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A New Decision-Making Optimization Approach for Sustainable Expressway Pavement Maintenance

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Abstract: We use actual pavement disease data, pavement performance data and pavement maintenance data to develop a data envelopment analysis (DEA) model to evaluate the effectiveness of repairing each type of pavement disease. Next, an optimization model is proposed to improve the pavement maintenance performance while reducing the pavement maintenance cost. Results indicate that repairing transverse cracking and rutting pavement diseases is more effective in improving the pavement maintenance performance. We also find that the pavement maintenance performance is enhanced prominently if the cost constraint increases from 0.1 to 0.2, while only slight improvements are observed if the maintenance cost keeps increasing. When the cost constraint is set to 0.2, the number of expressway sections with excellent condition increases by 71 and the average pavement condition index (PCI) increases by 0.27, implying that the generated pavement maintenance strategy can achieve a good performance while using much lower maintenance cost.

Keywords: data analysis; decision-making optimization; expressway pavement disease; pavement condition index; pavement maintenance strategy

1 INTRODUCTION

Expressway is an important type of regional transportation infrastructure for most countries in the world [1]. At every moment, there are huge volumes of goods and travelers moving on expressways all over the world [2]. Although expressways are characterized with the good features of high speed [3], and high capacity [4], they suffer various kinds of pavement diseases (e.g., boiling, cracking, and rutting) [5]. Expressway pavement diseases can decline the anti-skid and anti-aging performance of expressway pavement, which will not only threat the safety of vehicles, but also shorten the pavement servicing life [6]. To maintain expressway pavement in a good service condition and extend its servicing life, transportation agencies have to put tremendous investments for repairing pavement diseases [7]. Current expressway maintenance process usually follows fixed technical specifications, even though there has been a large amount of data which can facilitate the development of more flexible, effective, and cost-efficient maintenance strategies. The pavement disease data, the pavement performance data and the pavement maintenance data have not been sufficiently investigated and used. There are still lacking effective approaches to comprehensively evaluate the trade-off for maintaining different kinds of pavement diseases and the models which can simultaneously improve the maintenance performance and reduce the maintenance cost when the budget is limited.

The pavement condition index (PCI) is usually employed to quantify the condition of pavement structure and evaluate the effectiveness of pavement maintenance. Bianchini [8] used the pavement disease data and the PCI data to evaluate the pavement condition. Specifically, the researcher employed the principal component analysis (PCA) approach to evaluate the relative importance of different diseases on the decline of pavement condition. Kamenchukov et al. [9] proposed an algorithm based on PCI and design speed ratio (DSR) to evaluate the quality of pavement maintenance. The proposed method can achieve a balance among traffic quality, traffic safety, and maintenance cost. Some other models adopted the rutting depth (RD) data to assess pavement condition. For example, Pan et al. [10] used three indicators obtained from RD data, namely, performance jump, deterioration rate reduction and average deterioration reduction rate to quantify the effectiveness of four maintenance treatments. Recent studies have paid more attention to the maintenance cost issue. Dong and Huang [11] selected international roughness index (IRI) as an indicator of pavement condition. The authors proposed pre-rehabilitation and post-rehabilitation pavement performance models and adopted the multiple regression method to identify the major factors influencing maintenance performance. The authors also discovered that using reclaimed asphalt material was cost-effective and could achieve good maintenance performance. Dong et al. [12] further used single and multiple regression models to evaluate the effectiveness and cost-efficiency of applying maintenance treatments to asphalt pavements with low and medium traffic flows. The authors found that micro-surfacing was the most cost-efficient treatment because of its low cost. Yao et al. [13] conducted a life-cycle cost analysis to compare the effectiveness of different maintenance treatments. The authors recommended alternately using an asphalt overlays and preventive treatments to achieve cost-efficient pavement maintenance. Despite the various evaluation methods, most previous works either focused on evaluating the performance of maintaining a single kind of pavement disease or focused on evaluating the performance of maintaining the pavement diseases of one or several local expressway sections. There are still lacking comprehensive investigations on the effectiveness for maintaining different kinds of pavement diseases. Large-scale pavement disease data, pavement performance data and maintenance data have not been sufficiently applied. The methods for evaluating the effectiveness of maintaining different kinds of pavement diseases at a (large) regional scale are still lacking.

In addition to evaluating the effectiveness of pavement maintenance, many researchers focused on optimizing pavement maintenance strategies. Hicks et al. [14] proposed an asphalt pavement maintenance framework using a decision tree approach. The framework could be used to select proper maintenance strategies for different types of asphalt pavement diseases. Based on the characteristics of different maintenance treatments, Wang et al. [15] summarized the applicable and inapplicable occasions of pavement maintenance. The authors also established a pavement preventive evaluation system to determine the best time for asphalt pavement maintenance. Wang [16] employed a sorting optimization model with multi-objective and multi-attribute to determine the urgency and importance of pavement maintenance. To extend the pavement servicing life and improve the maintenance performance, Zhu et al. [17] developed a long-term preventive maintenance strategy. The proposed strategy could ensure the cost benefit during the maintenance period. Naseri et al. [18] proposed an optimization model to generate a maintenance strategy applicable to a large-scale pavement network. The model aimed to minimize the difference between the IRI of each road section and the ideal IRI. Multiple evolutionary and swarm intelligence algorithms were adopted to solve the model. The development of artificial intelligence methods could provide useful and accurate suggestions for maintenance management. Han et al. [19] proposed an intelligent decision-making model for pavement maintenance. The model was solved by a proximal policy optimization algorithm to provide accurate maintenance decisions. Despite these rapid developments, existing optimization approaches focused on strategies for maintaining expressway sections at a local scale (i.e., one or several expressway sections). We are still lacking approaches determining the priorities of maintaining different types of pavement diseases in a large regional scale. Furthermore, existing research usually focused on the maintenance effectiveness but seldomly considered the constraint of maintenance fund, making those methods not applicable when the maintenance fund is limited.

To fill the research gaps above, we employ large-scale pavement disease data, pavement performance data and pavement maintenance data to generate the data envelopment analysis (DEA) model. The DEA model is then used to evaluate the comprehensive effectiveness for repairing each kind of pavement disease. Consequently, we develop an optimization model of pavement maintenance strategy based on the obtained effectiveness of maintaining each kind of pavement disease. The proposed optimization model is applicable to the scenario of limited maintenance budget, which can potentially help transportation agencies to save considerable maintenance cost. We use actual pavement data of Hunan expressway to validate the effectiveness of the optimization model.

The major contributions of the present study are summarized as follows:

We comprehensively analyze the pavement disease data, pavement performance data and pavement maintenance data, proposing a data analysis and fusion framework for the evaluation of pavement maintenance effectiveness and the design of optimal maintenance strategy.

We propose a data envelopment analysis (DEA) model for evaluating the effectiveness of maintaining different kinds of pavement diseases at a regional network scale, which supplements the former methods focusing on the evaluation of pavement maintenance at the local section scale.

We develop a new optimization model for improving the pavement maintenance strategy under the condition of limited maintenance budget. The proposed strategy determines the priorities of maintaining different kinds of pavement diseases, which supplements the methods in this field.

The remainder of this paper is organized as follows. Section 2 describes the data used in the present study. Section 3 introduces the method for generating the DEA evaluation model. The optimization model of pavement maintenance strategy is presented in Section 4. Section 5 conducts a case study using actual pavement data and discusses the results. Section 6 concludes the findings and discusses future research directions.

2 DATA

2.1 Pavement Disease Data

The pavement disease data contain a total of 261,552 pavement disease records on 31 expressways in Hunan Province of China in 2019. As shown in Tab. 1, the data recorded the expressway ID, the expressway pile ID, the lane direction, the pavement type (asphalt pavement or concrete pavement), the pavement disease type, the pavement disease area, and the maintenance status (repaired or unrepaired). There are 11 types of pavement diseases recorded in the data, including alligator cracking, block cracking, longitudinal cracking, transverse cracking, depression, rutting, shoving, pothole, ravelling, bleeding, and patching. The numbers of different types of pavement diseases are shown in Fig. 1. As shown in Fig. 1, patching is the primary kind of pavement diseases, followed by transverse cracking and longitudinal cracking.

Table 1 Examples of the pavement disease data

Expressway ID	Expressway pile ID	Direction	Pavement type	Pavement disease type	Pavement disease area / m^2	Maintenance status
G65	2292.783	Upstream	Asphalt	Pothole	0.011	Unrepaired
G65	2297.136	Upstream	Asphalt	Transverse cracking	0.433	Unrepaired
G0421	878.916	Upstream	Asphalt	Longitudinal cracking	0.600	Unrepaired
G4	1396.89	Downstream	Asphalt	Transverse cracking	0.578	Unrepaired
G4	1720.522	Downstream	Asphalt	Pothole	0.032	Unrepaired

In the obtained pavement disease data, the severities of some pavement diseases were originally recorded by their lengths. In practices, expressway transportation agencies in general use affected area to evaluate the severity of a pavement disease. In this study, we estimate the affected area of a pavement disease by multiplying its length and the affected width. The affected width is set to 0.2 meters for longitudinal cracking and transverse cracking pavement diseases, and 0.4 meters for rutting pavement disease [20].

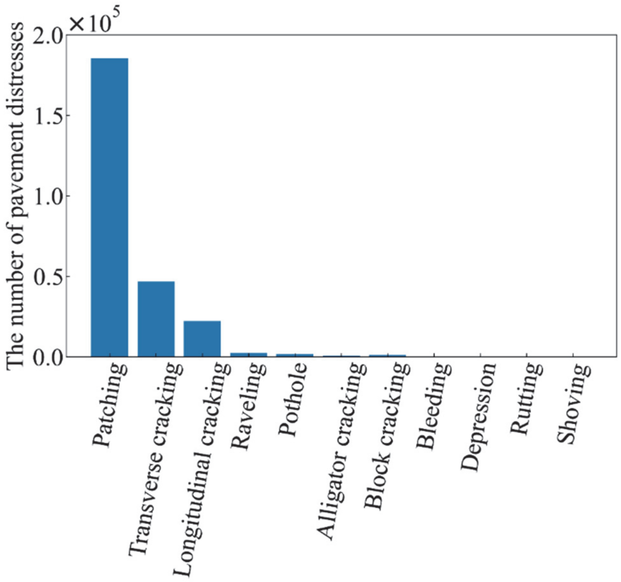

Figure 1 The numbers of different types of pavement diseases on 31 expressways in Hunan Province in 2019

2.2 Pavement Performance Data

The pavement performance data contain a total of 9703 pavement performance records of 31 expressways in Hunan province in 2019 and 2020. As shown in Tab. 2, the data recorded the section ID of expressway, the origin pile ID and the destination pile ID of each expressway section, the lane direction, the pavement type, the pavement condition index (PCI), the riding quality index (RQI) and the rutting depth index (RDI). The PCI of each expressway section is shown in Fig. 2. When the PCI of an expressway section is equal or larger than 92 [20], the pavement condition of the expressway section is regarded as "excellent". Fig. 2 shows that the pavement condition had been improved considerably from 2019 to 2020. There were 378 more expressway sections with excellent condition in 2020. The proportion of expressway sections with excellent condition increases from 92.9% in 2019 to 96.8% in 2020.

In order to calculate the numbers of different pavement diseases in each expressway section, we first match each pavement disease to the corresponding expressway section. The matching method is based on the origin pile ID and the destination pile ID of each expressway section (obtained from the pavement performance data) and the expressway pile ID of each pavement disease (obtained from the pavement disease data). Next, we infer the location of the pavement disease according to the lane direction of the disease and the lane direction of the expressway section. Finally, the number of pavement diseases in each expressway section is calculated. We also analyze the number of expressway sections with each kind of pavement disease, which is shown in Fig. 3.

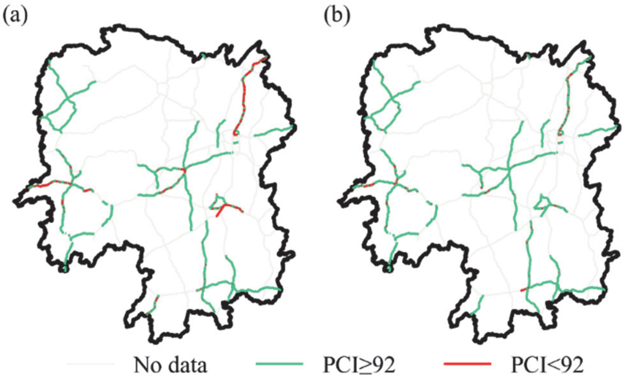

Figure 2 The PCI of each studied expressway section in 2019 (a) and 2020 (b)

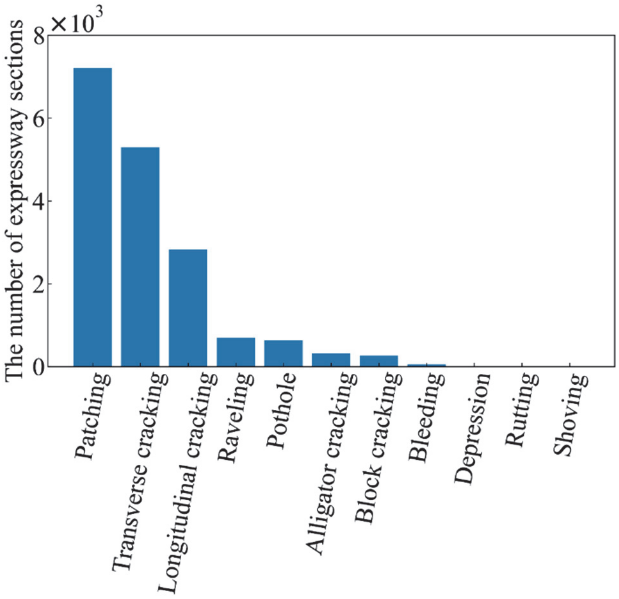

Figure 3 The number of expressway sections with each kind of pavement disease in 2019

Table 2 Examples of the pavement performance data

Expressway section ID	Origin pile ID	Destination pile ID	Direction	Pavement type	2019 PCI	2019 RQI	2019 RDI	2020 PCI	2020 RQI	2020 RDI
G0401	9	10	Upstream	Asphalt	99.39	95.29	91.83	99.38	95.18	90.40
G0422	621	622	Upstream	Asphalt	97.14	94.83	97.39	98.53	94.74	97.43
G59	1876	1877	Upstream	Asphalt	98.16	95.37	96.36	97.73	96.29	95.03
G60	1441	1442	Downstream	Asphalt	94.60	94.18	93.03	96.21	94.34	93.58
S99	127	128	Downstream	Asphalt	98.80	95.42	98.31	96.72	95.52	97.36

2.3 Pavement Maintenance Data

The pavement maintenance data recorded the maintenance treatments of Hunan expressway in 2019 and 2020. In the employed data, pavement maintenance was classified into moderate maintenance and minor maintenance. There were a total of 848 moderate maintenance records of 23 expressways, and a total of 512 minor maintenance records of 15 expressways. As shown in Tab. 3, the moderate maintenance data recorded the expressway ID, the origin pile ID and the destination pile ID of expressway section, the maintenance treatment, and the maintenance cost. The minor maintenance data recorded the expressway ID, the origin pile ID and the destination pile ID of expressway section, the pavement disease type and the maintenance cost.

Table 3 Examples of the pavement maintenance data

Expressway section ID	Origin pile ID	Destination pile ID	Maintenance type	Maintenance treatment	Pavement disease type	Maintenance cost / dollars
G4	1456.65	1456.8	Moderate	Pavement overlay	/	9 282.06
G56	1081	1081.84	Moderate	Pavement milling	/	41 090.26
G60	1433	1433.265	Moderate	Excavation & resurfacing	/	11 117.12
G0421	683	685	Minor	/	Pothole	139.38
G5513	176.789	176.789	Minor	/	Bleeding	247.13

3 EFFECTIVENESS EVALUATION MODEL OF PAVEMENT MAINTENANCE

3.1 Pavement Condition Index (PCI)

PCI is an important indicator of pavement condition, the value of which varies from 0 (poor condition) to 100 (excellent condition). Different maintenance treatments can pose different maintenance costs and achieve different levels of *PCI* improvement. To develop an optimal pavement maintenance strategy under limited budget, we first estimate the unit maintenance cost of each kind of pavement disease and analyze the *PCI* improvement after pavement maintenance. Specifically, we calculate the maintenance area of each kind of pavement disease and the corresponding maintenance cost to estimate the unit maintenance cost.

The unit maintenance cost of a kind of pavement disease q_i is calculated using Eq. (1):

$$q_i = \frac{Q_i}{A_i} \tag{1}$$

where Q_i is the total maintenance cost, and A_i is the total maintenance area of pavement disease i.

The short-term change of *PCI* and the mid-term change of *PCI* are calculated for further analysis. The short-term change of *PCI* of an expressway section after pavement maintenance is calculated using Eqs. (2) to (4) following reference [20]:

$$DR_i = \frac{\sum_{i=1}^{N} w_i A_i}{A} \times 100 \tag{2}$$

$$PCI'_{i,b} = 100 - a_0 DR_i^{a_1} \tag{3}$$

$$\Delta PCI'_i = PCI'_{i,a} - PCI'_{i,b} \tag{4}$$

where DR is the pavement disease ratio (%), $PCI'_{i,b}$ and $PCI'_{i,a}$ are the *PCI* values of the expressway section before and after repairing pavement disease *i*, $\Delta PCI'_i$ is the short-term change of *PCI* of the expressway section after repairing pavement disease *i*, A_i is the cumulative area of pavement disease *i* (m^2), and *A* is the total area of pavement examined (m^2). Given that the lane width of expressway is 3.75 m in China, and 1000 m is a common length for most expressway pavement examinations, the total area *A* is set to 3750 m^2. In Eq. (2), w_i represents the weight or conversion factor for pavement disease *i*, which can be obtained from the highway technical condition assessment standard [20]. Parameters a_0 and a_1 are set to 15.00 and 0.412 for the studied asphalt pavement [20].

In addition to the short-term change of *PCI*, the mid-term change of PCI of an expressway section is also employed to evaluate if the expressway pavement can maintain a good condition after pavement maintenance. To estimate the mid-term change of *PCI* of an expressway section, we first identify the expressway sections on which only one specific type of pavement disease was repaired. Consequently, for each type of pavement disease, the average change of *PCI* from 2019 to 2020 for the identified expressway sections (only with the type of pavement disease repaired) are used to estimate the mid-term change of *PCI* (Eq. (5)):

$$\Delta PCI_i^* = \frac{\sum_j^n (PCI_{i,j,a}^* - PCI_{i,j,b}^*)}{s_i^*} \tag{5}$$

where $PCI_{i,j,b}^*$ is the *PCI* of expressway section *j* before repairing pavement disease *i*, $PCI_{i,j,a}^*$ is the *PCI* of expressway section *j* after repairing pavement disease *i*, ΔPCI_i^* is the mid-term change of *PCI* of expressway sections after repairing pavement disease *i*, s_i^* is the area of expressway sections that only have pavement disease *i* being repaired in 2019.

Note that the *PCI* of each expressway section is calculated based on the types, the quantities, and the severities of the pavement diseases on it [20]. No traffic safety factors are used in calculating the *PCI* and the *PCI* change, but traffic safety factors are closely related with the pavement maintenance works because one of the core objectives of pavement maintenance is to improve expressway traffic safety. Given that pavement damage and diseases could induce traffic accidents [21], expressway transportation agencies check pavement conditions every year and repair the pavement diseases in time.

3.2 Data Envelopment Analysis (DEA) Model

The DEA model is introduced to evaluate the effectiveness of maintaining each type of pavement disease. There are two common types of DEA evaluation models: the BCC model which applies to the variable "returns to scale" situations and the CCR model which applies to the constant "returns to scale" situations [22-24]. Here, "returns to scale" indicates the maintenance returns achieved by reaching a certain maintenance scale. Given that transportation agency in general cannot repair all kinds of pavement diseases due to the limited budget, the BCC model, which applies to variable "returns to scale" situations, is here employed to evaluate the effectiveness of maintaining each kind of pavement disease [25]. The BCC model can evaluate the maintenance effectiveness from three aspects: technical benefit, comprehensive benefit, and scale benefit. Here, the technical benefit represents the benefit produced by the technical factors of pavement disease maintenance. If the technical benefit equals to 1, that means the mid-term change of PCI and the short-term change of PCI have both reached their maximum values under the maintenance cost invested. If the technical benefit is less than 1, the technical benefit could be further improved by improving the strategy of maintenance treatments.

The technical benefit for repairing pavement disease *i*, θ_i, is calculated as follows [26]:

$$\min \theta_i \tag{6}$$

$$\sum_{i=1}^{m} X_i \lambda_i + S_i^- = \theta_i X_i \tag{7}$$

$$\sum_{i=1}^{m} Y_i \lambda_i - S_i^+ = Y_i \tag{8}$$

$$\sum_{i=1}^{m} \lambda_i = 1 \tag{9}$$

$$\lambda_i \geq 0, \forall i \in \{1,2,...,m\} \tag{10}$$

$$S_i^- \geq 0 \tag{11}$$

$$S_i^+ \geq 0 \tag{12}$$

$$i \in \{1,2,...,m\} \tag{13}$$

where X_i and Y_i are the input vector and output vector of pavement disease *i* (i.e., decision-making unit (DMU) *i*), respectively, S_i^- and S_i^+ are the input and output slack variables, respectively, λ_i is the weight of repairing pavement disease *i* (DMU *i*), and *m* is the number of pavement disease types (i.e., $m = 11$). We use *SPSSAU* software to calculate the technical benefit for repairing each kind of pavement disease *i*, θ_i [27].

The comprehensive benefit for repairing pavement disease *i*, β_i, can be obtained using the following equations [28]:

$$\min \beta_i \tag{14}$$

$$\sum_{i=1}^{m} X_i \lambda_i \leq \beta_i X_i \tag{15}$$

$$\sum_{i=1}^{m} Y_i \lambda_i \geq Y_i \tag{16}$$

$$\lambda_i \geq 0, \forall i \in \{1,2,...,m\} \tag{17}$$

$$i \in \{1,2,...,m\} \tag{18}$$

We use *SPSSAU* software to calculate the comprehensive benefit for repairing each kind of pavement disease *i*, β_i [27].

The scale benefit refers to the benefit generated by repairing a type of pavement disease to a certain scale. If the value of scale benefit equals to 1, that means we do not have to expand or reduce the repairing scale of this type of pavement disease. If the value of scale benefit is less than 1, the repairing scale of this type of pavement disease needs to be further optimized. The scale benefit for repairing pavement disease *i*, α_i, can be calculated using Eq. (19):

$$\alpha_i = \frac{\beta_i}{\theta_i} \tag{19}$$

As shown in Fig. 4, the technical benefit θ_i and the comprehensive benefit β_i are first calculated using the corresponding linear programming models. Next, the scale benefit α_i is calculated based on θ_i and β_i .The scale benefit α_i is further used to calculate the coefficient of returns to scale, which plays an important role in the DEA model. When applying the *SPSSAU* software, the unit maintenance costs of different pavement diseases are used as the input, and the short-term and mid-term changes of *PCI* are the outputs. The *SPSSAU* software returns α_i, β_i and θ_i at the same time.

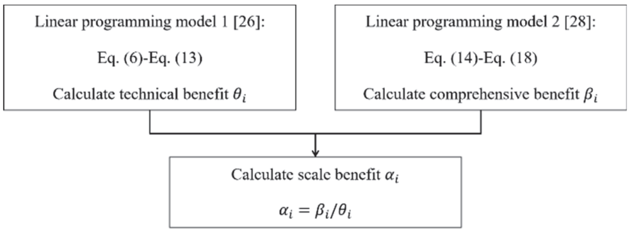

Figure 4 Flowchart for calculating α_i, β_i and θ_i

In general, the number of DMUs should be no less than the product of the number of input indices and the number of output indices. Moreover, the number of DMUs should be no less than three times of the number of input indices and output indices [29]. In this study, the unit maintenance costs of the studied 11 types of pavement diseases are selected as the input indices. The short-term change of *PCI* and the mid-term change of *PCI* of expressway sections are selected as the output indices. Therefore, the evaluation problem meets the requirements for building a DEA model after comparing the number of pavement disease types (DMUs) with the number of input indices and output indices.

4 OPTIMIZATION MODEL OF PAVEMENT MAINTENANCE STRATEGY

Currently, transportation agencies usually maintain expressway pavement following the fixed technical specifications for pavement maintenance, paying less attention on the comprehensive benefits for repairing different pavement diseases. Consequently, current maintenance strategy is often characterized with a huge amount of maintenance cost and a slight improvement of pavement condition. Here, we propose an optimization model of pavement maintenance strategy with a purpose of maximizing the comprehensive benefits of repairing different pavement diseases and simultaneously reducing the maintenance cost. The main constraints of the proposed model include the maintenance cost constraint and the *PCI* constraints.

The objective function is formulated as follows.

$$\max\sum\nolimits_j^n\sum\nolimits_i^m x_{ij}\cdot h_{ij}\cdot\beta_i \tag{20}$$

where x_{ij} is the decision variable, indicating whether to repair pavement disease *i* on expressway section *j*, h_{ij} is the area of pavement disease i on expressway section *j*, the comprehensive benefit of repairing pavement disease *i*, β_i, can be obtained using Eqs. (14) to (18), *n* is the number of expressway sections (i.e., $n = 9703$), and *m* is the number of pavement disease types (i.e., $m = 11$).

The constraints of the objective function are as follows. Firstly, to achieve a better maintenance effectiveness after implementing the optimal maintenance strategy, the average mid-term *PCI* change of the expressway sections should be no less than the average mid-term *PCI* change of the expressway sections before optimization of maintenance strategy (Eq. (21)):

$$\frac{\sum\nolimits_j^n\sum\nolimits_i^m x_{ij}\cdot h_{ij}\cdot\Delta PCI_i^*}{n}\geq\Delta\overline{PCI^*} \tag{21}$$

where $\Delta\overline{PCI^*}$ is the average mid-term *PCI* change of expressway sections before implementing the optimal maintenance strategy, and ΔPCI_i^* is the mid-term *PCI* change of expressway sections after repairing pavement disease i using the optimal maintenance strategy.

Secondly, the number of expressway sections featured with excellent pavement condition after implementing the optimal maintenance strategy should increase (Eq. (22)). Note that the pavement condition of an expressway section is regarded as "excellent" when the *PCI* of the section is equal or greater than 92 [20]:

$$n_{\geq 92}^*\geq n_{\geq 92} \tag{22}$$

where $n_{\geq 92}^*$ is the number of expressway sections with *PCI* equal or greater than 92 after implementing the optimal pavement maintenance strategy, and $n_{\geq 92}$ is the number of expressway sections with PCI equal or greater than 92 before optimization of maintenance strategy.

Thirdly, in order to save the maintenance cost, we assume that the maintenance cost after implementing the optimal maintenance strategy should not exceed σ $(0<\sigma<1)$ times of the original (actual) maintenance cost (Eq. (23)). Practically, the maintenance budgets for repairing pavement diseases are varying, therefore a variable parameter σ is proposed.

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$$\sum\nolimits_j^n\sum\nolimits_i^m x_{ij}\cdot h_{ij}\cdot q_i\leq S'\times\sigma \tag{23}$$

where q_i is the maintenance cost of repairing pavement disease *i*, and S' is the original maintenance cost.

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Finally, the decision variable x_{ij} is assumed to satisfy the constraints (24) and (25), where x_{ij} is a binary variable. When there is no pavement disease i on expressway section *j*, the optimal maintenance strategy is not required (i.e., $x_{ij}=0$).

$$x_{ij}=0\text{ , if }h_{ij}=0 \tag{24}$$

$$x_{ij}\in\{0,1\} \tag{25}$$

5 RESULTS

5.1 Evaluating the Maintenance Effectiveness

In order to compare the pavement conditions before and after pavement maintenance, we calculate the short-term and mid-term changes of *PCI* using Eqs. (2) to (5) (Tab. 4). The area and unit maintenance cost of each type of pavement disease for Hunan expressway are shown in Tab. 4. Taking the short-term change of *PCI* after repairing the pothole disease as an example, we assume that only this type of pavement disease exists in an expressway section, the area of pothole is 1 m^2 (i.e., $A_i=1$ m^2), and the *PCI* of the expressway section after pavement maintenance reaches 100 (i.e., $PCI'_{i,a}=100$). The weight w_i for pothole can be obtained from [20]. Using Eqs. (2) to (4), we calculate that the short-term change of *PCI* for pothole is 3.370. In order to estimate the mid-term change of *PCI*, we choose the expressway sections on which only one specific type of pavement disease was repaired. The *PCI* values of these identified expressway sections in 2020 and the *PCI* values of these identified expressway sections in 2019 can be obtained from the expressway pavement maintenance data (Section 2.2). Consequently, using Eq. (5), we can calculate the mid-term change of PCI for each kind of pavement disease.

Taking the unit maintenance cost of pavement disease as the input, and the short-term and mid-term changes of pavement condition index (PCI) as the outputs, the BCC model is generated to calculate the technical benefit, the scale benefit and the comprehensive benefit of repairing each type of pavement disease (Tab. 5). When the calculated technical benefit equals to 1, the technical benefit reaches the optimal. Otherwise, if the technical benefit is less than 1, it indicates that the technical benefit for repairing the corresponding pavement disease can be further improved. Based on the calculated scale benefit, we use *SPSSAU* software to calculate the coefficient of returns to scale [27]. The coefficient of returns to scale reflects the increase and decrease of "returns to scale" for repairing a type of pavement disease, which is automatically solved by *SPSSAU* [27]. When the coefficient of returns to scale equals to 1 (denoted as "crs"), it means that the returns to scale should not be changed, and the maintenance strategy is optimal. If the coefficient of returns to scale is less than 1 (denoted as "irs"), it means that the returns to scale could be further increased. In such a case, the maintenance areas of the corresponding pavement disease should be further increased. If the coefficient of returns to scale is more than 1, it means that the returns to scale should be decreased (denoted as "drs"). That is, we need to reduce the maintenance areas of the corresponding pavement diseases to save maintenance cost. The comprehensive benefit equals to the technical benefit multiplied by the scale benefit ($\beta = \theta \times \alpha$), which quantifies the pavement maintenance performance in a comprehensive manner.

Table 4 The short-term and mid-term changes of PCI for each type of pavement disease.

Disease type	Disease area / m^2	Unit maintenance cost / dollars	w_i	Short-term change of PCI	Mid-term change of PCI
Shoving	1.000	113.288	1.0	3.370	0.0769
Bleeding	65.773	542.541	0.2	1.736	0.7446
Raveling	736.074	898.594	1.0	3.370	0.9906
Rutting	1.448	121.554	1.0	3.370	1.7243
Depression	2.051	4986.515	1.0	3.370	2.8722
Patching	234694.900	6450.390	0.1	1.305	0.0026
Pothole	84.494	456.229	1.0	3.370	0.4850
Block cracking	987.207	32.648	0.8	3.074	0.0615
Alligator cracking	84.154	183.125	1.0	3.370	0.6638
Longitudinal cracking	30955.660	113.644	2.0	4.483	0.1318
Transverse cracking	62192.080	33.196	2.0	4.483	0.0267

Table 5 The evaluation results of the generated DEA model

Disease type	Technical benefit θ_i	Scale benefit α_i	Coefficient of returns to scale (state)	Comprehensive benefit β_i
Shoving	0.3	0.829	0.76 (irs)	0.249
Bleeding	0.127	0.788	0.494 (irs)	0.1
Raveling	0.092	0.969	0.893 (irs)	0.089
Rutting	1	1	1 (crs)	1
Depression	1	0.041	1.666 (drs)	0.041
Patching	0.005	0.296	0.291 (irs)	0.001
Pothole	0.122	0.922	0.819 (irs)	0.112
Block cracking	1	0.772	0.692 (irs)	0.772
Alligator cracking	0.356	0.943	0.845 (irs)	0.336
Longitudinal cracking	1	0.345	1.015 (drs)	0.345
Transverse cracking	1	1	1 (crs)	1

Tab. 5 shows that the comprehensive benefits of repairing transverse cracking and rutting are higher than those achieved by repairing other types of pavement diseases. It also suggests that the maintenance of transverse cracking and rutting is the most effective. With regard to other pavement diseases, technical factors or scale factors need to be considered for improving the comprehensive benefit. For the pavement diseases with both technical benefit and scale benefit less than 1 (e.g., shoving and bleeding), the maintenance strategy should consider both the technical factors and the scale factors. We also note that the scale benefits for repairing depression, block cracking and longitudinal cracking could be further improved, albeit that the technical benefits for repairing these pavement diseases have reached the optimal. Besides, given that the states of some pavement diseases (e.g., shoving, bleeding, pothole, raveling, alligator cracking and patching) are "irs", the evaluation result suggests increasing the maintenance areas of these pavement diseases. For longitudinal cracking and depression, the evaluation result suggests decreasing the maintenance areas of these pavement diseases.

5.2 Optimizing the Pavement Maintenance Strategy

Gurobi is a mathematical programming optimizer with fast speed and high precision [30]. It is used to solve the proposed optimization model of expressway maintenance strategy [31]. We solve the model using different cost constraints σ.

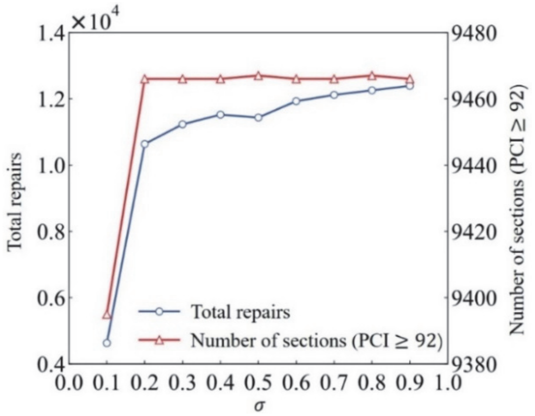

Figure 5 Total repairs and total number of sections with excellent PCI under different σ

As shown in Tab. 6 and Fig. 5, a prominent improvement of the maintenance performance is observed when σ increases from 0.1 to 0.2, while only slight improvements are observed when σ keeps increasing. This implies that the generated pavement maintenance strategy can achieve a good performance while using pretty low maintenance cost ($\sigma = 0.2$). The fundamental reason is that the original pavement maintenance strategy repairs the patching pavement diseases of many expressway sections. However, repairing patching pavement diseases is expensive (~6450.4 dollars per m^2), but has negligible effect on improving *PCI* (The average *PCI* only increases 0.0026). In the generated pavement maintenance strategies, other pavement diseases are repaired with higher priorities, which improves the pavement performance and reduces the maintenance cost. However, when the goal is to improve the pavement performance as much as possible rather than saving the maintenance cost, a larger σ can be considered.

In Tab.6, we also observe the slight fluctuation of the number of expressway sections with excellent *PCI* (*PCI* ≥ 92). An explanation is that in some maintenance strategies an expressway section with *PCI* close to 92 is not selected for repair.

Table 6 The performances of the pavement maintenance strategies generated under different σ

Strategy	Total cost / million dollars	Total repairs	Average *PCI* of a section	Number of sections		
				PCI ≥ 90	PCI ≥ 92	PCI ≥ 95
Strategy (σ = 0.9)	32.686	12 391	97.394	9 661	9 466	8 302
Strategy (σ = 0.8)	29.054	12 255	97.393	9 661	9 467	8 302
Strategy (σ = 0.7)	25.423	12 117	97.393	9 661	9 466	8 302
Strategy (σ = 0.6)	21.791	11 923	97.393	9 661	9 466	8 302
Strategy (σ = 0.5)	18.159	11 434	97.393	9 661	9 467	8 302
Strategy (σ = 0.4)	14.527	11 521	97.393	9 661	9 466	8 302
Strategy (σ = 0.3)	10.895	11 231	97.393	9 661	9 466	8 302
Strategy (σ = 0.2)	7.264	10 636	97.392	9 661	9 466	8 302
Strategy (σ = 0.1)	3.632	4 631	97.123	9 598	9 395	7 902
Original strategy	36.318	3 909	97.123	9 596	9 395	8 025

We further analyze and compare the pavement maintenance strategies generated under $\sigma = 0.2$ and $\sigma = 0.1$, which respectively represent the scenarios that the expressway maintenance budget decreases 80% and 90%. A small part of the optimized maintenance strategy is shown in Tab. 7, where '/' means that the expressway section has no certain type of pavement disease, 'Y' means that the expressway section has a certain type of pavement disease and is repaired, 'N' means that the expressway section has a certain type of pavement disease but is not repaired, and 'D' means the pavement disease is detected in the downstream direction of the expressway section.

When $\sigma = 0.2$, the proposed maintenance strategy costs 7.264 million dollars. Compared with the maintenance cost spent by the Hunan expressway agency in 2019 (i.e., 36.318 million dollars), the proposed maintenance strategy can save 29.054 million dollars. When $\sigma = 0.1$, the proposed maintenance strategy costs 3.632 million dollars, and 32.686 million dollars can be saved. The maintenance cost of each expressway is shown in Fig. 6. The expressway G60 and G4 took up most of the maintenance cost before the optimization of maintenance strategy, accounting for 31.91% and 23.79%, respectively. Nonetheless, the proposed maintenance strategy fully considers the comprehensive benefit of repairing each type of pavement disease, resulting in a more balanced maintenance cost on each expressway.

Table 7 Pavement maintenance strategies for some expressway sections when $\sigma = 0.2$

Expressway ID	Origin pile ID	Destination pile ID	Direction	Transverse cracking	Raveling	Patching	Block cracking
G0401	29	30	D	Y	/	N	/
G0401	30	31	D	Y	/	/	/
G0401	31	32	D	Y	/	N	/
G0401	32	33	D	Y	/	N	Y
G0401	33	34	D	Y	/	N	Y
G0401	34	35	D	Y	/	/	/
G0401	35	36	D	Y	/	Y	/
G0401	36	37	D	Y	/	N	/
G0401	37	38	D	Y	/	N	/

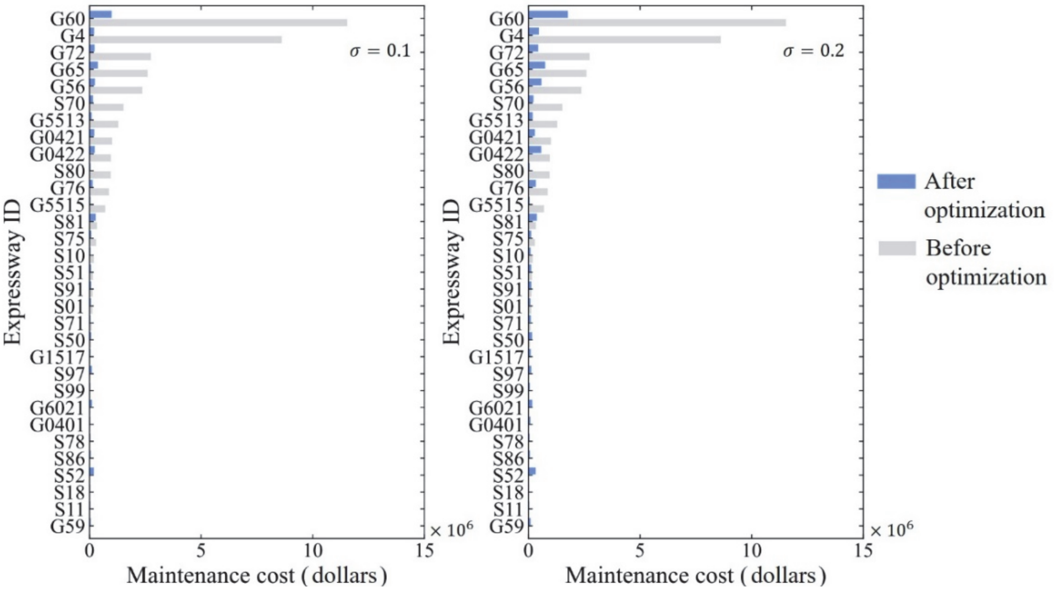

Figure 6 Comparison of the maintenance costs before and after implementing the optimal maintenance strategy

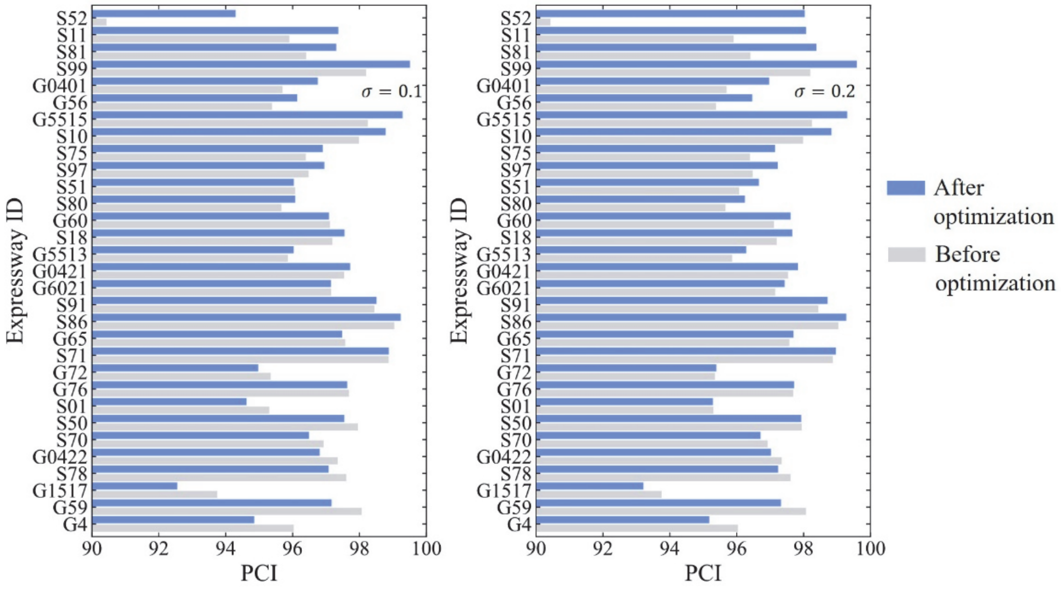

Figure 7 Comparison of mid-term change of PCI before and after implementing the optimal maintenance strategy

We also compare the mid-term changes of *PCI* of expressways before and after implementing the optimal maintenance strategy (Fig. 7). When $\sigma = 0.2$, a total of 10636 pavement diseases are repaired. The *PCI* values of all expressway sections increase by 6943.6 in total. Comparing with the original pavement maintenance strategy, the average *PCI* increases by 0.270. When $\sigma = 0.1$, a total of 4631 pavement diseases are repaired. The *PCI* values of all expressway sections increase by 4333.8 in total. Comparing with the original pavement maintenance strategy, the average *PCI* does not change. This implies that in the original pavement maintenance strategy, repairing some pavement diseases has negligible effect on improving *PCI*. In situations with limited budget, the maintenance of some pavement diseases could be temporarily postponed. Moreover, after the optimization of maintenance strategy, the number of expressway sections with excellent *PCI* ($PCI \geq 92$) in 2020 is 9466, 71 more than the number of expressway sections with ($PCI \geq 92$) when implementing the original maintenance strategy. The results suggest that the comprehensive benefit of pavement maintenance was not fully considered by the transportation agency. Repairing some types of pavement diseases cannot improve the *PCI* greatly.

6 CONCLUSION

Large-scale pavement disease data, pavement performance data and pavement maintenance data of Hunan expressway are employed to develop a decision-making optimization approach to improve the performance of pavement maintenance strategy. Compared with the original pavement maintenance strategy, the improved strategies can achieve a better pavement maintenance performance while requiring much less maintenance budget. An explanation for this finding is that the original maintenance strategy repairs the patching diseases of many expressway sections, which is expensive but has negligible effect on improving *PCI*. The improved strategies, however, repair other pavement diseases with higher priorities, therefore improving the maintenance performance and reducing the maintenance cost. In future studies, when more pavement performance data are available, the pavement performance prediction models can be developed and integrated with the proposed decision-making optimization approach to build an expressway pavement management system.

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