**Technical Paper**

ISSN 1997-1400 Int. J. Pavement Res. Technol. 7(2):159-167


# Development of an Asphalt Pavement Distress Evaluation Method for Freeways in China

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**Abstract:** Reasonable evaluation of the asphalt pavement distress condition is a very important part of the pavement management system. The objective of this research is to develop an effective method to evaluate asphalt pavement distress conditions in China. Three single evaluation indexes were proposed, namely the Transverse Cracking Evaluation Index (TCEI), Pavement Patching Condition Index (PPCI), and Pavement Surface Distress Condition Index (PSCI), to assess the severity of asphalt pavement distresses. The pavement distress condition index (PDCI) was then developed as a general evaluation index by using the analytic hierarchy process (AHP). The feasibility of this evaluation method was validated using the field distress data collected from Ning Hang freeway and Fen Guan freeway in Jiangsu Province, China. The results showed that the PDCI could reasonably represent the distress condition in asphalt pavements. The index value correlates well with the actual condition of the pavement. Therefore, a scientific and rational method has been established to evaluate Chinese asphalt pavement distress conditions.

**DOI**:10.6135/ijprt.org.tw/2014.7(2).159

***Key words**: Analytic hierarchy process; Asphalt pavement; Evaluating method; Pavement distress; Transverse crack.*

## Introduction

With the rapid development of freeway construction in China, its total freeway mileage is the highest in the world. In China, most of the asphalt pavement structures use semi-rigid base. However, because of the influence of traffic and the environment, distresses of various forms and severity levels occur on asphalt pavement, including rutting, cracks, potholes, subsidence, etc. Many asphalt pavements have to be repaired prematurely because serious distresses occur even before the end of design life. Pavement distresses not only damage the integrity and continuity, but also reduce the pavement structural capacity. Thus, they can affect the service level and service life of freeways and threaten driving safety as well.

Investigation and reasonable evaluation of the distress condition of asphalt freeway pavements is a very important part of pavement maintenance evaluation [1]. It is the basis for evaluating and predicting pavement performance, which then can be used to determine the preservation plan, make decisions on investment, and provide strong support for pavement decision makers. It is also significant for the construction and maintenance of freeways in the future.

The objectives of this study are to develop an effective method to evaluate the distresses condition of asphalt freeway pavements in China based on the damage mechanism and data analysis, and then perform an analysis on the maintenance treatment approach. This paper aims to provide reference and guidance for freeway maintenance management in China.

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Note: Submitted April 25, 2013; Revised October 17, 2013; Accepted October 28, 2013.

## Existing Evaluation Methods of Pavement Distresses

In the early 1960s [2], building a pavement evaluation model was one of the most essential achievements of the U.S. AASHTO road tests. The evaluation model had a profound impact on the development of pavement management technologies around the world. In the early 1980s [1], many other countries such as Canada, Britain, and Japan began to establish their own pavement performance evaluation models with in-depth study and extensive application of Pavement Management System (PMS).

### AASHTO Present Serviceability Index (PSI)

Present Serviceability Index (PSI) is the first index established by using the expert evaluation technology based on the practical engineering in the pavement management industry [2-3]. Road inspectors investigate the damage level of each experimental section, and conduct multiple regression analyses to establish the relationship between the damage situation and the Present Serviceability Rating (PSR) value based on experts' grading, which is the Present Serviceability Index (PSI).

For asphalt pavement:

$$PSI = 5.03 - 1.91\lg\left(1+\overline{SV}\right) - 0.21RD^2 - 0.01\sqrt{C+P} \qquad (1)$$

where $PSI$ = Present Serviceability Index;
$SV$ = discrete degree of the longitudinal smoothness at the wheel track;
$RD$ = rutting depth, cm;
$C$ = cracking degree, $m^2/1000m^2$;
$P$ = patching degree, $m^2/1000m^2$.

The model contains four variable parameters, namely smoothness, surface cracking, pavement patching degree, and rutting. Of the four factors, surface cracking and rutting take very small proportion, meaning their variation has little impact on the PSI. On the contrary, the smoothness has a significant influence on the PSI, especially when the SV is below 10. The PSI model is actually a riding quality model which is mainly related to the smoothness from the perspective of parameter weights.

### ASTM Pavement Condition Index (PCI)

The Pavement Condition Index (PCI) for roads is a single index value used to quantify all forms and severity levels of pavement distresses, developed by the U.S. Army Corps of Engineers and further verified and adopted by the Department of Defense (DOD) and American Public Works Association (APWA) [4]. In the Standard Practice for Roads and Parking Lots Pavement Condition Index Surveys (D6433-11), asphalt pavement distresses are classified into 20 types, in which the typical distresses are cracks, rutting, and weathering of the pavement surface. The PCI is determined by the following equation.

For asphalt pavement:

$$PCI = 100 - max\,(CDV) \tag{2}$$

where $PCI$ = Pavement Condition Index;
$CDV$ = the corrected deduct value ($DV$) obtained from total deduct value and $q$ by looking up the appropriate correction curve for AC pavements;
$DV$ = the deduct value ($DV$) for each distress type and severity level combination obtained from the distress deduct value curves.

The $PCI$ is a numerical rating of the pavement condition that ranges from 0 to 100, with 0 being the worst possible condition and 100 being the best possible condition. Since the deduct value curves and correction curve are obtained according to the circumstances of asphalt pavements in USA, the PCI index may not be suitable in China.

### Japanese Management Conservation Index (MCI)

Researchers from the Japanese ministry of civil engineering have developed the Management Conservation Index (MCI) by modifying the PSI model according to the Japanese situation [2]. Unlike the American PSI model, the MCI model emphasizes pavement surface cracking and rutting, while the smoothness only accounts for a small proportion, as shown in Eqs. (3) to (6).

$$MCI = 10 - 1.48C^{0.3} - 0.29D^{0.7} - 0.47\sigma^{0.2} \tag{3}$$

$$MCI_0 = 10 - 1.51C^{0.3} - 0.30D^{0.7} \tag{4}$$

$$MCI_1 = 10 - 2.23C^{0.3} \tag{5}$$

$$MCI_2 = 10 - 0.54\,D^{0.7} \tag{6}$$

where $MCI$ = maintenance and management condition index, 0-10;
$C$ = cracking ratio, %;
$D$ = rutting depth, mm;
$\sigma$ = smoothness, mm.

In order to accurately characterize different pavement conditions, the MCI model actually contains four relation models. So it is reasonable that Eq. (4) only contains two parameters: cracking ratio and rutting. For the pavement sections with severe rutting distress but little cracking, Eq. (4) provides a relatively high value, whereas Eq. (6) provides more reasonable value for this kind of pavement condition. For modelling purposes, different equations have been developed to deal with different pavement conditions, which confuse the users occasionally. This is the defect of multiple regression analysis techniques, as it is difficult to adapt one single set of formula to evaluate different road conditions due to the immutability of the regression coefficients.

### Chinese Pavement Condition Index (PCI)

In the most recent Chinese pavement maintenance specification, Highway Performance Assessment Standard (JTG H20-2007) [5], the Pavement Condition Index (PCI) model is recommended for evaluating pavement surface distress condition by using Eq. (7):

$$PCI = 100 - 15.00 \times DR^{0.412} \tag{7}$$

$$DR = 100 \times \frac{\sum_{i=1}^{21} \omega_i A_i}{A} \tag{8}$$

where $PCI$ = pavement surface condition index;
$DR$ = pavement distress ratio, %;
$A_i$ = distress area of distress type $i$, m$^2$;
$A$ = area of the investigated pavement sections, m$^2$;
$\omega_I$ = weight of distress type $i$; and
$i$ = severity of distress type $i$.

The PCI model does not consider the influence of pavement smoothness. It is only a function of pavement surface distress. The advantage of this method is that it can accurately calculate the overall extent of damage caused by a variety of distresses. Therefore, the PCI model overcomes the defect of the MCI model.

### Analysis of Existing Evaluation Models

Investigating the previous pavement condition evaluation models of different countries shows that the AASHTO PSI model is actually a smoothness related riding quality model. Given the specific situation of the freeway pavements in China, where cracking and rutting are the two main types of distresses, the PSI model is not suitable for the evaluation of the asphalt pavement distress condition in China.

In the Chinese specification, the PCI model covers 21 types of distresses. Although relatively comprehensive, it is too general to put all the distresses together [6]. In fact, the causes of these distresses are different, and their influences on pavement performance are different. As a result, high PCI values may not represent good pavement conditions, and vice versa. Different pavement distresses should be considered separately according to the specific circumstances.

To explain the limitation of the Chinese PCI model, the distress data obtained from Jing Hu freeway in Jiangsu province in China was collected and analyzed. The calculation results are summarized in Table 1.

**Table 1.** Example of the Distress Condition Evaluation Method in China.

| Pavement Section Number | Length of the Investigated Pavement Section (m) | PCI | PCI Level | Transverse Crack Amount | Length of Crack (m) | Transverse Crack Spacing(m) |
|---|---|---|---|---|---|---|
| 1 | 1000 | 90 | Excellent | 36 | 110.5 | 27.8 |
| 2 | 1000 | 92 | Excellent | 24 | 59.3 | 41.7 |
| 3 | 1000 | 87 | Good | 66 | 202.3 | 15.2 |
| 4 | 1000 | 88 | Good | 55 | 177.8 | 18.2 |
| 5 | 1000 | 90 | Excellent | 48 | 122 | 20.8 |
| 6 | 1000 | 90 | Excellent | 40 | 114 | 25.0 |
| 7 | 1000 | 93 | Excellent | 18 | 55 | 55.6 |
| 8 | 1000 | 88 | Good | 147 | 170.6 | 6.8 |

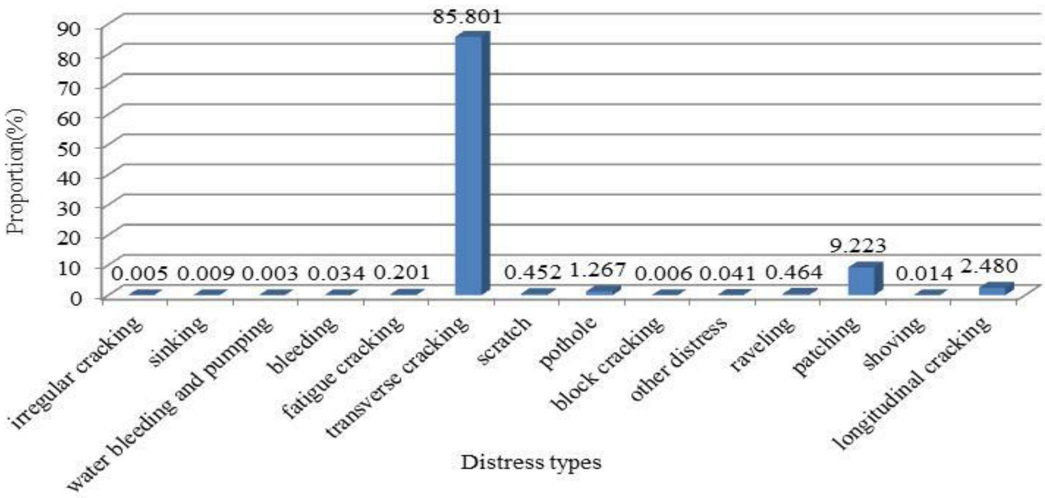


**Fig. 1.** Proportion of Each Pavement Distress Numbers to the Distresses Amount in 2011 in Jiangsu Province.

The PCI values of all sections are above 80 in Table 1, indicating that the pavement sections are in good condition. But the results are inconsistent with the actual condition. For example, the PCI values of section 4 and section 8 are the same, but the extent of transverse cracking in section 8 is much more than that of the section 4, which means the crack condition of section 8 is actually more severe than that of section 4. In other words, the PCI couldn't accurately reflect the different severity levels of transverse cracking condition. Therefore, the evaluation method needs improvement. Only using PCI index to evaluate pavement distress is too general. It is not reasonable, nor scientific.

Because pavement distress is an important part of pavement performance, it is necessary to develop a suitable evaluation model of pavement distress condition in order to provide guidance for developing a maintenance plan.

## Development of New Single Evaluation Indexes for Pavement Distress Condition

As of 2011, the total mileage of freeways in Jiangsu province has reached 4,121 km. The pavement structure of all freeways in Jiangsu is an asphalt concrete pavement with semi-rigid base layer, which is the typical pavement structure in China. There are varying degrees of cracking, rutting, shoving, pothole, etc., in Jiangsu freeways each year. The pavement distresses data used in the paper were collected by visual inspection in the field from 14 freeway sections that had been in service over 5 years. Fig. 1 shows the proportion of each pavement distress to the total in 2011 in Jiangsu province. It reflects the current distress condition of the whole Jiangsu freeways.

As shown in Fig. 1, transverse cracking and patching are the two major types of asphalt pavement distresses in Jiangsu province, whose total proportion is above 90%, followed by pothole and longitudinal cracking, and the proportions of other distress types are very small. Table 2 presents the pavement distress conditions of different freeways in 2011 in Jiangsu province.

The types and severities of pavement distress varied in different freeway pavements; however, transverse cracking is still the major distress. The proportions of the other distresses differed with the service time of the freeway, the degree of severity of the traffic load, and the effects of pavement maintenances. The longer service time and the heavier traffic load, the more types and higher severities of pavement distress; while the shorter service time and lower traffic load, the less the amount and types of pavement distresses.

The survey reveals that most of the transverse cracks are reflective cracks, but fatigue cracks also appear on freeway pavements that are older than 10 years, and longitudinal cracks are mainly caused by the differential settlement of subgrade. Generally, regardless of the type of pavement distress, based on the freeway preventive and timely maintenance requirements in China, the distress, which is dangerous to high-speed driving, should be repaired immediately. Thus, these distresses may be patched soon.

**Table 2.** Pavement Distress Conditions of Different Freeways in 2011 in Jiangsu Province.

| Freeway Name | Total Length of Freeway (km) | Service Life (Year) | Distress Amount | The Proportion of Each Distress Type to the Total Distresses (%) | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 1* | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
| Hu Ning | 248 | 16 | 10492 | 53.9 | 2.1 | 0 | 0.2 | | 5.2 | 1.6 | 37 | | 0 | | | | |
| Zhen Jiang | 10 | 16 | 620 | 62.3 | 6.8 | 0.2 | 11 | | 3.1 | 6 | 10.6 | | | | | | |
| Guangjing-Xi Cheng | 52 | 13 | 485 | 78.6 | 1.9 | | | | 7.4 | 1.9 | 7.3 | 2.5 | 0.4 | | | | |
| Jing Hu | 262 | 12 | 6052 | 82.2 | 8.2 | | 0.7 | | 0.3 | 0.2 | 8.4 | | | | | | |
| Ning Jingyan | 188 | 10 | 4590 | 96.5 | 0.3 | | | 0 | 0.1 | 0.1 | 1.3 | 1.4 | | | 0.2 | | 0.1 |
| Ning Hang | 114 | 9 | 2444 | 86.2 | 0.4 | 0.1 | 0.1 | | 0.6 | 0.3 | 10.6 | 1.4 | 0.1 | 0.1 | 0 | | 0.1 |
| Ning Suxu | 227 | 9 | 2564 | 95.1 | 0.6 | | | | 0.4 | | 2.6 | 0.8 | | | | 0 | 0.5 |
| Fen Guan | 85 | 8 | 3061 | 98.4 | 1.2 | | | | 0.15 | 0.1 | 0.15 | | | | | | |
| Yan Jiang | 104 | 8 | 8625 | 93.8 | 0.2 | | | 0 | 1.5 | 0.4 | 2.3 | 1.6 | 0 | 0 | 0.1 | | 0.1 |
| Xi Yi | 70 | 7 | 522 | 98.1 | | | | | 0.4 | 0.2 | 1.3 | | | | | | |
| Su Huaiyan | 214 | 5 | 4304 | 89.5 | 0.7 | | 0.1 | | 0.4 | 0.2 | 9 | | 0.1 | | | | |
| Yan Hai | 322 | 5 | 1282 | 83.6 | | | | | 0.9 | 0.3 | 14.9 | | | | | 0.1 | 0.2 |
| Zhen Li | 66 | 4 | 532 | 75.7 | 0.2 | | | | 0.6 | 0.2 | 23.1 | 0.2 | | | | | |
| Ning Chang | 87 | 4 | 161 | 86.3 | | | | | 1.9 | 0.6 | 3.7 | 7.5 | | | | | |

*Distress type: 1: transverse cracking;2: longitudinal cracking; 3: block cracking; 4: fatigue cracking; 5: irregular cracking; 6: pothole; 7: ravelling; 8: patching; 9: scratch; 10: shoving; 11: sinking; 12: bleeding; 13: water bleeding and pumping; 14: other distress.

Therefore, the area of patching can reflect the pavement condition indirectly. Besides the three distress types above, pothole is another common type of freeway distress. At the same time, because of the danger of potholes to motorists on the freeways, these damages are patched whenever they appears. Thus, the distresses in asphalt freeway pavements can be classified into three categories: cracking, patching, and other surface distress. In addition, the transverse cracking is the most common distress on freeway in China [1, 7]. In order to make the evaluation results more pertinent, the transverse cracking is listed separately as an individual evaluation index while other cracking types are classified into surface distress evaluation. Based on this method, in order to overcome the disadvantage of the Chinese PCI model, three single evaluation indexes are defined to evaluate the asphalt pavement surface damage conditions in freeways, namely the pavement transverse cracking condition index (TCEI), pavement patching condition index (PPCI), and pavement surface distress condition index (PSCI). The details of each index are described in the following sections.

## Pavement Transverse Cracking Evaluation Index (TCEI)

In China, the main distresses of semi-rigid base layer asphalt pavement are cracking and rutting. The rutting depth index (RDI) has already been a single evaluation parameter in the 2007 Chinese standard; as another typical distress, the cracking has not yet received enough attention. The asphalt pavement surface cracks in China are mostly transverse reflective cracks due to the semi-rigid base layer. For this reason, the transverse crack evaluation index (TCEI) was developed to indicate the severity of the transverse cracking in asphalt pavements [8]. The calculation method is shown as follows.

$$TCEI = \begin{cases} 100 & nocracking \\ 100 - 115.022 * e^{-0.1397 * TCCI^{0.5475}} & TCCI > 1 \\ 0 & TCCI \le 1 \end{cases} \quad (9)$$

$$TCCI = \frac{TCS}{TWR} \quad (10)$$

$$TCS = \frac{L}{TCN} \quad (11)$$

$$TCL = \frac{TCTL}{TCN} \quad (12)$$

$$TWR = \frac{TCL}{B} \quad (13)$$

where *TCCI* = Transverse Crack Index, dimensionless;
*TCS* = Average Transverse Crack Spacing, m;
*TWR* = Transverse Crack Width Ratio, dimensionless; If the TWR value is more than 1.0, the TWR should be considered to be 1.0.
*TCL* = Transverse Crack Average Length, m;
*TCN* = Number of Transverse Crack in Pavement Section being evaluated;
*TCTL* = Transverse Crack Total Length, m;
*L* = Total Length of the Pavement Section being evaluated, m; and
*B* = Width of the Pavement Section being evaluated, m.

Transverse Crack Spacing (TCS) indicates the longitudinal distribution of transverse cracks and transverse Crack Width Ratio (TWR) presents whether the transverse crack is full width or less, representing the severity level of the crack. The TCEI index characterizes the transverse crack damage condition comprehensively in asphalt pavements, which can be used to determine the proper maintenance timing and methods.

The transverse cracking condition is more serious when the TCS is smaller and the TWR is bigger. The pavement cracking is one of the important factors aggravating pavement roughness, and often causes pavement structural failure. The TCEI is divided into five performance levels: excellent ($TCEI \ge 90$), good ($80 \le TCEI < 90$), moderate ($70 \le TCEI < 80$), inferior ($60 \le TCEI < 70$) and poor ($TCEI < 60$). The pavement cracking severity can be assessed through the *TCEI*, and then the causes of the pavement damages can be analyzed, which then can be used to select proper treatments.

### Pavement Patching Condition Index (PPCI)

The pavement patching is the result of the pavement distress treatment, but not the distress itself. However, the pavement patching reflects the historical condition of pavement distresses. With the increase of the pavement service life, the performance of the pavement structure layers descends, and the patching area may increase rapidly. When the patching area exceeds a limitation, the pavement ought to be rehabilitated. The patching also affects the driving experience and the pavement appearance. It is related to the driving quality and safety in freeways. The patching has been treated as one of the pavement distresses in the recent Chinese specification, while its severity is ignored [13]. Therefore, it is necessary to deviate the patching from the PCI model and develop a single evaluation index to evaluate the pavement historical damage condition more specifically.

As shown in Eq. (14), the Pavement Patching Condition Index (PPCI) has been proposed by this study to evaluate the pavement patching.

$$PPCI = 100 - a_0 PPR^{a_1} \tag{14}$$

$$PPR = 100 \times \frac{\sum_{i=1}^{n} A_i}{A} \tag{15}$$

where $PPR$ = Pavement Patching Ratio, %；
$A_i$ = area of pavement patching type $i$ (m$^2$);
$A$ = the investigated pavement area (m$^2$);
$a_0$ = calibration coefficient, 15.634;
$a_1$ = calibration coefficient, 0.4032;
$n$ = the patching numbers.

The PPCI is divided into five performance levels: excellent (PPCI $\ge$ 90), good ($80 \le$ PPCI $< 90$), moderate ($70 \le$ PPCI $< 80$), inferior ($60 \le$ PPCI $< 70$) and poor (PPCI $< 60$).

### Pavement Surface Distress Condition Index (PSCI)

In addition to the patching and transverse cracking, there are still other types of surface distress in freeway asphalt pavement, for example, shoving, bleeding, shaving, and longitudinal cracking etc. The other pavement surface distress can be evaluated by pavement surface distress condition index (PSCI). The surface distress reflects the damage condition of the current pavement. Thus, it can also be named as pavement current damage condition index.

Refer to the evaluation method of pavement damage condition index PCI in Standard 2007, the mark reducing method is utilized to make the evaluation in PSCI as follows.

$$PSCI = 100 - a_0 SDR^{a_1} \tag{16}$$

$$SDR = 100 * \frac{\sum_{i=1}^{n} \omega_i A_i}{A} \tag{17}$$

where $SDR$ = Pavement Surface Distress Ratio, it is defined to be the proportion of the damage total areas to the pavement investigation areas (%).
$A_i$ = the surface damage area of type $i$, except the patching and transverse cracking (m$^2$);
$A$ = the investigated pavement area (the product of investigation pavement length and the effective pavement width)(m$^2$);
$\omega_i$ = the weight of the type $i$ pavement distress.
$a_0$ = calibration coefficient, 15.0 is adopted;
$a_1$ = calibration coefficient, 0.412 is adopted;
$n$ = the total number of damage types including the damage severity.

The PSCI is divided into five performance levels: excellent (PSCI $\ge$ 90), good ($80 \le$ PSCI $< 90$), moderate ($70 \le$ PSCI $< 80$), inferior ($60 \le$ PSCI $< 70$) and poor (PSCI $< 60$).

### Evaluation of the New Single Evaluation Index

In order to test the feasibility of the new single evaluation index, seven pavement sections that cannot be successfully evaluated by the old PCI model were selected from Jing Hu freeway in 2008 for analysis. Table 3 summarizes the evaluation results of *TCEI*, *PPCI*, *PSCI*, and *PCI*.

As shown in Table 3, the *PCI* values were all above 90, which means the pavement performance conditions were excellent. However, while using the *TCEI* to evaluate, the scores of some pavement sections were below 80, even less than 70. According to the *TCEI* evaluation standard, the *TCEI* index was under the moderate level. The transverse cracking condition was serious, which is consistent with the actual pavement performance. And the *TCEI* can appropriately reflect the pavement transverse cracking condition.

The *PSCI* values were larger than *PCI* values in Table 3. According to distress data, the surface distresses of these 7 pavement sections were not serious except for the transverse cracking. This result is consistent with the actual surface distress effective area condition. *PPCI* is used to evaluate the historical conditions of pavement distresses. According to the *PPCI*, the patching areas of these 7 pavement sections were section 2 > section 6 > section 7 > section 1 > section 4 > section 3 > section 5 before 2008.

## Development of General Pavement Distress Condition Evaluation Model

The three single indexes, TCEI, PCCI, and PSCI, as mentioned above, can be used to rationally characterize the pavement damage condition. However, single indexes are not good at evaluating macroscopically. Therefore, a general evaluation index, Pavement Distress Condition Index (PDCI), is developed to evaluate the pavement damage condition entirely by combining the three single indicators TCEI, PPCI, and PSCI.

Building reasonable and feasible pavement distress general

**Table 3.** Evaluation Results of the New Evaluation Indexes.

| Pavement Section | Pavement Section | PCI | TCEI | PSCI | PPCI |
|---|---|---|---|---|---|
| 1 | K 2+000-K 3+000 | 92.0 | 73.8 | 100 | 90.8 |
| 2 | K20+000-K21+000 | 90.1 | 73.5 | 93.1 | 88.8 |
| 3 | K57+000-K58+000 | 92.4 | 76.4 | 100 | 91.2 |
| 4 | K59+000-K60+000 | 92.0 | 76.7 | 96.4 | 90.9 |
| 5 | K60+000-K61+000 | 92.9 | 79.7 | 100 | 92.7 |
| 6 | K68+000-K69+000 | 91.1 | 74.5 | 94.8 | 89.5 |
| 7 | K69+000-K70+000 | 90.1 | 67.4 | 94.9 | 89.6 |

evaluation index and determining the weights of each single index are the keys to solve the problem. However, the relationships between each single index are qualitative; it is difficult to determine the weights. Analytic hierarchy process (AHP) [10-11] can avoid this problem effectively by considering the quantity and quality effects comprehensively and determining the weights of each single index.

AHP is one of the most typical systems engineering approaches that integrate the quantitative and qualitative analysis. This approach is suitable to cope with the problems which involved complex structures, many decision criteria, and difficulty on quantifying. It also can help people to keep the consistency of thought process. Therefore, AHP is widely used in determining the factor weights [10-11]. This study selected AHP to determine the weight of each single index to obtain a general index to evaluate the whole pavement distress condition.

## Basic Principles of Analytic Hierarchy Process

Analytic hierarchy process was first presented by American operations researcher T. L. Saaty. This method can make the decision thought behind a complicated system hierarchical, and make an organic combination of qualitative and quantitative factors in the determination process. AHP can calculate the weights of each factor while the quantitative and qualitative factors are both included. And it can reduce the probability of the contradiction between subjective judgments and actual problems. The process of AHP modeling and weight calculation contains four steps: 1) building the hierarchy model; 2) building the judgment matrix; 3) single level sorting and consistency check; and 4) hierarchy total level sorting and consistency check [12].

## Development of Pavement Distress Condition Index (PDCI)

The PDCI was the weighted average of three indexes, TCEI, PPCI, and PSCI. The PDCI is defined in the following equation.

$$PDCI = a*TCEI + b*PPCI + c*PSCI \tag{18}$$

Through analysis, it's rather rational to determine the weights of sub-indexes through AHP and obtain the comprehensive index on such a basis. In this case, the PDCI will be defined as target layer A. The analysis of the PDCI is based on two principles, rationality and feasibility, which are defined as two elements of criterion layer named $C_1$ and $C_2$. The PDCI is calculated from three indexes, TCEI, PPCI and PSCI, which are defined as three elements of scheme layer named $P_1$, $P_2$ and $P_3$. The hierarchical structure model is graphically shown in Fig. 2.

Monolayer Judgment Matrix A-C was built on two elements, the rationality and feasibility. These elements were determined by comparing their importance, and Matrix $A_{2*2}$ was built on such a basis. Then, matrix C-P was built, which included three elements, the TCEI, PPCI, and PSCI. Matrix $(C_1)_{3*3}$ and $(C_2)_{3*3}$ were built through multiple comparison and assignment of these three elements.

$$A=\begin{bmatrix}1 & \frac{1}{3}\\ 3 & 1\end{bmatrix} \qquad C_1=\begin{bmatrix}1 & 4 & 7\\ \frac{1}{4} & 1 & 4\\ \frac{1}{7} & \frac{1}{4} & 1\end{bmatrix} \qquad C_2=\begin{bmatrix}1 & 4 & 5\\ \frac{1}{4} & 1 & 3\\ \frac{1}{5} & \frac{1}{3} & 1\end{bmatrix}$$

First, matrix $A$ should be checked for consistency. $A$ is a two order matrix, and it fits the consistency principle. The maximum eigenvalue $\lambda_{max}$ is equal to 2, and its corresponding eigenvector $W$ is shown as $W = [W_1, W_2]^T = [0.25, 0.75]^T$.

Then, a consistency check was made to the matrix $C_1$ and $C_2$, and the weight of each element was calculated. The results of Monolayer Judgment Matrix are summarized in Table 4.
Monolayer matrix $C_1$ and $C_2$ pass the consistency check from the results of $CR$ in Table 4, which means they are availability matrix. Finally, a consistency check was made to the hierarchy total sort [9].

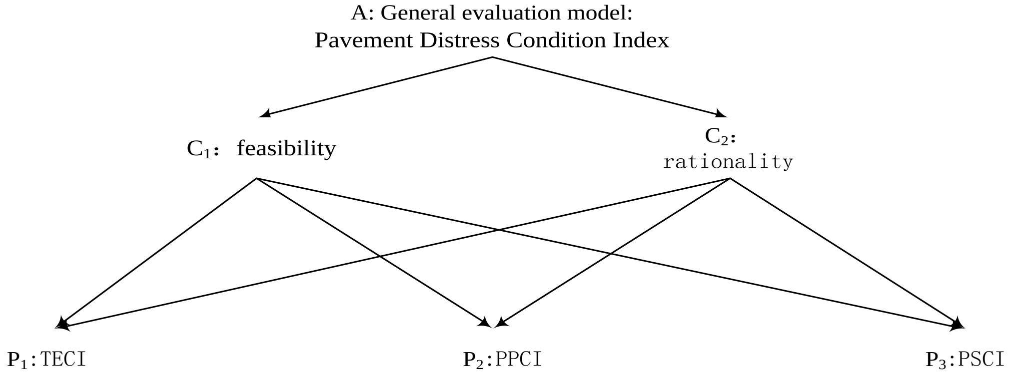


**Fig. 2.** Hierarchical Structure Model of Weight Analysis for Single Evaluation Index.

**Table 4.** Results of Monolayer Judgment Matrix.

| Element Weight | $W_{i1}$ | $W_{i2}$ | $W_{i3}$ | $\lambda_{max}$ | $CI_i$ | $RI_i$ | $CR_i$ |
|---|---|---|---|---|---|---|---|
| $W_{C1}$ | 0.6250 | 0.2385 | 0.1365 | 3.0183 | 0.0092 | 0.58 | 0.0158 |
| $W_{C2}$ | 0.6144 | 0.2684 | 0.1172 | 3.0735 | 0.0368 | 0.58 | 0.0634 |

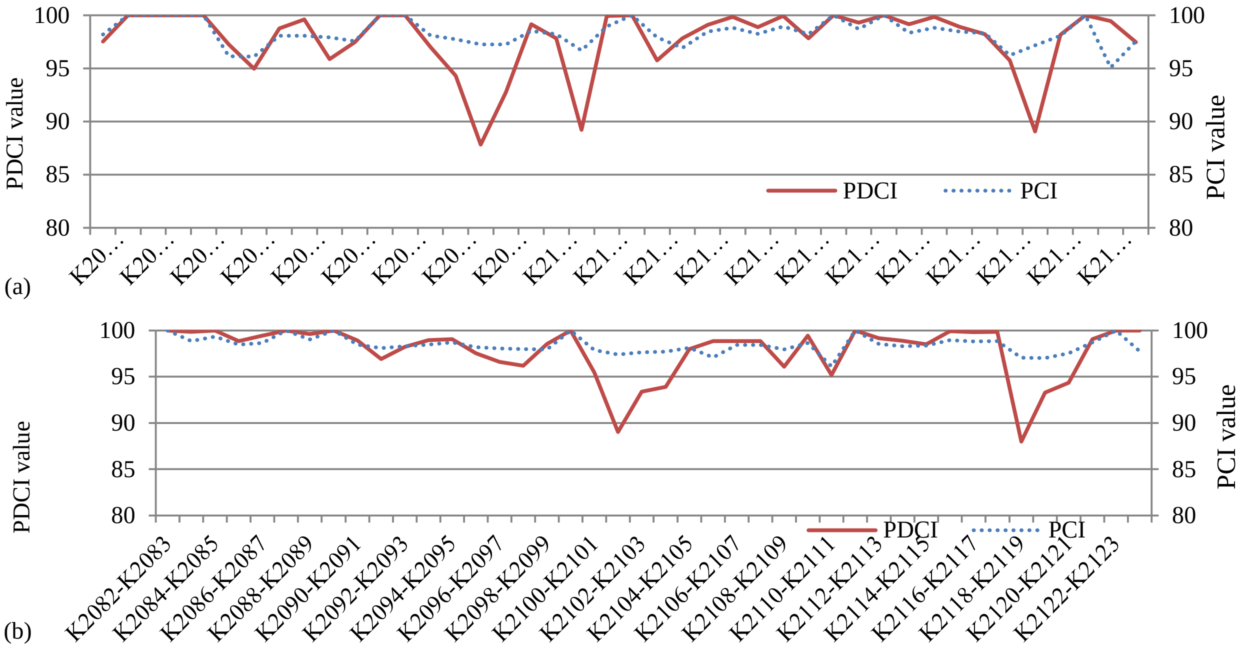


**Fig. 3.** Variation Curve of PCI Value and PDCI Value along (a) East Bound Direction, (b) West Bound Direction.

The corresponding weight $W_P$ of target layer of factors $P_1$, $P_2$ and $P_3$ is equal to $W_P = [W_{P1}, W_{P2}, W_{P3}]^T = [0.6179, 0.2585, 0.1236]^T$, where $W_{P1}$ is corresponding to *a*, $W_{P2}$ is corresponding to *b*, and $W_{P3}$ is corresponding to *c* in Eq. (19). Therefore, Eq. (18) can be described as follows.

$$PDCI = 0.6179*TCEI + 0.2585*PPCI + 0.1236*PSCI \quad (19)$$

The *PDCI* is divided into five performance levels: excellent ($PDCI \geq 90$), good ($80 \leq PDCI < 90$), moderate ($70 \leq PDCI < 80$), inferior ($60 \leq PDCI < 70$) and poor ($PDCI < 60$).

In summary, the new pavement distress condition evaluation model consists of three single evaluation indicators, namely *TECI*, *PPCI*, and *PSCI*, and one general evaluation indicator *PDCI*. The process of calculating the *PDCI* is as follows:

First, the data of pavement distresses should be collected, including the quantity and the area or the length. Second, calculate the three single indicators *TCEI*, *PPCI* and *PSCI* by Eqs. (9), (14), and (16). And finally, calculate the PDCI according to Eq. (19).

The general guideline of determining the pavement maintenance method is divided into three key steps: 1) calculating the *PDCI* index of each section and choosing the sections with *PDCI* values less than 75 as the maintenance sections; 2) comparing the corresponding single indicators (*TCEI*, *PPCI*, and *PSCI*) of these maintenance sections and finding the main distress type of each maintenance section; and 3) determining the proper maintenance method for each maintenance section based on the type and severity of the distress.

## Engineering Application

In order to validate the evaluation method proposed in this study, data were collected from Ning Hang freeway (open to traffic in 2003) and Fen Guan freeway (open to traffic in 2002) in Jiangsu Province. Both freeways have asphalt concrete surface on top of semi-rigid base layer, with two traffic lanes in each direction. The surface thicknesses of Ning Hang freeway and Yan Jiang freeway are 18 cm and 17 cm, respectively. Both freeways use cement stabilized macadam in the base layer. The base layer thickness for Ning Hang freeway is 36 cm and for Yan Jiang freeway is 38 cm. The traffic volumes of the two freeways have increased every year since they opened to traffic, and the proportion of the trucks also increased continuously. The overloading condition on the two freeways is also very serious.

### *Application of PDCI on Evaluating Pavement Distress Condition of Ning Hang Freeway*

To validate the performance of the *PDCI* model, the data were collected from Ning Hang freeway in 2011. The statistical results of some pavement sections are analyzed using *PCI* and *PDCI*. Fig. 3 shows the variation curves of comparison results of *PCI* and *PDCI*.

As shown in Fig. 3, when the pavement distress condition is not serious, there is no significant difference between *PDCI* and *PCI* within the scope of 95 to 100. However, in some sections where the *PDCI* values were below 90, the *PCI* values were above 95. These sections may miss the key appropriate maintenance opportunity if the *PCI* model is used to evaluate pavement distress condition. Five

**Table 5.** Statistics of Actual Pavement Distress Condition of Five Sections.

| Section Number | *PCI* | *PDCI* | Transverse Cracking Condition | | | Patching Condition | | | Surface Distress Condition | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Amount | Average Length | *TCEI* | Amount | Average Area | *PPCI* | Amount | Average Area | *PSCI* |
| 1 | 97.3 | 87.8 | 12 | 3.0 | 80.0 | 0 | 0.0 | 100 | 0 | 0 | 100 |
| 2 | 96.7 | 89.2 | 7 | 4.0 | 85.0 | 1 | 4.0 | 93.7 | 0 | 0 | 100 |
| 3 | 97.2 | 89.1 | 10 | 3.3 | 82.0 | 0 | 0.0 | 100 | 0 | 0 | 100 |
| 4 | 97.4 | 89.0 | 10 | 2.7 | 85.5 | 0 | 0.0 | 100 | 0 | 0 | 100 |
| 5 | 97.1 | 88.0 | 14 | 2.6 | 80.6 | 0 | 0.0 | 100 | 0 | 0 | 100 |

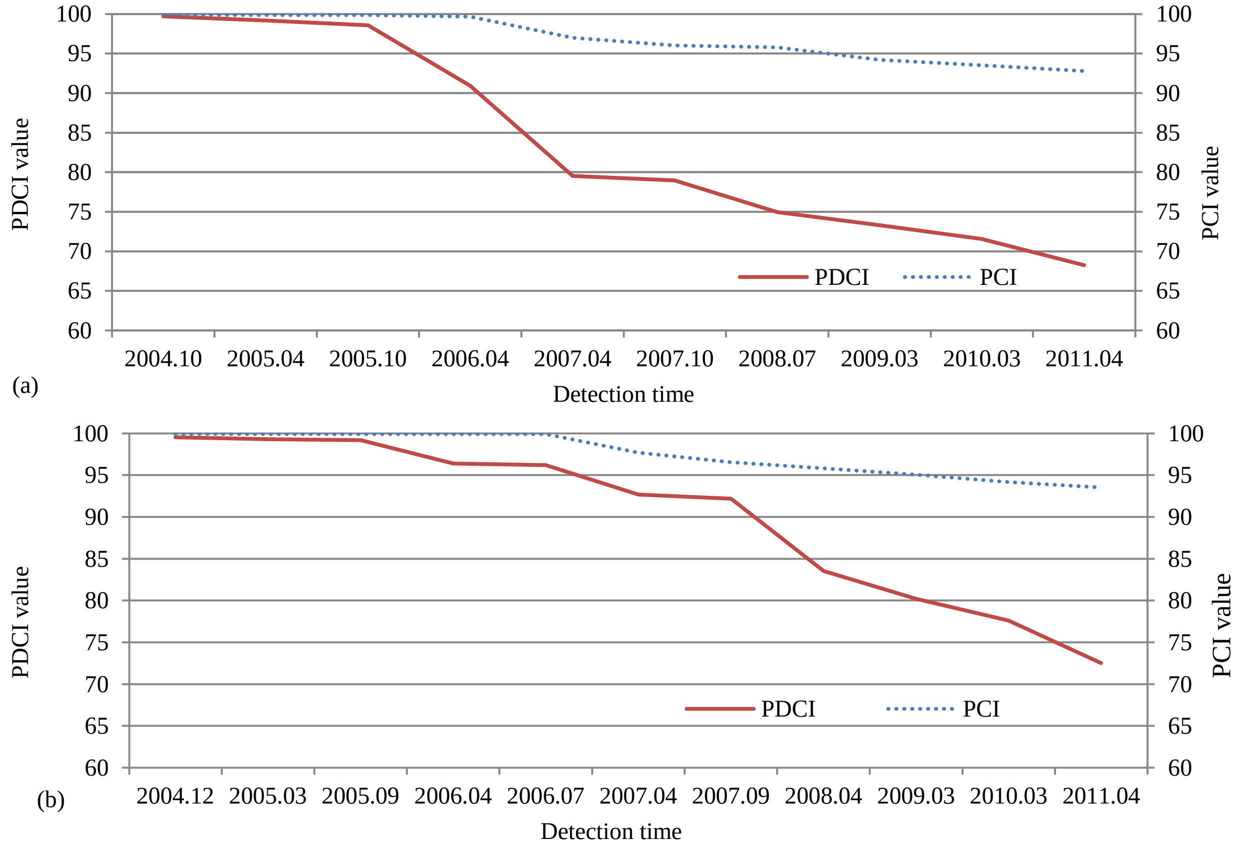


**Fig. 4.** (b) Development Trend of Pavement Distress Condition along (a) South Bound and (b) North Bound Direction over Time

pavement sections with *PDCI* lower than 90 and *PCI* higher than 95 were chosen for further analysis, and these sections are K2097-K2098, K2101-K2102, and K2119-K2120 in the east bound direction, and K2101-K210 and K2118-K2119 in the west bound direction. These five sections were named section 1, section 2, section 3, section 4, and section 5, respectively. Table 5 summarizes the statistics of the actual pavement distress condition of the five sections.

As shown in Table 5, the transverse cracking conditions of the five sections are serious with the TCEI around 80, which means the appropriate maintenance method should be taken to prevent further deterioration. The *PDCI* values are all less than 90, indicating that the overall distress condition is not bad. However, the *PCI* values are all more than 95 meaning the pavement is in good condition. The reason for the difference between *PDCI* and *PCI* is that the transverse cracking condition is serious, but other types of pavement distress were rare. Compared to *PDCI*, *PCI* is much more general and it reduces the importance of transverse cracking by mixing it with other pavement distresses. In conclusion, it is more reasonable to evaluate the asphalt pavement distress condition based on *PDCI* instead of *PCI*.

### *Application of PDCI on Evaluating Pavement Distress Condition of Fen Guan Freeway*

The pavement section chosen from Fen Guan freeway has never been maintained except for routine maintenance, like filling the cracks, since it opened to traffic. Therefore, by evaluating the historical condition of pavement distresses from 2004 to 2011, the distress development trend can be obtained by the *PCI* model and *PDCI* model respectively, as shown in Fig. 4.

Fig. 4 shows that when using the *PCI* model to evaluate the pavement distress condition, the *PCI* value dropped from 100 to 95 from December 2004 to April 2011. The *PCI* changed in eight years, and it could not capture the development of the pavement distress development trend. However, the *PDCI* value dropped from 100 to 70, which clearly reflected the development of pavement distress.

Taking the actual distress condition of Fen Guan freeway into consideration, the *TCEI* of the section in the south-bound direction in April 2011 is 51.1, while the *TCEI* in the north direction is 58.4. Thus, the transverse cracking conditions in both directions are very serious, and the section is in urgent need of specific maintenance. Correspondingly, the *PDCI* is below 75, indicating a moderate pavement distress condition. However, the *PCI* is around 95 which means the condition is excellent, and the *PCI* is unable to reflect the serious transverse crack condition. Thus, it can be seen that the *PDCI* model is more appropriate and reasonable than the *PCI* model in the pavement distress evaluation system for the Chinese freeways.

## Conclusions

The primary objective of this study is to establish an effective method to evaluate asphalt pavement distresses on Chinese freeways. Based on the current situation of asphalt freeway pavements and existing research in China, a scientific pavement distress condition evaluation method has been developed. The evaluation method is established based on three single evaluation indexes and one general evaluation index. The single evaluation indexes are the *TCEI*, *PPCI*, and *PSCI*. The general evaluation index *PDCI* enables a comprehensive description of the pavement damage condition in asphalt pavements.

Based on the analysis of pavement distress condition on Jiangsu freeways in 2011, the three single evaluation indexes were proposed to evaluate different situations of pavements. The feasibility of the three single indexes was also validated by the data from other freeways in Jiangsu province. The three single indexes are adoptable to reflect the different pavement conditions of freeways accurately.

AHP was used to develop the general evaluation index, *PDCI*, which is composed of three single indexes (*TCEI*, *PPCI* and *PSCI*). The validity of this index was proved by the data obtained from Ning Hang freeway and Fen Guan freeway in Jiangsu. The results indicated that the *PDCI* model is better, more appropriate and reasonable than the PCI model for Chinese pavement management purposes.

In summary, the establishment of a pavement distress condition evaluation model is valuable for the pavement maintenance decisions. This paper provides a very potential model for asphalt freeway pavement distresses research.

## Acknowledgements

The authors would like to thank the managers of Jing Hu Freeway Company, Ning Hang Freeway Company, and Fen Guan Freeway Company in Jiangsu Province for providing with the detection data of pavement distresses.

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