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Integrated Safety-Pavement Maintenance Management System (SPMS) for Local Authorities in Egypt

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Accidents, Pavement, Maintenance, Management, Safety, Optimization

Abstract

Road maintenance management is a fundamental strategy for achieving the infrastructure sustainability. In Egypt, maintenance decision depends only on the pavement condition, and traffic safety is not considered. This study aims to develop an integrated safety-pavement management system that enables managing roads network according to the available funds and assures the safety concept throughout the service life of roads. It develops a probabilistic performance model and an optimization decision tool based on roads condition, safety levels, and maintenance costs to provide a proper maintenance decision. The system was validated for the road network in southern Egypt. Results show that an inadequate maintenance budget causes a decrease in safety levels and pavement conditions in some sections due to late maintenance decisions. However, the results indicate the applicability for determining the economic maintenance plan which keeps safety at the targeted level and enhances the pavement performance through the network by saving 27 million Egyptian pounds through the analysis period.

1. Introduction

Road network as a means of national transportation is considered a supporting element for social life. Since the year 2014, the road network in Egypt has witnessed large developments in the field of construction. This development is aimed at increasing investments in the country. Since these improvements started, Egypt jumped from 118th to 28th globally in the road's quality index [1]. Moreover, the traffic accident rate has decreased by 24.5% [2]. Constructing new roads is important for the economic growth, but keeping these new roads and the existing ones in good condition is a challenge that road authorities must admit to find better solutions and promote the community's prosperity. On one hand, road pavement condition deteriorates with time due to many causes such as traffic loading, materials, aging, environmental effects, construction deficiency, design inadequacy, etc. [3]. If no suitable action is taken, the overall performance of the roads network will degrade. Maintenance of roads networks is an important solution to improve the system. A pavement management system (PMS) is a means which enables the decision-makers to maintain the roads network in a proper condition [4]. The PMS can help road agencies in identifying the state

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condition of the pavement; evaluate the required funds to improve the condition of pavement up to the needed level and selecting the best treatments based on the available funds [5].

On the other hand, traffic safety is an important aspect of the transportation system that must be preserved at a suitable level. However, previous PMS research has not considered traffic safety, or it has been studied separately during the analysis of PMS. This paper aims to incorporate traffic safety into PMS to develop an integrated safety-pavement management system (SPMS). The proposed system is mainly based on a performance model, a management decision technique, and a safety model. The performance model considers traffic volume classes and pavement deterioration rate and predicts the probability of pavement condition. Then, the system was adapted by a maintenance decision tool to analyze the maintenance strategies through the analysis period. The management decision is concerned with preserving pavement conditions and traffic safety to an acceptable level based on a performance model and a safety model. The applicability of the proposed integrated safety-pavement management system was tested for a case study on the southern road network in Egypt. The next section reviews the literature concerning PMS and section 3 describes the methodology of developing an integrated safety-pavement management system. Section 4 provides the results of applying the proposed methodology on an existing road network. Finally, section 5 presents a summary and the main conclusions of this research.

2. Literature review

Pavement condition evaluation is an important step in the PMS. The maintenance decision requires a good understanding of the deterioration rate of the pavement to predict the effect of the maintenance scenarios and reach the preferable treatment [6]. The pavement deterioration model is considered as a key element of the maintenance decision process for road networks [7]. Prediction models are classified into two types, deterministic and probabilistic. The deterministic models predict a single value of the dependent variable, while the probabilistic models produce a range of attributes and can recognize the random nature of pavement performance [8]. Probabilistic models are preferable to deterministic ones because the distribution range of pavement conditions that are produced by probabilistic models works on improving decision-making for maintaining the road network [9]. Moreover, probabilistic models are more realistic than the deterministic approach because they can capture uncertainty through the prediction process for pavement performance [10].

As a type of probabilistic model, the Markov chain model is widely used by many researchers to form the deterioration model. Abaza [11] developed a deterioration model using discrete-time Markov. The transition probabilities in the proposed model were based on two groups of pavement defects which represent cracking and deformation defects. It was found that the model gives a realistic image of the distribution profile of pavement condition through the analysis period. In addition, ref. [12] used the Markov technique to predict the future condition of the pavement. The results confirmed the feasibility of the Markov technique in predicting future pavement conditions.

The PMS should be capable of producing the optimum maintenance plan for road networks. Reaching the appropriate treatment options for pavement sections through the analysis period requires a maintenance decision tool [13]. Mathematical techniques such as linear, nonlinear, quadratic, and integer were the choice of many researchers to formulate their optimal decision for pavement management. Garza et al. [14] proposed a decision-making methodology for pavement maintenance optimization at the network level based on linear programming using the target level of pavement performance and annual budget as constraints. They tested the applicability of this system and the results showed that it was able to find optimal decisions for road maintenance. A mixed integer nonlinear programming model has been established in [15] to find optimal maintenance decisions by minimizing maintenance costs over the planning period of pavements. The complexity of the mathematical methods and the time needed to calculate the optimal solution are increased when maintenance decision involves many variables. So, they are not preferable to be applied for large networks [16]. Many researchers used the genetic algorithm (GA) technique to overcome these drawbacks. GA is one type of evolutionary algorithms (EAs) that solve optimization problems based on natural selection techniques [17]. Yang et al. [18] used GAs to schedule the optimal strategies for road maintenance based on maximizing the condition of the road sections and minimizing the maintenance cost for the whole network during the planning period. In ref. [19], an optimization model was developed for the overload roads network in Indonesia using GA. The constraints of their model were overloading and budget constraints. They found that the model reveals the optimal solution for maintenance cost and pavement condition.

Although the optimization methods help to find the suited maintenance solution for the road networks through their operating period, they may need many constraints to form the optimum decision through the targeted period of the analysis [20]. In most of these methods, the complexity and the time needed to calculate the optimal solution are increased when the maintenance decision embraces many variables [16]. Many researchers used the prioritization approach to overcome this problem. Building an efficient prioritization program for road maintenance requires a deep knowledge of all influencing factors. Rutting and the cracking extent have been considered as influencing factors in the maintenance prioritization process [21]. Dessouky et al. [22] considered road conditions, ride quality, and structural adequacy as effective items in prioritizing the road sections for maintenance. In [23] and [24], the influence of traffic volume was involved in the process of road prioritization for maintenance management. Also, in ref. [25], it was declared that the functional class of the road has significant importance in identifying and recognizing maintenance priorities. Similarly, pavement age and maintenance cost were also distinguished to be of high importance when setting maintenance priorities [26]. If several factors are considered, multi-criteria decision-making (MCDM) can be a suitable choice for the maintenance prioritization plan. MCDM works on structuring the problem of decision and helps in reaching a better understanding of it [27], [28]. The application of MCDM in the process of maintenance management for roads provides reasonable and effective maintenance plans. In the multi-criteria approach, the decision-maker assigns the weight of each factor, which helps in reflecting the relative importance of each factor in the prioritization process [29], [30].

Analytical Hierarchy Process (AHP) is one of the commonly applied MCDM methods. AHP can help in determining the prioritization solution for infrastructure projects [31]. The essential steps in the AHP are the hierarchy structuring, establishing the pairwise comparisons, and testing for consistency [32]. In the hierarchy structure, the specialists in the field of the decision problem make pairwise comparisons for all items in the hierarchy levels [24]. The pairwise comparisons work on identifying the relative weight of importance for the considered factors using a relative importance scale [33]. However, the traditional way of comparison will be complicated and ineffective for large variables [34].

The benefit of the AHP in identifying maintenance priorities is highlighted in many studies. Almeida et al. [23] developed a priority system to prioritize the road sections for maintenance management using AHP. They considered climatic conditions, some social aspects, and traffic as influencing factors. They concluded that the AHP was a valuable approach in dealing with the priority decision process for the sections in the road networks. Farhan and Fwa [35] worked on finding an approach that can help in the priority decision for road networks. Three AHP forms were used: the absolute AHP, the ideal-mode relative AHP, and the distributive-mode relative AHP. These three models were tested for the maintenance decision process. As a result, they found that the absolute AHP was more efficient than the other models.

Despite the advantages of the prioritization approach, it does not focus on finding long-term solutions to the maintenance management process for roads network [36]. This study is directed to overcome this limitation by developing a long-term prioritization system that corporates the maintenance solutions for road networks from a continuous vision. The system used probabilistic modeling to predict future performance and the AHP technique because of their benefits that were illustrated in the literature.

Despite these contributions, the PMS does not introduce a comprehensive solution that can provide safety, and the problem of road accidents still needs a solution as the systems of pavement management focus mainly on the condition of the infrastructure [37]. Road accidents represent a serious problem. At the global level, the number of deaths due to road accidents reaches more than 1.35 million people annually [38]. Safety on road networks is of the priority for all road stakeholders [39, 40]. Applying the appropriate prediction process can give accurate prediction for the studied problem. Regarding the prediction process, artificial neural networks (ANNs) have been applied and used in many engineering research [41, 42]. In the field of road accident prediction, many researchers identified accident occurrence probability using accident prediction models and sensitivity analyses [43]. Several techniques have been used to predict traffic accidents (e.g., regression models [44], fuzzy logic [39] and artificial neural networks [45], [46]).

Safety concerns are rarely considered in the maintenance decision. Many researchers showed a fundamental relationship between pavement conditions and safety on the road. In the previous study by [39], about the development of the road traffic accident model, the role of pavement condition on the accident rate was explored. Their results indicated that the accident rate increases in bad pavement conditions. Also, there are some researchers tried to predict accident frequency to measure the safety performance of road networks [47], [48]. Meanwhile, other researchers highlighted the social cost effect of road accidents [49], [50]. In addition, some researchers worked on studying the effect of road accidents on the national income [51]-[53]. Researchers suggested some measurements by which roads accidents occurrence can be eliminated [54], [55]. However, the improvements of safety concerns are always made separately and not considered during the analysis of PMS.

Few local studies focused on PMS, (e.g. [56]) developed a multi-objective optimization model using GAs for minimizing budget cost with maximizing area of the network. The model was applied to forecast pavement performance during lifetime of road networks with the use of pavement condition index. In [57] and [58], PMS was developed by predicting pavement condition index using Markov Chain models. In [59], a PMS framework including pavement condition evaluation using pavement condition index was introduced using Markov Chain models for repair fund allocation for planning maintenance actions. Transition probability matrix was developed based on historical data. Their pavement management optimization model was developed using GAs. In [60] and [61], regression and artificial neural network models were presented to predict international roughness index (IRI) as a function of distresses based on comprehensive long-term pavement performance database of 506 sections with 2439 observations. The models were proposed for IRI prediction as a function of age, initial IRI, severities of transverse and alligator fatigue cracks, and standard deviation of the rutting depth. The regression analysis and artificial neural network yielded reasonable prediction accuracy. As shown from Table 1 to the best of the authors' knowledge, there is no previous research that takes the safety concept through maintenance management analysis. In this paper, we consider the safety concept in the maintenance management decision for the short and long-term analyses.

The review of the literature indicates that the probabilistic model is preferable to the deterministic model. Therefore, it is used herein to predict pavement performance. Also, recent studies show the benefits of GA and AHP in the decision-making process, so they are used to find the optimal maintenance solutions and ranking pavements sections. Most studies in the pavement management field considered the budget as a constraint while doing life cycle analysis for road maintenance. Some studies dealt with safety concerns by developing a measurement to eliminate accidents and enhance the safety concept on the road without taking it as a main element in the analysis process. Literature sets limits in incorporating traffic safety within PMS due to data availability limitations. This paper aimed at developing a pavement management system that corporates the safety concept and the maintenance management for roads network from a sustainable vision and makes the safety concern impeded through the suggested strategies for road management. The contribution of this paper is twofold:

- Developing a PMS valid for short-term and long-term applications.
- Incorporating traffic safety into PMS to produce a new management system (SPMS).

3. Methodology

The methodology in this paper is aimed to develop SPMS which takes into consideration the characteristics of the roads network in Egypt. The proposed system classifies the roads network into three patterns (north-west-south). This paper focuses on the southern zone of Egypt. Desert and agricultural roads were selected due to data availability as shown in Figure 1 (the roads connecting the green nodes). These roads have the same climatic characteristics and a speed limit. Traffic volume has three levels (high-medium-low), and pavement condition for these roads was obtained from the Egyptian General Authority for Roads, Bridges, and Land Transport [62] and a field survey. As shown in Figure 2, the proposed SPMS is mainly based on a performance model and a safety model developed based on main inputs for this zone (network pavement and climatic conditions, traffic characteristics and analysis period). The estimations of these models provide the pavement and safety conditions of the studied zone. These estimations and the available budget are the inputs for a management decision technique that produces the suggested scheduling of pavement maintenance as will be described in the following sections. Firstly, the pavement condition performance is calculated, and then the optimum analysis is evaluated based on the optimization model and the prioritization approach which considers the safety level. Finally, the final maintenance management scheduling is done based on the prioritization model.

Table 1: Comparison with relevant studies

Reference	Optimization	Prioritization	Safety model	Finding long-term solutions to the maintenance cost for the whole network during the planning period
[14]	√	×	×	√
[15]	√	×	×	√
[18]	√	×	×	√
[19]	√	×	×	×
[21] to [25]	×	√	×	×
[35]	×	√	×	×
[39], [49], [50]	√	×	√ developed separately and not within PMS	×
[56]	√	×	×	√
[57], [58]	√	×	×	
[59]	√	×	×	√
[60], [61]	√	×	×	√
[11], [12]	√	×	×	√
This paper	√	√	√ Integrated in PMS	√

Fig. 1: The studied roads (the roads connecting the green nodes)

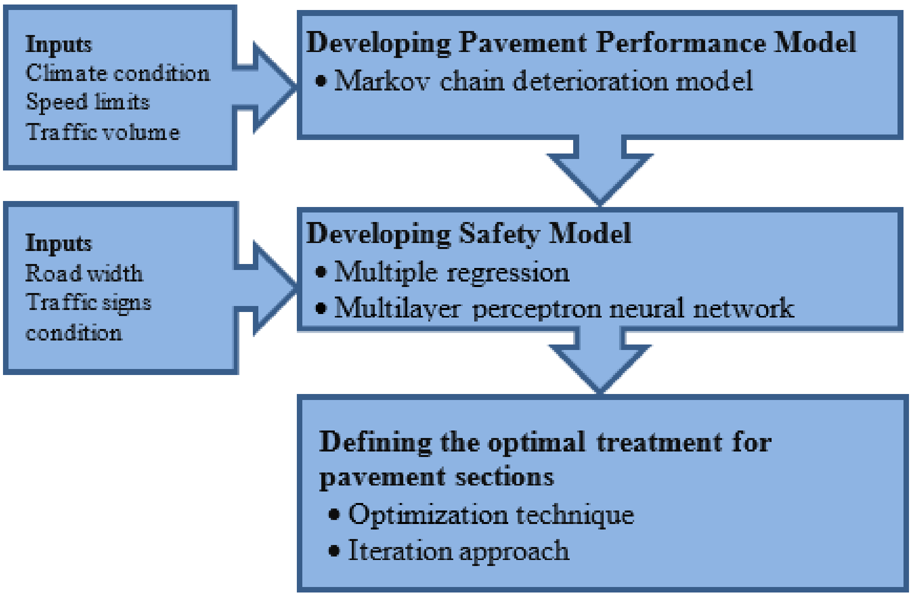


Fig 2: The steps of the proposed SPMS

3.1. Pavement Performance Model

Following many previous research (e.g., [11, 12, 57, 58, 59], Markov chain models were selected in this study to define condition performance models for the pavement management system. In this method, transition probability matrix (TPM) is used in order to predict future pavement conditions. This section discusses the generation of transition probability matrix from historical data which will be used in the forthcoming steps of the pavement management system. Markov chain model was applied to form a deterioration model which represents pavement performance deterioration. The transition probability matrix (TPM) as shown in Table 2, was used in the modeling methodology to present the probability of pavement condition transitioning from one condition state to another ($P_{i,j}$), and the proportion method was used to develop TPM as shown in Equation (1) [12]. If the pavement is currently in the state P_i, then it shifts to the state Pj at the next step with a probability represented by $P_{i,\,j}$, this probability is called transition probability.

$$P_{i,j} = n_{i,j} / n_i \qquad (1)$$

where n_i is the number of pavement sections in the condition state i before the transition and $n_{i,j}$ is the number of pavement sections that transition from state i to state j through a period. The initial road condition is expressed by the present vector-matrix [P_0] as indicated in Equation (2).

$$P_0 = [S5, S4, S3, S2, S1] \quad (2)$$

where, $S1$ to $S5$ indicate the percentages of road sections that are very bad, bad, fair, good, and excellent conditions, respectively. The pavement condition was represented by the pavement condition index (*PCI*) [63]. The distribution of pavements condition at any year t through the analysis period was calculated based on the TPM as shown in Table 2, according to Equation (3) [64] :

$$P(t) = P(t-1)*TPM \quad (3)$$

In TPM, pavement condition p is calculated for the overall road based on the conditions of different road sections. As the roads have the same climate condition and speed limit, *TPM* was developed based on the traffic volume. Table 3 shows the classification of traffic volume [62].

Table 2: Transition probability matrix

Condition state at year t	**Condition state at year t+1**				
	P1	1-P1	0	0	0
	0	P2	1- P2	0	0
	:	:	:	:	:
	:	:	:	:	:
	0	0	0	PS	1-PS
	0	0	0	0	1

Table 3: Classification of traffic volume [62]

Traffic volume classification	**Average daily traffic (ADT)**
Low	<4600 vehicle/day
Med	4600:10800 vehicle/day
High	>10800 vehicles/day

Identifying the present condition of pavement has a great importance in predicting future conditions. The pavement condition is represented by a vector matrix. The elements of the vector are the percentage of the of road sections that belong to each of the five different states of pavement condition (*S1-S5*). This vector is determined from the pavement condition survey data as detailed in Section 4. The present condition distribution was made based on the pavement condition for the period between years 2019 and 2020 according to the available data as shown in the following state vector:

$$P_0 = [0.1, 0.15, 0.15, 0.3, 0.3]$$

Then the distribution of pavement condition at any year (t) through the analysis period was calculated as follows [64]:

$$P(t) = P(t-1) * TPM = P(0) * TPM \quad (4)$$

where, p_0 is the condition state vector at t=0. After determining the distribution of pavement condition at any year t, the future state (FS) value can be determined by multiplying the state vector at year t by the index state vector [IS] as indicated in Equation (5) [64].

$$FS = P_0 * TPM * SI \quad (5)$$

3.2. Defining the safety limits

Road management means improving its performance through physical and sensible meanings. Physical meaning can be made by increasing the condition limit to a preferable degree while sensible meaning can be monitored from mobility and safety concerns. The SPMS in this paper takes into consideration the safety concern throughout the analysis period. Improvements in road width, speed, pavement condition, and traffic signs can reduce accidents on the roads. In this study, a moderate level of safety was involved based on the results of the safety model according to the available budget and limitations. The safety model was developed using simple regression and a multilayer perceptron (MLP) neural network modeling. In the simple regression model shown in Equation (6), the accident rate (AR) was taken as the independent variable while road width, speed, pavement condition, traffic signs condition, and traffic volume were taken as dependent variables. The MLP was used in developing the accident model as it is a common type of feed-forward network. Figure 3 shows the structure of MLP. The structure of MLP consists of three layers: a hidden layer, an output layer, and an input layer. In the input layer, the mission of the neurons is to distribute the input signals x_i to the other neurons in the hidden layer j. Then the neurons in the hidden layer work on summing and giving weights to the coming input signal W_{ij}. Then the value of the output Y_j can be calculated based on Equation (7). In developing the neural network model, several structures for the neurons in the input and the output layers were tested to reach the proper consistency between the actual and predicted results. The accuracy of these models was examined based on the coefficient of determination and the root mean square error.

$$Y_i=\beta_0 + \beta_1 X_1 + \beta_2 X_2 + ...+ \beta_n X_n \quad (6)$$

were,

Y_i= the dependent variable.

X_1 *to* X_n= the value of the n^{th} independent variable.

β_0 *to* β_n = regression coefficients

Improvements in these factors can reduce accidents on the roads. In this study, the medium level of safety was processed according to the results of the safety model, as the higher levels of safety require more money to be reached and may exceed the available budget.

$$Y_j = f\{\sum_{i=1}^{n} W_{ij}\, x_i\} \quad (7)$$

where, f is a radial basis function, a sigmoidal, or a simple threshold function. This process is reiterated in the output layer for developing the neural models.

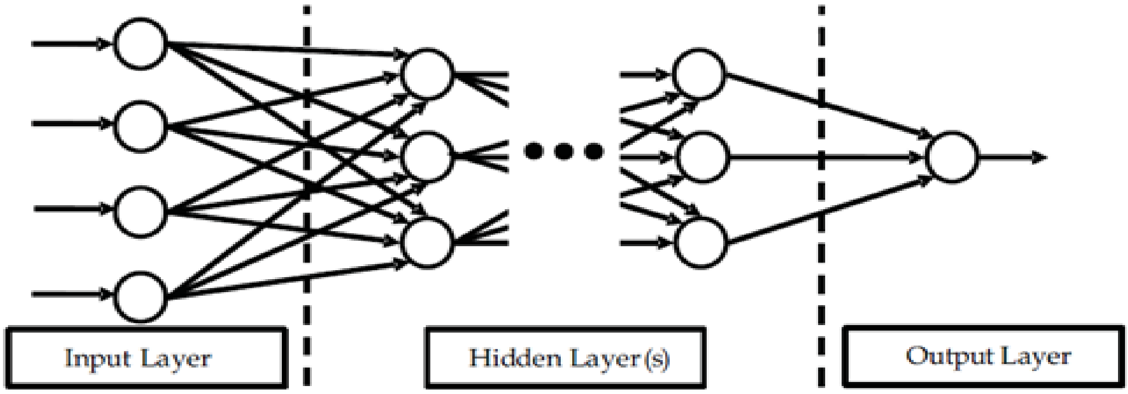


Fig. 3: The structure of the multi-layered perceptron networks

3.3. Defining the optimal treatment for pavement sections

The proposed SPMS in this study includes a maintenance decision tool to select the appropriate repair action for roads network sections. This study integrated optimization technique and iteration approach to provide two ways for the decision makers to take the optimal action. The decision-makers can find the best solution using optimization and make changes according to the situation using the iteration process at the same time in an easy manner. The form of the optimization is shown in the following equations:

$$\min f_1 = \sum_{S=1}^{S} \sum_{t=1}^{T} X_{rst} * C_0(1+g)^t \quad (8)$$

$$\max f_2 = \sum_{S=1}^{S} \sum_{t=1}^{T} PCI_{rst} \quad (9)$$

Subject to,

X_{rst}= [0,1] $1 \le t \le T, 1 \le s \le S$ (10)

$PCI_{rst} \le PCI_{thr}$ $1 \le t \le T, 1 \le s \le S$ (11)

$(\sum_{S=1}^{S} \sum_{t=1}^{T} \mathrm{X_{rst}} * \mathrm{C_T}) \le B_t$ $1 \le t \le T, 1 \le s \le S$ (12)

where,

S is the number of road sections

T is the number of study years

PCI_{rst} is the pavement condition index after a treatment r is applied to section s in a year t

X_{rst} equal 1 if a treatment r is applied to section s in a year t, otherwise it equal 0, $r \in R$ (0,1,2,3)

R (0,1,2,3): are the four predefined treatment strategies available

$\mathrm{C_0}$: is the cost of the road maintenance during at the base year

$(1+g)^t$ is the increase rate in maintenance cost during study period. The typical cost growth rate g in Egypt is assumed between 10.25 to 12.25 % [62].

B_t: is the road maintenance budget available within year t

As shown in Equations (8) and (9), the model formulated above considers minimizing the total cost of maintenance that can be conducted through the analysis period for pavement sections as the objective function for the maintenance and rehabilitation actions of roads. Equation (11) shows that the pavement conditions should be equal to or higher than a minimum threshold level of road condition (PCI_{thr}). The pavement condition threshold value considered in this study is based on the safety model. In this model, four decision variables are considered. They show the repair and rehabilitation frequency within the planning period. There are 4 predefined treatment strategies available, *R* (0, 1, 2, 3), where 0 means “no maintenance”, 1 refers to “minor maintenance”, 2 denotes “resurfacing” and 3 is “rehabilitation”. The maintenance decision is also constrained by economic limitation as shown in Equation (12) to assure that the needed cost for maintenance strategies is within the available budget throughout the analysis period.

3.4. Priority approach

The situation of road maintenance management in Egypt is based on the condition of the road and it does not take into consideration any other factors. The classification of road conditions is shown in Table 4 [62]. The proposed system works on overcoming this drawback. Therefore, it concentrates on identifying the essential factors that affect the prioritization process for the sections on the road networks based on a questionnaire analysis for the responses of 74 road experts. The final list of the most important factors was as follows: accident rate, traffic volume, cost of repair, pavement condition, road class, and failure probability. Then a questionnaire survey was conducted by the specialists to rate these 6 factors based on their ranking on a scale from 1 to 5. Where 1 represents the least importance and 5 represents the ultimate importance. A comparison matrix was set based on the survey questionnaire as shown in Equations (13) and (14). Then, the consistency ratio *CR* was defined as indicated in Equation (15). The consistency index was calculated using Equation (16). The value of *RI* is calculated as shown in Table 5 [65]. The six factors represent the main criteria in the prioritization process; these criteria involve sub-criteria as shown in Figure 4. Finally, the priority order degree for maintenance (POM) was calculated based on Equation (17). The value of *CR* is equal to zero. So, consistency is achieved as the value of *CR* is lower than 0.1. Then the priority score for maintenance was calculated based on the factors' weights and scales.

Table 4: Road condition classification [62]

PCI	Description
81:100	Excellent condition
65:80	Good condition: some minor deficiencies
45:64	Fair condition: cracking spread in a moderate stage within the section.
25:44	Bad condition: with high deterioration
<25	Very bad condition: out of service

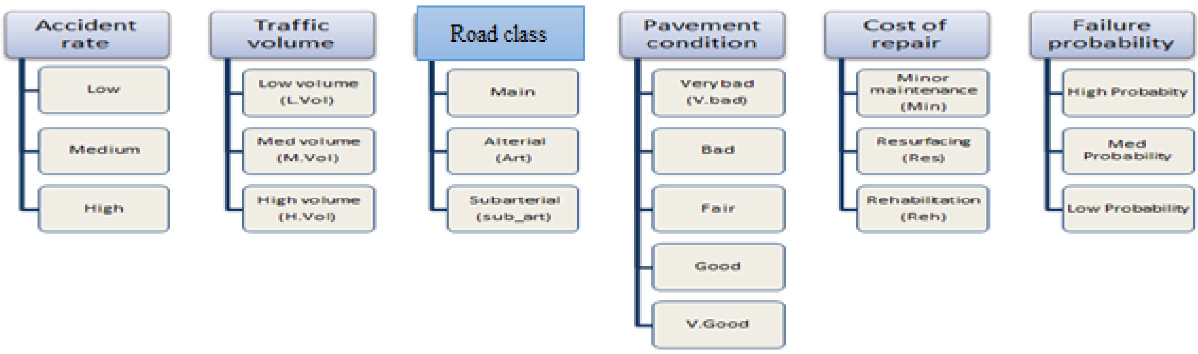


Fig. 4: The Considered Criteria and Sub-Criteria in the Prioritization Process

Table 5: The random index values [65]

n	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
R.I	0.00	0.59	0.90	1.12	1.24	1.32	1.41	1.45	1.49

$$A = \begin{vmatrix} a_{ii} & a_{ij} & \cdots & a_{in} \\ 1/a_{ij} & a_{jj} & \cdots & a_{jn} \\ : & : & : & : \\ 1/a_{ni} & 1/a_{nj} & \cdots & 1/a_{nn} \end{vmatrix} \quad (13)$$

$$A * y = n * y \quad (14)$$

$$CR = CI/RI \quad (15)$$

$$CI = \lambda max - n/n - 1 \quad (16)$$

where,
A: indicates the comparison matrix
y: indicates the eigenvector
n: represents the dimension of the matrix
CI: is the consistency index
RI: random index, and
λmax: is the largest Eigenvalue.

$$POM = \sum_j Y_j R_{ij} \quad (17)$$

Subject to,

$$C_T \leq B_t \quad (18)$$

Y_j: factor weight
R_{ij}: the scale of factor j for road i
C_T: is the cost of the road maintenance during the period T, and
B_t: is the road maintenance budget available within year t

4. Results and discussion

To test the proposed methodology, 8 sections from the southern zone road network in Egypt were selected. The characteristics of the selected sections are shown in Table 6. The system makes a comparison with the available budget to schedule the final list of road sections for maintenance management. As shown in Table 7, the system provides four strategies for maintenance decisions with their cost in Egyptian pounds (LE) (1$=24 LE). Table 8 describes a sample of the collected data. Table 9 shows the relative weights of the 6 factors resulting from the questionnaire survey that was calculated using the eigenvalue method (Equations10-12). The methodology of the proposed management system was applied and tested for the studied sections. At first, the pavement condition was identified, and the predicted condition was obtained using the deterioration model. The TPM was constructed based on the data between years 2019 and 2020 for the road sections [62]. Eighty-six (86) sections with section length of 2 km, are used for creating the TPM for the normal deterioration performance. Table 10 provides a sample for PCI values. The TPM was developed as shown in Table 11 and the models results were compared with the real data for each road. The results indicated a clear association between the real and predicted values for pavement condition from the developed models. Table 12 shows that the prediction accuracy of safety model is high with determination coefficients of 0.95 and 0.92 for neural network and regression models, respectively. Then, management decision actions through the analysis period were determined for each section based on the decision model. The GA was tested for the following characteristics: the population is 100, the iterations number is 10000, the crossover is 0.75, and the mutation is 0.3. The priorities of these sections for the maintenance management process are indicated in Table 13 and Figure 5. The results show that sec1 has the highest priority degree for immediate maintenance.

Table 6: The characteristics of the studied sections

Section	Length (km)	Type	Width (m)
SEC1	20	Two ways	11.5
SEC2	18		
SEC3	18		
SEC4	14		
SEC5	18		
SEC6	16		
SEC7	18		
SEC8	20		

Table 7: The available maintenance strategies

Strategy	Description	Cost
R_0	No Maintenance	--
R_1	Minor Maintenance	89 LE/m^2
R_2	Resurfacing	178 LE/m^2
R_3	Rehabilitation	300 LE/m^2

Table 8: Sample of accident data

Accident type	Alignment	road width	shoulder width	Weather	No. of deaths	No. of injuries
Car to truck	Straight	11.50	2	Fine	2	3
Single car		11.25			1	5
Car to car		11.50			0	2
Car to truck		11.25			1	2

Table 9: Relative weight of the factors

Factor	Weight
Accident rate	0.16878
Traffic volume	0.155122
Cost of repair	0.156098
Pavement condition	0.17561
Importance of road	0.182439
Risk of failure	0.161951
$\lambda_{max} = 6$	

Table 10: Sample of pavement condition index for road sections [62]

Road Section	PCI	
	2019	2020
1	76	78
2	77	69
3	65	59
:	:	:
85	73	71
86	81	72

Table 11: Transition probability matrix

Condition state at year 2019	Condition state at year 2020				
	0.5	0.5	0	0	0
	0	0.666667	0.333333	0	0
	0	0	0.454545	0.54545455	0
	0	0	0	0.75	0.25
	0	0	0	0	1

Table12: Fitting accuracy of safety models

Model fitting accuracy	Neural network	Regression model
R^2	0.95	0.919
RMSE	0.0004	0.00051

Table 13: The priority of sections for the first year

Road sections	Accident rate	Traffic volume	Cost of repair	Pavement condition	Road importance	Risk of failure
Sec1	High	High	Rehabilitation	V. bad	Main	High probability
Sec2	Medium	Med	Minor	Bad	Arterial	High probability
Sec3	High	Low	Resurfacing	Bad	Arterial	High probability
Sec4	Medium	Med	Resurfacing	Fair	Main	Med probability
Sec5	Medium	Med	Resurfacing	Bad	Main	High probability
Sec6	Medium	Med	Minor	Fair	Arterial	Med probability
Sec7	High	Med	Resurfacing	Bad	Main	High probability
Sec8	Medium	High	Resurfacing	Bad	Main	High probability

There are two scenarios to determine the maintenance management strategies for the whole network (which are presented here in those eight sections). In the first scenario, the allowable budget covers the network requirements so all sections will be maintained. The analysis of this scenario is shown in Figure 6 and Table 14. Figure 6 shows the overall condition for all roads sections through 5 years analysis period**.** The pavement condition and safety level were estimated using the developed prediction models based on the available data for the period between years 2019 and 2020 [62]. Table 14 indicates the maintenance strategies for all sections through the analysis period. All sections have taken the needed maintenance based on their condition. In section 1 for example the needed maintenance in the first year was rehabilitation because of its bad condition while for the second year there is no maintenance needed as the condition in this year is in the targeted performance level. Table 14 showed that the most suggested strategies based on the decision model results are 0 and 1 which are related to “do nothing” and minor maintenance, while strategies 2 and 3 which refer to resurfacing maintenance and reconstruction, respectively are not common through the analysis period (5 years). This seems logical because strategies 2 and 3 are more costly, so they should be practiced less than the other maintenance strategies. It gives a sign that the decision module is performing well.

Figure 6 illustrates the condition of pavement with maintenance and compared it with the situation when there is no maintenance will be applied. It reveals that the application of the optimization module causes an immediate increase in pavement state at the year of application and therefore an improvement in pavement service life.

The total cost of maintenance management for scenario 1 is indicated in Figure 7. The figure explains that the needed cost to reach the optimum performance level for all sections in the first year is 400 million LE because of the low condition of all road sections this year. But the cost in the second year is 25 million LE as the performance of the road sections requires fewer improvements this year. The total needed budget to do the maintenance requirements through the analysis period is 827 million LE. The safety concern was checked for all sections through the analysis period of maintenance management based on scenario one as shown in Figure 8. It can be shown that all sections achieve the desired safety level.

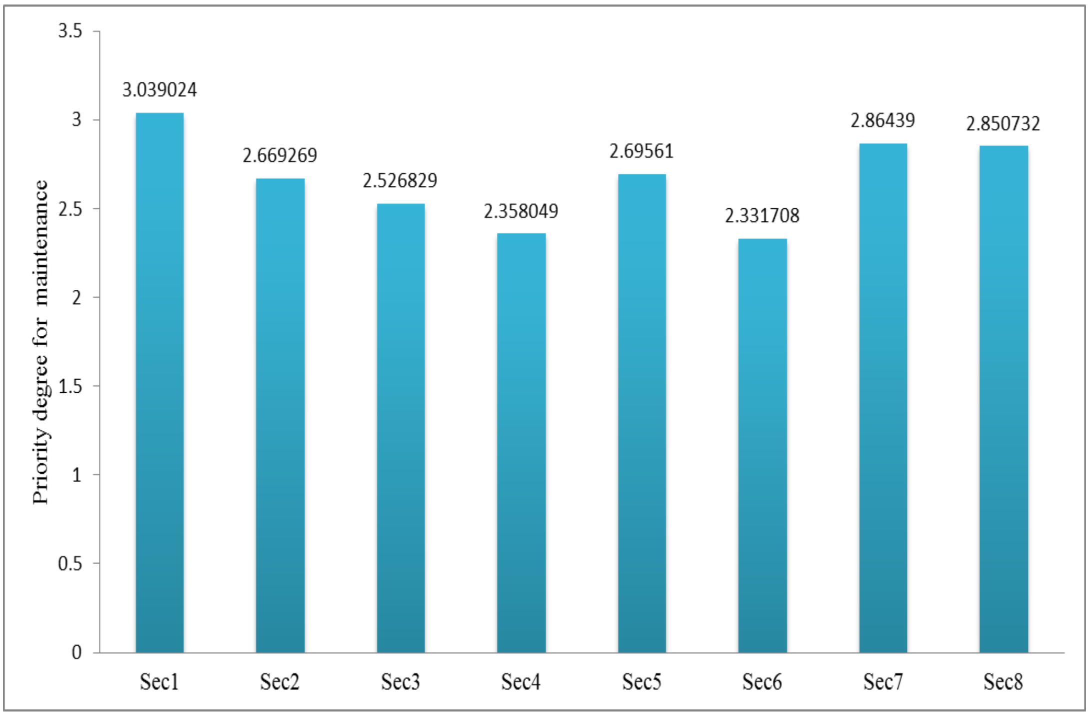
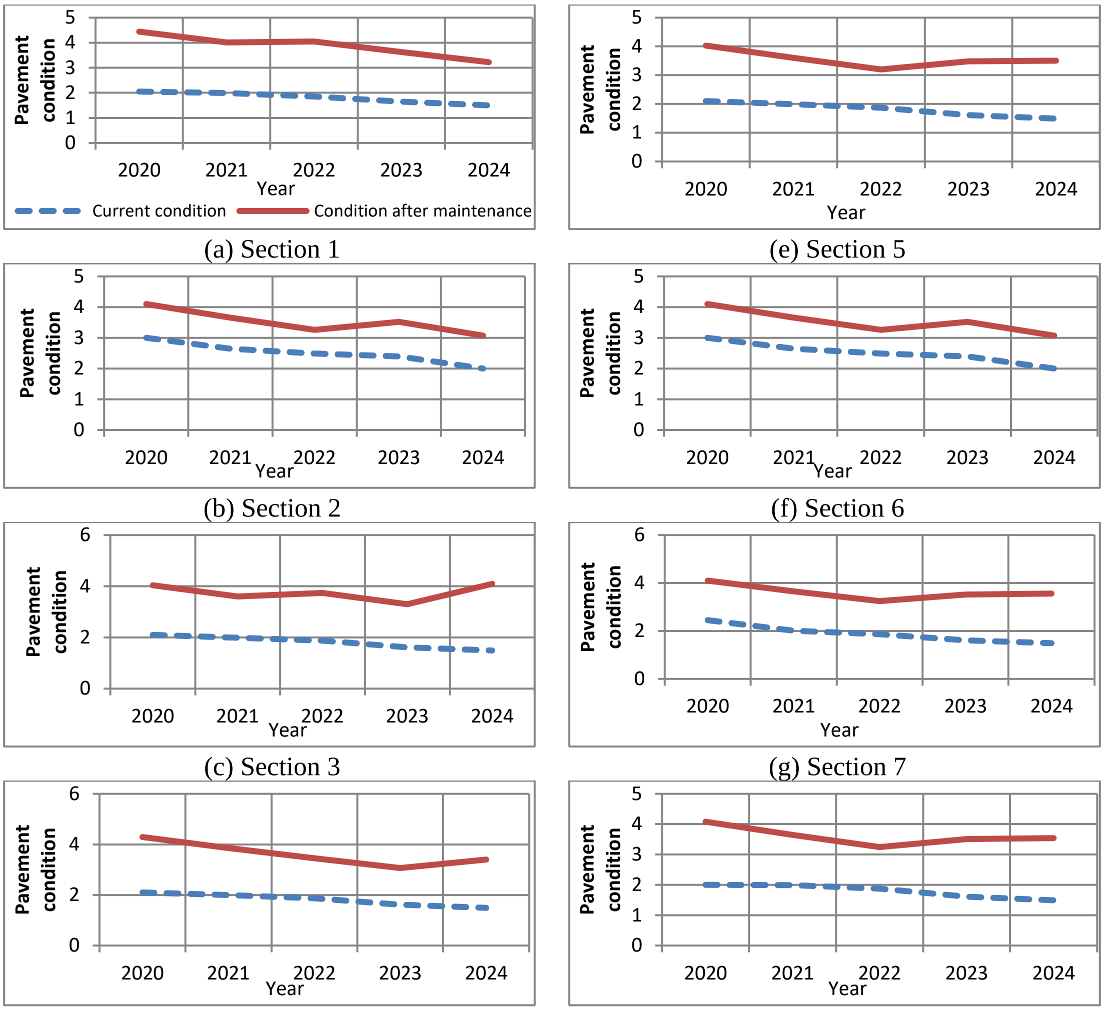


Fig. 5: The final rank of the road sections according to the POM value for Year 1

Table 14: Maintenance strategies for the road sections based on scenario 1

	Sec1						**Sec5**			
Year	2020	2021	2022	2023	2024	Year	2020	2021	2022	2023	2024
Strategy	3	0	1	0	0	Strategy	2	0	0	1	1
	Sec2						**Sec6**				
Year	2020	2021	2022	2023	2024	Year	2020	2021	2022	2023	2024
Strategy	2	0	0	1	0	Strategy	1	1	0	1	1
	Sec3						**Sec7**				
Year	2020	2021	2022	2023	2024	Year	2020	2021	2022	2023	2024
Strategy	2	0	1	0	2	Strategy	2	0	0	1	1
	Sec4						**Sec8**				
Year	2020	2021	2022	2023	2024	Year	2020	2021	2022	2023	2024
Strategy	2	0	0	0	1	Strategy	2	0	0	1	1



(a) Section 1
(e) Section 5
(b) Section 2
(f) Section 6
(c) Section 3
(g) Section 7
(d) Section 4
(h) Section 8

Fig. 6: Pavement condition for all sections through the analysis period on scenario 1

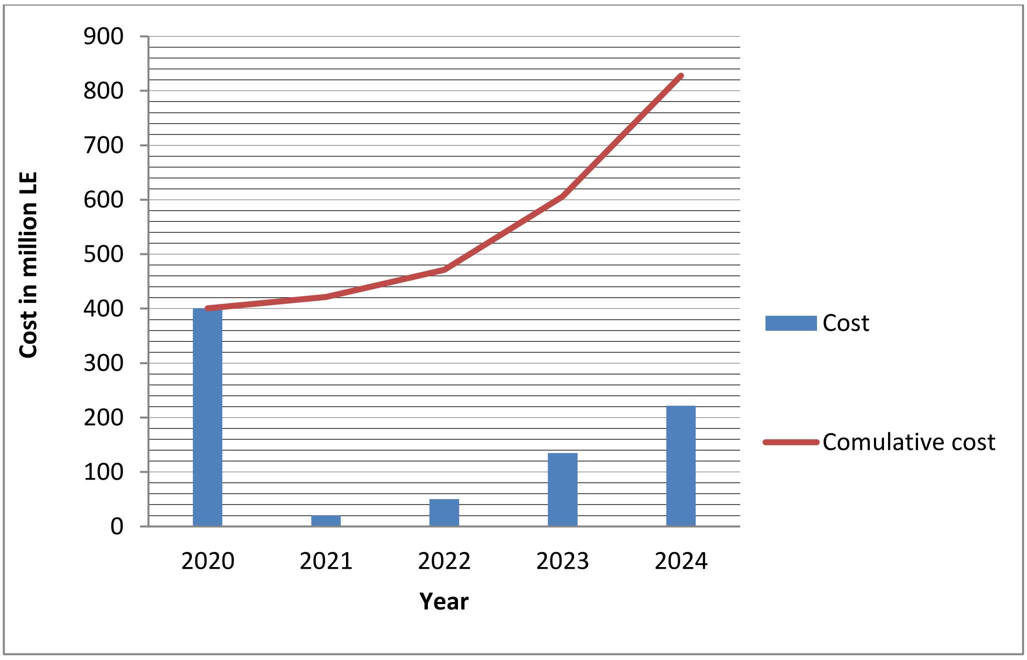
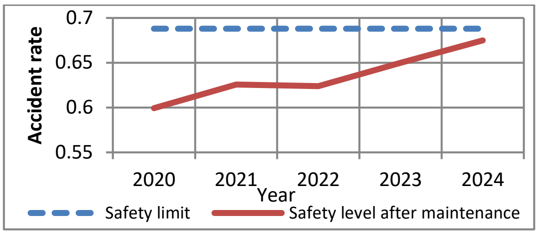
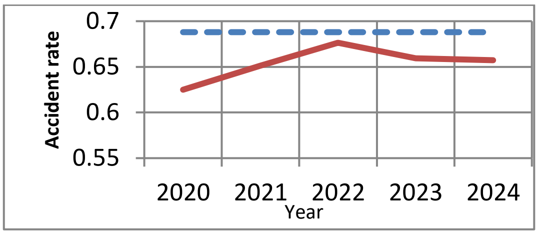


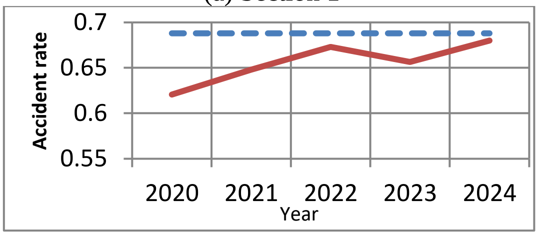
Fig. 7: Maintenance cost based on scenario 1



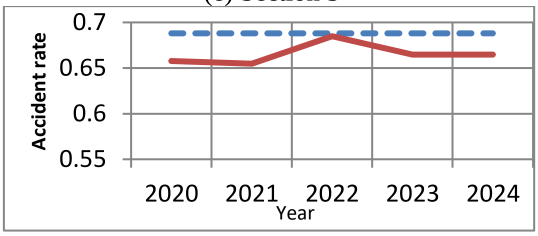
(a) Section 1



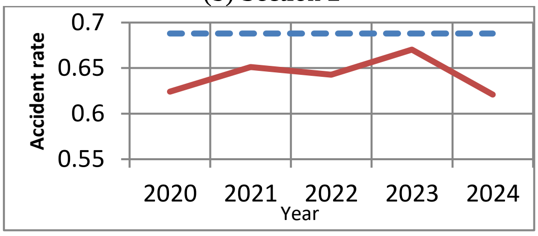
(e) Section 5



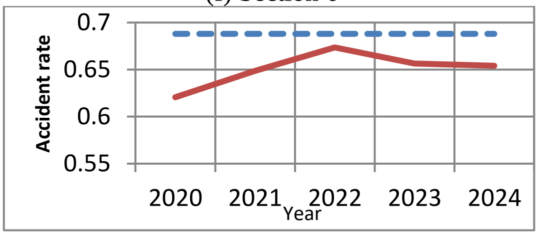
(b) Section 2



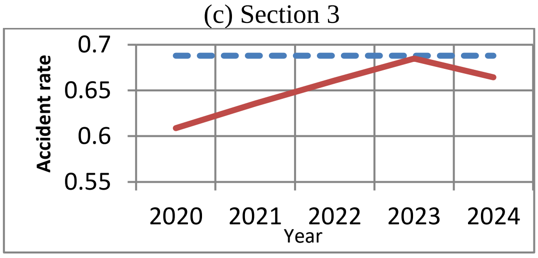
(f) Section 6



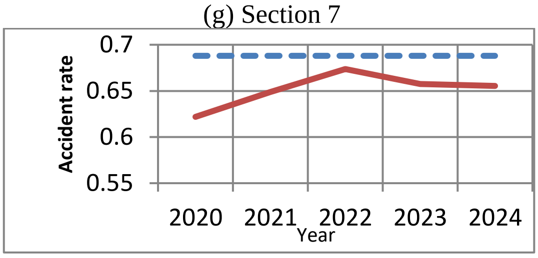
(c) Section 3



(g) Section 7



(d) Section 4



(h) Section 8

Fig. 8: The safety levels based on scenario 1

In the second scenario, the available budget for preserving the network is restricted. Therefore, the prioritization methodology was applied. Road sections were ordered based on their maintenance priority. The final ranking order of the road sections was compared to the available budget which was considered as 200 million LE/year. The analyses of this scenario are shown in Table 15 and Figure 9. Table 15 indicates the maintenance strategies for all sections through the first 5 years of the analysis period. Some sections have not acquired the needed maintenance because of the restricted budget and their priority results. In sec 6 for example, there is a shift in the maintenance program in the first year to be implemented in the second year. But in sec 1, there is no shift in its maintenance program due to the high priority of this section. Figure 9 indicates the effect of this scenario on the pavement condition performance through the analysis period. In sec 6 for example, there is a drop in the condition performance in the first year because of delaying the maintenance strategy.

The system provides a comprehensive and deep concept for the decision-makers to manage road networks and know the effect of the decision. Table 16 shows the effect of delaying maintenance on cost expenses for all road sections. In sec 6 for example, there is a saving in the cost expenses in the first year by 18.6 million LE. But there is over expense cost of 38 million LE in the second year. The negative sign was used to indicate the expenses, while the positive sign indicates the cost-saving due to the prioritization system. Figure 10 indicates the cost flow diagram for scenario 2. In this scenario, the maintenance program was applied based on restricted funding. Therefore, the road sections were maintained based on their prioritization degree. The restricted budget for the maintenance decision worked on delaying some repairs according to the priority of the section. Therefore, there would be a backlog for the fewer priority sections in some years. However, the total percentage of the backlog did not exceed 15%. The safety concern was checked for all sections through the analysis period of maintenance management based on scenario 2 as shown in Figure 11. It can be shown that there is a drop in safety level in some sections due to late maintenance decisions because of the inadequate budget for the maintenance decision work delaying some repairs according to the priority of the section. Therefore, there will be a decline in the safety level for some sections of the network. However, there is a cost-saving due to the prioritization program reaching 27 million LE.

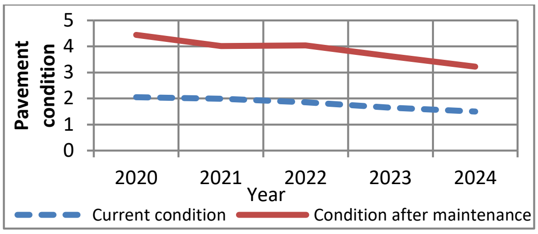
Compared with the previous relevant literature, the proposed SPMS differs from other road maintenance models and PMS as the previous systems of pavement management focus mainly on the pavement condition and did not regard the safety aspect in the analysis process as shown in the literature of [14,15,16,17,33]. Also, the proposed SPMS differs from the direction of some researchers in the safety field (e.g., [49], [50]) because they separately developed the safety model and not considered it in the PMS.

Table 15: Maintenance strategies for the road sections based on scenario 2

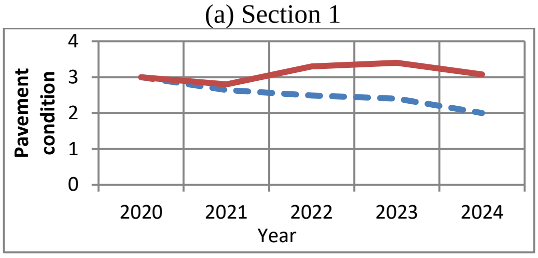
	Sec1						**Sec5**				
Year	2020	2021	2022	2023	2024	Year	2020	2021	2022	2023	2024
Strategy	3	0	1	0	0	Strategy	0	2	0	1	1
	Sec2						**Sec6**				
Year	2020	2021	2022	2023	2024	Year	2020	2021	2022	2023	2024
Strategy	0	2	0	1	0	Strategy	0	2	0	1	0
	Sec3						**Sec7**				
Year	2020	2021	2022	2023	2024	Year	2020	2021	2022	2023	2024
Strategy	0	0	2	0	1	Strategy	2	0	0	1	1
	Sec4						**Sec 8**				
Year	2020	2021	2022	2023	2024	Year	2020	2021	2022	2023	2024
Strategy	0	2	0	1	1	Strategy	2	0	0	1	1

Table16: The difference in expenses between scenarios 1 and 2

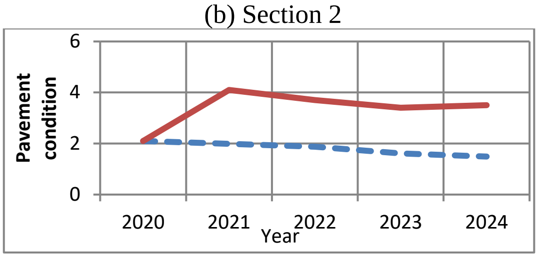
Year	**2020**	**2021**	**2022**	**2023**	**2024**
Sec1	0	0	0	0	0
Sec2	39377250	-43708748	0	0	0
Sec3	39377250	0	-23844646	0	35125037
Sec4	57753300	-64106163	0	-34900439	0
Sec5	42002400	-46622664	0	0	0
Sec6	18559200	-26021952	0	0	28174172
Sec7	0	0	0	0	0
Sec8	0	0	0	0	0



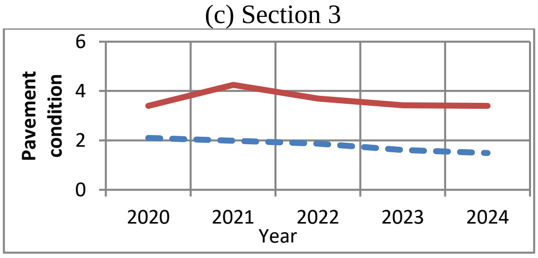
(a) Section 1



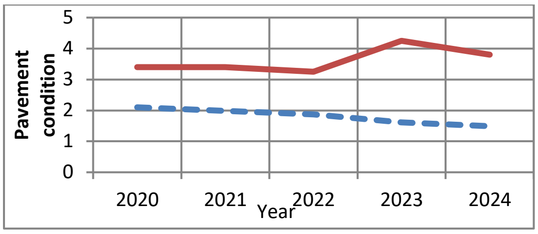
(b) Section 2



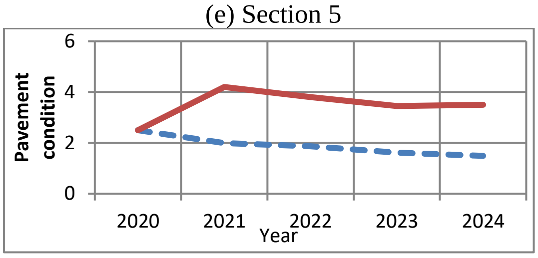
(c) Section 3



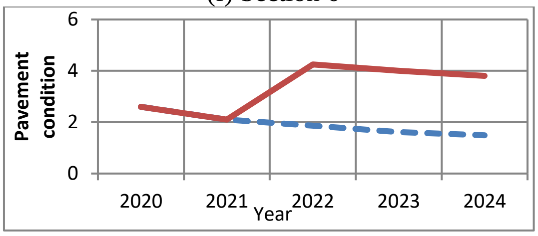
(d) Section 4



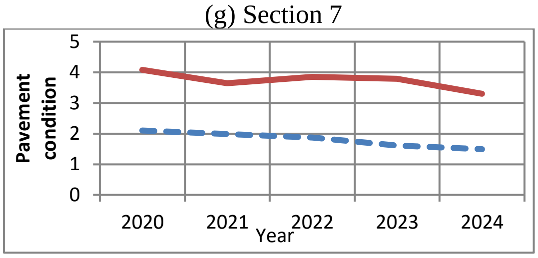
(e) Section 5



(f) Section 6



(g) Section 7



(h) Section 8

Fig. 9: Pavement condition through the analysis period on scenario 2

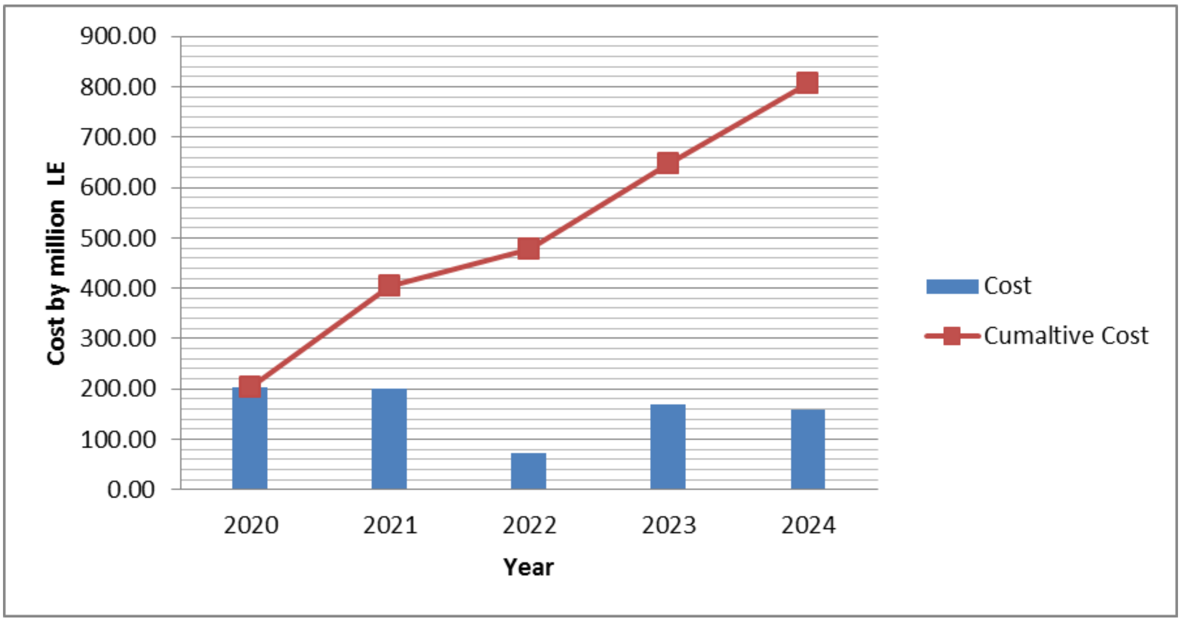
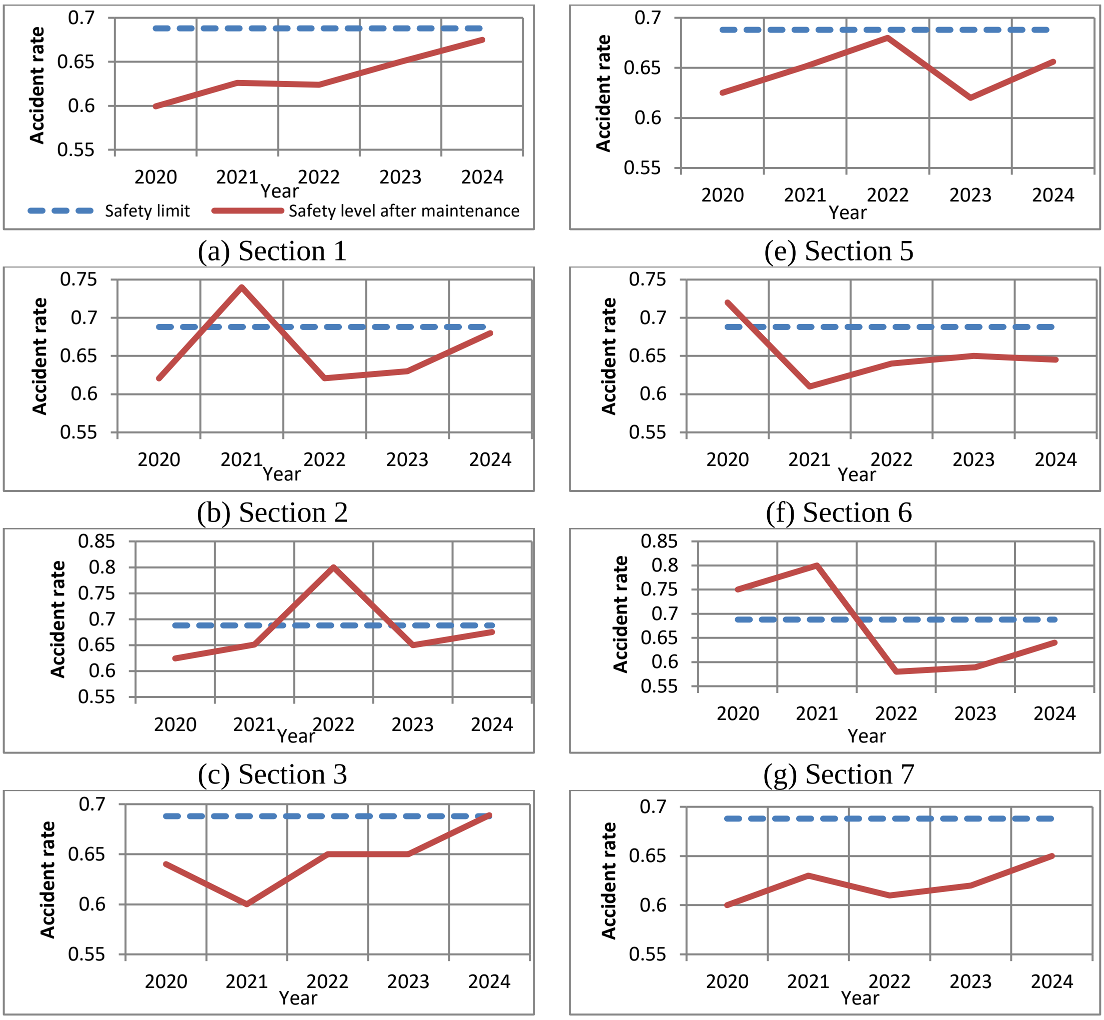


Fig. 10: Maintenance cost based on scenario 2



(a) Section 1 (e) Section 5

(b) Section 2 (f) Section 6

(c) Section 3 (g) Section 7

(d) Section 4 (h) Section 8

Fig. 11: The safety levels based on scenario 2

5. Summary and conclusions

In this paper, an integrated safety-pavement management system (SPMS) for local authorities in Egypt was developed. Firstly, the Markov technique was used to predict pavement condition performance in terms of pavement condition index (PCI). The performance model considered three traffic volume classes, high, medium, and low. The model also considered maintenance effects on the condition of the pavement. Then, the system was adapted by a maintenance decision tool to analyse the maintenance strategies through the analysis period for different sections in the road network. The management decision in this study tackled the economic solutions for maintenance decisions and the safety concern through the service life of roads using maintenance trigger value for pavement sections at a condition threshold equal to 3 which was obtained from the safety model. The applicability of the model was tested for a case study in the southern roads network of Egypt. The main findings of the proposed system can be listed as follows:

- The proposed system considers the integration between performance, cost, and safety in its analysis.
- The program works on accelerating the analysis process and facilitating it for the decision-maker as a user of the system.

- The proposed system can help decision-makers in finding the best strategies for maintenance management and keep safety through road networks based on any target level of funding.
- The results indicated the applicability of the system in determining the economic maintenance management plan which keeps the pavement performance at the targeted level and enhances the safety of the roads network in Egypt by saving 27 million Egyptian pounds ($1.13 million) through the analysis period.

Highway agencies in Egypt have limited facilities for the assessment of pavement conditions and maintenance requirements, such as equipment and funds, therefore, the detailed assessment of individual pavement sections may not be conducted. This research main goal is to develop a practical method for managing large road networks. PMMS is proposed to accommodate both the network level and project level needs. The proposed method can optimize decisions at the network level (which road should be repaired and when) as well as at the project level (best type of repair for road elements). Data availability limitation was the main challenge of this research, thus more up to date data should be applied in further researches on this topic.

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نظام متكامل لإدارة نظم صيانة الرصف وأمان المرور (SPMS) للهيئات المحلية في مصر

الملخص العربى

تعد إدارة صيانة الطرق من الإستراتيجيات الأساسية لتحقيق استدامة البنية التحتية. ويعتمد قرار الصيانة في مصر على حالة الرصف فقط، حيث لا يتم النظر في درجة أمان المرور. تهدف هذه الدراسة إلى تطوير نظام متكامل لإدارة الرصف وأمان المرور يمكّننا من إدارة شبكة الطرق حسب الميزانية المالية المتاحة ويحقق السلامة المرورية خلال العمر التشغيلي للطرق. يقوم النظام بتطوير نموذج أداء احتمالي (probabilistic performance model) وأداة اتخاذ قرار التحسين (optimization decision tool) بناءً على حالة الطرق ومستوى السلامة وتكلفة الصيانة وذلك لتوفير قرار صيانة مناسب وفى الوقت المناسب. تم التحقق من كفاءة النظام بالتطبيق على شبكة الطرق بجنوب مصر. وأظهرت النتائج أن ميزانية الصيانة غير الكافية تؤدي إلى تأخير صيانة بعض الطرق مما يؤدي إلى تدنى مستوى السلامة المرورية وحالة الرصف بتلك الطرق. إلا أن النتائج أشارت إلى إمكانية تطبيق خطة صيانة اقتصادية تحافظ على السلامة المرورية في المستوى المستهدف وتعزز أداء الرصف علي كامل الشبكة.