Assessment of Pavement Performance Management Indicators Through Analytic Network Process

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***Abstract*—Pavement industry is very critical for any public authority looking after the safety and comfort of its citizens because it is the backbone of many transportation networks. Studying the factors that affect the pavement performance is essential to increase the lifetime of pavement. The objective of this article is to identify the factors that affect pavement performance and rank their effect. From a detailed literature review, 29 factors are identified and a questionnaire is developed to examine perceptions of the industry professionals about the importance of each factor on pavement performance. A total number of 205 completed responses are collected. The collected data are analyzed by relative importance index and a multicriteria decision-making method, analytic network process. Based on the data analysis, it is found that the most three significant factors are related to surface conditions, namely, "high percentage of cracks," "extremely rough road surface," and "high rut depth." The outcome of this article will help the professionals in the pavement industry to improve pavement performance, extend the expected pavement life cycle, and reduce the maintenance requirements.**

***Index Terms*—Analytic network process, pavement distresses, pavement management, pavement performance, sustainability.**

I. Introduction

One of the main areas of awareness for a road infrastructure manager is to increase its efficiency under limited resources [22]. The pavement performance is a very complicated process because it is affected by many factors. Although these factors are various in kind, they are interrelated to each other and affect the pavement performance directly or indirectly. Therefore, an accurate method is needed to identify the most critical factors affecting the pavement performance to guide pavement experts to design economical roads with longer expected life and lower maintenance needs.

The objective of this article is to identify the factors that affect the pavement performance and rank their effect on pavement performance. This study differs from others in the literature by defining a broad list of performance indicators and analyzing them by defining relationships between them to assess the most critical factors. Consequently, the factors are ranked based on the importance of their effect on pavement performance according to analytic network process (ANP) to employ an effective management system and determine the most critical areas to consider during the design, construction, and maintenance of the pavement life cycle. This is the first article in the literature that measures pavement performance with ANP to the best of authors' knowledge.

II. Literature Review

Accurate pavement performance prediction represents an important role in prioritizing future maintenance and rehabilitation needs and predicting future pavement condition in a pavement management system [24]. While several road administrations are putting efforts in developing optimization methodologies to enhance their decision-making process, many still lack data that allow the development of reliable prediction models for pavement performance [22]. In order to close this gap, literature review was carried on factors affecting the pavement performance. Many studies focused on factors related to the traffic such as [42] which developed the "structure-traffic index" and considered the traffic load as a major factor affecting the pavement performance. Meegoda and Gao [19] considered the high speed as a critical factor affecting the pavement performance indirectly by reducing the skid resistance. Other studies were concerned about factors related to the mix design of the pavement like the asphalt content [38] or the enhancement additives in the design mix [45]. Behl *et al.* [3] compared the performances of two pavements constructed in different techniques. Moreover, another research team studied the effect of using the recycled aggregate in the slabs of concrete and compared its performance to slabs over bituminous base [20]. Similarly, various studies considered factors related to other categories such as highway design, quality and maintenance factors, surface conditions as well as environmental factors. The literature review listed a total of 29 factors that affect the pavement performance categorized into six categories and identified the relationship between them. Six categories and interdependencies among the factors were determined due to agreement among the researchers in the field. Table I presents all the factors that affect pavement performances with their corresponding references and the interdependencies among them.

According to the identified affecting factors from the literature review, a questionnaire was developed and distributed to experts

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TABLE I
REFERENCES FOR THE 29 FACTORS AFFECTING PAVEMENT PERFORMANCE AND INTERDEPENDENCIES

Factor number	Factor name	References	Interdependencies
1	Unexpected high traffic volume	(Wayne Lee, et al. 2017) (Yang, et al. 2016)	23 / 24 / 25 / 26
2	Higher operating speed than posted speed	(Premkumar and Vavrik, 2016) (Xiao and Wu, 2016)	8
3	Unconsidered heavy vehicles volume	(Meegoda and Gao, 2015) (McGhee and Flintsch, 2003) (V. Galambos, 1997)	23 / 24 25 / 26 / 12 14
4	Low asphalt content	(Xiao and Wu, 2016) (Wayne Lee, et al. 2017) (Premkumar and Vavrik, 2016)	23 / 26
5	Poor mechanical and thermal properties	(Yang, et al. 2016) (Liu et al. 2019)	14 / 15
6	Using additives in hot mix asphalt	(Wayne Lee, et al. 2017) (Zhang, et al. 2018) (Behl, et al. 2013) (Dinh et al. 2018)	23 / 24 / 25 / 26
7	Excessive use of recycled aggregate	(Mehta, et al. 2017) (Tian, et al. 2017) (Premkumar and Vavrik, 2016)	25 / 26 20
8	Substandard curvature degree	(Wayne Lee, et al. 2017)	24 / 25 20
9	Excessive use of rumble strips	(Wayne Lee, et al. 2017) (Mehta, et al. 2017) (Tao and Mallick, 2009)	20 / 26
10	Improper crosswalk location	(Mehta, et al. 2017) (Shirzad, et al. 2018) (Tran, et al. 2012)	20 / 1
11	Absence of safety edge	(Yi, 2017) (Erlichson, 1991) (Crisman and Roberti, 2012)	26 / 20
12	Steep slope	(Coffey and Park, 2016) (Daniel, 2007) (Watson, et al. 2008)	24 / 25 / 20
13	Thin asphalt layers	(Xiaodi, et al. 2017) (Duncan-Jones, 1998)	14 / 15 / 26
14	Low structural capacity	(Mehta, et al. 2017) (Tawalare and Raju, 2016) (Lau and Popik , 2014)	13 / 15 / 25 / 26
15	Short design life	(Linglin, et al. 2015) (Alexandra, et al. 2017) (Shuang Zheng, 2017)	14
16	Absence of drainage system	(Premkumar and Vavrik, 2016) (Yang, et al. 2016) (Wayne Lee, et al. 2017)	23 / 24 / 25 / 26
17	Insufficient drainage system	(Premkumar and Vavrik, 2016) (Wayne Lee, et al. 2017) (Yang, et al. 2016)	23 / 24 / 25 / 26
18	Lack of quality assurance (QA) procedures	(Premkumar and Vavrik, 2016) (Tian, et al. 2017) (Yang, et al. 2016)	23 / 24 / 25 / 26 20
19	Poor quality material used in road construction	(Tawalare and Raju, 2016) (Tiza, et al. August 2016) (Agbonkhese , et al. 2013)	23 / 24 / 25 / 26 14
20	Non-compliance with specification requirements	(Tawalare and Raju, 2016) (Tiza, et al. August 2016) (Agbonkhese , et al. 2013)	23 / 24 / 25 / 26 18
21	Improper field compaction	(Haiyan, et al. 2017) (Newland, 2015) (Guarin, 2013)	23 / 24 / 25 / 26 15
22	Lack of maintenance of the drainage system	(Haiyan, et al. 2017) (Mishalani and Gong, 1999) (Wayne Lee, et al. 2017)	17 / 23 / 24 / 25 26
23	Extremely rough road surface	(Hamdar, et al. 2015) (Ding, et al. 2017) (Newland, 2015) (Guarin, 2013)	24 / 25 / 26
24	Low skid resistance	(Bretreger, 2015) (Hamdar, et al. 2015) (Guarin, 2013) (Hughes, 1984)	23 / 25 / 26
25	High rut depth	(Tawalare and Raju, 2016) (Tiza, et al. August 2016) (Agbonkhese , et al. 2013) (Newland, 2015) (Zhang et al. 2019)	23 / 24 / 26 /21
26	High percentage of cracks	(Yang, et al. 2016) (Premkumar and Vavrik, 2016) (Wayne Lee, et al. 2017)	23 / 24 / 25 / 13
27	Extreme weather conditions	(Tawalare and Raju, 2016) (Yang, et al. 2016) (Meegoda and Gao, 2015) (McGhee and Flintsch, 2003) (V. Galambos, 1997)	28 / 29 / 25 / 26
28	High rainy seasons	(Tawalare and Raju, 2016) (Premkumar and Vavrik, 2016) (Wayne Lee, et al. 2017) (Yang, et al. 2016)	27 / 29 / 16 / 17
29	High repetition of freeze thaw cycles	(Premkumar and Vavrik, 2016) (Coffey and Park, 2016) (Tawalare and Raju, 2016) (Tian, et al. 2017) (Wayne Lee, et al. 2017)	27 / 28 / 6

TABLE II
DESCRIPTION OF (1–9) SCALE FOR THE IMPORTANCE OF THE FACTORS' EFFECT ON PAVEMENT PERFORMANCE

Score	1	2	3	4	5	6	7	8	9
Description	No impact	↔	Moderate impact	↔	Strong impact	↔	Very strong impact	↔	Extremely strong impact

TABLE III
NUMBER OF RESPONSES FOR EACH IMPORTANCE SCORE FOR THE FACTOR

	Number of responses for each importance score									
Importance score	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**total**
Unexpected high traffic volume	1	3	19	47	27	19	37	28	24	205

working in the pavement industry. The questionnaire was used to rank the impact of these factors on pavement performance.

III. METHODOLOGY

There are many methods such as analytic hierarchy process, ELECTRE, Global Utility, Onicescu methods, etc., used for decision-making processes. This article combines both quantitative and qualitative research methods based on knowledge-based theory. The method consists of three steps. The first step is the identification of pavement performance factors, followed by a questionnaire by expert in field of the study and analyzing the data results from the questionnaire according to relative importance index (RII) and ANP as the final step. These methods were selected because they are powerful decision-making tools to capture the interdependencies between pavement performance factors and quantify their impact.

This study recognized a list of 29 factors that affect pavement performance from the literature review. An online questionnaire as well as hardcopies was developed to capture perceptions of the pavement industry professionals on the importance of each factor's effect on pavement performance. Respondents were also asked about their organization type, job designation, field of experience, years of experience, and company size. Moreover, they were requested to evaluate the importance of the effect of each factor on the pavement performance based on a (1–9) scale shown in Table II below.

A total number of 205 completed questionnaire was collected. The number of responses for each importance score for the "Unexpected high traffic volume" factor are given in Table III. RII was applied on the collected data before it is fed into the ANP model. The detailed description of the RII and ANP are discussed in detail in the coming sections. Finally, recommendations to industry professionals were carried based on the outcomes of the data analysis.

IV. DATA CHARACTERISTICS

An online website application was used in developing, distributing the questionnaire and gathering the responses besides the hardcopies and manual collection during workshops, seminars, and other professional events related to pavement industry. Incomplete responses were eliminated to avoid misleading information. A total of 205 completed responses were collected from experts. Project managers and project engineers make 33.17% and 31.22% of the responses, respectively, while the owners, construction managers, and other job designations almost equally shared the remaining as shown in Fig. 1 below.

The largest portion of responses was received from constructions contractors with a percentage of 36.59% followed by owners with a percentage of 22.44%. Moreover, 35.61% of the participants are involved in construction projects followed by experts involved in design with 20.98% of responses. The participants were divided into five categories with five years of experience in each category. Participants with 6–10 years of experience with 11–15 years of experience make 32.20% and 31.71% of the responses, respectively. Participants working with large companies that have more than 500 employees make 54.15% of the responses followed by the ones working with medium size companies, which have between 200 and 500 employees with 36.59%.

V. DATA ANALYSIS

The main objective of this article is to quantify and model the perceptions of specialists involved in pavement industry. Participants were asked to rate the importance of the effect for each factor according to (1–9) scale. For example, for the factor "Unexpected high traffic volumes," the respondent was asked "How important is the impact of unexpected high traffic volumes on the pavement performance?"

The questionnaire was sent to pavement industry specialists. The analysis for RII is shown in the next section.

A. *Relative Importance Index (RII)*

A common and effective ranking approach implemented in this study is utilized to rank the effect of factors on pavement performance. This approach is called RII and it considers the importance resulted from responses scores in its formula as shown in the following equation:

$$\mathrm{RII}\,(\%) = \frac{\sum S}{H * N} \tag{1}$$

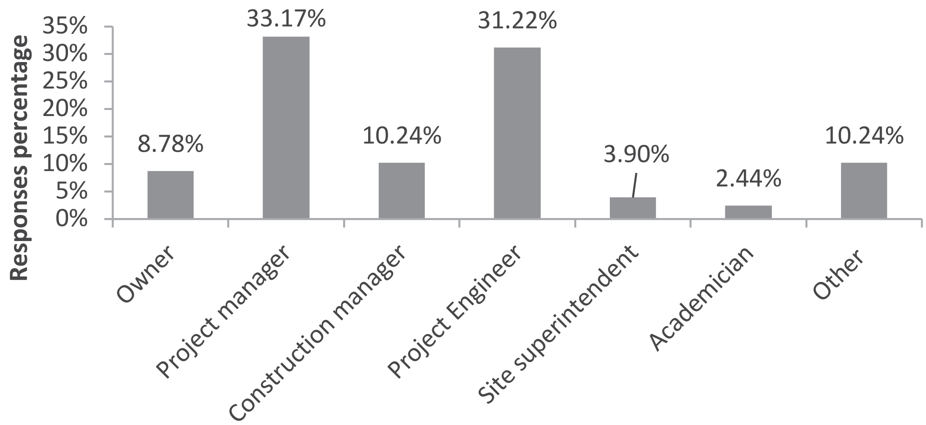

Fig. 1. Number of respondents according to job designation.

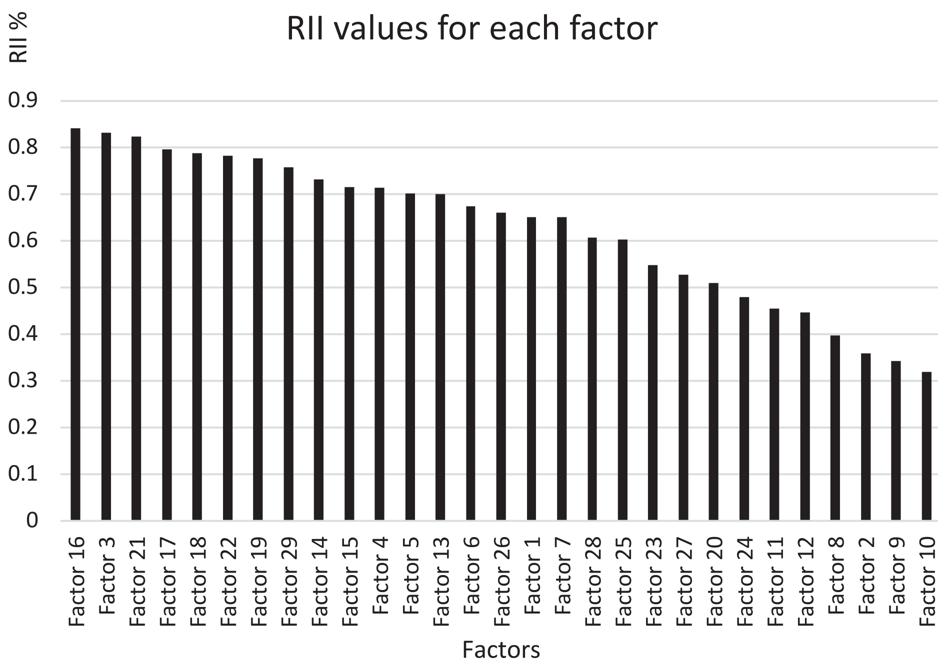

Fig. 2. RII values for pavement management factors.

where

ΣS the summation of each importance score multiplied by its number of responses,

H the highest possible number, which is 9 in this study,

N total number of respondents, which is 205 in this study.

For example, the RII for the factor "Unexpected high traffic volume" $\mathrm{RII}_{(\text{factor 1})}$is calculated as follows:

$$\mathrm{RII}_{(\text{factor 1})} = \frac{\Sigma\,(1*1)+(2*3)+(3*19)+(4*47)+(5*27)+(6*19)+(7*37)+(8*28)+(9*24)}{9*205}$$

$$\mathrm{RII}_{(\text{factor 1})} = 0.6504.$$

Fig. 2 below shows RII (%) values and ranking of the 29 factors affecting the pavement performance developed based on the completed responses from all 205 participants in the questionnaire. Factor numbering in the figure was presented in Table I. The rank is headed by the factor "absence of drainage system" and followed by the factors "unconsidered heavy vehicles volume," "improper field compaction," "insufficient drainage system," and "lack of quality assurance (QA) procedures," respectively. On the other hand, the factor "improper crosswalk location" is the least important factor affecting the pavement performance according to the RII(%) trailed by the factor "excessive use of rumble strips" and the factor "higher operation speed than posted speed."

The RII approach does not include the relationships between the factors and the RII rank depends on the raw data of the

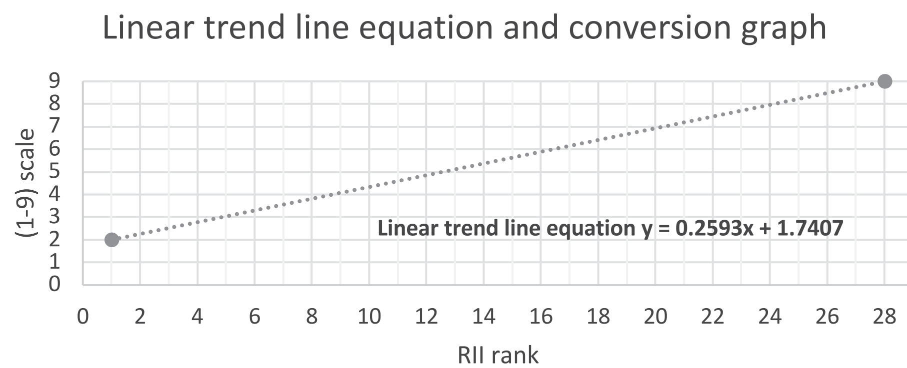

Fig. 3. Linear trend line equation and the conversion graph.

TABLE IV
CONVERSION OF RII RANK DIFFERENCE INTO (1–9) SCALE

RII rank difference	Conversation value	Difference in (1-9) Scale
1	2	2
2	2.2593	2
3	2.5186	3
4	2.7779	3
⋮	⋮	⋮
26	8.4825	8
27	8.7418	9
28	9.0011	9

questionnaire, while the ANP results consider the relationships between factors with respect to the categories. ANP analysis is discussed in the next section.

B. ANP Analysis

1) Scale Conversion for ANP: The RII rank in Fig. 2 is distributed among each category, where the difference between the maximum RII rank and the minimum RII rank in the category is calculated to be used in the conversion function for ANP. It was noted that the maximum difference in all the categories is 28 since the minimum RII rank and the maximum RII rank were located in the same category "Highway Design."

Since the value 1 in the (1–9) scale is given to compare the factor to itself only, then the minimum value for comparing two different factors in (1–9) scale is 2 and the maximum value is 9. Accordingly, the linear trend line equation can be seen in Fig. 3.

Next, the conversion table is developed using the linear regression equation as shown in Fig. 3 and (2) below. The regression equation will be used to convert the RII rankings into the (1–9) scale. An example of this conversion can be seen below. The regression is required to convert the numerical RII values into discrete values of (1–9) scale

$$y = 0.2593x + 1.7404. \quad (2)$$

For example, the (1–9) scale difference for the RII rank difference 4 is calculated by $0.2593\ x\ (4) + 1.7404 = 2.7779$ and rounded up to be 3. All the conversion factors are listed in Table IV.

2) Pairwise Comparison: The final step before starting the ANP analysis is the pairwise comparison between factors within the same category and among categories in accordance with the conversion table to develop unweighted super matrixes. The score 1 is given when comparing the factor to itself. When comparing two factors, the factor with higher value will get the score, while the factor with lower value will get the reciprocal of the score. For example, comparing the effect of factor "unconsidered heavy vehicles volume" to the effect of the factor "higher operation speed than posted speed" on the pavement performance resulted as 8. Table V below is an example of the pairwise comparison of the factors in traffic category.

Next step in ANP is to have a pairwise comparison at the level of categories to include their weight. Thus, this step is required to calculate the RII (%) for each category. The RII rank for the categories is headed by the "quality and maintenance" category followed by "traffic," "mix design properties," "highway design." and "surface condition," respectively, while the rank is tailed by the "environment category." The pairwise comparison among categories is shown in Table VI.

TABLE V
PAIRWISE COMPARISON OF THE FACTORS IN TRAFFIC CATEGORY

Factors number	1	2	3
1	1	5	1/5
2	1/5	1	1/8
3	5	8	1

3) ANP Network: ANP is a network of criteria alternatives (factors in this study) and clusters (categories in this study) for a decision-making problem. All the alternatives of the network could be isolated or in relation with one or more other alternatives. This feature provides better models of complex problems and accurately represents cases of real life.

According to previous studies, [43] and [49], ANP basically starts with identifying the main goal (which is the pavement performance in this study), elements, and clusters as well as the relationships between them according to the real life situation to build the problem as a network around the main goal. Next, a pairwise comparison between each pair of elements of each cluster and between elements with interdependencies relations to develop priority vector for each cluster which will be entered later as a column in the super matrixes. Similarly, the clusters are compared pairwise to provide the eigenvectors. Super matrix is developed by combining the local priority vectors of elements in each cluster. Then, the super matrix is weighted by summing the columns to unity by multiplying the matrix of each cluster by the eigenvector of the cluster. Finally, the weighted super matrix is raised to a power of large number to achieve convergence to form the limiting matrix, where the ANP values are determined. The ANP model was built graphically as shown in Fig. 4. The relationships between these factors were identified based on the nature of work, literature review and discussion with experts in the pavement field and shown in Fig. 4.

The pairwise comparison between factors and categories including the relationships between them was analyzed using Super Decision software. Pairwise comparison among the factors developed the local priority vector and pairwise comparison among the categories developed the eigenvectors. Multiplying all local priority vectors with eigenvectors provided the limit matrix. Finally, the limit matrix is converted to the ANP values for the factors as shown in Table VII.

It can be seen from the ANP results that factors under surface condition category such as high percentage of cracks, rough road surface, and rut depth are the main factors affecting pavement performance. These factors have been reported by many researchers that their impact on pavement performance is high. Also, surface condition is very much related with other factors given in the table. For instance, high rut depth can be a result of improper field compaction or unconsidered heavy vehicle volume and have also direct impact on other factors. Results also indicated that factors under highway design category such as steep slope, absence of safety edge, excessive use of rumble strips, and improper crosswalk location have very minimal effect on pavement performance since their damage on the pavement is much less compared to the factors under surface condition category. Therefore, it can be said that the ANP ranking results on pavement performance support the findings of researchers in the pavement field.

VI. DISCUSSION OF RESULTS

ANP ranking assists the pavement management professionals to identify the most important significant factors taking into account the interdependencies between factors. Table VII listed the importance of each factor.

Factors from the category "surface condition" ranked at the top of the table and this endorses the equation of pavement performance index developed in 2016 [30], which considers the cracks percentage, rut depth, surface roughness, and other surface conditions as main elements in evaluating the pavement performance. The factor "high percentage of cracks" is the most important factor because it has immediate direct impact on pavement performance and it impacts other factors as well. Similarly, the effect of the factors "extremely rough road surface" and "high rut depth" can accelerate the effect of many factors such as "unexpected high traffic volume" or "insufficient drainage system."

According to the ANP rank, the least important factor is "improper crosswalk location" because its effect is indirect and the damage to pavement performance is actually happening by the breaking vehicles. This indorses the result of the study conducted by [9], which provided many solutions and common practices to eliminate braking and aggressive maneuvering at the pedestrian crossings. Furthermore, the factor "excessive use of rumble strips" is the second least important factor, which confirms the results of a study in China that claimed the rumble strips great safety benefits supersede their minor impact on the pavement performance [5].

VII. RECOMMENDATIONS

Remarkable recommendations to the industry can be summarized based on the ANP rank since the most effective factors are identified. Due to the importance of factors in the surface condition category, pavement authorities are strongly recommended to establish an effective maintenance program and to highlight the damaged roads. This action would rectify the defects in the early stages before the performance is dramatically reduced and a costly and time-consuming solution with higher traffic disruption. In addition, due to the significant factors such as "the structural capacity" and "the design life" in ANP ranking, the supervision consultants should review the highway design by their specialists and advise the client about any amendments that can be implemented to improve the pavement performance. Finally, yet importantly, pavement construction contractors are recommended to internally inspect all the road surfaces and rectify the defects before handing the project over to the clients to ensure the efficiency and the durability of the pavement. Future studies would focus specifically on the surface condition factors and develop models to measure the performance of surface conditions.

TABLE VI
PAIRWISE COMPARISON OF CATEGORIES

Categories	Traffic	Mix design properties	Highway design	Quality and maintenance	Surface condition	Environment
Traffic	1	2	2	3	3	3
Mix design properties	1/2	1	2	2	3	4
Highway design	1/2	1/2	1	2	2	3
Quality and maintenance	1/3	1/2	1/2	1	2	2
Surface condition	1/3	1/3	1/2	2	1	2
Environment	1/3	1/4	1/3	1/2	1/2	1

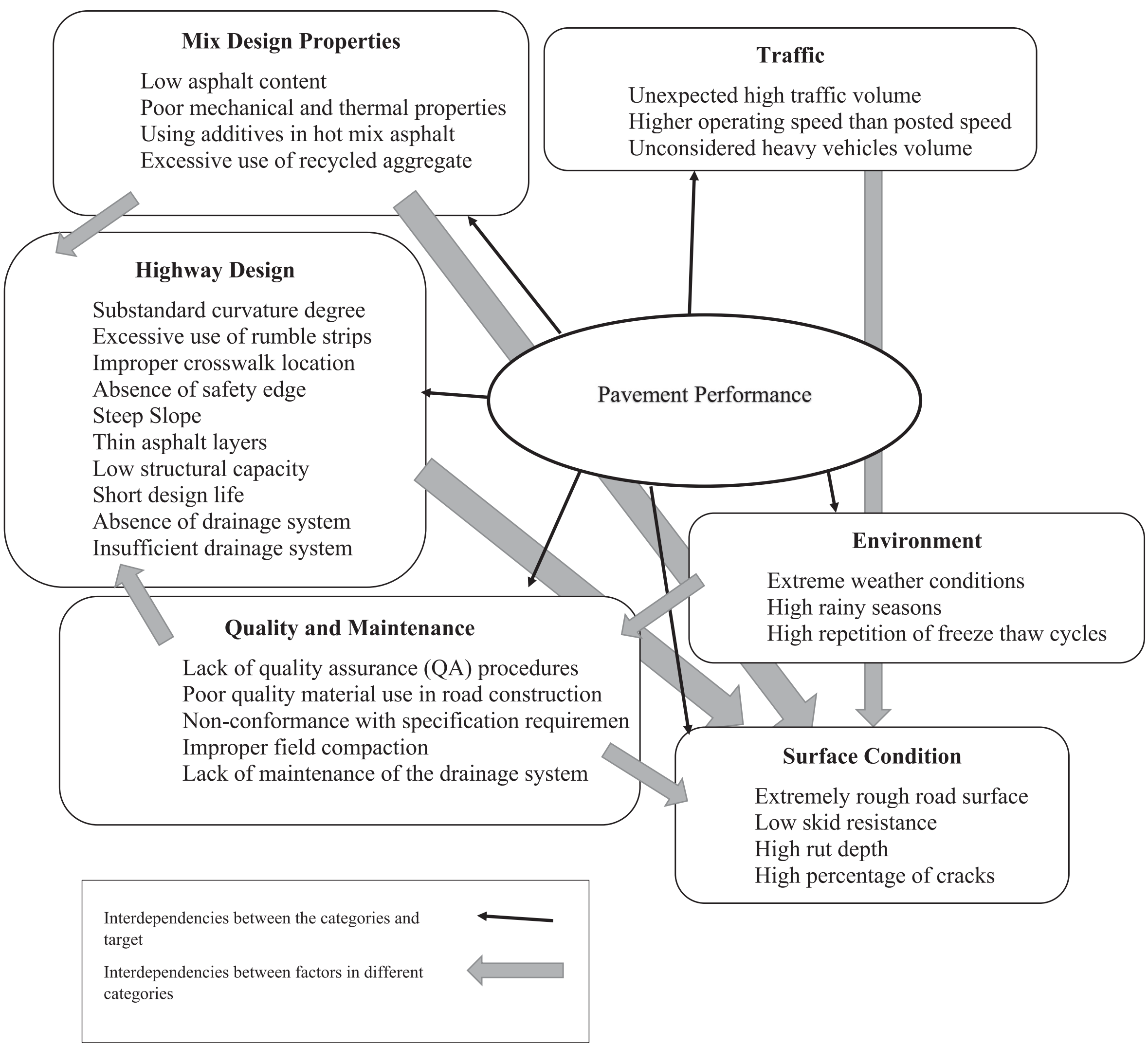

Fig. 4. ANP model.

TABLE VII
ANP Rank of Factors Affecting Pavement Performance

Category	Factor	ANP value	ANP rank
Surface condition	High percentage of cracks	0.2730	1
Surface condition	Extremely rough road surface	0.1555	2
Surface condition	High rut depth	0.0976	3
Highway design	Low structural capacity	0.0892	4
Traffic	Unconsidered heavy vehicles volume	0.0721	5
Surface condition	Low skid resistance	0.0409	6
Mix design properties	Low asphalt content	0.0337	7
Highway design	Short design life	0.0285	8
Mix design properties	Poor mechanical and thermal properties	0.0266	9
Highway design	Insufficient drainage system	0.0228	10
Traffic	Unexpected high traffic volume	0.0211	11
Highway design	Absence of drainage system	0.0166	12
Environment	High repetition of freeze thaw cycles	0.0163	13
Quality and maintenance	Improper field compaction	0.0150	14
Quality and maintenance	Non-compliance with specification requirements	0.0146	15
Mix design properties	Using additives in hot mix asphalt	0.0139	16
Quality and maintenance	Lack of quality assurance (QA) procedures	0.0130	17
Highway design	Substandard curvature degree	0.0075	18
Mix design properties	Excessive use of recycled aggregate	0.0073	19
Quality and maintenance	Lack of maintenance of the drainage system	0.0066	20
Traffic	Higher operating speed than posted speed	0.0062	21
Quality and maintenance	Poor quality material used in road construction	0.0050	22
Environment	High rainy seasons	0.0050	23
Highway design	Thin asphalt layers	0.0047	24
Environment	Extreme weather conditions	0.0020	25
Highway design	Steep slope	0.0018	26
Highway design	Absence of safety edge	0.0016	27
Highway design	Excessive use of rumble strips	0.0010	28
Highway design	Improper crosswalk location	0.0008	29

VIII. Conclusion

This article aimed to capture the most significant pavement performance factors to guide the decision makers during the design, construction, and maintenance stages. Detailed literature review identified 29 factors that affect the pavement performance and emphasized the interdependencies between them. A survey was developed to collect experts professional judgment on the importance of each factor‘s effect. The collected 205 completed responses were analyzed by RII and fed to ANP model. In this article, the ANP model was built and ran to develop the limiting matrix and determine the ANP value for each factor. The ANP model endorsed the relationship between factors and pairwise compared the factors to each other.

The results of this article proved that ANP accurately represents the real life situations and is suitable to simplify complex decisions. According to this study, the most critical factors that affect the pavement performance are the ones related to the surface condition such as "high percentage of cracks" followed by the factor "extremely rough road surface" and the factor "high rut depth," respectively. Moreover, the lowest ranked factors are "absence of safety edge," "excessive use of rumble strips," and "improper walk location" correspondingly and this confirms the results of previous studies that indicated minimum or ignorable impact of these factors on pavement performance.

A. *Limitations of the Study and Future Recommendations*

This study has been conducted by collecting expert opinions on pavement performance. In order to validate the ANP model, real field pavement performance data needs to be collected to compare the results obtained in the ANP model.

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