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Condition assessment model for residential road networks

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Abstract. While the pavement rating system is being utilized for periodic road condition assessment in the Eastern Region municipality of Saudi Arabia, the condition assessment is costly, time-consuming, and not comprehensive as only few parts of the road are randomly selected for the assessment. Thus, this study is aimed at developing a condition assessment model for a specific sample of a residential road network in Dammam City based on an individual road and a road network. The model was developed using the Analytical Hierarchy Process (AHP) according to the defect types and their levels of severity. The defects were arranged according to four categories: structure, construction, environmental, and miscellaneous, which was adopted from sewer condition coding systems. The developed model was validated by municipality experts and was adjudged to be acceptable and more economical compared to results from the Eastern region municipality (Saudi Arabia) model. The outcome of this paper can assist with the allocation of the government's budget for maintenance and capital programs across all Saudi municipalities through maintaining road infrastructure assets at the required level of services.

Keywords: Analytical Hierarchy Process; condition assessment; mathematical model; municipality practices; road networks

1. Introduction

Infrastructure assets are regarded as the backbone of a healthy economy, providing crucial services for the populace (Pribyl *et al.* 2018). These high-capital intensive assets provide vital services that lay the foundations of socio-economic development and prosperity in a society e.g., roads, railways, airports, seaports, bridges, sewage, and pipelines, among others (Chen and Bai 2019, Kim *et al.* 2016). The infrastructure sector of the Kingdom of Saudi Arabia is arguably the largest in the Middle East region and is pivotal in developing clear strategic plans to revamp and diversify the country's economy. To stimulate economic growth, the Kingdom strategically invests heavily in large-scale infrastructure projects. This includes giving high precedence to infrastructure projects as part of the Kingdom's Vision 2030 despite depleted revenues due to expenditure on non-infrastructure projects as well as fluctuations in oil prices in international markets.

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Accordingly, enhancing the Kingdom's infrastructure assets to support sustainable socio-economic development requires expanding municipal utilities like road infrastructure. Remarkably, the road development projects for both new roads and upgrades of existing road networks have been receiving greater funding in more recent years due to the growing demand for affordable housing and rapid urbanization.

While the significance of infrastructure assets in promoting socio-economic sustainability cannot be overemphasized, residential road networks remain the primary arteries through which the economy of any community in a society pulse and are vital to any development agenda (Shereena and Rao 2019). Residential roads provide the basic interconnectivity and ease of access to improve socio-economic development and are generally referred to as the lifelines for a community's growth and development. Remarkably, the quality of life in a society is often influenced by the safety of its road networks, which directly promotes sustainable socio-economic activities therein (Shahi *et al*. 2017, Nagarajaiah and Erazoa 2016). This calls for effective management of road infrastructure as well as strategic planning of road transportation. Although residential road maintenance is capital and labor intensive, nonetheless, the residential road networks should be proactively maintained regularly to curtail the rates of accidents and ensure the desired level of service. Thus, ascertaining the condition of residential road networks and managing it effectively can help to sustain the desired level of service, which will require obtaining valid and reliable information on the condition of the roads (Shereena and Rao 2019).

The condition of road infrastructure refers to the measurement of the road's physical state. In essence, road condition assessment is the evaluation of the roads throughout the period of their service validity (Stricker *et al*. 2019). Accordingly, required maintenance pavement programs can be decided by knowing the road condition (Li *et al*. 2018).

While the pavement rating system is being utilized for periodic road condition assessment in the Eastern Region municipality of Saudi Arabia (Dammam Municipality 2017), the condition assessment is costly, time-consuming, and not comprehensive as only a few parts of the road are randomly selected for the assessment. There is also the issue of high variability due to the subjective and inaccurate assessments produced by less experienced evaluators. The high variability could also be attributed to the non-utilization of technologies for the assessments and various individuals engaged to assess the road condition. These existing practices do not in any way provide reliable and valid results required to develop an effective maintenance management plan for the road. The road condition assessment becomes difficult to conduct and requires decisions that may not be made at the right time. Not that alone, there is hardly an established strategy that can systematically provide the approach to adopt in assessing the condition of road infrastructure particularly residential road networks. This makes it difficult for the policymakers to allocate resources and provide the required budget to adequately support various road management programs.

Given this, this study is aimed at developing a condition assessment model for a specific sample of a residential road network in Dammam City based on an individual road and a road network. Further, the obtained results from individual road networks will be compared and the developed model will be validated by municipality experts. The outcome of this paper can assist with the allocation of the government's budget for maintenance and capital programs across all Saudi municipalities through maintaining road infrastructure assets at the required level of services.

2. Review of road condition assessment models

The For any nation to witness significant socio-economic growth, it is essential to have effective road infrastructure in place and ensure that condition of the roads is up to the expected level (Li *et al*. 2016, 2014). Examining the road condition is fundamental to the road management process as it affects the safety, serviceability, and maintenance needs of the roads (Abu-samra *et al*. 2017). Various road condition assessment models have been developed to help control and regulate the basic processes of assessing the condition of roads (Dabous *et al*. 2019). The theory of evidential reasoning was applied by Dabous *et al*. (2019) to investigate conditions of the road and used the evidential reasoning approach to examine a distress-based condition assessment technique. The authors developed a condition matrix to investigate the basic probability of road conditions according to the severity level of various distresses identified in a road structure. Singh *et al*. (2018) developed a strategy for examining road conditions that adopt an array of performance indicators to assess various aspects of road performance. Roads with low scores tend to have a high chance of being scheduled for repairs based on the significance of the road and the availability of funds. Radopoulou and Brilakis (2017) used vehicle dynamic sensor data to understand the roughness of a pavement surface and estimating pavement profile. Staniek (2017) provided a solution for automatic asphalt pavement cracking detection based on image-processing technology whereas Buza *et al*. (2017) developed an unsupervised method for detection of high-severity distresses on asphalt pavements.

Similarly, Kırbaş and Karaşahin (2016) developed a distress-based model and assessed pavement condition indices for different segments of some roads that were subjected to various surface distress and later used the findings to examine the interrelationship between pavement condition indices and ride comfort of road users. Wu *et al*. (2016) proposed a novel crack defragmentation technique to evaluate pavement images while Hassan *et al*. (2015) developed the surface inspection rating index to analyze the surface conditions of roads based on distress records obtained from condition assessment surveys.

Although the contributions of the authors mentioned before now cannot be overestimated, yet most of these developed models and strategies require expensive tools, high level of expertise and are in most cases difficult to use particularly when dealing with residential road networks constructed on problematic soils. While the difficulty associated with the quantifications of road conditions is acknowledged in this study; mathematical modeling will be employed to examine and analyze the road conditions. This is expected to help in reducing the level of inconsistency in subjective judgment processes and provide a valid and reliable condition assessment for the roads. To do this, it is important to know some of the defects that affect road condition and the current practices adopted in conducting road condition assessments in the Eastern Province of Saudi Arabia.

2.1 Road defects

Despite the high significance of road networks to society, once the roads are constructed, their condition deteriorates over time (Rogulj *et al*. 2021). This calls for proactive intervention works in order to ensure satisfactory performance throughout their design life. Road defect simply refers to the noticeable indication of an unwanted condition in the road affecting its appearance, structural condition, or serviceability (Jia *et al*. 2021). A careful examination of the road is required to make a correct diagnosis of the causes of the defects.

Table 1 Types of road deterioration

Cracking	Surface deformation	Disintegration	Surface defects
Fatigue cracking	Rutting	Potholes	Raveling
Longitudinal cracking	Corrugations	Patches	Bleeding
Transverse cracking	Shoving		Polishing
Block cracking	Depressions		Delamination
Slippage cracking	Swell		
Reflective cracking			
Edge cracking			

Table 2 Severity grades for Water Research Centre (WRc) protocol

Condition grade	Description	Peak structural defect score found in a segment	Peak operational defect score found in a segment
1	Acceptable condition	< 10	< 1
2	Minimal collapse risk but potential for further deterioration	10-39	1.0 – 1.9
3	Collapse unlikely but further deterioration likely	40 - 79	2.0 – 4.9
4	Collapse likely in near future	80 - 164	5.0 – 5.99
5	Collapse imminent or collapsed	165 and above	> 10

The distribution of defects is based on their effect on the road (Espinet *et al*. 2017, Bäckman *et al*. 2005). Since the proposed residential road and network assessment model will be developed according to the defect types and their levels of severity; the categorization of the defect into the structure, construction, environmental and miscellaneous was adopted from the sewer coding system used by Chughtai and Zayed (2011). The authors established a system score to determine the condition of sewers using a CCTV camera. The system identifies sewer defects based on four categories: structural, operational, construction and miscellaneous. Each category includes several defects. For instance, structural defects include cracks, holes, deformation, etc., while operational defects include roots, debris, obstruction, etc. Further, each factor has a deductible value. The final deductible value is the summation of all defect scores. Accordingly, a condition grade is obtained, as seen in Table 2.

By way of affirmation, it should be pointed out here that the proposed residential road and network assessment model will be developed according to the defect types and their levels of severity; the categorization of the defect into the structure, construction, environmental and miscellaneous was adopted from sewer coding system. Although the defect classification may appear quite simple, it is the intent of the researchers to ensure the ease of application among all level of practitioners, who work in this field. More so, while the defect classification does not include the influence of many defects, it should be noted that the major categories of the defects and their factors have been duly identified. Nonetheless, the developed mathematical model is flexible to add more defects if it is necessary. The developed model is based on the AHP method and the objective of AHP is to compare the importance of the categories and factors through pair-

Table 3 Serial numbering system

City		Zone		Area			Road			Section			Direction		Feature	
0	1	0	2	0	1	4	0	2	6	0	0	1	0	1	0	1
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17

wise comparisons; and therefore the influence already exists.

2.2 Current practices

The pavement management system (PMS) is utilized for road condition assessment in the Eastern Region municipality of Saudi Arabia. The condition assessment is conducted periodically, specifically every 3 years. The process of obtaining a road condition assessment entails sending surveying teams to the roads to collect physical data (i.e., distress and defects from the roads based on and then recording data collected from specific surveying forms as shown in Table 3. The form includes a table, which is divided according to a serial numbering system.

The road evaluation can be carried out by dividing it into segments, just as shown via Equation 1. The “300” is a constant value that represents the unified area of the segment. Two factors are considered to obtain required samples of roads to be inspected. The first factor is 25%, which represents road scanning and inspection for a regular overview of the condition and budget estimation. The second factor is 50%, which is used when an operation or maintenance needs to be established, thereby requiring the inspection of more detailed samples as in Eq. (2).

$$\text{Number of Segment} = \text{Area of } \frac{Road}{300} \tag{1}$$

$$\text{Number of Segment} = \text{Factor} \times \text{Number of Segments} \tag{2}$$

The level of severity is divided into low, medium, and high. Each defect has a unique code for identification by Dammam Municipality (2017). Consequently, the density of the defect and a “deductions” value will be generated. Once all deducted values have been obtained, they are summed and then subtracted from 100% (condition of a new road). The final number represents the Pavement Condition Index (PCI). Fig. 1 depicts the processing steps of a PMS.

Using MicroPaver software, the final output is a color representing the condition of the inspected sample of the road (Onyango *et al*. 2018). MicroPaver is an integrated software suite with a Geographic Information System (GIS) map. The condition is labeled depending on the PCI value, where each color has a unique significance and specific responses, as shown in Fig. 2.

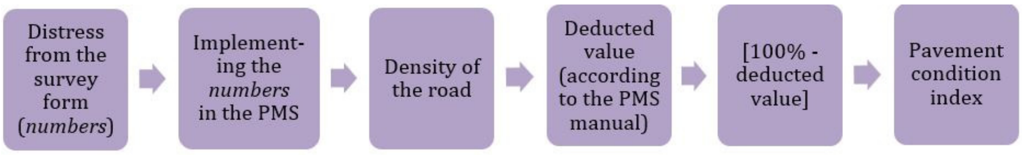

Fig. 1 Pavement management system

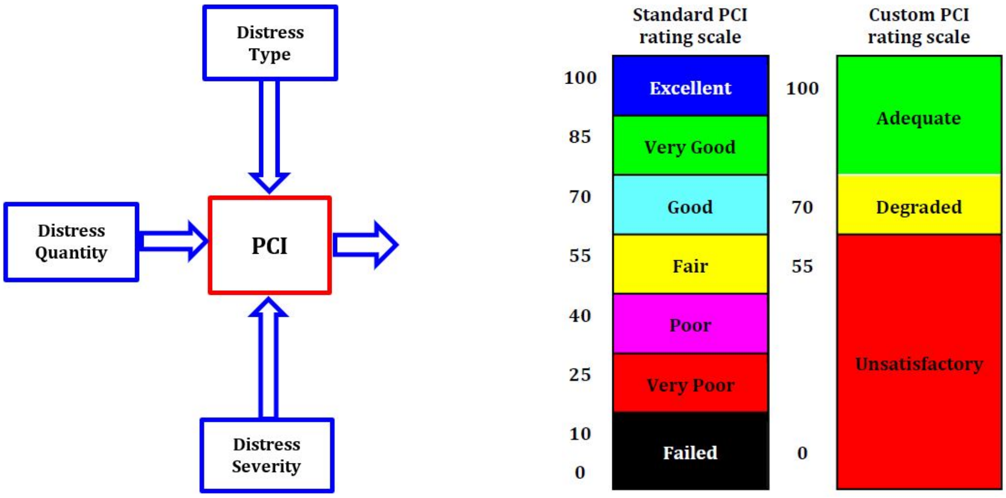

Fig. 2 Condition rating (Source: PMS Manual 2017)

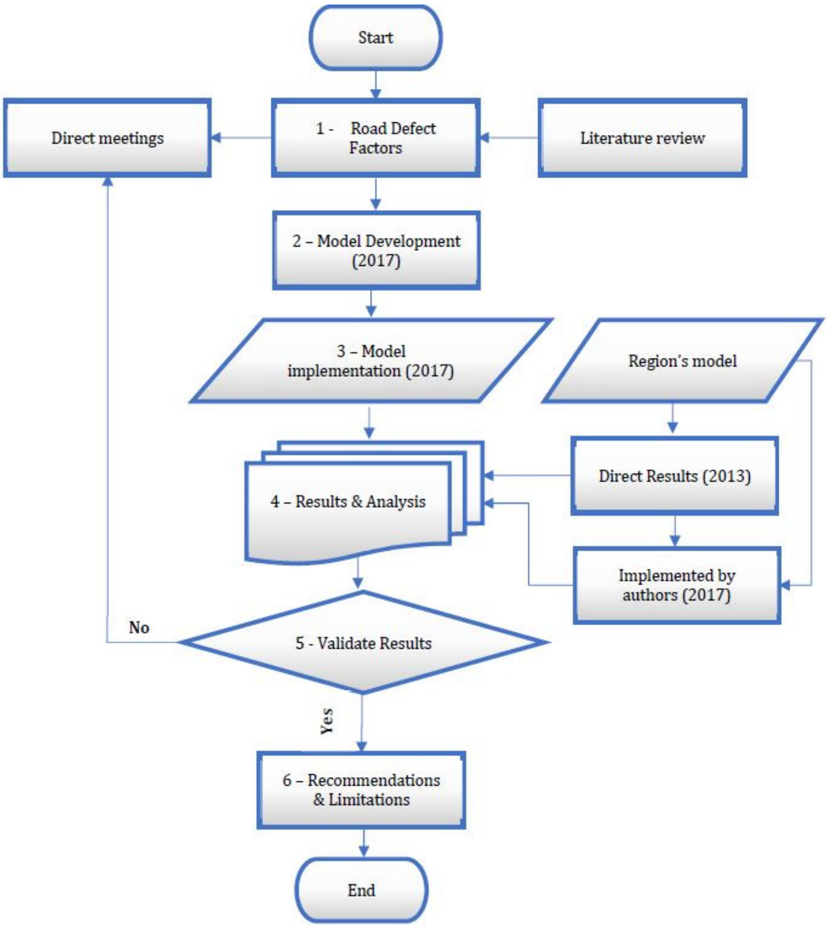

Fig. 3 Residential road condition assessment methodology

3. Methods

Fig. 3 outlines the main components of the developed models, which are undertaken in six stages. The first stage involves studying, collecting, and identifying road defect factors. This is based on two primary sources; an extensive literature review and direct meetings with several managers and engineers in the field of transportation and construction management. The second stage entailed developing the mathematical model is developed at this stage. The Analytic Hierarchy Process was applied to develop the mathematical model of a road and network condition assessment. Further in stage three, road samples were selected in the Eastern Province municipality of Saudi Arabia to implement the developed model. In parallel, the authors utilized the model that was adopted by the municipality. To do this, the direct condition assessment results of 11 roads were found, which were dated to 2013 and the authors then utilized the same procedure and model to obtain the condition assessment of the same roads in 2017. At the fourth stage, the results and analysis of the developed models were completed, and the results were compared to two sets of results of the municipality. Consequently, the results were validated by the municipality managers and engineers and recommendations and limitations were reported based on the obtained results of the developed model in the last stage.

4. Residential road condition assessment methodology

Managing tens of kilometers of roads is not an easy task, it needs huge resources, time, and effort and therefore, the mathematical model is required to help to manage such roads. The developed model helps decision makers, engineers, and technicians to identify roads based on their mathematical condition assessment and implement the suitable strategy accordingly. The development of residential road condition assessment includes three stages; the first stage is building a failure hierarchy of a residential road. The hierarchy includes four categories: structure, construction, environmental, and miscellaneous. These four categories are adopted from a sewer condition protocol (Chughtai and Zayed 2011). The second stage is developing a mathematical model to obtain the condition assessment value. The final stage is translating the condition assessment value to a subjective condition.

4.1 Defect hierarchy

Fig. 4 depicts a hierarchy of residential road defects. The defect hierarchy includes four categories with their factors. A road with specific defects can be visualized easily based on each defect.

4.2 Development of mathematical model

Eq. (3) is applied to obtain the defect score of an individual residential road. It includes three parameters: weight (w), score (s), and defect frequency (Q) of each defect. The weight is the generic value of a defect, which is in the range of 0.0 - 1.0. The AHP is employed to identify the weight (Masoumi *et al*. 2017). It is selected because it is easy to be applied and results can be obtained rapidly. The defect score is a specific value, which has a range of 1-100. Each defect can be categorized into three types according to size, severity, or effect, just as illustrated in Table 4. Low, Medium, and High are given scores of “10”, “30” and “60”, respectively. For instance, more

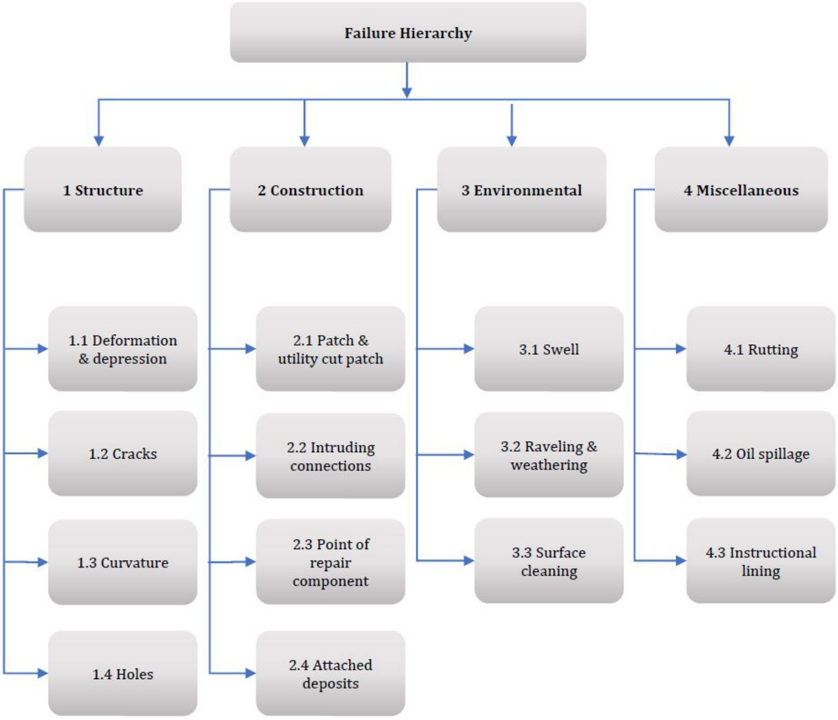

Fig. 4 Road defects hierarchy

than 150 mm of a hole is considered "High", and therefore is given a score of "60". The third parameter of Eq. 3 is the frequency of a defect. For instance, a road has 3 cracks, hence Q is equal to "3". By multiplying defect weight, score and frequency, a defect score is obtained. Adding the scores of all the defects, the defect score (DS) is identified for each individual road. If the "DS "is more than 100, it can be considered 100. A score of 100 is the maximum defect score of a residential road. Equation 4 represents the condition assessment value of an individual residential road. If an inspected road has no defect, the condition assessment value is maximum, which is 100 in this case. One defect or more means that the condition assessment value is less than 100, and might reach 0, when the defect score is maximum (DS = 100). To establish the condition assessment of a residential road network, Eq. (5) is applied. Each individual road in the network shares its part of the network condition assessment based on its area. When the road area is large, the opportunity of obtaining a defect will be great, as well, and vice versa.

The final weights from the entire 21 questionnaires was obtained using the AHP. The number of the questionnaires analyzed is considered sufficient for an expert-based study of this nature involving the use of AHP (Dano 2020, Saaty and Özdemir 2014). Each pair of the defects was compared based on the respondent's judgments denoted by $n\ (n - 1)/2$, where n indicates the number of the experts in the matrix. By adopting the pairwise comparison technique, the significance of each defect was obtained. Subsequently, the comparison matrix output was utilized to obtain the strength of the AHP analysis performed for the road condition assessment model. For instance, if the score of the calculated matrix is K, the priority weight is acquired from an equation Kw = λmax, w, where w and λ indicate eigenvector and eigenvalue, respectively (Dano 2020). Accordingly, based on the output of the generated pairwise comparisons, the largest eigenvalue

Table 4 Defect severity according to experts' opinions

Assign score (for the developed model)					10	30	60
Code	Category	Factor	Definition	Unit	Low (L)	Medium (M)	High (H)
1.0	Structure						
1.1		Deformation and depression	Settlement in foundation and collection of water	%	5	30	70
1.2		Cracks	Longitudinal separation of asphalt layer	mm	2-5	5-10	> 10
1.3		Curvature	Displacement in parts of the sections of the street horizontally	°	1-5	5-10	> 10
1.4		Holes	A gap with depth within the road	mm	< 90	90-150	> 150
2.0	Construction						
2.1		Patch and utility cut patch	Shape with convexity or concavity	cm	< 2	2-5	> 5
2.2		Introducing connections	Projection in the transitional area between streets	cm	0.1-2	2-5	> 5
2.3		Point of repair component	Change in construction material, dimension, shape or point repair curvature	Yes/No	No		Yes
2.4		Attached deposits	Material attached to the surface	m^2	< 1.0	1-2	> 2
3.0	Environment						
3.1		Swell	Frost action in sub-grade	cm	< 4	4-6	> 6
3.2		Raveling and weathering	Wearing of the pavement surface by loss of asphalt binder	Yes/No	No		Yes
3.3		Surface cleaning	Presence of solid deposits on the surface	%	< 10	10-20	> 20
4.0	Miscellaneous						
4.1		Rutting	Surface depression in wheel path	Yes/No	No		Yes
4.2		Oil spillage	Spillage of oil or other solvents	Yes/No	No		Yes
4.3		Instructional lining	Inability to recognize the instructional lines in the road	Yes/No	No		Yes

indicated by λmax, which indicates the consistency index (CI) of the matrix is computed as CI = (λmax − n)/(n − 1). Likewise, a consistency ratio (CR) was obtained to analyze the reliability of the experts' judgments using an equation represented by CR = CI/RI, where RI implies random inconsistency. The value of the CR is considered reliable when it does not go above 0.10 though, if the value surpasses 0.10, the set of judgments are presumed to be unreliable. The last stage is the calculation of the relative weights obtained from the local priorities of each defect, which was done by computing the average of all scores in each row of the normalized comparison matrix.

$$DS_k = \sum_{j=1}^{m} \sum_{i=1}^{n} W_j \times S_{ij} \times Q_{ij} \quad \text{if} \quad DS_k > 100, \quad \text{then} \quad DS_k = 100 \tag{3}$$

$$CA_k = 100 - DS_k \tag{4}$$

$$CA_N = \sum_{k=1}^{K} \left[\left(\frac{a_k}{A} \right) \times CA_k \right] \tag{5}$$

where

$\boldsymbol{DS_k}$: defect score of road $\mathrm{k^{th}}$, $(0.0 - 100)$
$\boldsymbol{W_j}$: weight of road defect based on expert's judgment. It is obtained using AHP
$\boldsymbol{S_{ij}}$: score of road defect. It is identified directly by the term (L: 30; M: 30; H: 60)
$\boldsymbol{Q_{ij}}$: number of same defects on the same road.
$\boldsymbol{CA_k}$: condition assessment score of road $\mathrm{k^{th}}$, $(0.0 - 100)$.
$\boldsymbol{m}$: total defect category (j).
$\boldsymbol{n}$: total defect factor (i)each category (i).
$\boldsymbol{CA_N}$: condition assessment score of residential road network, $(0.0 - 100)$.
$\boldsymbol{a_k}$: area of road $\mathrm{k^{th}}$.
$\boldsymbol{K}$: total number of roads in each network.
$\boldsymbol{A}$: area of a road network.

4.3 Development of subjective condition scale

The condition score of a residential road ($\boldsymbol{CA_k}$) and network ($\boldsymbol{CA_N}$) will be evaluated using the developed subjective condition scale, as shown in Fig. 5. The scale reflects the condition of a road and network according to its condition assessment numerical value. When the condition assessment value of a road (or a network) is below 50, then its condition is poor, and required action should be taken accordingly. The scale is not divided into the same ranges because that the consequences of poor conditions are very high.

4.4 Model implementation

To implement the developed mathematical model in the previous section, a case study is required to implement it. With the cooperation of the Eastern region municipality, a network of 11 connected roads in Dammam (Saudi Arabia) was selected, as portrayed in Fig. 6. The roads were inspected, and the developed mathematical model was applied to obtain the results. The structural periods of the selected buildings were ≤ 1.0 seconds and these were.

4.5 Data collections

Table 5 lists the collected required data to implement the developed model. It is divided into two categories. The first is related directly to the road, such as the road samples, their dimensions and defect type and severity. Such data can be collected directly by technicians or using new technologies. The second category is subjective via a questionnaire. Both set of data are utilized

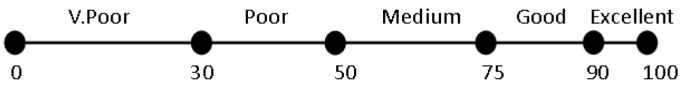

Fig. 5 Subjective condition scale

Fig. 6 Google map of the selected road network

Table 5 Data collection

Target	Road network sample		Subjective criteria	
Data source	Direct from the field		Questionnaire	
	Name	Unit	Name	Unit
Collected data	Road samples	No.	Pair wise comparison of defects (Fig. 7)	1-9
	Road dimension	m	Defect severity (Table 3)	
	Defect	Type		
	Defect severity	L; M; or H		
	Defect frequency	No.		

individually to determine the condition assessment of each road.

Table 6 features the actual data obtained directly from the field. Each type is given a score according to its type, the severity of this defect (L, M, H) and the frequency of this defect. For instance, Road 6 has defect 1.1 (deformation and depression). This defect is repeated three times but with different severities - Low, Medium, and High. Therefore, the defect score is 100 (10 for low + 30 for medium + 60 for high).

Table 7 shows a sample of a questionnaire sent to experts to complete the pair-wise matrix for the defect factors and categories. Each expert filled the cells below the diagonal to supply an opinion regarding the relative importance between each of the two defects. The questionnaire was sent to more than 50 experts in the field of transportation and construction management - 21 responses were collected.

The weights of the defect categories and factors obtained through the AHP method are shown in Table 8. Structure defects have more weight than other categories - 55% of the total weight. Meanwhile, construction defects have a second weight, being 24%. The environment is the third defect category at 12%. Finally, miscellaneous had the lowest weight at 9%. For the structure

Table 6 Road data collection

Road No.	3	4	5	6	7	8	9	21	23	178	180
Width (m)	12	14	11	12	7	7	12	13	15	19	7.5
Length (m)	883.2	59.8	156	149.7	67	66.5	159.5	220.3	419.8	60.1	30.5
Defect 1.1	L,M,H		L,M,H	L,M,H		H		L,M,H	M,H		2M,2H
Score	100		100	100		60		100	90		180
Defect 1.2	L,M	2H	L,M,H	L,H	L,H	L	3H	L,M,H	L,M	L,H	2H
Score	40	120	100	70	70	10	180	180	40	70	120
Defect 1.3											
Score											
Defect 1.4	M,H	L,2H	H	H			2H	M,H	M,H	2H	
Score	90	130	60	60			120	90	90	120	
Defect 2.1	L,M	L,M,H	H	L,M,H	L	L	2H	L,M,H	L,M		
Score	40	100	10	100	10	10	120	100	40		
Defect 2.2	L		L,M	H	L	L	H	M	L,H		
Score	10		40	100	10	10	60	30	70		
Defect 2.3	M,H		L,M	L,M,H		M	H		M,H		
Score	90		40	100		30	60		90		
Defect 2.4	L,H	2H	M	H	L	2H	H	L,M	M,H		H
Score	70	120	30	60	10	120	60	40	90		60
Defect 3.1	L,M		H				H	H			
Score	40		60				60	60			
Defect 3.2	L,M,H	L	M	M		M	H		L,M,H		
Score	100	10	30	30		30	60		100		
Defect 3.3					L		H		L		
Score					10		60		10		
Defect 4.1											
Score											
Defect 4.2											
Score											
Defect 4.3	H	H	H	H	H		H	H	H	H	H
Score	60	60	60	60	60		60	60	60	60	60

Table 7 Sample of the distributed questionnaire

Structure	Deformation & Depression	Cracks	Curvature	Holes	**Weight**
Deformation & Depression	1.00	0.59	0.67	0.56	**0.16**
Cracks	1.70	1.00	0.77	0.59	**0.23**
Curvature	1.50	1.30	1.00	0.56	**0.24**
Holes	1.80	1.70	1.80	1.00	**0.37**
Sum	**6.00**	**4.59**	**4.24**	**2.70**	**1.00**

Table 8 Defect weights based on the AHP method

Code	Category	Factor	Weight
1.0	Structure		0.55
1.1		Deformation and depression	0.20
1.2		Cracks	0.22
1.3		Curvature	0.25
1.4		Holes	0.33
2.0	Construction		0.24
2.1		Patch and utility cut patch	0.20
2.2		Introducing connections	0.24
2.3		Point of repair component	0.26
2.4		Attached deposits	0.30
3.0	Environment		0.12
3.1		Swell	0.28
3.2		Raveling and weathering	0.33
3.3		Surface cleaning	0.39
4.0	Miscellaneous		0.09
4.1		Rutting	0.29
4.2		Oil spillage	0.33
4.3		Instructional lining	0.40

Table 9 Calculations of Road "4"

Defect category	Structure				Construction				Environmental			Miscellaneous		
Defect code	1.1	1.2	1.3	1.4	2.1	2.2	2.3	2.4	3.1	3.2	3.3	4.1	4.2	4.3
Defect size & number		2H		L,2H	L,M,H			2H		L				H
Score		120		130	100			120		10				60
Factor weight	0.2	0.22	0.25	0.33	0.20	0.24	0.26	0.30	0.28	0.33	0.39	0.27	0.33	0.40
Category weight	0.55				0.24				0.12			0.09		
Category defect score	38.28				13.43				0.40			2.14		
Road defect score	54.24													
Road condition assessment	45.76													
Road condition	Poor													

category, holes have the maximum weight, which is 33%. In construction, attached deposits have the maximum weight, being 39%. For Environment defects, surface cleaning has the maximum weight, which is 39%. Finally, the instructional lining had the maximum weight in the miscellaneous category at 40%.

4.6 Final results

Table 9 depicts a calculation sample of Road 4. The dimensions of the road are 14 m in width and 59.8 m in length. Therefore, the area is 837.2 m². The total area of the 11 roads is 28,324.55 m², which is used in the calculation of the condition assessment of the road network. Road 4 represents 3% of the total area of the network.

According to the direct inspection of Road 4, six types of defects were found as follows:

- Defect 1.2: two big cracks. The score is 2 by 60, which is 120.
- Defect 1.4: one small hole and one big hole. The score is 1 by 10 plus 2 by 60, which is 130.
- Defect 2.1: small, medium, and large sizes of patch and utility cut patch. The score is 1 by 10, 1 by 30, and 1 by 60. The total score is 100.
- Defect 2.4: two large-sized attached deposits. The total score is 120.
- Defect 3.2: one small size raveling and weathering. The total score is 10.
- Defect 4.3: one large size of the instructional lining. The total score is 60.

By applying Eq. (3), the total defect score of Road 4 is 54.24. Moreover, its condition assessment is 45.76 according to Eq. (4). This score is more than 30 and less than 50, and therefore the condition of this road is "Poor". The condition assessment of the network is 48.8, which is definitively considered poor. This result was obtained using Eq. (5). It is based on the summation of the multiplication of the condition assessment of each road by its area percentage. For instance, Road 4 contributes to the condition assessment of the network by the value equal to 3% by 45.76. Figs. 7 and 8 illustrate the final results of the 11 residential roads and the road network. Each road has three values - the first value is according to the municipality practice in 2013, the second value shows the result of the team according to the same model of the municipality practice in 2017 and the third value is obtained from the developed mathematical model. Furthermore, the road network is determined via the three models (the last three columns in Fig. 7).

The condition assessment of all roads in 2013 is better than in 2017. The exceptions are Road 7 and Road 8 owing to maintenance activities after 2013. The differences between the second and third models (developed model) are slight. The maximum difference occurred for Road 23, specifically where the difference was roughly 11%. The reason for this is related to a large number of defect types and severities found in this road, which may affect the results. Additionally, the

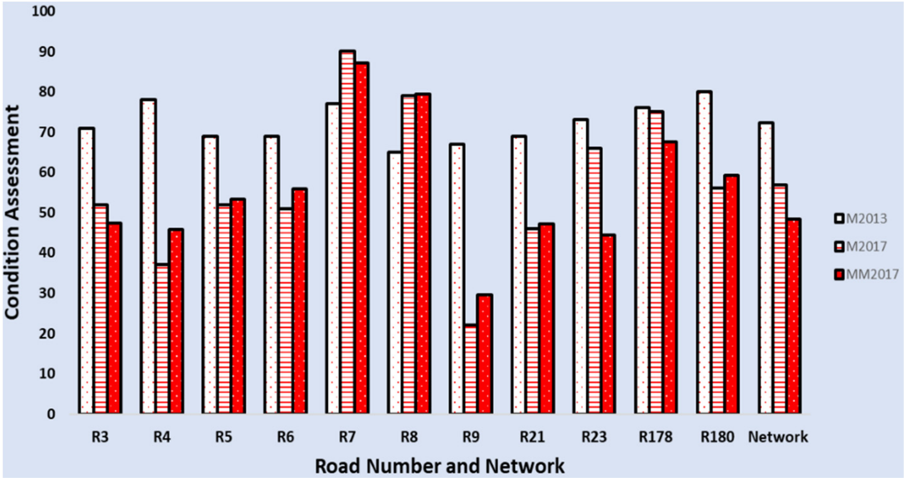

Fig. 7 Final results of road and network condition assessment (Left: direct region results, 2013; Middle: region practice, 2017; Right: de+veloped mathematical model, 2017)

Fig. 8 Final results (GIS application) (Left: direct region results, 2013; Middle: region practice, 2017; Right: developed mathematical model, 2017)

Table 10 Final results of condition assessment model for residential road networks of the selected sample

Model	Road Number											Network
	3	4	5	6	7	8	9	21	23	178	180	
1 (2013)	M	M	M	M	M	M	M	M	M	G	G	M
2 (2017)	M	P	M	M	E	G	VP	P	M	G	M	M
3 (2017)	P	P	M	M	G	G	VP	P	P	G	M	P

difference is found in the results for Road 9, however, both models offer indications that the road is in very poor condition. The final conditions of the 11 roads and the network using the three models are depicted in Table 10. Based on the large difference in Road 23, the condition of the network is modified accordingly. Though it is graded Medium in the second model, it is poor in the developed mathematical model.

4.7 Model validations and limitations

The results of the developed model were introduced to several experts. The feedback was based on comparing the final results of the developed model with the results of the municipality model (obtained in 2013 and 2017) and checking the actual condition of the selected residential roads directly. The developed model, according to the experts, yielded more satisfactory results. Although the model is cost-effective, practical, and less complicated than the current practice of the municipality; the model can still be modified to include other types of roads since the developed model is suitable for residential roads only. More so, considering the traffic flow, the current model was developed based on the same capacity of the roads. Not that alone, the road thickness and pavement materials were presumed to be the same for all roads. Thus, future research shall be expanded to cover these limitations.

Although the selection of model can be considered relatively simple, and the classification of weight factors not very pertinent, it should be emphasized here that the selection of the mathematical model is to help decision makers, engineers, and technicians to identify the condition assessment of the roads mathematically, it is not complicated to l*et al*l practitioners understand the concept and accordingly implement it. The classification of the weight factors is necessary to calibrate the model based on the type of defects, which are studied thoroughly.

5. Conclusions

A new residential road and network assessment model was developed according to the defect types and their levels of severity. The categorization of the defect into the structure, construction, environmental and miscellaneous was adopted from the sewer coding system. Each category was divided into several factors (defects), and each factor was divided into Small, Medium, and High severity. Accordingly, scores were allocated among these factors to represent severity. The AHP was utilized to determine the generic weights of these factors and categories to develop the condition assessment of the roads. It is necessary to mention that the AHP method is relied on expert opinions, and the results might be changed accordingly. However, checking the consistencies of the developed matrices, which is part of the AHP process ensures that the differences in the final results of the residential road condition assessment are considerably minimized. The Eleven residential roads in Dammam city (Saudi Arabia) were chosen to implement the developed model. The obtained results of the developed model were found to be acceptable and more economical compared to results from the Eastern region municipality (Saudi Arabia) model.

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