A New Approach in Estimating the Overall Condition of Asphalt Pavements Using a Combined Index: An Iranian Case Study

Jalal Barzegaran, M.Sc.
Ph.D. Student, Carleton University
Department of Civil and Environmental Engineering
Carleton University, Ottawa
Advanced Road & Transportation Engineering Lab (ARTEL)
Ottawa, Ontario, K1S 5B6, Canada
Email: jalalbarzegaran@cmail.carleton.ca

Mansour Fakhri, Ph.D.
Professor, K.N. Toosi University of Technology
Department of Civil Engineering
K.N. Toosi University of Technology, Tehran, Iran, 1996715433
Email: fakhri@kntu.ac.ir

Reza Shahni Dezfoulian, Ph.D.
Head of Bitumen and Asphalt Department
Road, Housing, and Urban Development Research Centre (BHRC), Tehran, Iran, 1463917151
Department of Civil Engineering
K.N. Toosi University of Technology, Tehran, Iran, 1996715433
Email: rdezfoulian@mail.kntu.ac.ir

Kamal Hossain, Ph.D., P.Eng.
Associate Professor, Carleton University
Department of Civil and Environmental Engineering
Carleton University, Ottawa
Advanced Road & Transportation Engineering Lab (ARTEL)
Ottawa, Ontario, K1S 5B6, Canada
Email: kamal.hossain@carleton.ca

Paper prepared for presentation at the Innovations in Pavement Management, Engineering and Technologies

2023 TAC Conference & Exhibition, Ottawa, ON

Abstract

Maintenance activities are of the utmost importance during the pavement lifecycle. Pavement assessment methods can be implemented to discover the leading cause of deterioration and select a proper maintenance activity. Agencies use economical and rapid pavement condition assessment approaches to address maintenance needs. It is understood that recruiting pavement engineers or technicians for field surveys or using automatic equipment for data acquisition are costly approaches. Past studies suggest that a more attractive solution can be using pavement surface images to inspect the condition based on an inclusive subjective index such as Pavement Surface Evaluation and Rating (PASER). Besides, it is also understood that any individual indices do not represent the overall condition of the pavement. The use of only the International Roughness Index (IRI) or visual surface distresses in the maintenance decisions may not be adequate. Therefore, this study proposed a new combined condition index that compensates for the insufficiency of each index. The pavement conditions in 367 sections in Kermanshah, Iran, were evaluated using PASER and IRI. Then, by combining both indices using a weighted summation approach, an Overall Surface Condition Index (OSCI) was developed that can supremely express the overall condition of the pavement and propose a superior maintenance strategy compared to PASER and IRI. The outcome or result gained from this study could be a practical approach for road agencies to estimate the road network condition cost-effectively and make proper decisions for pavement maintenance at the network level.

Keywords: Pavement Maintenance, PASER, IRI, Combined Condition Index, Weighted Summation.

Introduction

Roads are essential infrastructures as they interconnect states, cities, and local districts to perpetuate social and economic relationships. These valuable assets are consistently in the service of their users. Like many other infrastructures, road conditions also deteriorate as they age due to traffic loadings and climatic factors. Therefore, road maintenance has always been a concern for agencies that may affect their policies in setting priorities and budget allocations. Pavement preservation at a high serviceability level requires a significant budget, making it difficult for the agencies to cope with. In this case, a pavement management system (PMS) can help to investigate the current pavement condition, prioritize maintenance strategies, and allocate limited treatment budgets [1-3].

Pavement condition assessment is a key element of a PMS that requires collecting pavement condition data, the most expensive part of pavement management. Different methods have been used to manually, automatically, or semi-automatically acquire the current pavement condition. Nowadays, many agencies utilize specific equipment such as road surface profiler (RSP), laser crack measurement system (LCMS), or ground penetration radar (GPR) mounting on high-speed vehicles to automatically collect pavement characteristics such as roughness, rut depth, macro-texture, types of cracks, and sub-layer thicknesses that can expedite the investigation of the road network within a short time [2, 4]. However, regarding the high cost of using equipment, some agencies prefer to gather pavement data manually by employing recruits to make the investigation more cost-effective [5]. An example of these approaches includes the determination of the Pavement Condition Index (PCI) according to ASTM D6433 [6]. Although these types of approaches provide more detailed information about the pavement distresses and their origin, the procedure of the survey is labor-intensive, time-consuming, and costly.

Hence, employing comprehensive subjective indices such as Pavement Surface Evaluation and Rating (PASER) can be a suitable solution for pavement condition assessment in terms of cost-effectiveness, simplicity, and saving time.

While many agencies inspect their road networks based on individual indices and make decisions regarding their outcomes, using these indices separately may not represent the overall condition of the pavement. Hence, the proposed treatments will not necessarily lead to the best pavement quality. A pavement section lacking visual distresses but experiencing undesirable ride quality due to construction inaccuracies, insufficient compaction, or freeze-thaw heave from the subgrade swelling may not be effectively addressed by treatments based on a visual distress index. Conversely, a pavement section with scattered distress areas but providing a smooth ride might not benefit from roughness treatment criteria. To address these issues comprehensively, combining multiple condition indices with different origins can lead to effective maintenance decisions at the network level using an overall condition index.

Objective and Scope

The objective of this work is to:

- Develop a combined index to evaluate the overall condition of asphalt pavement in Kermanshah, Iran, based on surface distress and roughness indices.

The scope of this study is to:

- Inspect the pavement visual distresses using PASER, as it is presumed to be less time-consuming, more cost-effective, and less hazardous in terms of safety compared to commonly used indices such as PCI.
- Assess the pavement roughness by calculating the International Roughness Index (IRI) of left and right wheel paths, as it is a straightforward and common approach in the estimation of pavement conditions based on roughness.
- Develop a combined condition index originating from PASER and IRI, namely, the Overall Surface Condition Index (OSCI) using the weighted summation approach.
- Determine the status of pavement conditions based on OSCI quantities using the k-means clustering method.
- Validate the performance of OSCI in comparison to PASER and IRI in new sections by estimating the maintenance costs.

Literature Review

Studies have been carried out to develop pavement condition indices depending on the needs of road agencies and the available condition data. This section reviewed the development of combined condition indices, as the representatives of pavement overall condition, based on the subjective and objective approaches.

Subjective Combined Index

A subjective condition index is a simple approach that defines a discrete numerical rating and assigns descriptors to each of the rates [2]. The Pavement Surface Evaluation and Rating (PASER) condition survey procedure developed by the University of Wisconsin is an example of a subjective combined index. This method considers four major categories of common asphalt pavement surface distress including, surface defects (raveling, flushing, polishing), surface deformation (rutting, distortion, settling, frost heave), cracks (transverse, longitudinal, reflection, slippage, block, and alligator cracks) and patches and potholes. The pavement surface is rated from 1 to 10 according to the descriptions provided in the PASER manual for asphalt pavements. A rate of 1 denotes the deteriorated surface and 10 represents the newly-built pavement with an excellent appearance [7].

Present Serviceability Rating (PSR) is another subjective method of developing a condition index that is performed by panel rating, which ranges from 0 (very poor condition) to 5 (very good condition). This method employs a panel of experienced raters to investigate the condition of pavements based on the raters' experience [8].

Although these approaches are straightforward and cost-effective to implement at the network level assessment, the only problem can be the evaluation outcome, which is based on engineering judgment that differs among individuals and leads to inaccurate results.

Objective Combined Index

The objective methods are commonly used solutions for determining combined condition indices, often perceived as either the distress-based or index-based approaches. The indices with distress basis typically rely on the combination of type, severity, and extent of the distresses observed in the field. As a result, some points are subtracted from the index associated with a perfect score. The calculations vary depending on the types of distress information included in the survey procedure and each agency's relative importance on the combination of distress type and severity [2]. The most well-known index of this type is PCI, developed by the United States Army Corps of Engineers, which has been officially presented as ASTM standard D6433. It considers the recorded distress type, severity, and extent in the calculation and a value will be generated in a range from 0 (failed) to 100 (excellent). [4, 6]. Another example of a distress-based quantitative condition index is the Distress Manifestation Index (DMI) developed by the Ministry of Transportation of Ontario (MTO). This indicator estimates the surface distresses using the weighted summation approach mentioned in the MTO condition rating manual. The DMI ranges from 0, representing the poor condition of the pavement, to 10, denoting a newly constructed pavement segment [9, 10]. The Surface Condition Index (SCI), for instance, was proposed by the South Dakota Department of Transportation (SDDOT) which is a 0-5 scale index with 5 maintaining minimal distresses, and it is based on the mean and standard deviation (SD) of all the individual indices for a given section. [11].

In another research for assessing the performance of rural roads in India, Tawalare and Raju developed the Pavement Performance Index (PPI). Various pavement parameters such as roughness, rut depth, skid resistance, raveling, potholes, patching, drainage, and shoulder condition were inspected for Indian rural roads. The rating criteria and weighting for each parameter were carried out through the literature review and questionnaire survey, respectively [12]. Using survey documentation on PMS in the United States, Juang and Amirkhanian developed the Unified Pavement Distress Index (UPDI) to report the overall pavement condition by deploying a priority ranking model based on the ratings and weights of six types of distresses and the theory of fuzzy sets [13]. Shoukry et al. introduced the Fuzzy Distress Index

(FDI) as a more generalized approach for pavement evaluations by combining the extent of structural distresses such as alligator cracking and linear cracking with traditional performance parameters such as roughness. The results of comparing FDI and corresponding PSI for selected sections indicated that the FDI outperformed PSI in terms of consistency and accuracy of the overall pavement condition [14].

The index-based combined models are defined integrating of individual condition indices using combination approaches such as weighting methods, mathematical formulas, fuzzy theories, and to name a few. A simple approach to determine the combined indices is to use an average weighted index concept. An example of this approach is the road inventory program for the National Park Service (NPS) conducted by the Federal Highway Administration (FHWA), in which a weighted combination of two condition indices, namely, Surface Condition Rating (SCR) and Roughness Condition Index (RCI), resulted into the Pavement Condition Rating (PCR) ranges from 0 (failed pavement) to 100 (perfect pavement). In this method, the effectiveness of the distress index (0.6) outweighs the roughness index (0.4) in PCR [15, 16].

The Ohio Department of Transportation (ODOT) developed a combined condition index known as Pavement Quality Index (PQI). This indicator includes the combination of IRI and PCR, where IRI treats as a deduction from PCR. The developed model for PCR calculation is obtained by the subtraction of deducting values from 100. The deduction associated with any distresses is a function of distress type, severity, and extent [17]. In another study in Canada, Golroo and Tighe developed a Pervious Concrete Condition Index (PCCI) that represented the overall condition of a previous concrete pavement at any time. This approach was produced by using the weighted summation of the surface distress index (SDI) denoting the concrete pavement distresses and the functional performance index (FPI) expressing the rate of permeability in concrete pavement. Both indices range between 0 representing the poor condition, and 10 indicating the best condition in terms of distress and permeability. A series of weighting factors was developed for FPI (α), and SDI (β) based on the magnitude of permeability rates. The weights of both parameters change with respect to the magnitude of FPI [18].

Ndume et al. conducted a research study in Tanzania to improve the estimation of pavement conditions using the combination of IRI and distress parameters. Investigating 36,292 km of road network in Tanzania, they managed to develop a combined condition index, which outperformed a single index, i.e. IRI, in terms of reliability and accuracy of pavement assessment and improve the evaluation by 24% [19]. Zhang et al. conducted a study to capture the subjective judgments of pavement engineers and users and integrate the essential factors in pavement assessment including roughness, surface distresses, structural capacity, and skid resistance into one index. As a result, the Overall Acceptability Index (OAI) was proposed using the fuzzy set concept [20]. Using the four main attributes in pavement evaluation, namely surface distress, roughness, skid resistance, and structural capacity, Shah et al. introduced a combined condition index entitled Overall Pavement Condition Index (OPCI) to use the output in decision-making for maintenance. The higher value of weight assigned to structural characteristics indicated the importance of this feature in pavement evaluations, compared to roughness, skid resistance, and distresses. The outcomes of this study indicated the reliability and efficiency of OPCI in selecting the appropriate treatments [21]. Semnarshad et al. developed a Pavement Overall Deterioration Index (PODI) using the weighted summation method of PCI, IRI, and maximum deflection (D_0). The study was conducted on 52 sections of two-lane highways with a total length of 458 km in Iran. The results indicate that D_0 as a representative of the 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 weights of 0.291 and 0.218, respectively [22].

To determine the level of agreement between the developed combined condition models, Gharaibeh et al. scrutinized six condition indices, namely Condition Score (CS), Distress Score (DS), Surface Condition Index (SCI), Pavement Condition Rating (PCR), Overall Pavement Index (OPI), and Overall Index (OI), from five DOTs in the United States. The results stated significant differences among similar pavement condition indices which could be affected by mathematical formulas, weighting approaches, and types of deteriorations [23]. In addition, it can be perceived from previous studies that the aims of developing combined condition models to meet the requirements in a particular situation were distinctive and exclusive. Selecting the appropriate treatments for pavement maintenance in a developing country like Iran pertains to three essential factors: the use of economical approaches in pavement evaluation, how fast they can be performed, and their accuracy in condition estimation. Hence, in this study, the PASER and IRI indices were used to mitigate the costs, time, and risks of evaluation, and subsequently, the OSCI was developed as a comprehensive combined condition index based on PASER and IRI, to rectify the weakness points of each of the individual indices and enhance the accuracy of pavement assessment.

Methodology

In the subsequent steps of this research, pavement distresses were investigated manually with the PASER approach while the roughness was assessed by a high-speed road profiler and IRI was calculated as a result. Then, a combined condition index as OSCI was developed for asphalt pavement evaluation at the network level in terms of roughness and visual distresses by applying IRI as an objective index and PASER as a subjective one. Afterward, the validation procedure of the developed model was carried out by employing a new set of data. Ultimately, the treatments proposed by IRI, PASER, and OSCI were assigned to the new sections and their maintenance costs were calculated. The most proper treatment among the three options was selected for maintenance.

Data Collection

In this study, the asphalt pavements in two main roads of Kermanshah province, Iran, with a total length of 34 kilometer's, were investigated regarding roughness and surface distress. As shown in Table 1, the selected routes had different ages with annual average daily traffic (AADT) of around 3000, and semi-arid climate classifications which were acquired by the 10-year precipitation and temperature data (Table 1). Accordingly, a high-speed road profiler was employed to collect roughness and rutting data. Furthermore, a camera was mounted on top of the vehicle's roof to capture the forward view of the road focusing on the pavement surface, as shown in Fig. 1(a). The camera was set to be focused on the pavement surface so that the distresses would be distinguished with superior resolution Fig. 1(b). The longitudinal profiles of the road were collected in consecutive 10-meter intervals according to the profiler's setup system. Regarding the synchronization between the profiler and camera, the images were captured in 10-meter distance intervals while the profiler was operating and collecting data. The images were stored in a specific folder in the vehicle's computer system.

Table 1. Specifications of the Selected Roads

Route	Length (km)	Age (years)	Pavement type	AADT	Climate	Average annual temperature (℃)

Babazeid-Police	8.9	7	AC	3100	Semi-arid	15.5
Bisotun-Sonqor	25.1	15	AC	2800	Semi-arid Mediterranean	13.1

(a) (b)

Fig. 1(a). Road Surface Profiler mounted on a vehicle, (b). Forward view image captured by the camera placed on the vehicle's roof

Data Processing and Panel Rating

After field investigation, the profiler's collected data were processed by specific software to calculate the IRI and rut depth values of left and right wheel paths that were compiled as longitudinal and transverse profiles, respectively, for each road in a database file format. To inspect the surface distresses, it was decided to deploy the captured images of pavement and evaluate the asphalt surface using the PASER manual, instead of undertaking a field survey that would be costly and hazardous. However, random field inspections were conducted on limited sections for quality control of image-based distress ratings. In the case of rut depth measurement, it was collected by an automated profiler and the average value of right and left wheel paths was considered as the section's rutting indicator. As detecting rut depth through images is not applicable, the measured average rut depths were considered in the PASER rating. Studies have demonstrated that the high accuracy of the rating procedure can be acquired by involving more raters with a variety of ages and experiences [24-27]. In this case, a panel of raters was established including 10 pavement engineers aged from 23 to 45 with sufficient pavement knowledge to manually rate the pavement condition using the PASER approach.

First, the PASER manual for asphalt pavements was given to the raters to study and learn the requirements of rating procedures prior to their inspection for superior consistency in distress identification. Then, the images of each road accompanied by a rating form which was designed according to the PASER manual in a spreadsheet were given to all raters. It is imperative to note that the initial segmentation of each road was performed based on the traffic level and changes in pavement condition before the beginning of the rating. Therefore, raters were supposed to assign a rate between 1 and 10 to pavement sections with 1 representing the failed condition of the road and 10 indicating the newly constructed pavement in excellent condition. After two weeks, the completed inspection results were gathered, and their consistency was checked to find the outliers in the data.

To check the consistency of panel rating data, Chebyshev Theorem was performed which indicates that at least $(1-1/k^2)$ of all observations in a sample or population will lie within k standard deviations of the mean, as indicated in Equation 1.

$$P(|X-\mu| \leq k\sigma) \geq (1-\frac{1}{k^2}) \tag{1}$$

Where X is the observed data, μ is the data mean, σ is the standard deviation of the data, and k represents the number of standard deviations from the mean. For the approximately bell-shaped normal distribution of observations, an empirical rule-of-thumb suggests that 95% of the observations will fall within two standard deviations of the mean. It can be perceived that at least 75% of the data would fall within two standard deviations (k = 2) from the mean. Therefore, considering k = 2, the observations that fell out of the limits were considered outliers and they were excluded from the dataset [28].

Model Development

Pavement condition depends on several criteria, such as roughness, surface distresses, and structural capacity, that must be considered for developing a comprehensive condition index. Since evaluating the load-bearing capacity of pavement layers was not primarily aimed at this research, the model did not consider the structural capacity index. However, the other two main factors, namely, pavement roughness and distress indices, were incorporated for developing the Overall Surface Condition Index (OSCI) of the asphalt pavements as hypothesized in Equation 2.

$$OSCI = f\ (PASER, IRI) \tag{2}$$

Where OSCI indicates a combined index of asphalt pavement surface condition, PASER is a subjective surface distress index defined on a scale of 1 to 10 (PASER = 1 represents a fully deteriorated pavement, while PASER = 10 indicates an excellent condition of pavement), and IRI denoted an objective index for roughness and ride quality of asphalt pavement that is defined from 0 stating a smooth surface and increases by ride quality aggravation.

The 10-meter IRI data in each section were averaged and the mean panel ratings of PASER for 367 sections were calculated. Therefore, the corresponding values of IRI and PASER in each section were provided. The descriptive statistics of the obtained data are shown in Table 2.

Table 2. Descriptive Statistics of the Collected Data

Variable	Count	Mean	StDev	Minimum	Q1	Median	Q3	Maximum
PASER	367	4.670	1.997	1.000	3.000	4.000	6.000	9.000
IRI	367	3.791	2.125	1.261	2.542	3.262	4.361	18.188

As mentioned, IRI values can begin from 0 and increase without limitation. Thus, they are required to be transformed into a 0-10 scale similar to PASER, if so, they can be included in the combined condition index. The breakdown of IRI according to the previous observations and studies conducted in Iran was indicated in Table 3 in which the six ranges of IRI with their descriptions and required treatments were comparable to each other. Thus, a value between 0 and 10 as the modified IRI (IRI_mod) corresponded to each range as shown in Table 4. The minimum quantity of IRI_mod corresponded to IRI values up to 1.5 m/km according to ASTM E1926 stating that the undulation is barely perceptible in the range from 1.3 to 1.8 m/km [29]. Regarding the previous field investigations in Iran in terms of roughness, the IRI of 2.85 m/km is a threshold where pavement preservation could be taken into consideration. Accordingly, the pavement may require major treatment as the IRI reaches 4.5 m/km [30]. Furthermore, the IRI of 6 m/km and 10 m/km can represent the major rehabilitation and reconstruction intervention, respectively [31].

Table 3. General Condition of IRI Ranges and Suggested Treatments

IRI (m/km)	**General Condition**	**Required Maintenance or Repair**
IRI ≤ 1.5	Comfortable ride at a speed of 120 km/h or more. Undulation is barely perceptible at 80 km/h.	No maintenance required/ little maintenance
1.5 < IRI ≤ 2.85	Moderate undulations may be felt at 80 km/h. Rare depressions or moderate corrugations with bare existence of surface defects.	
2.85 < IRI ≤ 4.5	Moderately perceptible movements or large undulations may be felt at 80 km/h. Occasional depressions, patches or potholes, or many shallow potholes. For surfaces without defects: moderate corrugations or large undulations.	Resurfacing
4.5 < IRI ≤ 6	Usually associated with defects; Frequent moderate and uneven depressions or patches or occasional potholes. For surfaces without defects: strong undulations or corrugations.	Thin overlay
6 < IRI ≤ 10	Frequent deep and uneven depressions and patches, or frequent potholes	Thick overlay
IRI > 10	Many deep depressions, potholes, and severe disintegration	Reconstruction

Table 4. IRI Ranges and Defined Scales

Group No.	**IRI (m/km)**	**IRI_mod**
1	0 ≤ IRI ≤ 1.5	0
2	1.5 < IRI ≤ 2.85	2
3	2.85 < IRI ≤ 4.5	4
4	4.5 < IRI ≤ 6	6
5	6 < IRI ≤ 10	8
6	10 < IRI	10

In the next step, the regression analysis was performed in which the mean of IRI was considered as the independent variable and the IRI_mod scale was a dependent one. After several tries to find the best fit, the Natural Logarithmic model yielded a superior correlation between parameters than the others as indicated in Fig. 2. It should be noted that the IRI_mod will be predicted between 0 and 10 if the actual IRI ranges from 1.36 to 12.7 m/km. Otherwise, for IRI less than 1.36 m/km and more than 12.7 m/km, the IRI_mod will be equaled to 0 and 10, respectively. The statistics of the model associated with Equation 3 were given in Table 5.

$$IRI\_\text{mod} = \begin{cases} 0 & IRI < 1.36 \\ 4.48 \times \ln(IRI) - 1.38 & 1.36 \le IRI \le 12.7 \\ 10 & IRI > 12.7 \end{cases} \tag{3}$$

Table 5. Summary of Modified IRI Model and Parameter Estimates

Equation	**Model summary**			**Parameter estimates**	
	R-square	**df**	**Std. error of the estimate**	**Constant**	**a**
Natural Logarithmic	0.989	4	0.428	-1.38	4.48

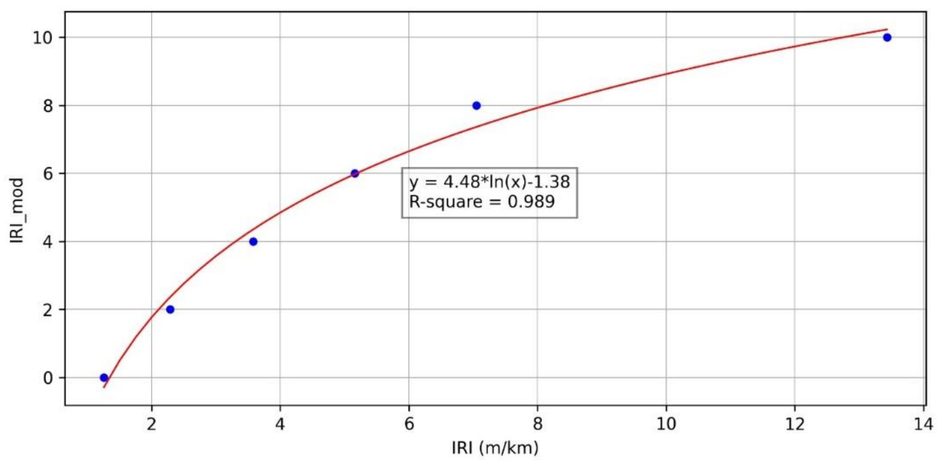

Fig. 2. Relationship between IRI and IRI_mod scales

To develop a combined condition index including PASER and IRI_mod, their correlation needs to be analyzed as they cannot be incorporated into the model with a high correlation coefficient due to the multicollinearity [32]. In this regard, correlation analysis was performed to identify the strength of the relationship between these two parameters. As a result, it was observed that the correlation between the parameters was not significantly high, so they were allowed to be considered as the independent parameters of the model. The correlation analysis result is illustrated in Fig. 3.

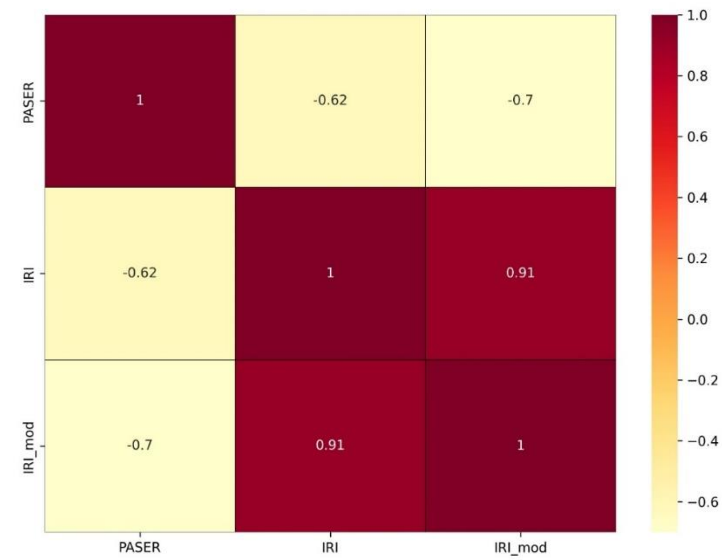

Fig. 3. Correlation Analysis between PASER, IRI, and IRI_mod

The OSCI represents the combination of PASER and IRI_mod with a weighted summation approach. Regarding the reverse correlation between PASER and IRI, it was considered to subtract the PASER variable from 10, so that both variables change in the same direction and the effects of weighting factors on each variable would be more sensible. Weighting factors can be determined by asking a panel of experts, such as pavement engineers, to assign a weighting factor corresponding to PASER and IRI_mod. These values depend on the impact of each variable on OSCI which should be examined. As pavement distresses have a significant effect on pavement condition rather than the roughness, the weighting classification was performed based on PASER rates in 5 categories. As the category changes, the factors vary. Then, a pair of weighting factors were assigned for each category by 10 experienced pavement engineers based on their engineering judgment in different conditions. They were asked to select the weighting factors in the range from 0 to 1 with 0.05 step and a sum equals to 1 ($\alpha+\beta=1$). Consequently, by averaging their responses for α and β, the ultimate weighting factors were determined as shown in Table 6. Equation 4 indicates the OSCI formula regarding the weighting factors given in Table 6.

$$OSCI = \alpha \times (10 - PASER) + \beta \times (IRI\_\text{mod}) \quad (4)$$

Table 6. Weighting Factors Associated with PASER and IRI_mod

PASER rates	**α (PASER factor)**	**β (IRI_mod factor)**
PASER = 1 or 2	0.92	0.08
PASER = 3 or 4	0.76	0.24
PASER = 5 or 6	0.58	0.42
PASER = 7 or 8	0.27	0.73
PASER = 9 or 10	0.07	0.93

Data Clustering

To specify the status of pavement conditions based on OSCI, the data obtained from the OSCI model were clustered into five groups using the k-means clustering method. K-means is a simple clustering algorithm that attempts to find k non-overlapping clusters which are represented by their centroids. This method can be expressed by an objective function that depends on the proximities of the data points to the cluster centroids as given in Equation 5.

$$\min_{\{m_k\},1\le k\le K} \sum_{k=1}^{K} \sum_{x\in C_k} \pi_x dist(x, m_k) \quad (5)$$

$$m_k = \sum_{x\in C_k} \frac{\pi_x x}{n_k} \quad (6)$$

Where π_x is the weight of x, n_k is the number of data objects assigned to cluster C_k, m_k is the centroid of cluster C_k (Equation 6), K is the number of clusters set by the user, and the function “dist” computes the distance between object x and centroid m_k. While the selection of the distance function is optional, the squared Euclidean distance, i.e. $\|x-m\|^2$, has been most widely used in both research and practice. The iteration process is a gradient-descent alternating optimization method that helps to solve Equation 5, although often converges to a local minimum or a saddle point [33, 34].

The Elbow method was conducted to determine the optimal number of clusters in k-means, and the Sum of Squared Errors (SSE) between a cluster centroid and its data points was calculated for nine clustering scenarios. When the number of clusters is set to approach the optimum number of clusters, SSE shows a rapid decline. As the number of clusters exceeds the optimum number, SSE will continue to decline, but it will quickly become slower [35, 36].

The clustering process for the corresponding values of PASER, IRI, and OSCI began with selecting five initial centroids which indicated the desired number of clusters (Fig. 4). Every datapoint was then assigned to the closest centroid, and the collection of these points formed a cluster. The centroid of each cluster was then updated based on the assigned data points. This process was repeated until no point changed clusters. The clustering results were provided in Table 7 and Fig. 5.

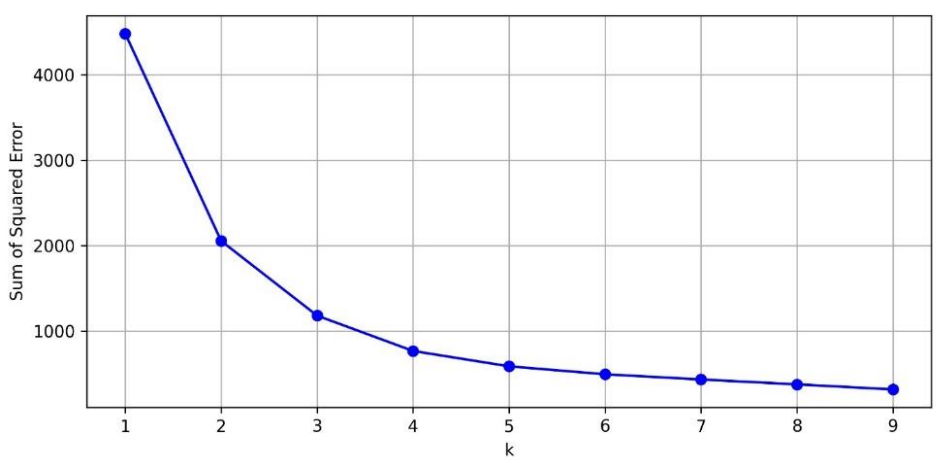

Fig. 4. Elbow method for finding the optimal number of clusters

Table 7. PASER, IRI, and OSCI Data Clustering Results and Status

No.	Cluster Centroid (PASER, IRI, OSCI)	PASER	IRI Range		OSCI Range		Condition Status
			Lower Bound	Upper Bound	Lower Bound	Upper Bound	
C1	(1, 13.07, 9.05)	1	9.81	18.18	8	9.08	Poor
C2	(3, 5.38, 7.15)	2, 3, 4	3.22	8.7	6	8	Fair to Poor
C3	(4, 3.39, 5.66)	3, 4, 5	1.26	5.65	4.5	6	Fair
C4	(6, 2.9, 3.87)	5, 6, 7	1.73	4.35	3	4.5	Good to Fair
C5	(8, 2.24, 2.29)	7, 8, 9, 10	1.26	2.81	0.1	3	Good

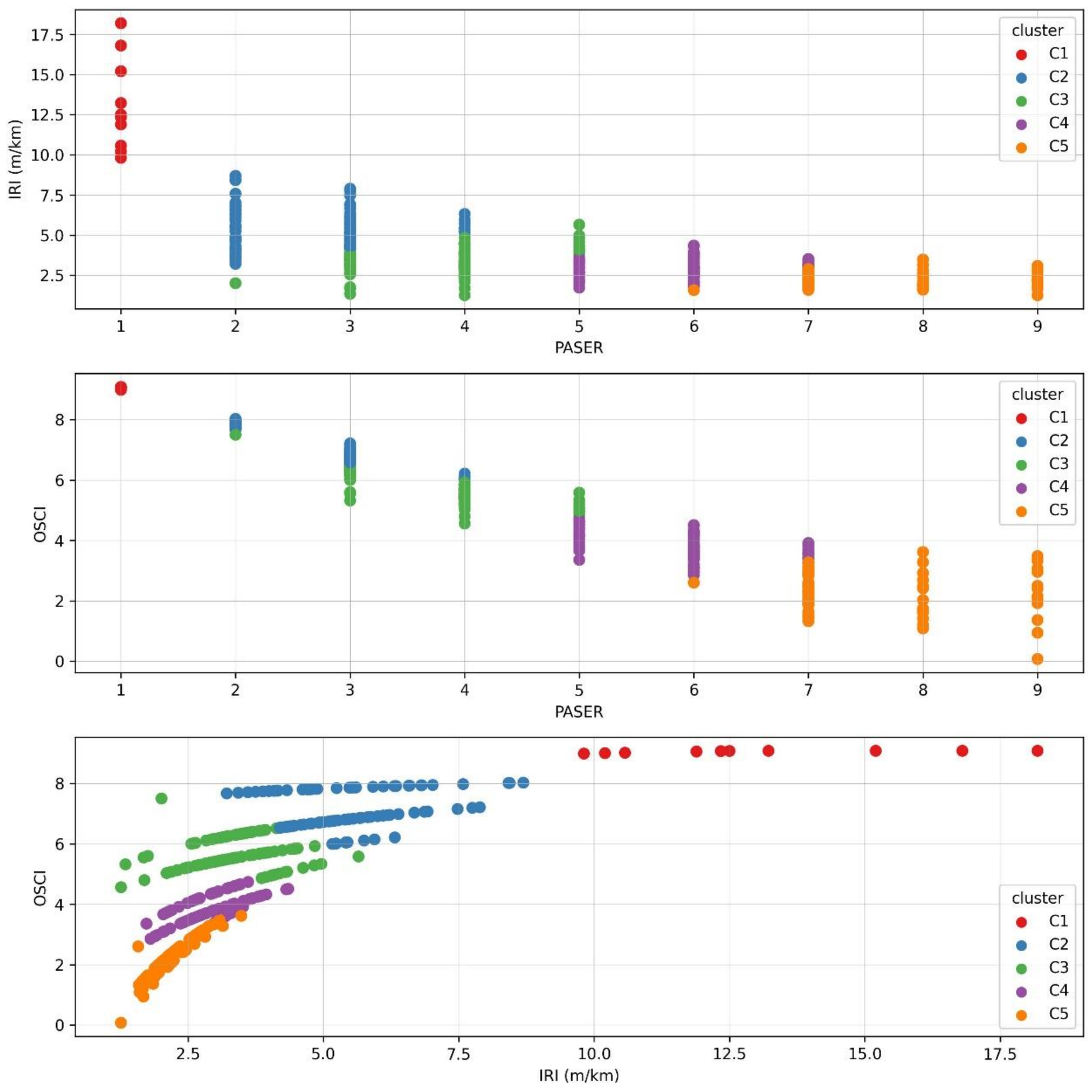

Fig. 5. PASER, IRI, and OSCI clustering with 5 centroids

Model Validation

After the development of the OSCI, the performance of the model was required to be examined in some sample sections in the field. In this case, five additional sections from the inspected routes were selected, that had not been incorporated in the model development. Then, they were assessed based on roughness (IRI) and surface distresses (PASER) in the same way that was noted in the data collection section. The treatments of all sections were assigned based on the maintenance strategies defined in the PASER manual for asphalt pavements and in compliance with the suggested interventions offered by ASTM E1926, HDM-4, and domestic research experiences for roughness improvement (Table 3). Hence, the conditions of the selected sections were initially investigated and rated based on IRI and PASER, then the OSCIs of all sections were calculated and the treatments were assigned according to the status specified for each section in Table 8.

Table 8. Overall Surface Condition Index Ranges and Required Treatments

OSCI Ranges	**Required Maintenance or Repair**
OSCI ≤ 3	No maintenance or routine maintenance required
3 < OSCI ≤ 4.5	Resurfacing
4.5 < OSCI ≤ 6	Thin overlay
6 < OSCI ≤ 8	Structural overlay
8 < OSCI	Reconstruction

The assigned treatments for all sections accompanied by the costs of the activities have been provided in Table 9 and Fig. 6 for PASER, IRI, and OSCI. The unit prices for all items related to a particular treatment were adapted from the price lists for the maintenance and construction of roads in Iran.

Table 9. Treatments and Costs of the Selected Sections Suggested by PASER, IRI, and OSCI

Section No.	**Length (m)**	**Index**	**Value**	**Treatment**	**Cost ($CAD)**
1	850	PASER	7	Routine maintenance, crack sealing	379
		IRI (m/km)	4	Resurfacing	6,617
		OSCI	4.33	Resurfacing	6,617
2	430	PASER	8	No maintenance	-
		IRI (m/km)	4.7	Thin overlay	3,495
		OSCI	4.59	Thin overlay	3,495
3	180	PASER	4	Structural overlay	2,438
		IRI (m/km)	2.3	No maintenance	-
		OSCI	5.12	Thin overlay	1,463
4	510	PASER	5	Resurfacing, sealcoat	3,970
		IRI (m/km)	3	Resurfacing	3,970
		OSCI	4.38	Resurfacing	3,970
5	810	PASER	3	Structural overlay	10,972
		IRI (m/km)	2.2	No maintenance	-
		OSCI	5.83	Thin overlay	6,583
Sum		PASER			17,759
		IRI (m/km)			14,082
		OSCI			22,128

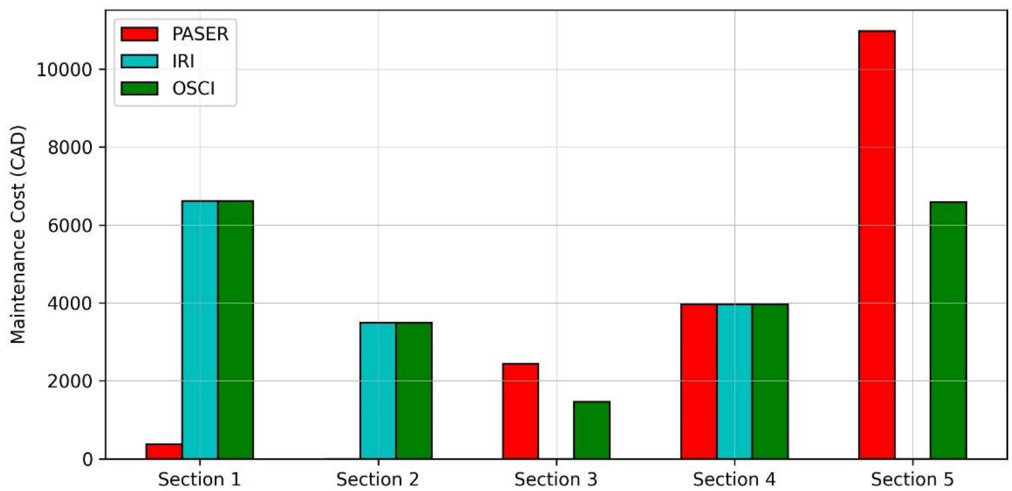

Fig. 6. Maintenance Costs of the Selected Sections Based on PASER, IRI, and OSCI

Discussion

To develop a combined condition index including PASER and IRI, first, the IRI quantities were converted to a scale from 0 to 10 as modified IRI (IRI_mod) shown in Table 4. As indicated in Figure 2 and Table 5, the natural logarithmic regression model indicated a desirable performance for the IRI between 1.36 and 12.7 m/km with R^2 = 0.989. Then, a pair of weighting factors, as illustrated in Table 6, with a summation of 1 was assigned by a panel of experts to five categories of PASER including two rates in each group with similar characteristics and treatment strategies. The impact of surface distresses in lower rates of PASER is more significant than roughness (IRI) so the weighting factor for PASER was expected to be higher than the one for IRI. For instance, for PASER 1 or 2, the proportion of the factors would be 9 to 1 in favor of PASER indicating the dominant impact of deteriorated surface in comparison to IRI. As PASER increases, the severity of distress is mitigated until no distresses or defects are visible on the pavement surface. Therefore, the IRI effect will become more sensible since more value of the weighting factor is assigned to IRI.

As indicated in Table 7 and Figure 5, the clustering of data points including the variables of PASER, IRI, and OSCI was conducted with five centroids using a k-means algorithm. The results expressed a reasonable clustering of data points in which the corresponding rates of all variables in each cluster had similar qualities and features. Regarding the acquired results of the clustering, the breakdown of OSCI was provided according to Table 8, in which the maintenance activities were specified based on surface conditions in terms of PASER and IRI.

The specified maintenance treatments and the associated costs for the new sections were provided in Table 9 and Figure 6 based on PASER, IRI, and OSCI. It can be observed that for sections 1 and 2, the suggested treatments by IRI outweighed the ones by PASER because of the strong undulation on the surface with slight or no distresses. In this case, the treatments suggested by OSCI mainly tended to the ones proposed by IRI. In sections 3, the surface condition was in fair condition according to PASER and the ride quality or roughness status indicated a relatively smooth pavement. The OSCI-recommended treatment (Thin overlay) seemed to strike a balance between the options recommended by PASER and IRI. This was because the road surface was not severely deteriorated to warrant a complete structural overlay, but it also wasn't in good enough condition to be left without maintenance. In section 4, it can be perceived that both indices, namely, PASER and IRI suggested similar approaches for repair, and consequently the suggested treatment and associated cost by OSCI were also the same as the others. This seems to be due to the almost similar effects of PASER and IRI in the OSCI formula which resulted in a unique treatment. Lastly in section 5, the surface was in poor condition according to PASER, that required a structural overlay. However, the roughness condition was sound enough that did not need any maintenance. The OSCI value in this section was 5.83, which suggested a thin overlay as a treatment, while the surface needed structural maintenance. This can be counted as a slight uncertainty in OSCI estimation, as the calculated OSCI was very close to the threshold of fair to poor condition category ($6 < OSCI \leq 8$) that would have suggested a structural overlay instead of a non-structural overlay. So, it can be observed that the treatments suggested by OSCI traded off the ones proposed by PASER and IRI. Furthermore, the total costs for maintenance of all five sections were estimated according to PASER, IRI, and OSCI as demonstrated in Table 9 and Figure 6. It appeared that the maintenance cost based on OSCI was significantly higher than the ones suggested by IRI and PASER. This means that the proper treatments for all sections were selected by OSCI, and the true costs of required maintenance were estimated. Therefore, OSCI could properly balance the lack of accuracy in evaluation based on the other indices.

Conclusion

In this study, the asphalt pavement distresses were evaluated by PASER, and the roughness (IRI) was measured by operating a high-speed profiler in Kermanshah province, Iran. Then, a combined condition index (OSCI) was developed that aggregates the PASER and IRI using the weighted summation method. The maintenance strategies for pavement sections were specified based on the three indices and the results are as follows:

- PASER and IRI individually cannot necessarily estimate the overall condition of the pavement, which constitutes improper decisions for maintenance and, consequently, the low quality of the pavement.
- OSCI can properly cover the deficiencies of the other two indices and determine an acceptable estimation of pavement conditions using these indices together.
- OSCI can successfully demonstrate the functional behavior of the pavement at the network level and propose appropriate maintenance activities.

As a suggestion for road agencies in estimating the OSCI, the PASER index can be used as a cost-effective condition monitoring approach in combination with IRI prediction models developed over the years of collecting IRI data instead of employing an expensive profiler to collect IRI. Therefore, the overall condition evaluation of road networks based on the OSCI index is expected to be completed more quickly and economically than any other approach.

Contributions and Limitations

This research was a preliminary step along with pavement maintenance management and ameliorating the survey procedure. The new contributions of this study were as follows:

- PASER was considered to evaluate the surface distresses through pavement images, which was more straightforward, more economical, and less hazardous than prevalent approaches like PCI.
- IRI values were transformed into a range of 0 to 10 similar to PASER rates, using a nonlinear regression model, so that the procedure for developing a combined index became sensible.
- The development of OSCI resulted in five different equations in various pavement conditions according to PASER categories instead of generating a single equation that would significantly increase the uncertainty.
- The condition status associated with OSCI values was specified using the k-means clustering algorithm and the corresponding values of PASER, IRI, and OSCI were obtained in five categories.

This work had also some limitations, namely:

- The study was conducted in a specific region in Iran and did not cover a broad range of locations.
- The number of routes for investigation was limited; hence, the dataset was not comprehensive.
- The historical information including layer thicknesses and maintenance activities for selected routes was not available which can negatively affect the condition evaluation of pavement and the assigned treatments.
- Other pavement assessment criteria such as structural condition evaluation can enrich the developed model and make a superior assessment for further maintenance.

References

1. Fakhri, M. and Dezfoulian, R.S. 2019. "Pavement structural evaluation based on roughness and surface distress survey using neural network model." *Construction and Building Materials*. 204: p. 768-780.
2. American Association of State Highway and Transportation Officials (AASHTO). 2012. *Pavement management guide*. Washington D. C.
3. Robinson, R., Danielson, U. and Snaith, M.S. 1998. "Road maintenance management: concepts and systems." Macmillan International Higher Education.
4. Shahin, M.Y. 1994. "Pavement management for airports, roads, and parking lots."
5. Pierce, L.M., McGovern, G. and Zimmerman, K.A. 2013. "Practical guide for quality management of pavement condition data collection."
6. ASTM D6433. 2020. *Standard Practice for Roads and Parking Lots Pavement Condition Index Surveys.* ASTM International.
7. Walker, D.E. 2002. "Pavement Surface Evaluation and Rating; PASER Asphalt Roads Manual." *Transportation Information Center University of Wisconsin-Madison*.
8. Sharma, M., Kumar, P. and Suman, S.K. 2019. "A review of pavement condition rating models for flexible pavements." *International Research Journal of Engineering and Technology*. 6(6): p. 2218-2223.
9. Kuhn, K.D. 2012. "Pavement network maintenance optimization considering multidimensional condition data." *Journal of Infrastructure Systems*. 18(4): p. 270-277.
10. Tighe, S.L., Ningyuan, L. and Kazmierowski, T. 2008. "Evaluation of semiautomated and automated pavement distress collection for network-level pavement management." *Transportation research record*. 2084(1): p. 11-17.
11. Zimmerman, K.A., Grogg, M.G. and Bozkurt, D. 2002. "Effects of maintenance treatments on asphalt concrete pavement management."
12. Tawalare, A. and Raju, K.V. 2016. "Pavement performance index for Indian rural roads." *Perspectives in Science*. 8: p. 447-451.
13. Juang, C. and Amirkhanian, S. 1992. "Unified pavement distress index for managing flexible pavements." *Journal of transportation engineering*. 118(5): p. 686-699.
14. Shoukry, S.N., Martinelli, D.R. and Reigle, J.A. 1997. "Universal pavement distress evaluator based on fuzzy sets." *Transportation research record*. 1592(1): p. 180-186.
15. Federal Highway Administration (FHWA). 2009. Pavement distress identification manual for the National Park Service Road Inventory Program. *FHWA Washington, DC*.
16. Pantuso, A., et al. 2019. "Analysis of pavement condition survey data for effective implementation of a network level pavement management program for Kazakhstan." *Sustainability*. 11(3): p. 901.
17. Reza, F., Boriboonsomsin, K. and Bazlamit, S. 2006. "Development of a pavement quality index for the state of Ohio."
18. Golroo, A. and Tighe, S.L. 2011. "Alternative modeling framework for pervious concrete pavement condition analysis." *Construction and Building Materials*. 25(10): p. 4043-4051.
19. Ndume, V., Mlavi, E. and Mwaipungu, R. 2020. "Development of Road Pavement Condition Index Using Combined Parameters." *Civil Engineering Research*. 10: p. 53-62.
20. Zhang, Z., Singh, N. and Hudson, W.R. 1993. "Comprehensive ranking index for flexible pavement using fuzzy sets model." *Transportation Research Record.* (1397).
21. Shah, Y.U., et al. 2013. "Development of overall pavement condition index for urban road network." *Procedia-Social and Behavioral Sciences*. 104: p. 332-341.

22. Semnarshad, S., Golroo, A. and Kavousi, A. 2021. "Development of a Pavement Overall Deterioration Index (Case Study: Iran)." *AUT Journal of Civil Engineering*. 5(3): p. 1-1.
23. Gharaibeh, N.G., Zou, Y. and Saliminejad, S. 2010. "Assessing the agreement among pavement condition indexes." *Journal of Transportation Engineering*. 136(8): p. 765-772.
24. Chou, C.-P. and Wu, C.-L. 1997. "Evaluation of panel characteristics and user-based pavement serviceability." *Transportation Research Record*. 1592(1): p. 98-106.
25. Garg, A., Horowitz, A. and Ross, F. 1988. "ESTABLISHING RELATIONSHIPS BETWEEN PAVEMENT ROUGHNESS AND PERCEPTIONS OF ACCEPTABILITY (WITH DISCUSSION AND CLOSURE)".
26. Nick, J. and Janoff, M.S. 1983. "Evaluation of panel rating methods for assessing pavement ride quality."
27. Riverson, J.D., et al. 1987. "Evaluation of subjective rating of unpaved county roads in Indiana." *Transportation Research Record*. 1128: p. 53-61.
28. Washington, S., et al. 2020. "Statistical and econometric methods for transportation data analysis." *Chapman and Hall/CRC*.
29. ASTM E1926. 2021. *Standard Practice for Computing International Roughness Index of Roads from Longitudinal Profile Measurements.* ASTM International.
30. Fakhri, M. 2010. "Determining International Roughness Index (IRI) for Roads in Iran." *Ministry of Road and Transportation: Transportation Research Institute*.
31. Archondo-Callao, R. 1996. "Applying the HDM-4 model to strategic planning of road works."
32. Neter, J., et al. 1996. "Applied linear statistical models."
33. Sahari Moghaddam, A., et al. 2020. "Estimating stripping of asphalt coating using k-means clustering and machine learning–based classification." *Journal of Computing in Civil Engineering*. 34(1): p. 04019044.
34. Wu, J. 2012. "Advances in K-means clustering: a data mining thinking." *Springer Science & Business Media*.
35. Barzegaran, J., Dezfoulian, R. S. and Fakhri, M. 2021. "Estimation of IRI from PASER using ANN based on k-means and fuzzy c-means clustering techniques: a case study." *International Journal of Pavement Engineering*. p. 1-15.
36. Syakur, M., et al. 2018. "Integration k-means clustering method and elbow method for identification of the best customer profile cluster." in *IOP conference series: materials science and engineering*. IOP Publishing.