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Development of a Pavement Overall Deterioration Index (Case Study: Iran)

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ABSTRACT: The main core of pavement management systems is pavement evaluation. A more sophisticated index is essential to evaluate a pavement so that authorities can optimize budget allocation for maintenance and rehabilitation activities. Several single and combined indices have been applied to assess pavement conditions in developed countries based on a comprehensive pavement condition database. However, in developing countries, the lack of an extensive pavement condition database leads to insufficient attempts on developing such an index. As a result, the budget cannot be assigned appropriately on pavement preservations. This research aims to develop a combined pavement condition index using the weighted summation of the pavement condition index, international roughness index, and central deflection of falling weight deflectometer testing device. The weights are attained through the application of the analytical hierarchy process via a questionnaire completed by a panel of experts. The data captured from the questionnaire was entered into the expert choice software. Results indicate that the central deflection as a representative of structural adequacy of pavement has the highest weight (0.491). The other indices were ranked as the second and third criteria in evaluating the pavement performance with the weights of 0.291 and 0.218, respectively, which make logical and engineering sense over the case study. The combined index would express the overall condition of pavement which could be applied in pavement maintenance planning.

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1- Introduction

Pavement management system (PMS) has been used widely to determine the current pavement conditions and to predict its future characteristics. The PMS provides road authorities with the systematic approach to manage highways cost-effectively and to propose the most appropriate maintenance and rehabilitation (M&R) treatments [1, 2]. PMSs are established on two levels, namely, the network level as well as the project level. The network-level evaluation requires less detailed data than the project-level. The network-level PMS consists of a data bank is the premier source of pavement performance evaluations and future M&R planning [3].

Pavement performance indicators play important roles in describing the characteristics of the pavements [4, 5]. Different indices are determining functional and structural performance as well as safety characteristics of the pavement [6]. Functional assessment can be performed using pavement surface attributes such as unevenness. Structural performance considers the physical deficiencies and the strength of pavement layers in bearing applied loads. One of the first indicators proposed in 1960, was the present serviceability rating (PSR) based on experts' opinions concerning pavement condition [7]. Based on the concept of PSR, the pavement serviceability index (PSI) was proposed. In 1982, one of the most important indices named pavement condition index (PCI) was developed [8]. In the 1970s, the international roughness index (IRI) was proposed to evaluate ride quality utilizing advanced and automated data collection equipment [9]. In addition to these, another pavement performance indicator named structural condition index (SCI) was derived to consider the structural attributes and to identify M&R treatments [10]. Various types of indices such as pavement condition rating (PCR), pavement condition score (PCS) [11], pavement quality index (PQI) [12], overall condition index (OCI) [13] were proposed to address the inefficiency in pavement performance evaluations [14].

Several pavement functional failures are occurred due to insufficient pavement structural attributes. While some of these failures do not result from structural issues. Therefore, consideration of both functional and structural characteristics, simultaneously, would lead to efficient analysis of the condition of pavements. This would lead to the development of a combined indicator. This indicator would yield pavement performance evaluation, maintenance planning, and life cycle cost analysis.

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2- Background

2- 1- Single Pavement Performance Index

Surface Distress

Proposed by the U.S. Army Corps of Engineers, the PCI has been used by different road agencies throughout the world [8]. The PCI is a numerical rating considering pavement distress types, extents, and severities ranging from 0 to 100. The index depends on the deduct values determined for pavement surface deteriorations based upon their types, severities, and quantities, and is calculated by subtracting those values from 100 [15].

Roughness

In the late '70s, National Cooperative Highway Research Program (NCHRP-Report 228) introduced the concept of the IRI which was then accepted as the criterion for pavement smoothness evaluation [9]. The IRI reflects the pavement roughness condition and is expressed in terms of m/km collected by the Road Surface Profiler (RSP) mounted on a special vehicle [16].

Structural Adequacy

The falling weight deflectometer (FWD) device is a Non-Destructive Testing NDT method used globally to collect accurate data regarding structural characteristics of pavements [17]. This testing device applies an impulse load to the pavement being identical to an 8.2-Ton single axle load. While loading, the sublayers' deformations in the distance of 1.8 meters from the center of the circular load plate are measured using 7 to 9 geophones. The results are useful in the estimation of structural capacity and ability of pavements to withstand the traffic load in a design period [18]. Various indicators have been proposed for structural evaluations being based on maximum deflection under the loading plate (D_0). Other parameters such as overlay thickness, effective structural number (SN_{eff}), required SN (SN_{req}), subgrade modulus (M_r) and pavement modules (E_p) can be derived using the maximum deflection (D_0) beneath the loading plate of the FWD device known as central deflection [6].

2- 2- The Relationships between Pavement Performance Indicators

Several researchers have studied the relationships between the IRI and PCI. In 2007, a study was conducted in which the IRI was used as the predictor of PCI [19]. A developed power regressing model revealed that PCI values were not projected accurately by the IRI. It was concluded that other pavement performance indicators must be considered to increase the efficiency and accuracy of the proposed model. By the means of neural network modeling, in 2011, the IRI was estimated using PCI values overwork zones [20]. The predicted IRI values were validated using MERLIN (Machine for Evaluating Roughness using Low-cost Instrumentation). According to the R-square and mean sum of square (MSE), the appropriate performance of the IRI prediction model was confirmed. Subsequently, the PCI coefficient of determination were determined with respect to the IRI [16]. As a result, different linear models were provided for freeways, arterials, collectors, and local roads, and the R-square values were 0.56, 0.71, 0.73, and 0.74, respectively. In 2015, PCI and IRI values were collected in two provinces located in the central part of Iran [21]. Using Minitab software (linear regression method), the relationships between those criteria were examined. Findings indicated that the model resulted in the direct correlation between selected indices when PCI values were 0 to 70.

Because the PCI and the IRI origins from various types of pavement deteriorations, researchers have attempted to realize their correlations concerning distresses exist on pavements. In 2003, a research study was carried out based on the back-propagation neural network analysis (NNA) to consider the correlation between the IRI and different distress [22]. It was revealed that the IRI and pavement distress collected by automatic inspection devices had a high correlation with each other, and the IRI successfully reflected pavement surface conditions. It was also revealed that each distress had a specific effect on the IRI which must be taken into consideration. In another research study, the best IRI prediction models were selected which considered the correlations between the IRI and the pavement age [13]. The relationships between the models with pavement deteriorations were studied. It was concluded that the deterioration characteristics were correlated to increasing changes of the IRI as time passes. In 2012, a study was undertaken to evaluate the effects of different types of distress on IRI using multiple linear regression analysis [11]. Results revealed that several patches, length of longitudinal cracks, and rut depth affected IRI variations significantly. Similarly, various modeling approaches were adopted to investigate the effects of various types of deteriorations on IRI values [23]. In doing so, linear and nonlinear regression analysis, as well as the ANN technique, were used. Analysis of variance demonstrated that the nonlinear model performed better than the linear one, while the ANN model had the highest accuracy in the prediction of the IRI. In 2016, research was conducted in which the relationships between the IRI and specific types of pavement deteriorations were examined [24]. The relationships between the IRI with cracking, rutting and raveling were investigated separately using the regression method. The Pearson correlation analysis was used for statistical analysis. The best IRI prediction model was developed based on three above-mentioned distresses. From a statistical standpoint, it was concluded that only cracking and raveling affected the IRI. However, their correlations in the modeling procedure were not high enough to prove the reliability of results obtained by the IRI for pavement evaluations.

Apart from the functional deficiencies of a pavement, which can be defined by the IRI or PCI; structural conditions have gained popularity in the field of PMS and prioritizing the sections in need of M&R operations [10]. One of the earliest research on the concepts of structural adequacy of pavement dates back to 1998 in New Jersey [25]. the structural characteristics of pavements were integrated into PMSs. Using the deflections derived from the FWD testing device, it was revealed that consideration of structural capacities would improve the budget allocation to those sections in urgent need of M&R treatments. Another research was carried out in 2009 to study the correlations between the D_0 measured by FWD and the IRI, PCI, and rut depths as functional indicators of pavements [26]. Results showed that there were low statistical correlations between these indicators. The results confirmed the importance of considering the structural capacities in PMSs to obtain the most accurate results on pavement performance. In 2013, concerning the importance of functional and structural indices in the establishment of efficient network-level PMSs, various types of structural capacity indicators were reviewed to choose the ones with the highest sensitivity to pavement distresses [27]. The SCI and SSI were chosen, and the results obtained by the SCI in network-level evaluations were accurate and similar to ones predicted by the project-level evaluations. As far as the network-level analysis was concerned, it was concluded that both structural characteristics (e.g., the FWD data), as well as deterioration types and severities, must be considered to reach accurate results.

2- 3- Combined Pavement Performance Indices

Owing to the mathematical relationships that exist between various types of pavement performance indices, and their potential to evaluate the pavement efficiently, different combined performance indices have been proposed to consider pavements' functional and structural characteristics. In 1992, a priority ranking PMS model was proposed considering six types of pavement distresses [28]. The distresses were weighted using experts' opinions, and the model was developed using the theory of fuzzy. As a result, a unified pavement distress index (UPDI) was proposed. The index was used to report the pavement overall conditions. Another research was conducted in which the level of acceptability of pavement was studied by proposing the overall acceptability index (OAI) [29]. Parameters such as roughness, distress, structural capacity, and skid resistance were combined to develop the index using fuzzy set theory. The index was simple and could be applied easily to network-level evaluations. In 1997, a fuzzy logic approach was utilized to develop a fuzzy distress index (FDI) for pavement evaluations, and prioritization of M&R operations [30]. The FDI combines structural distress such as alligator cracking and linear cracking, as well as raveling, rut depth, and roughness with traditional performance parameters (i.e., the PSI). The index was used to determine the overall condition of the pavement sections. Results indicated that the FDI is a reliable index for further assessment of pavement performance. In 2008, a combined indicator named overall condition index (OCI) was proposed which considered both the PCI and normalized IRI [13]. The pavement condition was undesirable if the OCI was zero to 70, and was acceptable provided the OCI was 70 to 100. In 2010, various types of pavement performance indicators in the United States were studied, and it was revealed that the mathematical formula, weighting approaches, and types of deteriorations could affect the final results on the determination of pavement overall conditions [31]. In 2013, a combined index was developed entitled the overall pavement condition index (OPCI). The index was developed based on pavement distress, roughness, structural attributes, and skid resistance. Those indicators were developed separately to form individual indices regarding pavements evaluations (i.e., $PCI_{Distress}$, $PCI_{Roughness}$, $PCI_{Structure}$, and PCI_{Skid}). The indices were weighted and combined to form the OPCI. Results indicated that the weight of structural characteristics of the pavement was higher than that of roughness, skid, and distress types, showing the importance of structural attributes in pavement evaluations. To examine the results obtained from OPCI, the conditions of the pavement were evaluated by the combination of individual indicators and the consideration of the OPCI [4]. The results obtained by the OPCI were similar to pavement conditions evaluated by the index entitled $PCI_{Distress+Roughness+structure}$. Outcomes indicated that as the number of criteria increased, the pavement condition rate degraded which confirmed the positive effects of considering both functional and structural indicators in precise pavement evaluation. In 2016, another combined index entitled pavement performance index (PPI) was developed. The proposed index considered the weights and rates of different types of surface distress, skid resistance, unevenness, bearing capacity as well as roadway shoulder [32]. The PPI was validated and its application to PMS was examined.

2- 4- Analytical Hierarchy Process (AHP)

Analytical Hierarchy Process (AHP) is a technique, which has been used widely in Multi-Criteria Decision Making (MCDM) problems based upon pairwise comparison measures [33]. In general, the AHP focuses on scaling matters and what types of values or numbers to use [34]. It uses decision makers' pairwise comparison to form different pairwise matrices including the rates allocated to different criteria and alternatives. Therefore, the weight of criteria, as well as their prioritization, can be explored. This would indicate the importance of each criterion and alternative over the others, as well as their effects on the main goal of the MCDM problem [35]. PMSs include various types of decision-making procedures in which the AHP and experts' opinions have been used for weighting approaches [4, 32, 33].

To sum up, the lack of a comprehensive pavement condition databank in developing countries such as Iran would be a primary reason for the absence of a reliable and accurate combined pavement condition index considering both functional and structural performances. Such an index yield efficient and optimum recognition of segments in need of maintenance and rehabilitation operations and relevant planning that reduces the required budget for annual pavement network maintenance which is a crucial issue in developing countries. This paper is to fill this gap to take a few steps towards the development of a novel combined pavement condition index using pavement condition data captured by an automated data collection vehicle in a case study of Iran encountering limited pavement condition data.

3- Objective and Scope

The main objective of this research is to develop a comprehensive pavement deterioration index which is a combination of pavement surface condition, pavement roughness, and structural adequacy through the application of pavement condition index (PCI), international roughness index (IRI), and the center deflection of falling weight deflectometer (D_0) using collected data in 2016 from a road pavement network in the eastern part of Iran. The scope of this research is limited to asphalt pavements located in major primary roads in dry and cold weather conditions.

4- Research Methodology

Firstly, the databank was created encompassing PCI, IRI, and D_0 values relevant to primary roads located in the eastern part of Iran. The segmentation procedure was performed using AASHTO cumulative difference approach (CDA) to define homogenous sections. Then, the correlations between PCI-IRI, PCI-D_0, and IRI-D_0 were examined. Based on the correlations, a combined pavement condition index was proposed considering both functional and structural indices. Having applied the analytical hierarchy process (AHP), a weight was determined for each index; therefore, a combined index was developed. Finally, the index was applied to the case study to support its reliability and efficiency in pavement assessments. Fig. 1 illustrates the research methodology.

5- Data Collection

The case study applied in this research was the major road network located in the eastern part of Iran shown in Fig. 2 which consists of 458 Kilometers of two-lane highways. Table 1 presents the name, code, and length of each highway. Having used the pavement condition data collected from the case study, the functional and structural indices (PCI, IRI, and D_0) were calculated which are described below.

PCI

In this research, ASTM D6433 was used to compute PCI for the visual inspection of pavement surface deteriorations using the images captured from the pavement by the automated data collection vehicle. This is not possible to implement pavement visual monitoring for the entire length of a highway. Hence, there must be several sample units to ease the monitoring process. The allowable area of 230±90 square meters has been determined for sample units of flexible pavements [1].

In this paper, the length of 50 meters and the width of 3.6 meters were chosen as dimensions of any sample unit (Area=180 m^2). The total number of units can be calculated by dividing the length of a highway by that of a sample unit. A minimum number of sample units, as well as the distance between consecutive sample units, were calculated using Eqs. (1) and (2) [36].

$$n = \frac{NS^2}{\left(\left(\frac{e^2}{4}\right) \times (N-1) + S^2\right)} \tag{1}$$

$$i = \frac{N}{n} \tag{2}$$

Where, n is the number of sample units, N denotes the total number of sample units, e is the allowable error in PCI calculation (±5), S denotes the standard deviation (for flexible pavement is 10), and i is the distance between sample units. In this research, 19 types of distress along with their quantities and severities were collected and entered into the Micropaver software (Version 5.2) to calculate PCI.

IRI

Using the RSP vehicle, the IRI values of the first lane of the selected highways were captured. The driving speed of the RSP vehicle was 60 km/h, and the IRI was represented per 100 meters. The measured IRI values were categorized by the Implex Software and were reported in the format of Excel files. The IRI data related to the left and right wheels of the vehicle were collected, averaged, and applied for further analysis.

FWD (D_0)

In this research, the Falling-Weight-Type Impulse Load device [37] was used to collect the required data. The defection responses were reordered by applying the tension of 900 kPa. The most accurate assessment of the pavement structural performance was carried out using the maximum deflections of sublayers i.e., the center of the load plate (D_0) indicating layers' stiffness. Pavement deflection attributes are functions of pavement structure, traffic load, and ambient temperature. The latter highly affects the deflections; therefore, the central deflections were corrected based on the reference temperature. The details regarding the FWD data collection are displayed in Table 2.

6- Segmentation Method

There are several methods to generate homogenous pavement segments; namely, AASHTO CDA, Bayesian method, and MINimization Sum of Squared Error (MINSSE) [38]. In this research, owing to the network-level evaluation, the AASHTO CDA method was utilized to create homogenous segments using Eq. (3). Hence changes in any set of data to recognize the homogenous sections, which was proposed to be used in PMSs [39].

$$z_k = \sum x_i - k\bar{x} \quad , \quad \bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{3}$$

Where, x_i is a variation, $\bar{x}$ denotes an average value of x_i, n is some recorded data, and k denotes a constant variable. The IRI and D_0 were utilized as independent variables to perform segmentation on the selected road network.

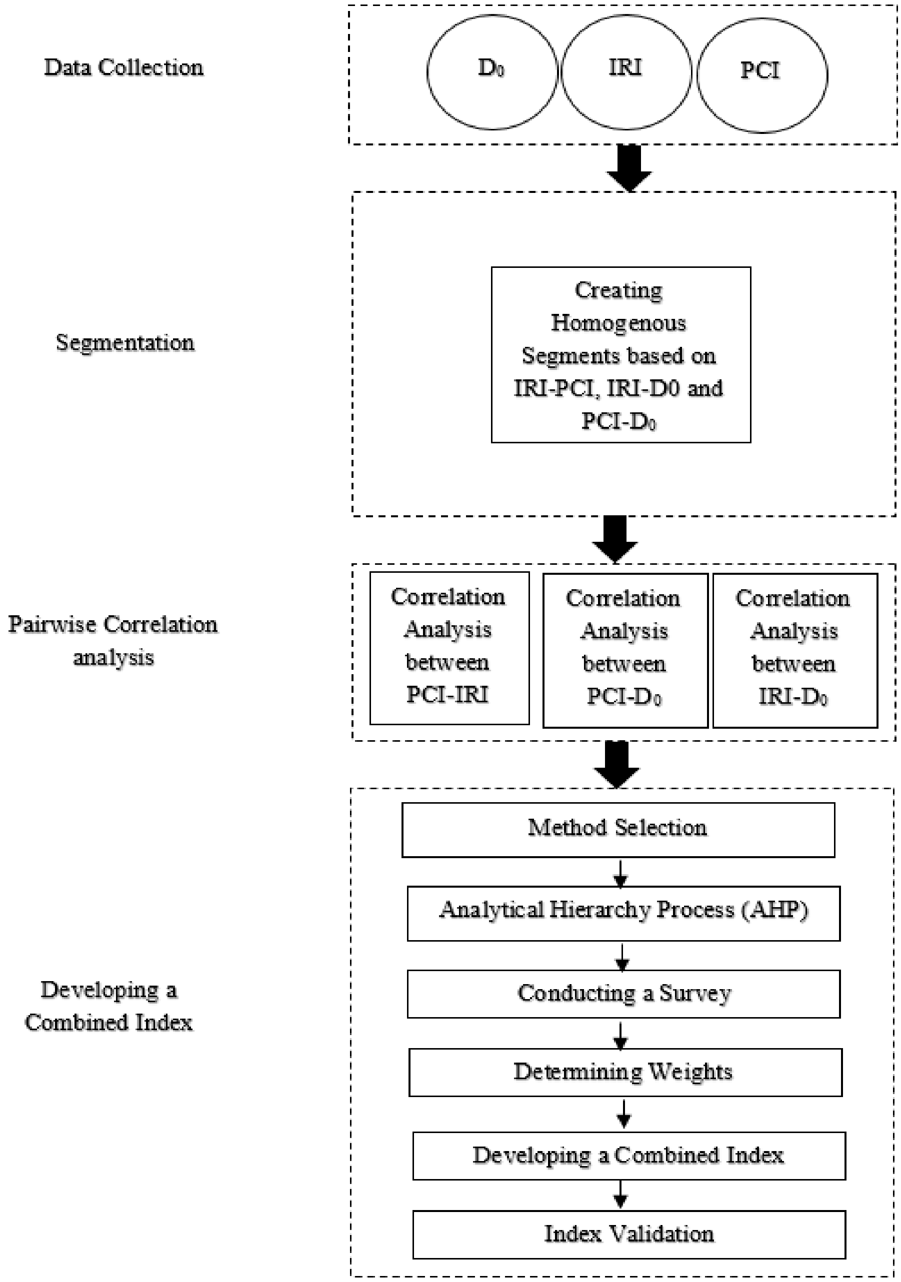

Fig. 1. Research methodology.

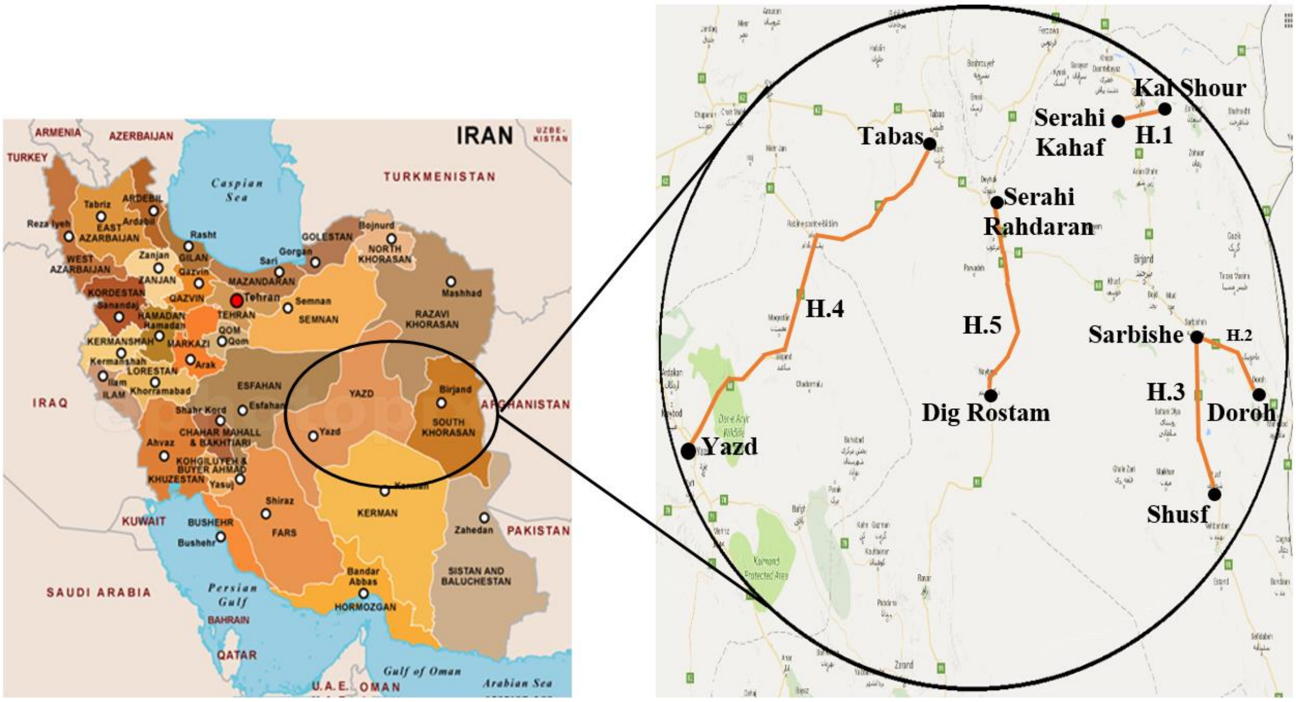

Fig. 2. Selected rural road network (case study).

Table 1. The lengths of highways located in the roads network.

Highway Name	Highway Code	length (km)
Serahi khaf-Kal Shour	H.1	40.7
Sarbisheh-Doroh	H.2	78.4
Sarbisheh-Shusf	H.3	88.3
Tabas-Yazd	H.4	146
Serahi Rahdaran-Dig Rostam	H.5	104.6

Table 2. FWD data collection

Parameter	Value
Applied tension (kPa)	600-900-1300-1900
Loading plate radius (mm)	150
The sensors arrangement (Cm)	0-30-60-90-120-150-180
Data collection intervals	400 Meter
The location of the loading	Lane 1 (60 cm from the shoulder marking)

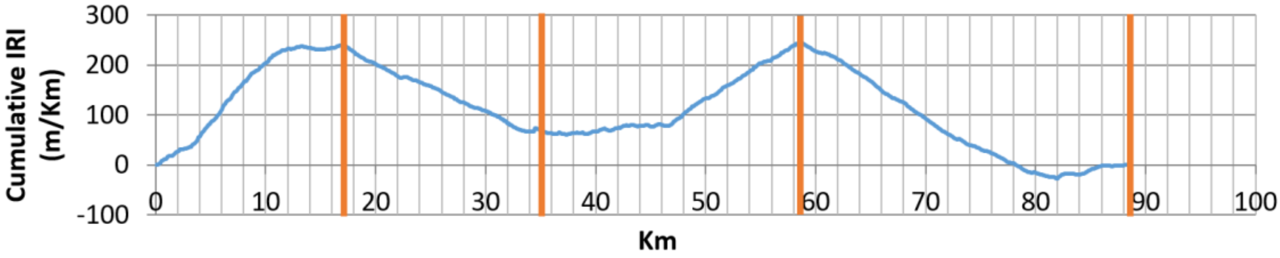

Fig. 2. CDA results to identify homogenous segments based on IRI variations.

Table 3. Description of homogenous segments with the average value of IRI.

highway code	Segment number	Start point (km)	Endpoint (km)	IRI (m/km)
H.3	1	0+000	17+100	4.86
	2	17+100	35+000	2.50
	3	35+000	58+800	4.16
	4	58+800	88+300	2.61

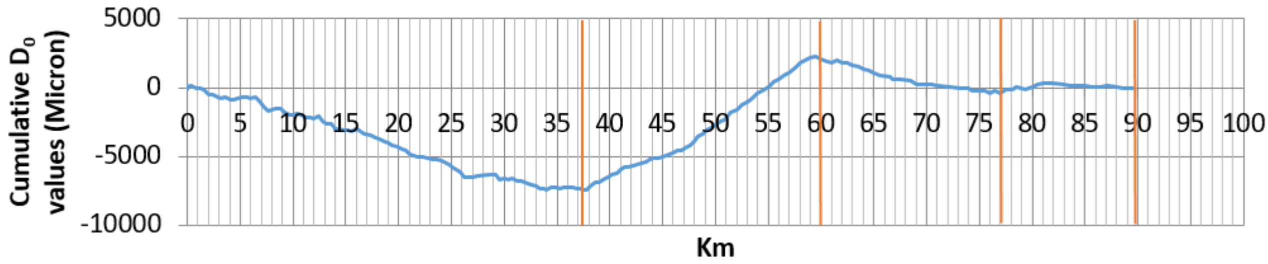

Fig. 4. CDA result to identify homogenous segments based on D0 variations.

Table 4. Description of homogenous segments with the average value of D_0.

highway code	number of segment	Start point (km)	Endpoint (km)	D_0 (Micron)
H.3	1	0+000	37+400	432
	2	37+400	60+000	701
	3	60+000	77+000	424
	4	77+000	88+300	527

6- 1- Homogenous Segmentation Based on IRI

In the first step of segmentation, the average value of the IRI collected data was calculated for each highway. The average IRI was deducted from every single recorded data. Then, the outcomes were accumulated and plotted against the distance. To recognize the homogenous segments, spots where the sign of curve slope changes from positive to negative (or vice versa) called change-point was applied to divide the curve into some segments [40]. This method of segmentation was implemented on the entire road network. Fig. 3 demonstrates the application of CDA to one of the highways (i.e., H.3) to define initial homogenous sections based upon the IRI variation concerning the determined average value. Table 3 shows the detailed description of segments including the IRI values.

6- 2- Homogenous Segmentation Based on D_0

To indicate initial homogenous segments including a constant variation of pavement structural capacity, the CDA method was performed on D_0. The detailed descriptions of homogenous segments of H.3 were listed in Table 4. These segments are where the variation of D_0 concerning the calculated average value is constant.

Table 5. Description of homogenous sections based on PCI values

Parameter	Value
Applied tension (kPa)	600-900-1300-1900
Loading plate radius (mm)	150
The sensors arrangement (Cm)	0-30-60-90-120-150-180
Data collection intervals	400 Meter
The location of the loading	Lane 1 (60 cm from the shoulder marking)

Table 6. The final homogenous segments based on PCI and IRI (H.3)

Distance	PCI	IRI (m/km)
0+000 – 17+100	30	4.86
17+100 – 28+000	93	2.5
28+000 – 33+400	69	2.5
33+400 – 35+000	19	2.5
35+000 – 58+800	19	4.16
58+800 – 88+300	55	2.61

6- 3- Highway Segmentation Based on PCI

The CDA method was utilized to determine homogeneous segments based on the PCI calculated for the entire sample units using Micropaver. The detailed descriptions of homogenous segments based on PCI values are represented in Table 5 for a sample highway i.e., H.3.

6- 4- Final Homogenous Segment

Pavement condition indices should be constant over the final homogenous segments. For this purpose, homogenous segments were provided combining boundaries of the above-mentioned segments. Table 6 expresses a sample of final homogenous segments based on the PCI and IRI, where both factors are constant. Towards this end, boundaries determined for initial segments provided in Tables 3 and 5 were employed.

To generate final homogenous sections based upon PCI-IRI, PCI-$D_{0,}$ and IRI-D_0 for other roadways of the road network, the same tables were created. The descriptions of final segments were used to study the relationships between selected pavement condition indices using different modeling approaches.

7- Correlation Analysis

This part is devoted to analyzing the pairwise relationship between the PCI, IRI, and D_0 in homogenous segments. The regression analysis method was utilized to define relationships and study the correlations that exist between these indices.

7- 1- Correlation between PCI and IRI

Linear, polynomial, logarithmic, and power curves were fitted to the PCI and IRI of final homogenous segments built based on a constant variation of these two indices. Table 7 expresses the detailed descriptions of each curve fitted to the data including mathematical equation, coefficients of determination (R^2), and Root Mean Square Error (RSME). Concerning Table 7, low values of R^2 demonstrate no strong relationship exists between selected indices i.e., PCI and IRI according to different types of the curve. This fact is similar to what was achieved by the other researcher [26]. The linear model (the best-fitted curve) with R^2 values of 0.11 is illuminated in Fig. 5 for an example. According to Fig. 5, data is scattered along the axes without significant increase or decrease patterns owing to low correlations between the PCI and IRI. For instance, as for the poor condition of pavements i.e., PCI equals 30, IRI values vary from 2.5 to 5 m/km expressing the fact that when the PCI is low, the IRI might be in between good and poor condition levels. The PCI is a function of distress types, severities, and the amount or density of deteriorations. It must be noted that not all types of distresses yield an increase in IRI values. A case in point is edge cracking which has a high deduction value in PCI calculation [1]. However, due to the location of edge cracking (i.e., not in the wheel path), it does not affect the roughness. Hence, in the resulting homogenous segments, both indices must be considered to assess the pavement overall condition.

Table 7. Correlations between PCI and IRI

Curve type	Mathematical equations	R^2	*RMSE*
Linear	y = -0.0108x + 3.6359	0.1154	0.7
Logarithmic	y = -0.466ln(x) + 4.8582	0.0999	0.7
Polynomial	y = -0.0012x^2 + 0.1337x	-0.509	0.93
Power	y = 5.3974x$^{-0.155}$	0.1009	0.7

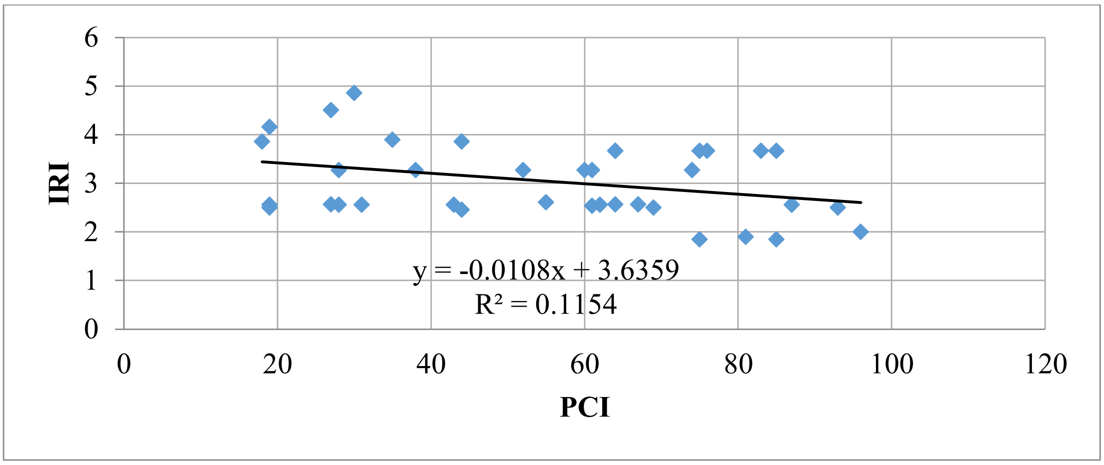

Fig. 5. The linear correlation between PCI and IRI.

Table 8. Correlations of PCI with D_0

Curve type	Mathematical equation	R^2	*RMSE*
Linear	y = 0.6756x + 495.55	0.0172	117.7
Logarithmic	y = 28.12ln(x) + 423.31	0.0139	117.9
Polynomial	y = 0.004x^2 + 0.2447x + 505.05	0.0175	129.7
Power	y = 420.81x$^{0.0544}$	0.0156	130.7

7- 2- Correlation between PCI and IRI with D_0

For pavement evaluation, the correlation of the PCI and IRI with measured maximum deflection (D_0) was assessed based on initial homogenous segments. First, to analyze the relationships between the PCI and D_0, different curves were attempted to fit the data as shown in Table 8. This is apparent from the information in Table 8 that there are too low correlations between PCI and D_0 regarding various curves employed. The same funding was derived from another research work [26]. A significant correlation was not expected since the PCI is the criterion representing pavement surface condition, while D_0 is a parameter used to characterize structural capacity. Although some types of distresses are initiated and propagated as a result of inefficient structural supports, not all types of distress are consequences of structural weakness. Therefore, both indices must be studied to understand the source of distress. Fig. 6 illustrates the polynomial model (the best-fitted curve) fitted to PCI and D_0 values of associated final segments. It can be observed that for a specific PCI value, there are different values of D_0. This shows the lack of correlations of the PCI with the D_0. It can be argued that low PCI values are not the convincing reasons for inefficient structural attributes and vice versa.

In the second stage, the relationships between IRI and D_0

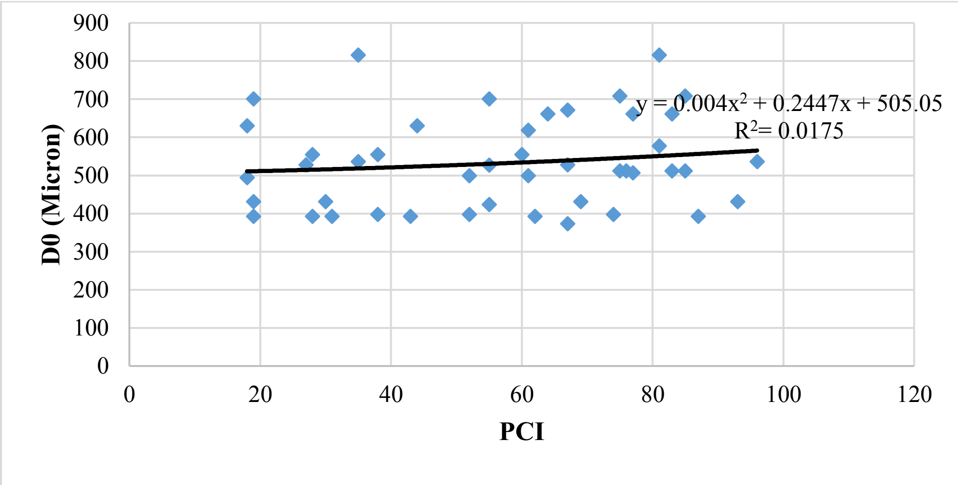

Fig. 6. The correlations between PCI and D_0

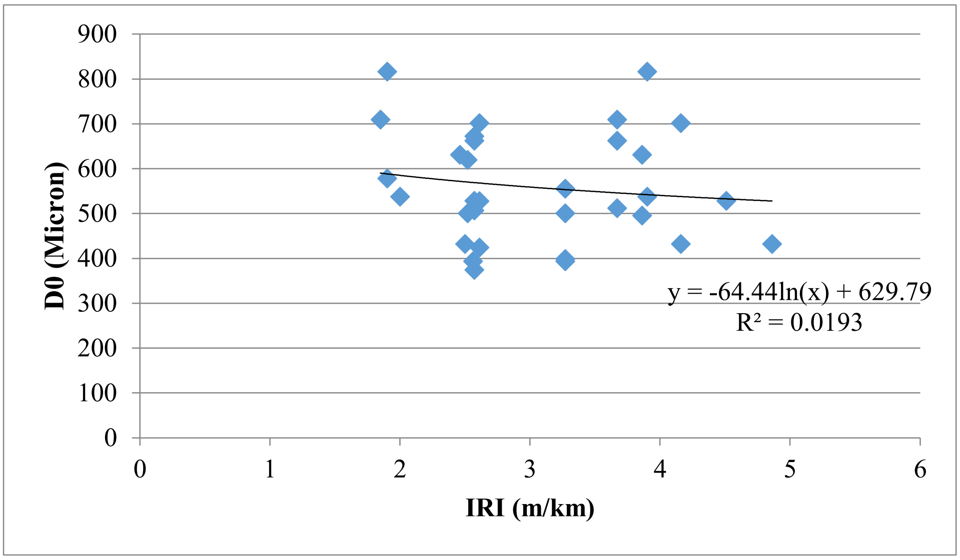

Fig. 7. The correlations of IRI with D_0.

were investigated. Table 9 demonstrates the results obtained by different attempts conducted on various types of the curve showing a weak correlation between IRI and D_0. To explain the lack of correlation between IRI and D_0, the logarithmic model (highest R^2) is plotted in Fig. 7. It can be observed that there are clusters of data around any specific IRI values. It shows the variation of the D_0 in a constant IRI value. This fact confirms the need to consider both indices for pavement overall assessment. Such a result is consistent with other research work [26].

According to the low correlations that exist between different pavement performance indices, it can be concluded that there are no effective and strong relationships between the PCI, IRI, and D_0 in various homogenous segments. Therefore, these indices can be utilized to develop a combined index to evaluate pavement overall performance. Towards this end, a combined index can be proposed by the weighted summation of these indices. As a result, a new combined index can be developed to reflect the level of pavement deterioration and its efficiency to serve the road users combining three main criteria: pavement surface distresses (PCI), roughness (IRI), and structural adequacy (D_0).

Table 9. Correlations between IRI and D_0

Curve type	Mathematical equations	R^2	*RMSE*
Linear	y = -16.763x + 611.15	0.0122	120.12
Logarithmic	y = -64.44ln(x) + 629.79	0.0193	119.7
Polynomial	y = -57.159x2 + 368.49x	-0.18	131.3
Power	$y = 617.22x^{-0.111}$	0.0181	120.28

Table 10. Questionnaire form

Index i									Rate									Index j
PCI	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	IRI
PCI	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	*D0*
IRI	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	*D0*

Table 11. The rating scheme (Saaty 1990)

Rate	Priority	Concept
1	Equally Preferred	The selected criterion is equal to the other criterion concerning their priorities (i.e., one is not preferred over the other)
3	Moderately Preferred	The selected criterion is slightly more important than the other criterion
5	Strongly Preferred	The selected criterion is strongly more important than the other criterion
7	Very strongly Preferred	The selected criterion is very strongly more important than the other criterion
9	Extremely Preferred	The selected criterion is dominant and cannot be compared with the other criterion
2, 4, 6, 8	Intermediate values	Demonstrates the other rates. For example, 8 means that the selected criterion is very strongly preferred but not extremely preferred over the other criterion

8- Pavement Overall Deterioration Index (PODI)

To develop a combined index through the application of IRI, PCI, and D_0, AHP was utilized to attain weights for each of these indices. The AHP was chosen since it is easy to understand and apply, and adequate for assigning weights to criteria. Since a novel index should be developed, and the outcomes of the index do not exist at the initial stage, no quantitative MCDM methods such as decision trees can be applied. The best approach would be a qualitative approach such as AHP through which experts can prioritize the criteria without a mathematical supporting process. For this purpose, a questionnaire was designed to make the pairwise comparison between the indices as shown in Table 10 with the rating scheme presented in Table 11. For instance, if an expert believes that PCI is 9 times more important than IRI, he/she should select number 9 on the left-hand side in the related row. Or, if one supposes that PCI and D_0 are equally important, he/she must select number 1 in the associated row. The questionnaire was filled out by a panel of 17 pavement engineer experts.

8- 1- Indices Weigh

Data obtained from the forms filled by experts was entered into the Expert Choice Software developed based upon the AHP concept. The consistency of expert panel rating was examined. Expert Choice Software calculates the inconsistency of pairwise judgments made by experts using inconsistency ratio (IR). The IR values of pairwise comparison matrices were less than 0.05 which is less than the acceptable threshold equal to 0.1 i.e., it is proved that the panel ratings are consistently leading to verification of the approach applied in this research.

The software outcomes showed that D_0 is the most important index with a weight of 0.491. Other indices i.e., PCI and IRI weights were indicated equal to 0.291 and 0.218, respectively. Therefore, the pavement overall deterioration index (PODI) can be formalized as expressed in Eq. (4).

$$PODI = 0.291 \times (PCI) + 0.218 \times (IRI) + 0.491 \times (D_0) \tag{4}$$

The results obtained from the weighting procedure showed that the maximum deflection beneath the FWD testing device (D_0) had the highest weight. In general, the values of the D_0 can indicate pavement structural capacity. This parameter was selected as the most important index to define the pavement deterioration condition. Appropriate and advanced construction technologies play crucial roles in pavement structural efficiency. Concerning experts' opinions and the pairwise comparison, it can be argued that in developing countries such as Iran, the lack of efficient construction methods equipped with the latest technologies has been recognized as contributing factor to inefficient pavement structural strength.

The low-technical compaction equipment, insufficient compaction of underlying layers, incorrect execution of underlying layers thicknesses, inadequate subgrade capacity, and unsuitable subgrade drainage are primary reasons for inappropriate pavement structure adequacy. It is generally believed that the unsuitable construction methods would result in high values of D_0. Various pavement surface problems such as high IRI and low PCI would also stem from the underlying layers deficiency that could be reflected in the upper layers as time passes and vehicle loads apply continuously. Therefore, it can be concluded that although the PCI and IRI may be in reasonable conditions, the high value of D_0 can be considered as an alarming factor for pavement managers to maintain and rehabilitate the pavements. Because, otherwise, the pavement would deteriorate rapidly, and high costs must be spent on its maintenance and rehabilitation treatments.

The importance of structural capacity has been reported in other research works [4, 10, 25, 27, 29, 32]. For instance, to derive a combined index, the weighting approach on several indicators was performed in which the weight of structural capacity was higher than roughness as well as selected types of distresses exist on the pavement [1]. The validation of the proposed index confirmed the significant effect of structural capacity in pavement performance evaluations. In another research, results were obtained from the weighting procedure based on a questionnaire survey and AHP to develop a combined index. The findings revealed that bearing capacity in terms of the CBR had the highest weight in comparison to unevenness, various distress, carriageway width, thickness, drainage, age, and roadways shoulders [32]. In addition, to validate the proposed index the field survey was conducted, and the above-mentioned criteria were collected. The analysis showed that according to actual experiments and field inspection the weight of the CBR, as a representative of structural capacity was higher than others.

Although the D_0 was determined as the most important index with the highest weight, PCI and IRI are still of significance and must not be overlooked. Concerning the aim of the research, to suggest a numerical value of the PODI, in the first step, the entire roads network must be segmented using AASHTO CDA based upon the PCI, and mean values of IRI and D_0 to generate final homogenous sections. The segmentation method resulted in 52 homogenous segments. According to the basic concept of AASHTO CDA, where there were any changes in the values of the selected criteria, a new homogenous section must be introduced since all the factors must be constant in all homogenous sections.

8- 2- Normalized PODI

There is a problem in the definition of PODI which is different indices i.e., PCI, IRI, and D_0 are of various scales that is PCI ranges between 0 and 100, while that of other indices (i.e., IRI and D_0) is one order of magnitude less. In this case, the weighs would not have the related contribution in PODI. To overcome this problem, the indices were converted into identical scales. In doing so, the indices were normalized applying Eq. (5) through which all indices were adjusted to the same scale varying from 0 to 1.

$$X_{i\ (Normalized)} = \frac{X_i - Min(X_i)}{Max(X_i) - Min(X_i)} \tag{5}$$

Where, X_i is the value of each index for a segment, $Max(X_i)$ and $Min(X_i)$ denotes the maximum and minimum of the associated index among all segments, respectively. It should be noted that the higher the IRI and D_0, the worse condition the pavements have, while PCI has the reverse meaning i.e., the higher the PCI the better the pavement condition. To solve this inconsistency, PCI was converted into (1-PCI) meaning the higher this value the lower the pavement condition is. Therefore, Eq. (6) was proposed to address such a reverse trend.

$$PODI = 0.291 \times (1 - PCI) + 0.218 \times (IRI) + 0.491 \times (D_0) \tag{6}$$

Table 12. PODI definition

PODI	Description	Color code	Treatment strategy	Suggested treatment action	Treatment action abbreviation	Treatment action unit cost ($/m^2)
0-0.2	Very good		Preventive	Crack Sealing	CS	2.18
0.2-0.4	good		Preventive	Slurry Seal	SS	1.34
0.4-0.6	Fair		Routine	Mill (5 Cm) & Overlay (5 Cm)	M&O 5	4.42
				Mill (10 Cm) & Overlay (10 Cm)	M&O 10	8.64
0.6-0.8	Poor		Minor Rehabilitation	Cold In-Place Recycling (10Cm) & Overlay (10Cm)	CIR&O 10	10.5
0.8-1	Very poor		Major Rehabilitation	Full-Depth Reclamation (15 Cm Asphalt layer & 15 Cm base)	FDR	9.8

According to Eq. (6), the PODI is a combined index ranging from 0 to 1, where zero means that the overall performance of the pavement is very good, and 1 means that the pavement is being prone to be failed. Table 12 illustrates the PODI range, definition, color code, preservation strategy, related treatment action, and associated unit cost based on expert opinions.

Table 13 presents the final values of PODI in each homogenous segment considering the normalized values of PCI, IRI, and D_0. Using this table, the PODI values were taken into consideration to assign each segment a color code, related treatment action, and associated costs.

9- Discussion

It should be mentioned that the PODI could be widely applied in regions with the same characteristics, namely, vehicle loading, pavement structure, and ambient environment as a case study in this research, while this index should be further investigated in a region with a large difference from the applied case study in the above-mentioned characteristics.

Using Table 13, one can easily identify the segments in need of maintenance or rehabilitation. This would help the managers to prioritize the segments based on their overall condition. For instance, Segments 3 and 23 are selected as the ones with very poor conditions associated with the highest PODI values. However, the value of PODI in the third segment is higher than that of the 23rd one. Although the PCI decreases and the IRI increases, reduction in the PODI can be attributed to the drop in D_0 values since this index has a significant effect on PODI (refer to Eq. (6)).

As for the fourth homogenous segment, where the PCI and D_0 are identical to those of the third section (the one in the very poor condition); PODI values decrease and this reduction results in categorizing the fourth segment in the fair condition. The reduction is owing to the lower amount of the IRI (1.9 m/km) as well as its normalized value (0.017). Although the PCI and the D_0 are in unacceptable ranges, the amount of IRI is far lower than the undesirable limit. This yields to considering the fourth segment in the fair condition.

Concerning PODI values of segments 23 and 24 (the ones in very poor and fair conditions, in turn), it can be argued that while D_0 values are constant and high since the PCI and the IRI of segment 24 are in better conditions, the segment is considered as the fair one. Regarding segments 7 and 8, where the PCI and D_0 do not change, due to the increase in IRI, it can be observed that the PODI values vary from 0.45 to 0.582. However, the segments remain in fair conditions. It can be claimed that as the IRI had the lowest weight in the weighting approach, its effect on PODI would be expected to be less than other indices. In these cases, such influence results in the rise in PODI values.

In segments 12 and 13, although PCI and IRI values are constant since the D_0 increased in segment 13, the PODI increases, and the overall condition changes from good (light green) to poor (yellow). This demonstrates the higher effects of the D_0 on the PODI leading to changes in overall pavement condition. Such evaluations would increase the priority of the 13th segment for the implication of treatment actions. In the 29th segment, the PCI is in very poor condition, but in the successive segment, the index is in a very good range. Concerning the improvements in the PCI and constant values of IRI and D_0, the PODI decreases, and the overall pavement condition changes from good to very good conditions. Due to acceptable values of IRI and D_0, the 29th segment

Table 13. PODI calculation over the selected roads network.(Continude)

High way code	Segment Number	Distance	Segment Length	PCI	IRI (m/km)	D_0 (Micron)	Normalized PCI Values	Normalized IRI Values	Normalized $D0$ Values	PODI	Treatment action	Total Costs ($)
H.1	1	0+000 – 8+000	8	96	2	537	1.000	0.050	0.369	0.192	CS	**6540**
	2	8+000 – 11+400	3.4	35	3.9	537	0.218	0.681	0.369	0.557	M&O5	**108202**
	3	11+400 – 21+400	10	35	3.9	816	0.218	0.681	1.000	0.867	FDR	**705600**
	4	21+400 – 24+000	2.6	81	1.9	816	0.808	0.017	1.000	0.551	M&O10	**161741**
	5	24+000 – 40+700	16.7	81	1.9	578	0.808	0.017	0.462	0.286	SS	**161122**
H.2	6	0+000 – 26+700	26.7	85	1.85	709	0.859	0.000	0.758	0.413	M&O10	**1660954**
	7	26+700 – 27+500	0.8	75	1.85	709	0.731	0.000	0.758	0.450	M&O5	**25459**
	8	27+500 – 28+300	0.8	75	3.67	709	0.731	0.605	0.758	0.582	M&O10	**49766**
	9	28+300 – 32+000	3.7	75	3.67	512	0.731	0.605	0.312	0.363	SS	**35698**
	10	32+000 – 39+800	7.8	76	3.67	512	0.744	0.605	0.312	0.360	SS	**75254**
	11	39+800 – 46+400	6.6	85	3.67	512	0.859	0.605	0.312	0.326	SS	**63677**
	12	46+400 – 49+400	3	83	3.67	512	0.833	0.605	0.312	0.334	SS	**28944**
	13	49+400 – 60+100	10.7	83	3.67	662	0.833	0.605	0.652	0.500	M&O5	**340517**
	14	60+100 – 65+900	5.8	64	3.67	662	0.590	0.605	0.652	0.571	M&O5	**184579**
	15	65+900 – 67+000	1.1	77	3.67	662	0.756	0.605	0.652	0.523	M&O5	**35006**
	16	67+000 – 71+400	4.4	77	2.57	662	0.756	0.239	0.652	0.443	M&O5	**140026**
	17	71+400 – 78+400	7	77	2.57	507	0.756	0.239	0.301	0.271	SS	**67536**
H.3	18	0+000 – 17+100	17.1	30	4.86	432	0.154	1.000	0.131	0.529	M&O5	**544190**
	19	17+100 – 28+000	10.9	93	2.5	432	0.962	0.216	0.131	0.123	CS	**7820**
	20	28+000 – 33+400	5.4	69	2.5	432	0.654	0.216	0.131	0.212	SS	**52099**
	21	33+400 – 35+000	1.6	19	2.5	432	0.013	0.216	0.131	0.399	SS	**15437**
	22	35+000 – 37+400	2.4	19	4.16	432	0.013	0.767	0.131	0.519	M&O5	**76378**
	23	37+400 – 58+800	21.4	19	4.16	701	0.013	0.767	0.740	0.818	FDR	**1509984**
	24	58+800 – 60+000	1.2	55	2.61	701	0.474	0.252	0.740	0.571	M&O5	**38189**
	25	60+000 – 77+000	17	55	2.61	424	0.474	0.252	0.113	0.264	SS	**164016**
	26	77+000 – 88+300	11.3	55	2.61	527	0.474	0.252	0.346	0.378	SS	**109022**

Table 13. PODI calculation over the selected roads network.(Continude)

H.4	27	0+000 – 3+900	3.9	43	2.56	393	0.321	0.236	0.043	0.270	SS	**37627**
	28	3+900 – 6+100	2.2	62	2.56	393	0.564	0.236	0.043	0.199	CS	**1090**
	29	6+100 – 19+200	13.1	19	2.56	393	0.013	0.236	0.043	0.360	SS	**126389**
	30	19+200 – 24+300	5.1	87	2.56	393	0.885	0.236	0.043	0.106	CS	**3863**
	31	24+300 – 35+000	10.7	31	2.56	393	0.167	0.236	0.043	0.315	SS	**103234**
	32	35+000 – 38+000	3	28	2.56	393	0.128	0.236	0.043	0.326	SS	**28944**
	33	38+000 – 43+500	5.5	28	3.27	393	0.128	0.472	0.043	0.378	SS	**53064**
	34	43+500 – 48+500	5	28	3.27	555	0.128	0.472	0.410	0.558	M&O10	**311040**
	35	48+500 – 62+000	13.5	60	3.27	555	0.538	0.472	0.410	0.438	M&O5	**429624**
	36	62+000 – 70+000	8	38	3.27	555	0.256	0.472	0.410	0.520	M&O5	**254592**
	37	70+000 – 71+700	1.7	38	3.27	398	0.256	0.472	0.054	0.346	SS	**16402**
	38	71+700 – 78+000	6.3	74	3.27	398	0.718	0.472	0.054	0.212	SS	**60782**
	39	78+000 – 83+500	5.5	52	3.27	398	0.436	0.472	0.054	0.294	SS	**53064**
	40	83+500 – 89+200	5.7	52	3.27	500	0.436	0.472	0.285	0.407	M&O10	**354586**
	41	89+200 – 98+000	8.8	61	3.27	500	0.551	0.472	0.285	0.373	SS	**84902**
	42	98+000 – 111+000	13	61	2.52	500	0.551	0.223	0.285	0.319	SS	**125424**
	43	111+000 – 146+000	35	61	2.52	619	0.551	0.223	0.554	0.451	M&O5	**1113840**
H.5	44	0+000 – 12+000	12	44	2.46	631	0.333	0.203	0.581	0.524	M&O10	**746496**
	45	12+000 – 12+800	0.8	44	3.86	631	0.333	0.668	0.581	0.625	CIR&O10	**60480**
	46	12+800 – 26+000	13.2	18	3.86	631	0.000	0.668	0.581	0.722	CIR&O10	**997920**
	47	26+000 – 36+000	10	18	3.86	495	0.000	0.668	0.274	0.571	M&O10	**622080**
	48	36+000 – 49+600	13.6	67	2.57	374	0.628	0.239	0.000	0.160	CS	**28693**
	49	49+600 – 73+800	24.2	67	2.57	672	0.628	0.239	0.674	0.491	M&O10	**1505434**
	50	73+800 – 76+100	2.3	67	2.57	528	0.628	0.239	0.348	0.331	SS	**22190**
	51	76+100 – 78+000	1.9	27	2.57	528	0.115	0.239	0.348	0.481	M&O5	**60466**
	52	78+000 – 104+600	26.6	27	4.51	528	0.115	0.884	0.348	0.621	CIR&O10	**2010960**
						Average	0.478	0.401	0.367	0.419		
						Standard Deviation	0.300	0.240	0.269	0.164		

is not considered very poor. The reduction in PCI in 29th segments might be due to a specific type of distress such as edge cracking that has high deducted values but does not directly affect the IRI and D_0. Hence, the 29th segment is not considered for urgent preservation.

Regarding segments 46 and 47, the 46th segment is in the poor condition with PCI, IRI, and D_0 values of 18, 2.86 m/km, and 631 Microns, respectively. Both the PCI and the IRI values are in unacceptable ranges and the D_0 values are reasonable. In the 47th section, owing to the decrease in D_0 values (495 Microns), the PODI decreases, and the segment condition is determined to be in a fair state. This means that the 47th section might require preservation in the future, but the 46th segment must be maintained earlier. As it was discussed above, the results obtained from PODI can be reliable seeing that the index considered all the selected indices correctly based upon their effects on the overall pavement condition. Such an index can aid pavement managers to identify and prioritize the deteriorated segments being in critical condition.

Fig. 8 illuminates the percentage of highway lengths in the selected road network derived from the PODI values. It can be seen that the highest proportion of the roads network is in fair condition (roughly 42 %) and the lowest percentage is in very good condition (8.69 %). The percentages of poor and very poor conditions are approximately equal, and it can be suggested to consider those segments in upcoming treatment actions. Table 13 provides a platform on which pavement managers would recognize the overall conditions of the pavements at a network level. In addition to this, such graphs enable road agencies to identify the percentage of the road network in immediate need of treatment actions and to allocate the required budget to those sections adequately.

10- Conclusion

One of the most challenging aspects of pavement management systems is to evaluate pavement performance conditions. Assessment of pavement performance requires an index. Several single and combined indices have been developed so far in developed countries. Due to the lack of a pavement condition database, pavement condition indices have not received enough attention in developing countries such as Iran. To fill this gap, this paper is to develop a combined index employing the pavement condition index, International Roughness Index, and maximum deflection (D_0) beneath the loading plate of the Falling Weight Deflectometer testing device through the application of a primary road network located in the eastern part of Iran. The selected road network was divided into homogenous segments using the AASHTO CDA for further analysis on the relationships between different pavement performance criteria as well as developing a new combined index.

From a statistical standpoint, the relationships between PCI, IRI, and D_0 values were analyzed using linear, logarithmic, polynomial, and power modeling approaches. Concerning R^2 values, it was concluded that there were no strong correlations between pairs of the indices since R^2 values were less than 0.2 in the entire pair comparisons. Therefore, a pavement overall deterioration index (PODI) was developed utilizing PCI, IRI, and D_0. In doing so, the AHP method was used, and the weights of those indices were calculated to form the basic equation for PODI. It was concluded that D_0 had the highest value (0.491) highlighting its importance, and the weights of PCI and IRI were 0.291 and 0.218, in turn. Having applied a case study, PODI was computed for the entire segments (52 homogenous ones) to identify those sections in need of M&R treatments. The PODI values would assist decision-makers to generally assess the road network at the pavement network level and also provide them with required treatment actions along with associated costs.

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