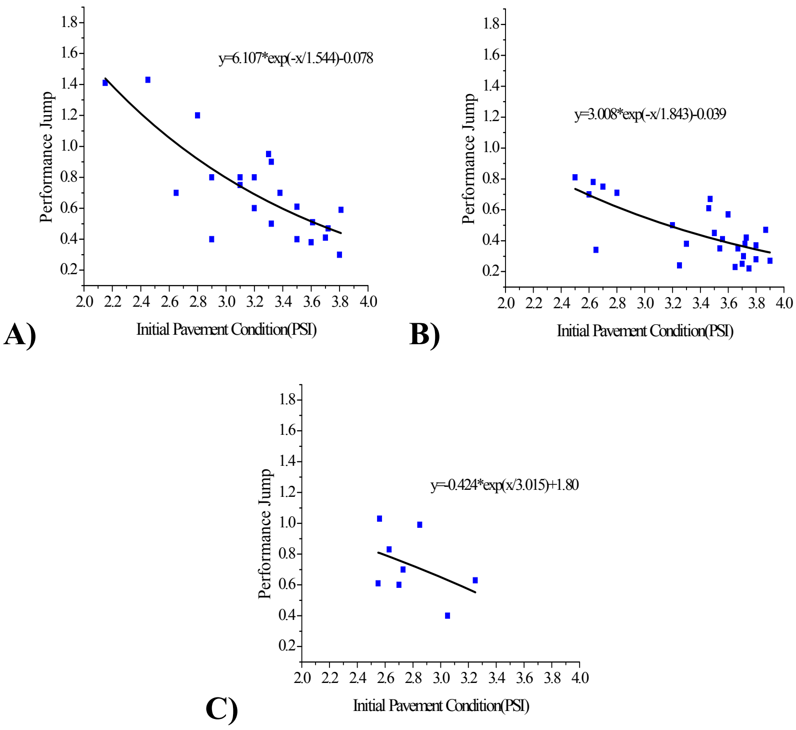
The treatment service life (TSL) as a long-term effectiveness measure is commonly used approach for determining service life uses pavement condition data to develop a treatment performance curve and extrapolate the curve to the point at which the treated pavement reverts to an established threshold (Khurshid, 2009).

Equivalent Annual Cost

The equivalent annual cost (EAC) is the average of pavement treatment cost over the number of years until another treatment is required. EAC is determined as follows (Huang, Y. 1995).

$$EAC = \frac{Unit\ \ cost\ \ of\ \ treatment}{Expected\ life\ of\ treatment\ (years)} \qquad (7)$$

Data Preparation



a) Thin overlay **b) Chip seal** **c) Micsufacing**

Figure 2. Performance jump of treatments by initial pavement condition

The primary sources of data, including preventive maintenance treatment type, performance jump in PSI, and the initial condition of PSI, is the survey data from INDOT (Labi 2001), which is presented in Figure 2. Generally, a new pavement has a PSI around 4.5 and, when the PSI drops below 1.5, the pavement is considered to be in failure condition (Jorge 2010). It is assumed that if the initial pavement condition of PSI equals 3.2, three types of maintenance treatments, such as thin overlay, chip seals and micro-surfacing, maybe needed to restore pavement condition and retard future deterioration. According to the effectiveness of treatments based on the initial pavement condition, the PJ of the PSI is computed and presented in Table.1. It also shows the treatment service life of each treatment and equivalent annual cost (Hicks 2000).

Table 1. Evaluation indicators of three maintenance treatment

Treatment	Performance Jump (PSI)	Treatment Service Life(year)	Equivalent Annual Cost($)
Thin Overlay(U_t)	0.69	7	0.25
Chip Seals(U_c)	0.57	5	0.17
Micro-surfacing(U_m)	0.49	6	0.21

Calculation results and analysis

Results of IPM Model

According to the ideal point method (IPM), the multi-object optimization model is established. The indicators including performance jump, treatment service life, and equivalent annual cost, are introduced in the optimization model. It is assumed that the performance jump is higher and the service life is extended as long as possible, while the cost is lower. Therefore, among these three treatments, the highest and the lowest value are selected as the ideal treatment. The positive ideal treatment $U_i(+)$ has the highest PJ, longest TSL and lowest EAC, while the negative ideal treatment $U_i(-)$ has the lowest PJ, shortest TSL and highest EAC, as shown in Table 2.

Table 2. Evaluation indicators of ideal treatment

Ideal Treatment	Performance Jump (PSI)	Treatment Service Life(year)	Equivalent Annual Cost($)
$U_i(+)$	0.69	7	0.17
$U_i(-)$	0.49	5	0.25

In order to apply the multi-objective optimization model framework, the data needs to be standardized according to Eq.2. The standardized results are presented in Table 3.

Table 3. Standardized evaluation indicator of maintenance and ideal treatment

Treatment	Performance Jump (PSI)	Treatment Service Life	Equivalent Annual Cost
Thin Overlay(U_t)	0.24	0.23	0.24
Chip Seals(U_c)	0.20	0.20	0.20
Micro-surfacing(U_m)	0.17	0.17	0.16
Positive Ideal Treatment $U_i(+)$	0.24	0.23	0.16
Negative Ideal Treatment $U_i(-)$	0.17	0.17	0.24

The importance of long-term performance, short-term performance and cost are all important. So the weights of the three indicators (performance jump, treatment service life, and equivalent annual cost) are considered as 0.33, 0.33, and 0.33. By applying Eq.4, Eq.5and Eq.6, D_1, D_2 and T are obtained, which are illustrated as follows.

$$D_1 = \lambda_p (PJ_t - PJ_{i(+)})^2 + \lambda_l (L_t - L_{i(+)})^2 + \lambda_C (C_t - C_{i(+)})^2$$
$$= 0.33 \times (0.24 - 0.24)^2 + 0.33 \times (0.23 - 0.23)^2 + 0.33 \times (0.24 - 0.16)^2 = 0.0019$$
$$D_2 = \lambda_p (PJ_t - PJ_{i(-)})^2 + \lambda_l (L_t - L_{i(-)})^2 + \lambda_C (C_t - C_{i(-)})^2$$
$$= 0.33 \times (0.24 - 0.17)^2 + 0.33 \times (0.23 - 0.17)^2 + 0.33 \times (0.24 - 0.16)^2 = 0.0030$$
$$T = \frac{D_2}{D_1 + D_2} = \frac{0.0019}{0.0019 + 0.0030} = 0.61$$

The closeness (T) of other treatments is computed similarly. For more details of treatment effects, Table 4 shows a series of results for estimating treatment effects by applying the IPM model. The evaluation value of a thin overlay (U_t) is the greatest and it is indicated that the distance from the positive ideal point is the shortest and the one from the negative ideal point is the longest. It is suggested that the thin overlay treatment (U_t) is more effective for this segment than other treatments.

Table 4. Evaluation value using IPM model

Treatment	IPM	Rank
Thin Overlay(U_t)	0.61	High
Chip Seals(U_c)	0.45	Medium
Micro-surfacing(U_m)	0.39	Low

Results of BCR Model

The BCR is a ratio of the equivalent uniform annual value, net present value or present worth of all benefits to 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. Thus, the alternative with the highest BCR value is considered the best alternative.

It can be constructed as follows:

$$BCR = \frac{\sum_{i=1}^{n} \lambda_i B_i}{C} \quad (5)$$

Where λ_i is the weights of the benefit indicators, B_i is the benefit, C is the cost.

It is assumed that the weights of long-term and short-term effective are equally important, so the weights of the two benefit indicators are 0.5 and 0.5. According to Eq.2, the evaluation for thin overlays is constructed as follows:

$$U_{\text{t-BCR}} = \frac{\lambda_p PJ_t + \lambda_l L_t}{C_t} = \frac{0.5 \times 0.691 + 0.5 \times 7}{0.25} = 15.38$$

Table 5 presents the results using BCR model. It presents the treatment of micro-surfacing (U_m) has the highest benefit-cost ratio. Therefore, micro-surfacing (U_m) treatment seems to be the most cost-effective determined using the BCR model.

Table 5. Evaluation value using BCR model

Treatment	BCR	Rank
Thin Overlay(U_t)	15.38	Low
Chip Seals(U_c)	15.65	Medium
Micro-surfacing(U_m)	16.15	High

Comparison

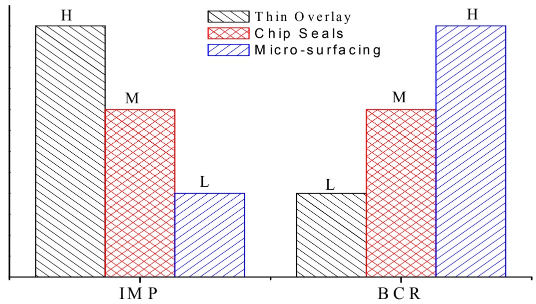


Figure 2. Comparison between the two models

On the basis of the two evaluation models for each treatment, a summary of the results is given in Figure 2. It shows that there are some differences from using those two models: the order of the optimal treatment program options determined using the IPM model was U_t, U_c, U_m; while the order of the optimal treatment program options determined using the BCR model was U_m, U_c, U_t. It seems unreasonable that, in the BCR model, different benefit and cost values may lead to the same BCR. It may lead to choosing a high benefit at a high cost, which is not needed. Since the IPM model helps highway agency to select the best option which is close to the good and far away from the bad, the result of IPM model, compared with the BCR model, are more reliable.

CONCLUSIONS

This paper presents an approach for a multi-objective optimization of maintenance treatment considering the Performance Jump of PSI, Treatment Service Life, and Equivalent Annual Cost as criteria. The Ideal Point Method (IPM) for the optimization of maintenance is proposed and its advantage over Benefit-Cost Ratio (BCR) method is investigated. A case study using the survey data of INDOT, USA, is also given.

The following conclusions and observations can be made.

1) The idea point method (IPM) is simple and calculated conveniently, which is easy to understand. The IPM model is a multi-objective optimization model which provides a new way to select the optimal maintenance treatment.

2) Pavement evaluation indicators should be further completed and the reasonable weights of the indicators should be determined to make the selected results more effective-cost.

3) The ideal point method (IPM) is applied in maintenance and rehabilitation treatment optimization and can be used in related fields with comprehensive multi-objective evaluation. It has wide application prospects in the future.

In summary, the methodology of this study can be used to facilitate pavement management by selecting more cost-effective treatments. Thus, M&R funds can be distributed more effectively at both project and network levels.

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REFERENCES

Herabat P., Songchitruks A. P. (2003). "A Decision Support System for Flexible Pavement Treatment Selection" *Computer-Aided Civil and Infrastructure Engineering*.18 (2):147-160.

Hicks R.G., Moulthrop J. S., Daleiden J.(2000). *Selecting a Preventive Maintenance Treatment for Flexible Pavements*. Foundation for Pavement Preservation (FPP), Washington, DC,USA.

Huang, Y. and Xin, A. (1995). *Engineering Economy*. Shanghai: Tongji University Press.

Jorge A. Prozzi, A.M., Feng H.(2010). "Average Treatment Effect for Modeling Maintenance Work" *Journal of Infrastructure Systems.* 16(2): 122-128.

Labi S., Kumares C. S.(2004). "Effectiveness of Highway Pavement Seal Coating Treatments" *Journal of Transportation Engineering*. 1:14-23.

Labi S.(2001). *Impact Evaluation of Highway Pavement Maintenance Activities.* Prudue University.

Ling, J. (2003). *Decision analysis*. Beijin: Higher education press.

Ling, J., Guan, S., Zhao, H. and Gao, Z. (2008)."Multi-hierarchy Fuzzy Decision Making Model for PPM Treatment Selection of Highway Asphalt Pavement" *Journal of Highway and Transportation Research and Development*.25(6): 25-29.

Muhammad B. K., Muhammad I., Labi S.(2009). "Comparing the Methods for Evaluating Pavement Interventions–A Discussion and Case Study" *Proceedings of the 88th Transportation Research Board Annual Meeting,* Washington D.C.,TRB. (Compendium of Papers, CD-ROM), No. 09-2661.

Nader M. Okasha, Dan M. Frangopol.(2010). "Novel Approach for Multi-Criteria Optimization of Life-Cycle Preventive and Essential Maintenance of Deteriorating Structures" *Journal of Structural Engineering*.2:1-51.

Wang, C., Wang, X., Ma S. and Yuan, Y. (2006) "Optimizing Maintenance Decision-making of Highway with Undetermined Attribute" *Journal of Hebei University of Technology*.35(3):108-111.

Wei, J., Kong Y. and Guan, Y. (2007). "Multi-objective Optimization in Pavement Maintenance and Rehabilitation Programming" *Journal of Beijing Jiaotong University*.31(1):115-118.