Int J Syst Assur Eng Manag (April 2022) 13(2):832–843
https://doi.org/10.1007/s13198-021-01344-z

ORIGINAL ARTICLE

Development of overall pavement condition index for maintenance strategy selection for Indian highways

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Received: 21 December 2020 / Revised: 1 June 2021 / Accepted: 30 August 2021 / Published online: 9 September 2021

Abstract Punctually and appropriate maintenance of pavement black top surface using suitable material and method is significant for the preservation of road assets and to serve the intended purpose. An adequate maintenance management system that would be useful to highway agencies in regularly planning pavement maintenance strategies to ensure the minimal maintenance fund is used rationally. The target of this paper is to develop a hypothetic overall pavement condition index (OPCI) for the maintenance strategy selection for Indian Highways, exclusively for flexible pavements. This index incorporates salient indicators as distress, structural capacity, roughness and skid resistance. The distress index has been computed considering the maximum allowable extent principle. Multiplicative Index Approach was applied to develop OPCI. An expert opinion survey was conducted to evaluate the weightage for each indicator using the relative impact on pavement condition. The results reveal that the weight factor is 0.6 for structure capacity, 0.5 for roughness and 0.15 for skid resistance which is lower than the distress weight factor. The relative importance that should be given to each indicator are calculated to be 80% for distresses, 10% for structural capacity, 8% for roughness and 2% for skid resistance. The combined distress pavement condition index infests in almost one higher rating scale than PCI whereas OPCI is 21% lower than the PCI. This indicates the requirement of a conservative maintenance alternative. However, a condition indicator that consists of multiple indices is much more important in identifying suitable maintenance alternative approaches to fully restore the structural integrity and riding quality of the pavement.

Keywords Flexible pavement · OPCI · PCI · Expert opinion · Weight factor · Maintenance strategy

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1 Introduction

A well developed and maintained road transport sector functions as a catalyst in evolving the country's status. The construction and maintenance of roads have become a gigantic task for road engineers, with the ever-increasing demand for road transport. The existing road network has fallen greatly short of the required capacity and adequacy. To meet the demands, overstraining the existing infrastructure and the vehicle fleet, is followed and the result is a higher transportation cost. It is of great concern to note that, the large network established at huge cost is showing signs of accelerated deterioration. This happening may be due to (i) unexpected rise in traffic and higher loads than permissible, and (ii) shortfall in funds for construction and maintenance of roads. Because of the fund's constraints and the need for judicious spending of available resources, the maintenance planning and budgeting are required to be done based on scientific methods.

Pavement Management is a systematic process for maintaining, upgrading and cost-effectively operating physical pavement assets. Nonetheless, since a single pavement condition index does not reflect the pavement condition of different types of roads. For this reason, each road management agency must create its own pavement condition index to determine the road conditions. The degree, to which the pavement serves its function, or its efficiency, must be quantified. Such quantification may be rendered concerning the conditions of distress that the pavement experiences at any time after construction.

Evaluation of paving quality or pavement efficiency seems to be a significant factor in the construction, restoration and management of pavements. Once, the pavement evaluation process is completed then it is easy to reveal the maintenance and rehabilitation (M&R) strategy. The M&R action is one of the most important cost-effective parameters in the Pavement Management System (PMS) (Mubaraki 2014). Pavement evaluation is governed by various parameters or measures which is termed as condition indicators. The structural and functional properties of pavement are explained through these indicators. Pavement performance is described as a pavement's ability to serve traffic satisfactorily over time (AASHTO 2012). Structural performance, safety and functional performance are accepted measures of pavement performance. Structural performance is directly related to the load-bearing capacity and defective physical issues whereas functional performance is linked to comfort. It is evaluated in terms of pavement surface roughness or quality of the ride. The safety performance is generally described in terms of the pavement's frictional properties. Since functional performance and structural performance are related, therefore it is difficult to segregate the cause of distresses (Haas and Hudson 2015). For example, rough roads would generate high dynamic loads that could lead to structural distresses. Roughness leads to increases in vehicle operating cost, user delays, accidents and user dissatisfaction since friction loss leads to an increase in wet weather accidents. Therefore, there is a need of single indicator that incorporates the effect of all the performance measures to decide long term cost-effective and durable maintenance strategy (Huang 2008).

Several methods and strategies for evaluating paving efficiency have been introduced. The present serviceability index (PSI) was developed based on the AASHO road test data and expressed on a scale from 0–5 (Desolminihac et al. 1986). PSI is a function of slope variance, rut depth, cracking and patching. It's the first technique used to assess pavement performance subjectively. The International Roughness Index (IRI) was developed by the World Bank to measure the pavement roughness (Sayers et al. 1986). IRI provides a ride quality classification in term of longitudinal profile, traveled by a wheel path. Pavement roughness is directly linked to ride quality, comfort and safety because it is one of the causes of load loss accident (Burns 1981). After few years, the US Army Corps of Engineers has invented the Pavement Condition Index (PCI) to evaluate pavement condition and their performance as a quantitative measure and produce an output in a range of 0–100 (Shahin and Walther 1990). The PCI is an objective-type method for visually evaluating pavements, which considers the extent and severity of the defects (distress) found in a particular study site (Pinatt et al. 2020).

Other methods and approaches are revealed as performance monitoring approaches, which are termed as pavement condition rating (PCR) and Pavement Quality Index (PQI) and reveal their output in a range of 0–100 and 0–10. IRC: 82–2015 method is a direct rating system which does not consider the severity index of the distresses in evaluation (IRC:82 2015). This classifies pavement condition only into Good, Fair and Poor. It admires the engineering judgment process for distress data collection and measurements. However, for a project having scarce resource and fund such method can be adopted (Sinha et al. 2020). An index, called unified pavement distress index (UPDI) used to measure the pavement distress condition. The model uses the theory of fuzzy sets to process the information obtained from a typical pavement condition survey (Juang and Amirkhanian 1992). Pavement Performance Index (PPI) was developed by using distress parameters of rural roads. Opinions of highly experienced industrial experts were taken through questionnaire survey regarding weightage for severity of each parameter causing distress of the pavement. PPI reported as easy for field engineers and will be useful to decide priority list of rural roads for repair and maintenance schedule (Tawalare and Vasudeva Raju 2016).

Shiyab (2007) established a performance index that integrates main condition indicators such as surface defects, skid resistance, deflection and roughness (Shiyab 2007). The weightage for each pavement indicator is also evaluated considering the relative impact on pavement condition. The study confirmed that deterioration and performance of the pavement condition can best be predicted and evaluated based on four main indicators of the condition. Six different types of pavement indicators are used and results are compared using pavement distress and ride quality obtained from the Texas Department of Transportation. The result obtained from these indicators are discussed and a level of agreement is decided (Gharaibeh et al. 2010). Shah et al. (2013) developed a combined OPCI for urban roads network based on four performance indices. The proposed index is a good indication of the condition and performance of the pavement for the decision of maintenance strategy (Shah et al. 2013). The pavement condition is also evaluated using the fuzzy inference system. The densities of different types of pavement distresses are considered as input value whereas PCI is selected as output of the fuzzy model for the evaluation of pavement serviceability and the maintenance strategy is selected using PCI (Al-Haddad and Al-Haydari 2018). A research develops a comprehensive condition-rating model that incorporates a wide range of possible factors (effect of climate, traffic, and operational) impacting flexible-pavement performance. The condition of the pavement was assessed using multi-attribute utility theory (Abu-Samra et al. 2017). Road pavement condition index was developed using both IRI and distress to improve estimation of pavement condition. A total of nine parameters were taken including potholes, crack, rutting, patching, raveling, overall condition, drainage, bleeding and shoulder condition. The Pavement Condition Index showed very reliable and yields correct results compared to those using single parameter (Ndume et al. 2020). US Corps of Engineers method is used throughout the world for computation of PCI which incorporates all the possible distress (defects) that appear on the pavement surface (Shahin 2009).

Keeping highways pavement in satisfactory condition is a major challenge that the road construction and maintenance agency strive to overcome. In order to speed up and prioritize investments in pavement recovery, it is necessary to quantify defects and asses condition in certain interval of time. Prevailing pavement condition rating system are developed either using single indicator (mainly surface distresses) or couple of indicators (e.g., surface distresses and riding quality). Facilities to apply calibration or correction to the system for local levels are unavailable. Therefore, there is a need for development of pavement condition rating system based on the structural and functional performance of all the categories of roads under varying climatic, traffic and environmental conditions. Also, a need of rating system that can capture said drawback. Utilizing such an index in the PMS may create good systems that lead to scientifically planning and judicious allocation of maintenance funds.

The novel work of this paper is to develop a hypothetic OPCI for the maintenance strategy of Indian Highways. It is based on the maximum allowable extent of distress in a particular level of severity as well as weight factor assigned to all four indicators like distresses, structural, roughness and skid resistance. The pavement condition indicators weight factors were developed considering the practical experiences of the expert panel engineering judgment and pavement maintenance and rehabilitation (M&R) specialist. This mathematical formulation of OPCI will enable us to compute quickly and precisely. It will be useful for pavement engineers to track road performance in service, coordinate M&R work and maintain roads that deteriorate according to their needs (Suman and Sinha 2012).

2 Overall pavement condition index (OPCI)

A reliable pavement performance indicator is a need for highway engineers in the development of an efficient PMS which can predict the rate of deterioration (Kameyama et al. 1998). Many researchers have carried out their study for the development of a serviceability index that can manage the road network in a systematic way (Shiyab 2007). It is expected that this OPCI will show a good representation of pavement surface conditions and also able to produce future pavement performance accurately. Also, the process of optimizing the cost of the life cycle in the selected M&R option will be enhanced by using the acceptance levels of the four condition indicators indices mentioned above. Using such an index in PMS will generate better systems which would lead to further road maintenance funds savings and improve the road network's ability to provide better network service (Suman and Sanjeev 2012). It is also generally understood today that if the PMS is unable to schedule the M&R works over a planning cycle of several years, the full benefits of the PMS cannot be completely achieved (Butt et al. 1987; Fwa et al. 1990).

As per ATM D 6433, PCI (0–100 scale) is equal to hundred minus deduct value (ASTM D6433 2011). Where 100 represent a road in excellent condition and 0 represents a road in poor condition. Deduct value represent the amount of damage caused by the defects present at the time of observation and it is a function of their density, severity and weight. Distresses are of two dimensions namely severity and density. An effort has been made to convert all distress types into distress scores on scale 0–100. In addition, an effort has been made with single dimension parameters to convert the results of the roughness, skid resistance and structural evaluation into scores on scale 0–100. A linear conversion is used between distress deduct value and density value with each severity level. First individual indicator is calculated with assigning appropriate weights and finally aggregated all indicators to obtain a single index on a scale 0–100. Individual indices namely Combined distress pavement condition index ($CDPCI_{distress}$), pavement condition structural capacity index ($PCI_{structure}$), pavement condition roughness index ($PCI_{roughness}$) and pavement condition skid resistance index (PCI_{skid}) are first calculated, afterward they are multiplied to yield one single index. The Multiplicative Index Approach (MIAP) reveals the general form of OPCI as indicated in Eq. (1).

$$\mathrm{OPCI} = 100 * \left[\prod_{i=1}^{n}\left\{1 - \left(1 - \frac{\mathrm{PCI_i}}{100}\right) * \mathrm{W_i}\right\}\right] \quad (1)$$

where OPCI is varied in the range of 0 to 100, PCI_i is the pavement condition index corresponding to i^{th} indicators (0 to 100 scales), W_i is the weightage or impact factor for various types of distresses or condition indicator (0 to 1) and n is the number of distresses or condition indicators.

Equation (1) is developed considering the deduction scale, which would reveal that an index score of 100 means perfect pavement. The deduct values for each distress are increasing as distress accumulates. Therefore, this process will reduce the value of the pavement performance index. The Eq. (1) is known to be the general method dealing with condition indicator irrespective of the dimension.

2.1 Maximum allowable Extent (MAE)

The two-dimensional distress is converted into a pavement distress index using the MAE. The severity level and density or extents are expressed as the two dimensions of each distress. The MAE for low, medium and high severity levels for each type of distress has been taken from the Indian code of practice and guidelines for highways maintenance (IRC:82 2015; MoRTH 2018). CDPCI is formulated using the severity level and MAE.

2.2 Weight factor

The pavement distresses weight factor is assessed in terms of severity and their frequency of occurrence. The severity is categorized as not severe, severe and very severe whereas the frequency of distresses is considered as frequent, occasional, rare or none. Frequency categories are expressed as the percentage of a region that is affected by specific distress within the unit section area being surveyed. For each combination of severity and distress, the rating is assigned from 0 to 9, as shown in Table 1 where zero represents the excellent performance and 9 represents the worst performance of the pavement. Table 1 is used for computation of weight factor when responses taken from the expert opinion corresponding to distresses appeared on the particular stage.

Table 1 Rating factor

Frequency	Severity		
	Not severe	Severe	Very severe
None	0	0	0
Rare	1	2	3
Occasional	2	4	6
Frequent	3	6	9

The weightage of pavement indicators or distresses are determined considering both the engineering judgment and the expert's field experience and the pavement assessment specialist. For this purpose, questionnaire form was designed and circulated among the fifty experts to give their responses. This consist of two sets of questions where first set include questions relevant to weight of distress types and second set include questions relevant to relative importance of pavement performance parameters.

Fist set of questionnaire form comprises of questions related to all possible distress types. In this study, ten different types of pavement distresses are considered which are frequently observed in the field (IRC:82 2015). The responses of distress occurrence and severity level are collected in terms of rating numbers as mentioned in Table 1. Expert responses were collected and compiled in terms of percentage against rating numbers. Table 2 shows summaries of the data and calculated value of weight (0–1 scale) using weighted average method for distress types.

Second set of questionnaire form comprise questions related to pavement performance parameters like structural capacity, roughness and skid resistance. Questions were asked in terms of their importance regarding how much they are important in selecting maintenance and rehabilitation. Responses were collected in five-point rating scale (9, 7, 5, 3, 0) where 9 represent highly important followed by 0 represent can't say. Similarly, weight is calculated using weighted average method as shown in Table 2 and finally placed in Table 3.

Table 3 shows all distress types with severity level as low (L), medium (M), & high (H) that are observed in the flexible pavement of highways along with MAE and weight factor. MAE value is indicated corresponding to the severity level of the particular distress types. MAE value can be perceived in the order of left to right corresponding to the order of severity levels. It is found that MAE value is maximum against low severity and minimum against high severity for all distress types. It means particular distress with low severity occurrence is dominant. Comparison of MAE value reported by Shiyab (2007) and MoRTH (2018) shows significant difference. Shiyab (2007) determined the value of MAE for Dubai emirates whereas this paper presents the MAE value for Indian condition. This difference in MAE may be due to the environment conditions, material characteristics and designed standard. In addition, Dubai is located in an arid desert area whereas India is situated in the humid sub-tropical region.

The comparison of weight factor has been shown between the Dubai Emirates and Indian context. The weight factor is calculated using a weighted average of rating responded by fifty numbers of experts as indicated in

Table 2 Calculation of weight factor

Distress types	Frequency of responses in percentage							Weight factor = Product sum ÷ 100 (0–10 scale)	Weight factor (0–1 scale)
Rating →	9	6	4	3	2	1	0		
Alligator Cracking	96	4						8.88	0.888 ≈ 0.9
Rutting	94	6						8.82	0.882 ≈ 0.9
Longitudinal Cracking	50	26	24					7.02	0.702 ≈ 0.7
Transverse Cracking	46	34	20					6.98	0.698 ≈ 0.7
Patching	16	26	34	24				5.08	0.508 ≈ 0.5
Raveling		8	44	16	14	18		3.18	0.318 ≈ 0.3
Potholes	12	34	28	26				5.02	0.502 ≈ 0.5
Bleeding			14	16	42	16	12	2.04	0.204 ≈ 0.2
Settlement, Depression			20	16	34	16	14	2.12	0.212 ≈ 0.2
Shoving				14	20	28	38	1.1	0.11 ≈ 0.1
$\sum$									5.0
Rating →	9	7	5	3	0	–	–		
Structural Capacity	18	22	54	6				6.04	0.604 ≈ 0.6
Roughness	8	32	36	14	10			5.18	0.518 ≈ 0.5
Skid Resistance			14	28	58			1.54	0.154 ≈ 0.15
$\sum$									1.25

Blank cell represent data has not been found

Table 3 MAE and Weight factor for flexible pavement distresses

Distress Type/ Condition Indicator	Severity levels	MAE (%)		Weight factor (w_i)	
		Shiyab (2007)	MoRTH (2018)	Shiyab (2007)	Expert
Alligator Cracking	L, M, H	50,25,15	30,21,8	1	0.9
Rutting	L, M, H	30,15,10	50,26,8	1	0.9
Longitudinal cracking	L, M, H	25,20,10	30,21,8	0.3	0.7
Transverse cracking	L, M, H	25,20,10	30,21,8	0.3	0.7
Patching	L, M, H	50,15,10	30,17,4	0.65	0.5
Raveling	L, M, H	100,50,20	30,14,3	0.4	0.3
Potholes	L, M, H	1,1,0.5	1,1,0.5	0.1	0.5
Bleeding	L, M, H	100,70,70	5,3,1	0.4	0.2
Settlement &Depression	L, M, H	40,20,10	5,3,1	0.4	0.2
Shoving	L, M, H	20,15,5	1,1,0.1	0.1	0.1
Structural capacity index	—			0.75	0.6
Roughness index	—			0.50	0.5
Skid resistance index	—			0.25	0.15

L: Low, M: Medium, H: High

Table 3. The weightage of distresses is not required to sum to a value of 1. The calculated weight factor for each condition indicator is different from Shiyab (2007) studies since expert's responses and their willingness varies person to person. Highest and lowest weight factor is assigned by the experts based on the appearance of distresses. Alligator cracking and rutting are observed as the highest weight factors whereas raveling, bleeding, settlement & depression and shoving are expressed as the lowest weight factors according to expert responses.

Relative importance for distress, structural capacity, roughness and skid resistance are calculated using their weight factor by method of proportions. Sum of weight for all distress and other performance parameter is 5.0 and 1.25 respectively as shown in Table 2. Overall sum of weight become 6.25 for all the parameters. Therefore, relative weight of distress = (5.0/6.25) X 100 = 80%. Similarly, relative weight of others is calculated as values reported herewith of structural capacity = 10%, roughness = 8% and skid resistance = 2%. It means distress measurement and evaluation is highly important against selection of M&R. Where skid resistance shows less importance and others fall in between. However, all defects are almost interrelated to each other so can't neglect even though have less importance.

3 Combined distress pavement condition index ($CDPCI_{distress}$)

The first step towards the planning of maintenance operations is the evaluation of the existing pavement surface in terms of its physical condition i.e. distress. The pavement condition distress index is computed by using Eq. (2) that depends upon the individual distress index (IDI_j) and their weight factor (W_j).

$$CDPCI_{distress} = 100*\left[\prod_{j=1}^{m}\left\{1-\left(1-\frac{IDI_j}{100}\right)*W_j\right\}\right]. \quad (2)$$

For this purpose, pavement condition surveys are undertaken by the visual assessment of the surface by identifying type, extent and severity of the distress. The familiar types of distress are reported in Table 3 (MoRTH 2018). Among which alligator cracking, rutting, patching, raveling, bleeding, depression and shoving are measured in square meter or square feet of surface area. Whereas longitudinal and transverse cracking is measured in linear meter or feet of surface area but pothole is measured by counting the number. Therefore, the multidimensional distress types are converted into a unified dimension called density represented in percentage. The density of respective distresses (area measurement, linear measurement and counting in numbers) is computed in percentage using Eq. (3–5) respectively.

Severity levels (low, medium and high) of individual distress are identified as per laid standard guidelines (ASTM D6433 2011; IRC:82 2015). A particular distress index is computed using the relevant relationship from Eqs. (6) to (15). These relationships are the function of deduct value, MAE and percentage of respective distress extent in low severity (PEL), in medium severity (PEM) and in high severity (PEH). The threshold index value for all distresses has taken 60 to indicate that the pavement needs repair (Shah et al. 2013). Hence deduct value becomes 40 as considered in all distress index equations. The denominators of all small brackets are the MAE for each severity. In other words, for example, 30% of low severity, 21% of medium severity and 8% of high severity for alligator cracking is allowed and mathematically it is expresses as mentioned in Eq. (6). Similarly, other individual distress index is also formulated (as shown in Eq. (7–15)) using the maximum allowable extent as mentioned in Table 3.

Aigator cracking Index (ACI)

$$A = 100 - 40\left[\left(\frac{PEL}{30}\right) + \left(\frac{PEM}{21}\right) + \left(\frac{PEH}{8}\right)\right] \quad (6)$$

Rut Index (RI)

$$RI = 100 - 40\left[\left(\frac{PEL}{50}\right) + \left(\frac{PEM}{26}\right) + \left(\frac{PEH}{8}\right)\right] \quad (7)$$

Longitudinal cracking Index (LCI)

$$LCI = 100 - 40\left[\left(\frac{PEL}{30}\right) + \left(\frac{PEM}{21}\right) + \left(\frac{PEH}{8}\right)\right] \quad (8)$$

Transverse cracking Index (TCI)

$$TCI = 100 - 40\left[\left(\frac{PEL}{30}\right) + \left(\frac{PEM}{21}\right) + \left(\frac{PEH}{8}\right)\right] \quad (9)$$

Patching Index (PI)

$$PI = 100 - 40\left[\left(\frac{PEL}{30}\right) + \left(\frac{PEM}{17}\right) + \left(\frac{PEH}{4}\right)\right] \quad (10)$$

$$Density_{am}(\%) = \frac{\text{distressed area per defect in } m^2 \text{or feet}^2}{\text{road section length}(\text{m or feet}) \text{ x average width}(\text{m or feet})} x100. \quad (3)$$

$$Density_{lm}(\%) = \frac{\text{amount of defect in m or feet}}{\text{road section length}(\text{m or feet}) \text{ x average width}(\text{m or feet})} x100. \quad (4)$$

$$Density_{nm}(\%) = \frac{\text{Number of potholes of same diameter and depth}}{\text{road section length}(\text{m or feet}) \text{ x average width}(\text{m or feet})} x100 \quad (5)$$

4 Raveling Index (RAI)

$$RAI = 100 - 40\left[\left(\frac{PEL}{30}\right) + \left(\frac{PEM}{14}\right) + \left(\frac{PEH}{3}\right)\right] \quad (11)$$

Pothole Index (PHI)

$$PHI = 100 - 40\left[\left(\frac{PEL}{1}\right) + \left(\frac{PEM}{1}\right) + \left(\frac{PEH}{0.5}\right)\right] \quad (12)$$

Bleeding Index (BI)

$$BI = 100 - 40\left[\left(\frac{PEL}{5}\right) + \left(\frac{PEM}{3}\right) + \left(\frac{PEH}{1}\right)\right] \quad (13)$$

Depression & Settlement Index (DSI)

$$DSI = 100 - 40\left[\left(\frac{PEL}{5}\right) + \left(\frac{PEM}{3}\right) + \left(\frac{PEH}{1}\right)\right] \quad (14)$$

Shoving Index (SI)

$$SI = 100 - 40\left[\left(\frac{PEL}{1}\right) + \left(\frac{PEM}{1}\right) + \left(\frac{PEH}{0.1}\right)\right] \quad (15)$$

The multiplicative index approach (MIA) is used to combined the distress types, severity and extents in a single index. The individual distress indices are combined together using MIA to formulate the CDPCI.

4.1 *Pavement condition structural capacity Index ($PCI_{structure}$)*

Structural evaluation is assessed by using non-destructive testing, which is desirable in most cases. The structural condition index (Eq. (16)) is developed using the structural number which reveals the pavement layer strength and load-carrying capacity.

$$PCI_{structure} = 100*\left[\left\{1 - \left(1 - \frac{SN_{eff}}{SN_o}\right)*w_{str}\right\}\right] \quad (16)$$

where SN_{eff} is the effective structural number, SN_o is the required structural number of a newly-constructed pavement and w_{str} is the weight factor as shown in Table 3.

The effective pavement structural number is calculated using Eq. (17) or Eq. (18) based on their availability of equipment. An established correlation between effective structural number and deflection (mm) measurement by Benkelman Beam equipment is indicated in Eq. (17) (Reddy 2001). Otherwise, Eq. (18) (AASHTO 2012) can be used for effective structural number determination which depends on the total pavement thickness (D) in inch above the subgrade and effective modulus (E_P) of pavement layers above the subgrade in psi, measured using Falling Weight Deflectometer (FWD) (Setyawan et al. 2015).

$$SN_{eff} = 3.2*def - 0.63 \quad (17)$$

$$SN_{eff} = 0.0045 * D * E_p^{1/3} \quad (18)$$

$$SN_o = 0.0394*\sum_{k=1}^{NL} a_k d_k m_k + MSN \quad (19)$$

$$MSN = 3.57\log_{10} CBR - 0.85(\log_{10} CBR)^2 - 1.43 \quad (20)$$

Equation (20) is applicable for CBR $\geq 3\%$, otherwise zero.

The required structural number (SN_o) is calculated using Eq. (19) and Eq. (20). Where a_k is the strength coefficient of a layer k, d_k is the thickness of a layer k in mm m_k is the drainage coefficient of a layer k, MSN is the modified structural number depends on CBR value (MoRTH, 2018). Strength coefficients of layers DBM (Dense Bituminous Macadam), SDBC (Semi Dense Bituminous Concrete), WMM (Wet Mix Macadam) and GSB (Granular Sub Base) are 0.28.0.25, 0.14 and 0.11respectively taken for computation in comparison section. Drainage coefficient was taken for base and sub base layer equal to 1 (MoRTH, 2018).

4.2 *Pavement condition roughness index ($PCI_{roughness}$)*

Many research works have shown that the scale of IRI is strongly correlated with the PCI scale since both measures are based on the perception of vehicle riding and the response of different vehicle performance modes. A highly correlated relationship between PCI and the IRI measurements was found to take the following forms (Shiyab 2007) as shown in Eq. (21) and Eq. (22). IRI can be expressed either in mm/m or m/km.

$$PCI_{roughness} = 0.6*IRI^2 - 15.2*IRI + 100 \quad (21)$$

$$PCI_{roughness} = 100*e^{-0.518*IRI} \quad (22)$$

4.3 *Pavement condition skid resistance index (PCI_{skid})*

The skid resistance index is used separately in PMS or in combination with other pavement condition indicators if necessary, to notify pavement condition. Many tools are available through which Skid resistance numbers can be measured physically. The structural number is included in the pavement performance index to reveal the surface skidding impact (Meegoda and Gao 2014). The pendulum skid tester is used to determine the skid resistance on a scale of 0–100 from the field. Pavement condition due to skid resistance is determined by using Eq. (23).

$$PCI_{skid} = 100*\left[\left\{1 - \left(1 - \frac{SKN_{eff}}{SKN_o}\right)*w_{skid}\right\}\right] \quad (23)$$

where, SKN_o is the maximum allowable skid number corresponding to good condition (IRC:82 2015) equal to 65, SKN_{eff} is the effective skid number measured on the in-service pavement and w_{skid} is the weight factor for skid resistance specified in Table 3.

The multiplicative index approach is used to formulate the OPCI using the various pavement indicators and their weight factor. Individual distress indices are obtained using the Eq. (6) to Eq. (15) and multiplied them with weight factor as shown in Table 3. Similarly, structural capacity index, roughness index and skid resistance index are calculated as mention from Eq. (21) to Eq. (23). Using MIA, each pavement indicator is integrated to create a single index known as OPCI. The mathematical expression for OPCI is illustrated through Eq. (24).

5 Comparison between PCI, CDPCI and OPCI

A total of 100 sections of highways pavement were used for the determination of pavement conditions for the comparison point of view. Each section consists of 100 m length and 7 m width of two-lane highways. This highway was plying 2000–2500 commercial vehicles per day. The cross section of the highway pavement is shown in Fig. 1. The top layer of flexible pavement is the wearing course of 25 mm semi dense bituminous concrete and binder course of 60 mm dense bituminous macadam. The base course is constructed with 250 mm wet mix macadam and followed by the subbase course of 335 mm thick granular sub base. The bottom layer is the subgrade layer which is the compacted soil of thickness 500 mm. The pavement layers and their thickness are mentioned in the Fig. 1.

The visual condition survey method is used for distress measurement. The pavement distresses and their severity

$$\begin{aligned} OPCI = 100*\Bigg[&\left\{1-\left(1-\frac{ACI}{100}\right)*0.9\right\}*\left\{1-\left(1-\frac{RI}{100}\right)*0.9\right\}*\left\{1-\left(1-\frac{LCI}{100}\right)*0.7\right\}*\left\{1-\left(1-\frac{TCI}{100}\right)*0.7\right\}*\\ &\left\{1-\left(1-\frac{PI}{100}\right)*0.5\right\}*\left\{1-\left(1-\frac{RAI}{100}\right)*0.3\right\}*\left\{1-\left(1-\frac{PHI}{100}\right)*0.5\right\}*\left\{1-\left(1-\frac{BI}{100}\right)*0.2\right\}*\\ &\left\{1-\left(1-\frac{DSI}{100}\right)*0.2\right\}*\left\{1-\left(1-\frac{SI}{100}\right)*0.1\right\}*\left\{1-\left(1-\frac{PCI_{str}}{100}\right)*0.6\right\}*\left\{1-\left(\frac{PCI_{rough}}{100}\right)*0.5\right\}*\\ &\left\{1-\left(1-\frac{PCI_{skid}}{100}\right)*0.15\right\}\Bigg] \end{aligned} \quad (24)$$

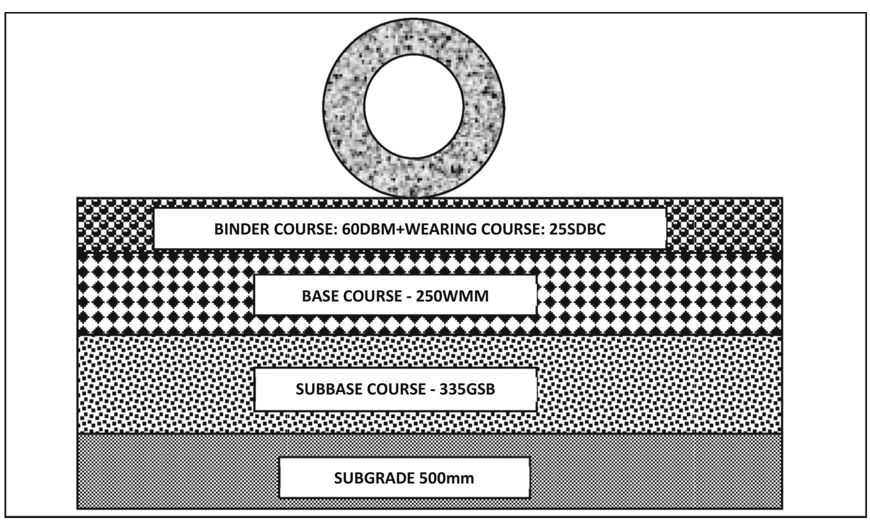

Fig. 1 Pavement cross section

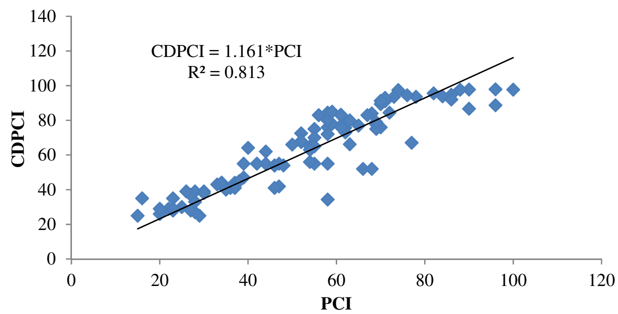

Fig. 2 CDPCI versus PCI

level are observed from the field. Similarly, structural capacity, roughness and skid resistance data are also collected from the field. The PCI value is calculated using the distress data in accordance with ASTM D 6433 guidelines. On the other hand, CDPCI is calculated using the individual distress index (as stated from Eq. (6) to Eq. (15)). The structural capacity of flexible pavement is determined using the Benkelman beam (IRC:81 1997) and also helpful in estimating the overlays for weak sections. The pavement deflection data is collected from the field using Benkelman Beam and effective structural number is calculated using the Eq. (17). The structural capacity of pavement is converted in to an index termed as $PCI_{structure}$ (as shown in Eq. (16)) based on the SN_{eff}, SN_o and $W_{structure}$. The pavement unevenness or roughness is determined using the Auto Bump Integrator (IRC:SP:16 2004) and $PCI_{roughness}$ is developed (shown in Eq. 21). British pendulum (IV) (2002) is used to calculate the skid resistance of the pavement. The PCI_{skid} is determined using the effective skid resistance and weight factor. Finally, OPCI is calculated as stated in Eq. (24). The relationship between PCI and CDPCI; PCI and OPCI are determined.

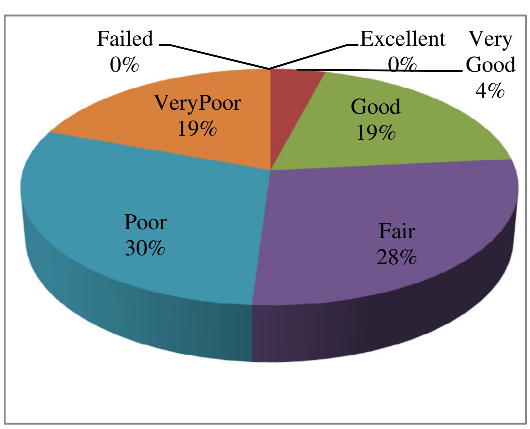

Fig. 3 Composition of pavement condition (PCI)

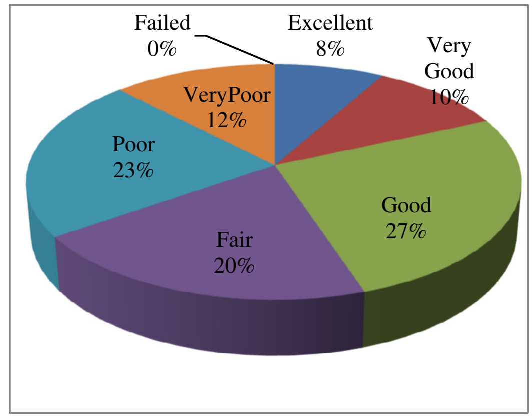

Fig. 4 Composition of pavement condition (OPCI)

5.1 Relationship between PCI and CDPCI

The PCI and CDPCI is determined as per the guidelines and their results have been compared. The relationship between PCI and OPCI has been obtained using the linear regression. The correlation of the linear regression between PCI and CDPCI is determined and shown in Fig. 2. It was carried out for selected data to know the functional relationship between the two. The graphical representation between PCI and OPCI has been done and coefficient of determination is obtained. The goodness of fit parameter such as coefficient of determination (R^2) equal to 0.813 has presented a very good correlation. It is observed that CDPCI value reveals 16% higher than the PCI value. This implies CDPCI corresponds to almost one higher side of the pavement condition state.

5.2 Relationship between OPCI and PCI

The PCI and OPCI values are calculated for 100 pavement sections and the rating system are assigned using their respective values. The composition of pavement condition based on PCI and OPCI is shown in Fig. 3 and Fig. 4 respectively. The rating of pavement sections with PCI and OPCI value has been compared and observed that OPCI

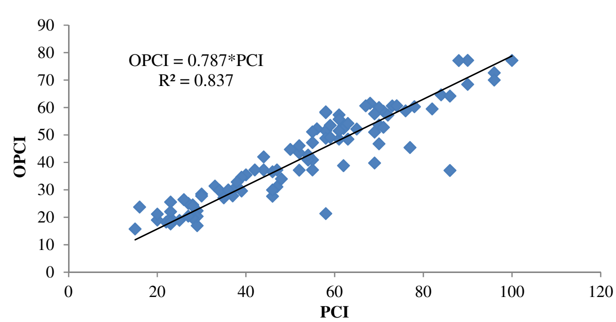

Fig. 5 PCI versus OPCI

method has presented more accurate pavement state than PCI method. The OPCI method has shown that the pavement section with excellent, very good and good rating are 8%, 10% and 27% whereas PCI has 0%, 4% and 19% respectively. From the graphical representation, it is observed that the OPCI method has lower pavement rating values compared to PCI method since OPCI method included the structural capacity, roughness and skid resistance values. It is also observed that some highways sections are in the same condition state and rest are in lower condition state.

The linear regression method has been adopted to establish a relationship among the PCI and OPCI values. Most of the pavement section are nearer to the line drawn with 45^0 angles which reflects less scatter data points. The coefficient of determination values is also used to support the relationship between these two methods. The linear regression plot has been drawn between PCI and OPCI values of various flexible pavement sections and R^2 values is also shown in Fig. 5. It is observed that the OPCI value has been obtained 21% lower than the PCI value since the structural capacity, roughness and skid resistance has been added in OPCI. The coefficient of determination is observed as 84% which reflects the good relationship between PCI and OPCI approach. It shows that the calculated OPCI provides a clear indication of the state of the pavement including both functional and structural defects.

6 Selection of maintenance strategy based on PCI and OPCI

The maintenance strategy changes with an increase in pavement age and level of pavement deterioration. At the initial stage when the pavement condition is very good the application of preventive maintenance treatments is very cost-effective. While on the other end, costly restoration would be necessary at the end of pavements design life. Five different types of M&R strategies are adopted for the maintenance which is (i) Routine Maintenance (ii) Preventive Maintenance (iii) Minor Rehabilitation (iv) Major Rehabilitation, and (v) Reconstruction. Typical pavement M & R strategies (Shahin and Walther 1990) corresponding to PCI or OPCI and rating is shown in Table 4.

Table 4 Typical pavement M&R strategies

PCI/OPCI	Rating	Strategy
85–100	Excellent	Routine Maintenance (RM)
70–85	Very Good	Preventive Maintenance (PM)
55–70	Good	Minor Rehabilitation (MIR1)
40–55	Fair	Minor Rehabilitation (MIR2)
25–40	Poor	Major Rehabilitation (MAR)
10–25	Very Poor	Reconstruction (RC1)
0–10	Failed	Reconstruction (RC2)

Range for different M&R strategies is decided based on conceptual pavement performance curve. Routine maintenance includes cleaning block drains, restoring surface drainage, maintaining rain cuts on shoulders, and correcting the cross slope of an earth shoulder. Bituminous surface dressing is also included in the routine maintenance. A curve which is plotted between pavement conditions rating over pavement age, known as pavement performance curve. Preventive maintenance has been undertaken when drop in quality of pavement surface is less than 30% as quantified by pavement condition rating criteria. Surface treatment, such as fog seal, chip seal, slurry seal, and micro-surfacing, is mostly included in preventative maintenance. By fixing the crack area and potholes, the service life or residual life of pavement is extended by one or two monsoon seasons. Fine cracks, texturing, void filling, rut filing, bleeding and minor levelling are also addressed in preventative maintenance but structural failures are not. In minor rehabilitation, the minor cross slope, pavement roughness, patching, raveling, potholes with low and moderate severity are treated thin hot-mix or cold mix bituminous overlays. Flexible base overlay is used to resist the propagation of reflective cracks from the old structure. The structural capacity of the pavement is improved using flexible base thickening. The low and medium level of

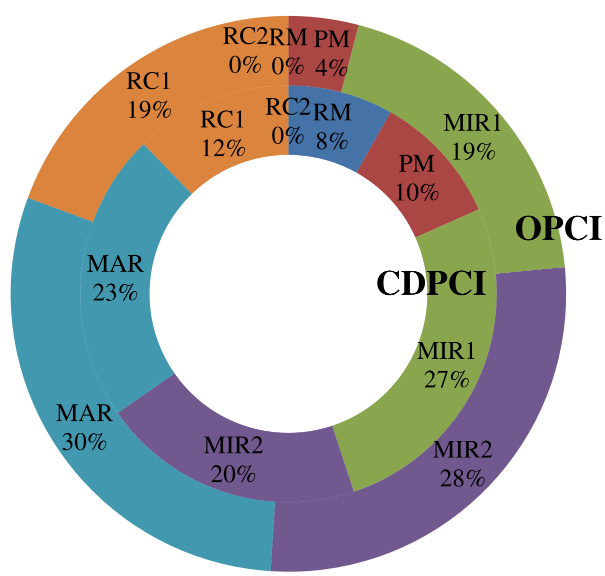

Fig. 6 Composition of maintenance strategy based on $CDPCI_{distress}$ & OPCI

structural damages are treated for low and medium volume of highways (IRC:82 2015).

For Indian Highways threshold value is taken equal to 40 (OPCI value). It means pavement surface is fully deteriorated and condition is not enough for the movement of traffic efficiently and safely. Full depth reclamation has been used to address the high level of structural damages up to 12-inch depth. The structural capacity, ride quality, weather proofing and skid resistance have been improved in the major rehabilitation. The proper strengthening of pavement has not been addressed on time which laid to deterioration in pavement layers with rapid rate and further delay in the maintenance work causes extensive damage in the various pavement layers. Hence reconstruction is carried out to restore the excellent pavement surface condition (IRC:82 2015).

The maintenance alternatives distribution is explained in Fig. 6 based on the CDPCI and OPCI for suggested pavement sections. It has been observed that 20–27% of pavement sections need minor rehabilitation while 23% needed major rehabilitation based on CDPCI. While in the case of OPCI, 19–28% of pavement sections require minor rehabilitation and 30% are in need of major rehabilitation. This comparison shows that structure strength, roughness and skid resistance of pavement have a significant effect on condition rating and thus on the selection of suitable M&R alternatives. The weak pavement strength is the reason for expensive rehabilitation type treatments for most of the sections.

7 Conclusions

Currently, available PMS across the globe is mainly focused on a single index system and major of them depends on the distress data. This paper focused on the evolution of a hypothetical OPCI for the maintenance strategy of Indian highways have black top surface. The OPCI comprehends all liable indicators. This OPCI is observed as a good performance indicator and also helpful in restoring both structural capacity and other essential functional and safety features. This index can be used individually or in conjunction with the individual condition indicator indices to report on the condition of the pavement. The weight factor for structure capacity, roughness and skid resistance have been embraced based on expert's opinion as 0.6, 0.5 and 0.15 respectively which reveals the lower weightage compare to distresses. The structural capacity has shown greater value in comparison of skid resistance and roughness in terms of weight factor; since structural characteristics have a deleterious impact on OPCI. The roughness weight factor is reduced to avoid reduplication because it is generated by several distresses also. The relative importance that should be given to each indicator are proposed to be 80% for distresses,10% for structural capacity, 8% for roughness and 2% for skid resistance. Based on the data of a hundred sections of highways, CDPCI infests in almost one higher rating scale than PCI. A comparison state that OPCI is 21% lower than the PCI. This downgrade of rating requires a high-quality maintenance alternative. However, it may be performed for a longer duration.

This amalgamated index is formulated to reflect the pavement condition and also able to predict the pavement performance accurately. Based on the developed OPCI, the selection of the M&R strategy will be easy and very supportive in the restoration of road structurally and functionally. Further research is recommended to carry out case studies to validate the overall pavement condition index approach for selection of M&R strategy.

Acknowledgements The authors declare that the contents of this article have not been published previously. All the authors have contributed to the work described, read and approved the contents for publication in this journal.

Funding This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declarations

Conflict of interest All the authors have no conflict of interest with the funding entity and any organization mentioned in this article in the past three years that may have influenced the conduct of this research and the findings.

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