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Research Article

A Data-Driven Road Management Application for Automated Pavement Condition and Safety Assessment

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Abstract

Road infrastructure management in many developing countries is hindered by the absence of integrated systems for evaluating pavement conditions, road safety, and maintenance planning. This challenge is particularly evident in Iraq, where existing road management practices lack standardized assessment mechanisms and centralized databases. This study presents a Road Management Application (RMA), a data-driven, semi-automated system that integrates structural pavement evaluation and road safety assessment within a unified platform. Developed using Python 3.12.7, the application stores comprehensive road information, including road classification, pavement age, material properties, pavement layer configuration, and geometric characteristics, enabling efficient data management and periodic updates. The RMA applies standardized evaluation criteria to identify and rank pavement defects and safety issues, providing decision support for maintenance planning. The system was validated through case studies on Airport Street and Hilla–Najaf Street in Najaf Governorate, Iraq. The results demonstrate that the application effectively identifies critical pavement and safety deficiencies, prioritizes road sections according to their condition, and establishes a reliable database for long-term infrastructure management. Compared with conventional descriptive surveys, the proposed approach provides a data-driven, reproducible, and integrated framework for road condition assessment and maintenance decision-making. The developed application can be readily adapted for use by road agencies in Iraq and other regions facing similar infrastructure management challenges.

Keywords: Road Defects; Road Management System; Python; Maintenance; Road Condition.

INTRODUCTION

In previous periods, the transportation system in Iraq experienced numerous problems. The road management system in road agencies became a focus of interest for researchers at universities and various contracting companies due to the discrepancy in the standards used for road network assessment management systems. This effort aimed to identify the most important standards or systems that could streamline the road maintenance management process and avoid randomness and selectivity in the application of maintenance assessment standards [1, 2]. Despite this long-standing interest, there remains a gap in the literature related to research on road assessment management, as it is generally limited to countries in the region, particularly Iraq [3, 4]. The Iraqi specifications and standards for roads and bridges were issued by the General Authority for Roads and Bridges of the Ministry of Construction and Housing (revised version up to February 14, 2007), known as SORB - Standards and Specifications for Roads and Bridges. These standards lack any specific regulations or laws regulating them, allowing for selectivity and decentralization in many decisions related to road maintenance [4].

These specifications primarily concern the structural and technical aspects of roads, including the design of pavement layers, materials, geometric dimensions, and drainage systems. Still, they require an integrated system for evaluating and managing road performance, and this, in turn, may not take into account all the requirements and standards to be evaluated for roads before developing a plan or maintenance cost, which causes variance between different projects, according to the experience of engineers in the evaluation committees [5, 6]. The importance of this research lies in creating a model of the road management system for road agencies by bridging the gap in variance, according to the experience of different engineers, and serving as a basis for evaluation to refer to, so that evaluations are based on a fixed system that changes with the change of data. Therefore, the results of this study will contribute to future studies of policies. Research and projects related to road construction are positively impacted by providing a clear picture of the areas of the roads that need to be focused on [7, 8].

This study creates a stable database for roads to manage their regular maintenance in the future. This model (RMA) is based on a comprehensive assessment of the current condition of the network according to a set of criteria. Each criterion records a specific scale and is weighted based on the specific importance of the criterion. The study was implemented to simulate the situation faced by a road authority without a road management model. The research structure is to create a model of the proposed road management system and create a digital database for the road network. An example of a digital road data collector for two different roads was also explained, as well as an evaluation and classification of the case, and thus the model was applied to evaluate the usability and efficiency of the proposed road management model (RMA). A case study of two roads was taken, and the model (RMA) was applied to them; thus, the required results and conclusions were formulated.

RESEARCH GAP

A clear gap exists in the development of low-cost, integrated road management models that incorporate safety standards and are specifically designed to meet the needs of modern road authorities. This gap persists despite the emergence of GIS-based and AI-powered road assessment tools, as well as the widespread use of traditional pavement condition indicators.

Previous study utilized an old pavement assessment method named overall condition index (OCI) and then plotted the results on another program Arc GIS. It is a method of data visualization rather than functional system integration. This old method is subjective and it relies on engineering/ expertise judgment for interpreting scores. In addition, the entire process was conducted manually, which may be time intensive and susceptible to error [9]. Moreover, the overall condition index (OCI) method implemented in this study ignored significant element such as rutting, settlement and safety aspects in decision making.

Other studies combined both Provincial/Regency Road Management System (PKRMS) and Analytical Hierarchy Process (AHP) to manage road maintenance [10, 11]. PKRMS is a management tool that is able to identify road defect based on the survey data. However, there are a number of issues with this method such as primarily technical tool, inaccurate surface distress index (SDI) could cause the system to ignore a road that needs urgent repair, in addition focuses only on the structural conditions of the road and ignoring safety aspects and road importance. Therefore, a number of studies combined both PKRMS and AHP to connect safety aspect, road importance, economic impact and public service facilities [10, 11]. However, it is important to note that previous studies did not combine both methods into one software or program. In addition, AHP in both studies relies on pairwise comparisons from experts only. It is important to note that, reliance on expert opinions of this qualitative input and the absence of established safety standards remain significant concerns for reliable road management.

Pavement condition index (PCI) is well known as a numerical rating system relay only on the pavement structural conditions. PCI score ranges from 0 to 100, as 0 indicating the pavement reached the end of its life and 100 representing brand-new road. Previous study indicated that PCI is more suitable for flexible pavement rather than rigid pavement [12]. PCI score does not recognize if the road needs a simple treatment, major maintenance or a full reconstruction. In addition, corrected deduct value (CDV) calculates manually using curves and tables which makes it time consuming and more susceptible to human mistake [13].

It is important to note that issues addressed by the proposed road management application is the gap, through the provision of an automated road condition recording system based on Python. This system integrates statistics on recurring defects, safety metrics, and sensitivity-tested weighting factors into a single digital database, enabling coordinated and scalable road maintenance decisions.

The comparison in Table 1 illustrates the differences between the model systems used and the various criteria, as shown. The importance of the road management system and its recommendations for a more systematic approach to road management evaluation are clearly demonstrated in the following section, Contribution Beyond State of the Art.

Table 1. Criteria for choosing between models

Criterion	RMA	PCI [14]	Khahro ANP low-cost [15]	GIS-Iraq [16]	AI-vision systems [17, 18]
Automation level	A straightforward, sequential automation process using Python, based on a recurring, input-based database.	Based on manual calculations than automated ones	Using ANP requires expert input which may be different from one country to another.	OCI-based manual calculations do not keep pace with project the speed and the accuracy of its details.	Highly automated , but also highly error-prone.
Cost	Low cost to implement	It requires larger networks but is also relatively inexpensive.	Moderate cost for decision-making modelling requirements	Geographic Information Systems software only used to present the data rather than a functional system integration	Relies on numerous sensitive devices, which greatly increases its cost.
Safety integration	Safety aspects are fully integrated in the system.	Safety aspects are not implemented	Safety standards are variable depending on decision-making criteria and are not fixed.	Safety aspects are not implemented.	High risk detection capacity, but may not always be accurate.
Prediction capability	prediction based on sensitivity weights and scores but this is still in the experimental stage.	More limited than other models.	Predictions are made based on the importance of the strategy followed.	Network-level evaluation	High predictive potential, but not highly accurate
Validation scale	Practice simulation of selected methods	Extensively applied beforehand	It relies on case studies to verify the feasibility of verification.	Extensively Implemented	Applied as a model in very different forms

CONTRIBUTION BEYOND STATE OF THE ART

In general, road management or evaluation systems may differ in principle, but the core of the management structure and the nature of the area being evaluated, such as the area under study, remain crucial. Systems relying solely on Geographic Information Systems (GIS) and AI-powered prediction models are still not effectively suitable for capturing the intricate details and problems of this area, despite numerous trials [19]. This is what we addressed at RMA, where practical contributions focused on surpassing the latest technologies in terms of application to the area. This was achieved by clearly integrating criteria and assigning specific weights to the pavement condition index, the structural deterioration index, and traffic safety standards within a defined framework [20]. Thus, decisions are made clearly based on stable information.

The main contributions of this study are listed below:

- Fully integrated road management system into one software combined both structure and safety aspects.
- Store all the data related to road conditions in one file can easily access and check the main issue.
- Suitable for both rigid and flexible roads.
- Transparent decision-making and tracking to avoid errors.
- Scoring criteria based on clear and firm standard.

The initial cost of RMA is low, but its effectiveness is very high. Unlike other systems, it does not rely on hierarchical analysis, as illustrated in Table 2 [21, 22].

Table 2. Comparing systems in terms of contribution that goes beyond the latest technologies

Aspect	Traditional PCI	Property management system based on GIS	AI-Based Models	Proposed RMA
Engineering inspection	Recognized	Popular	Assumed	Adopted
Safety Integration	✕	✕	limited	Clear
Plainness	High	Intermediate	Low	High
implementation outlay	Low	Intermediate	High	Low
Demand for data	Low	Intermediate	High	Low
Decision follow ability	Accept	Partial	✕	Accept
Delicacy Analysis	✕	✕	Limited	Accept

METHODOLOGY

This research proposes a Python-based road condition assessment model that transforms road investigation into an automated, objective, and reproducible road condition evaluation system. The methodology integrates empirical defect data, computational scoring algorithms, and decision-support outputs into a single framework designed to be both robust and user-friendly. The proposed methodology operationalizes recurring road defects into a programmable structure, enabling rapid evaluation, reduced subjectivity, and improved consistency across inspections.

Field Investigation and Data Collection

Road condition data were collected through a systematic field investigation conducted on two main roads [23]. Road inspections followed a structured survey format to ensure data consistency and repeatability.

For each inspected road, the following information was collected

- Geometry data
- Construction data
- Defect type
- Defect severity
- Accident data

All inspection data were digitized and stored in a structured format suitable for direct integration into the Python-based program.

Identification of Recurring Defect

The principle of recurring pavement defects was adopted using statistical analysis of the frequency of collected data. The incidence rate of each defect type was determined as a percentage of the total defects detected in each project. A chi-squared test was then applied at a 94% confidence level to determine the statistical significance of the specific road sections requiring maintenance using equation (1). Accident records were compiled and categorized according to cost, speed, and quality into organized subgroups to prioritize maintenance. Specifically, weighting factors (Wi) were assigned to each defect category based on serviceability, traffic safety, and structural integrity. Initial weights were derived from engineering judgment supported by relevant pavement management literature to ensure the robustness of the proposed assessment model. Sensitivity analysis was performed to assess the impact of weight changes of ±10% to determine the final decision. The RCS software is available upon request.

$$\chi^2 = \sum \frac{(O_i - E_i)^2}{E_i}. \quad (1)$$

Where:

χ^2 - Tested chi-square value.
$\sum$ - Road summation coefficient.
O_i - Actual road values.
E_i - Expected road values.

Program Structure and Implementation

The road management application was created using Python version 3.12.7 programming language, distributed via the Anaconda package manager. All Python coding was performed on a Windows 10 (64-bit) operating system. The program is organized into the following interconnected modules

- Input module (accepts field investigation data through a structured interface, minimising manual entry error)
- Defect database module (stores recurring defects, allowing future updates or monitoring).
- Condition scoring engine (applies rule-based algorithms to calculate defect scores and overall road condition indices).

- Output and decision-support module (generates condition ratings).

Data Collection and Evaluation

Sources of data on road pavement surface condition of the selected roads were obtained from a visual survey of pavement condition evaluation. Classification of road conditions was based on the condition survey rating scores built into the Road Scoring Application (RSA). The scoring was estimated on a scale of 1–5 units, where 1 and 5 denote excellent and worst conditions, respectively. The approach adopted in this study was similar to some extent to the IRC: 82-2015 guidelines, with implementing new safety aspects and also joint conditions in case of evaluating rigid pavement, as shown in Table 3 [24]. Safety aspects and joint conditions rating are explained in more detail in the next section. Input parameters used for classifications included the following.

Table 3. Pavement defects and safety rating for roads

Defect (Types)	Range of Distresses			References
Rut depth in mm	> 10	5 to 10	< 5	[24]
Potholes %	> 1	0.1 to 1	< 0.1	
Cracking %	> 10	5 to 10	< 5	
Settlement & Surface damage %	> 5	1 to 5	< 1	
Bleeding %	> 10	5 to 10	< 1	
Joint conditions (spall width) mm	> 150	75 to 150	< 75	[25]
Accident rate	> Critical Rate (R_c)	R_c> accident rate < average rate	<average rate	[26, 27]
Safety concerns	High frequency of fatal accidents	1-3 serious accidents	No fatal accidents in 5 years	
Road importance	Arterials (main)	Collectors	Minor (local)	
Rating	5	3-4	1-2	
Conditions	Bad (Red flag)	Reasonable (Amber flag)	Good (Green flag)	NA

Condition Scoring

Each defect is evaluated using a weighted scoring system that accounts for severity, extent, and relative importance. The overall road condition scoring (RCS) is calculated as:

$$RCS = \sum_{i=1}^{n}(S_i \times W_i) \quad (2)$$

Where:

S_i - represents the severity rating of defect i.
W_i - represents the importance weight assigned to defect i.

Weights were determined based on defect impact on pavement structural integrity, durability, serviceability, and safety (more details are explained in sub-section called condition assessment and rating).

RECURRINGPAVEMENT DEFECT IMPLEMENTED IN THIS MODULE

Rutting (Permanent Deformation)

It's crucial to assess permanent deformation and conduct regular maintenance, as it is considered a permanent deformity that can extend for significant lengths, sometimes several kilometres, especially on Iraqi roads. There's a general lack of road markings on all roads, allowing most drivers to use one side of the road over the other. This makes areas of weak shear resistance more visible, especially in high temperatures. Furthermore, some trucks don't adhere to the permitted limits, further exacerbating rutting [28-30].

Longitudinal and Transverse Cracks

Longitudinal and transverse cracks are caused by poor compaction during implementation, as well as high temperature differences, which lead to cracking at weak points in the longitudinal joints. Additionally, the long age of roads, combined with the lack of periodic maintenance, causes aging in the asphalt, particularly in the surface layers, leading to the appearance of longitudinal and transverse cracks. It is worth noting that most road foundations are exposed to differential settlements in the foundation soil for the same reasons mentioned earlier, which exacerbates the situation [31-34].

Longitudinal Joint

In some cases, problems with the longitudinal joint are very obvious and must be taken into account permanently in road evaluation, due to the occurrence of cracks in the same joint, which makes it lose its resistance against the road when temperatures change, as it is the weakest point of the road, and sometimes leads to a significant separation of the two layers [35, 36].

Transverse Joint

One of the most important joints to preserve roads and protect them from large changes in temperature is the transverse joint, which is usually every four to six meters, depending on the required road design. However, one of its problems is that it may allow water to leak, leading to erosion in the lower layers of the road. This is due to the joint not being treated well or poor compaction in the joint areas. It also causes weak endurance and cracking of the upper layers. The same applies when the joint is not used during implementation, which leads to cracking of the tiles or sometimes to their subsidence [37-39].

Pothole

Potholes mostly look like bowl-shaped holes with different sizes occurring in the pavement surface, and the minimum dimension is 150mm [40]. Potholes are a series of failures in a road. They first begin as a small portion of the top layer of the road. Over time, this type of failure will progress toward the lower layers of the road. The size of the pothole will increase and deepen as water collects and penetrates the underlying layers of the road, such as the base layer and subgrade, weakening the support of the area [41]. Potholes typically occur under severe weather conditions, heavy traffic, and poor drainage [42]. The existence of potholes in the road causes severe damage to vehicles, delays traffic and leads to loss of control. For instance, in 2021, a study showed that 0.8% of road accidents were due to potholes, results into 1.4% fatalities, and 0.6% injuries [43].

Fatting (Bleeding)

This type of failure occurs when there is an excess of asphalt in the road surface. The asphalt binder can move toward the surface as vehicles pass through in hot weather due to the excess bitumen content in the asphalt mixture or through the movement of aggregate particles deeper into the underlying bituminous layer. Fatting can be considered a safety defect, mainly when it happens in a bend or downhill road for a long distance. Fatting is considered dangerous for vulnerable road users and may cause loss of control for vehicles [44].

Settlement

Settlement or depression appears as a difference in the elevation between localized pavement surface areas with a lower elevation than the surrounding areas. Settlement becomes very clear after a rain, as localized pavement settlement fills with water. The main cause of settlement is a subgrade issue or frost heave [45].

Adding a new carriageway to an old road is considered one of the most common solutions to maintain the level of service. However, differential settlement usually occurs in road widening projects between the old and the new widened portion of the road [46]. Transverse cracks will appear on the pavement surface as a result of differential settlement developing in the middle of the embankment [47]. In addition, differential settlement will cause different types of defects on the pavement surface, such as loose bitumen, spalling, a change in the horizontal slope of the road, and longitudinal cracks at the joint between the original and the added width of the road constructed on weak soil [48].

Surface Damage

Surface damage is a significant change of a road surface from a flat surface with proper dimensions into a surface that compromises the safety of vehicles and vulnerable road users [49]. Surface damage occurs due to deep-seated issues such as deep rutting, severe moisture damage, joint sealant failure, and major fatigue cracking. Surface damage impacts a vehicle's stopping distance, misalignment of vehicle wheels, and loss of control, increasing the risk of accidents [49].

PROPOSED ROAD MANAGEMENT SYSTEM MODULE

This research showed clear gaps in the current practice of Iraqi road agencies, such as the lack of a centralized digital asset register, the absence of regular surveys of pavement condition, and a lack of a prioritization method for selecting maintenance plans. This research aims to cover most of the issues highlighted in the previous studies [50, 51]. For instance, traditional decisions are often made without systematic situation assessment.

Such decisions contributed to worsening road conditions, road users' dissatisfaction, and budget overruns.

This research proposes a structured, data-driven road management (RMA) model tailored to the needs and capabilities of Iraqi road agencies and any other agencies operating without such a system. The model includes basic components such as construction data, geometry data, and condition assessment, which can then be used in maintenance strategy, budgeting, and performance monitoring.

Implementing such a model will help road agencies move from reactive to proactive maintenance. This paper also presents a case study application of the model to demonstrate its effectiveness and benefits.

Components of the Proposed Road Management System Model

The components of this model (RMA) are drawn from global management models. It is implemented to be suitable for road agencies operating without a management system. The model includes six main components. Those core components are shown in the model schematic diagram, see Figure 1. Initially, any road agency should have a database of its entire network. This can be done using the model designed in this research. This model allows users to complete all of the required fields for each road segment, along with its geometry and construction data, as illustrated in Figure 1. A real example is provided in Figure 2.

The main part of the version (Road Scoring Application) is used to evaluate road conditions. According to those assessments, it prioritizes maintenance or monitors the performance of roads based on their rankings. The complete process is shown in Figure 3. After the entire network has been scored, the results can be ranked and stored in a CSV (Comma-Separated Values) document, with every road ranked based on its individual rating, as shown in

Figure. These two steps offer most of the information required for budgeting and work planning for any road maintenance work.

The system (RMA) is designed to guide maintenance planning, prioritization, and implementation, to support data-driven, transparent, and sustainable decision-making. The first and most essential step in this version is twofold: setting up a digital database of the network and training workers. For developing road agencies, the main challenge of this model lies in the necessity of a preliminary data collection, followed by periodic updates derived from field surveys.

The following algorithm in Figure 1. defines the overall rule for the road management strategy adopted in the model. It specifies the most important criteria based on which one segment is preferred over another for maintenance, or the maintenance of certain sections of a road at the cost of others, if the fund is insufficient to look after all sections of the road.

The first section of the construction data is a database containing the most important information, such as the number of layers, their thickness, the surface type, and the type of construction materials. The process continues with geometric information, including the number of lanes for each road, their width, and the names of the sections if there are different geometric properties of road sections. Finally, the road class or classification is presented. The next segment is the strategy of the prioritization matrix and its components, mainly based on the pavement condition scoring, road importance, traffic volume, and safety concerns. The model is based on a prioritization matrix, which is based on visual condition surveys, video recording surveys, a general report, and map findings.

Based on that information, the budget, work plan, and funding scenarios are specified, which may be shortlisted.

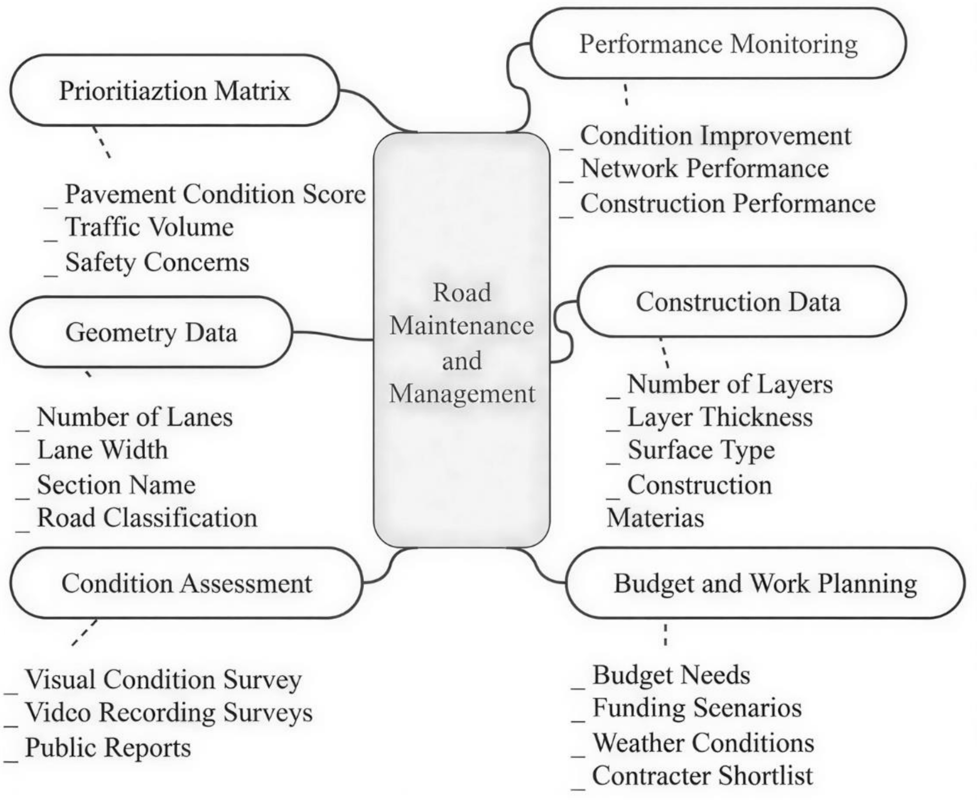

Figure 1. Proposed road management system model schematic diagram

Establishing a Digital Database of the Road Network

It is fundamental to establish a digital database of the road network. Therefore, the authors of this research implemented the Python coding language to create a digital road database collector. An example of the digital road database program with the necessary details created in this research is shown in the Figure 2. It can be seen from Figure 2 that each road segment was recorded with its location, geometry data, and construction data, and this information was then stored in a CSV file as a digital database record for the entire network. The digital database is essential for providing the necessary information to the two main components of the proposed road management application model (RMA). Iraqi road agencies can adopt this digital database to collect road data and then use this information in the proposed road management application model shown earlier in this research. Having such information for the entire network helps to plan and budget the maintenance, mainly for emergency repair (like-for-like design).

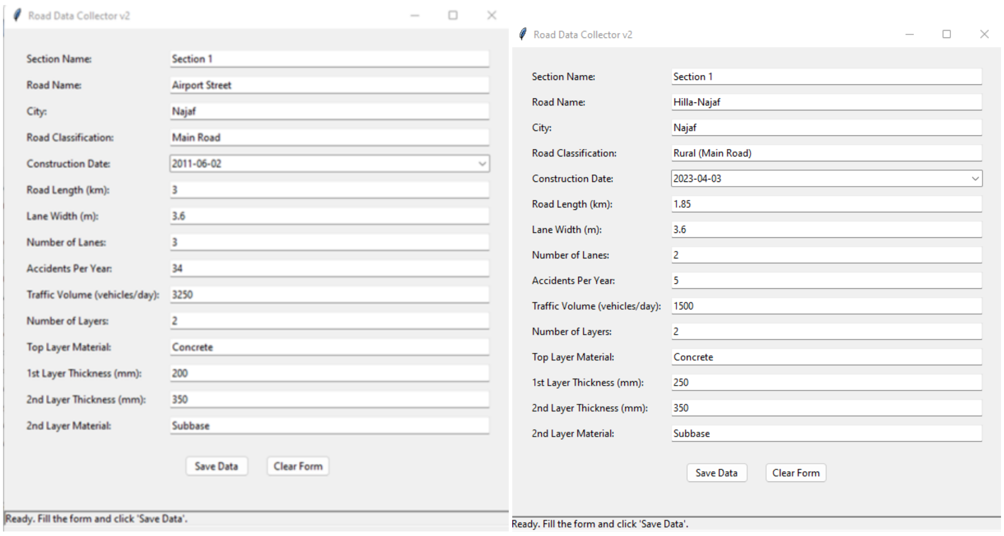

Figure 2. Example of the digital road database collector front page of two different roads

Condition Assessment and Rating

In order to provide an overall assessment of the current network condition, an assessment model was developed that makes it possible to score and weight several criteria. The model matrix is presented in Table 3 and Table 4. Each criterion is scored on a scale of 1 to 5 and then weighed depending on the criterion's perceived level of importance. The analytical hierarchy process (APH) is used to assign a weighting score to each defect. The process follows four main mathematical steps. The first step compares each criterion against each other criterion in terms of importance on a scale of 1 to 9 using a Pairwise comparison matrix. A higher weighted score is given to any defect that has the potential to be a safety concern and/or lead to premature damage. For instance, the safety aspect is considered extremely more important than minor surface defects and moderately more significant than structural defects. The following equations 3 to 7 are used to normalize the defect matrix and to calculate the priority weights, respectively. The final calculated weights are shown in Table 4.

$$a_{ij}^{'} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \tag{3}$$

Where:

a_{ij} is the Pairwise comparison value.

i: is the row of the defect under consideration.

j: is the column of the other defect are comparing it against.

$$w_i = \frac{\sum_{j=1}^{n} a'_{ij}}{n} \tag{4}$$

Where:

w_i is criterion weight

Consistency ratio was calculated according to 4, 5 and 6 to ensure that the comparisons implemented in this study are not random.

$$\lambda_{max} = \frac{1}{12}\sum\frac{W_{si}}{w_i} \tag{5}$$

Where:

$\lambda_{max} \approx 12.78$

λ_{max} is principal Eigenvalue

$$CI = \frac{\lambda_{max} - n}{n - 1}$$

$$\text{CI} = \frac{12.78-12}{12-1} = 0.0709 \tag{6}$$

Where:

CI is the consistency index,

Consistency ratio (CR) was calculated according to the following equation

$$CR = \frac{CI}{RI} \tag{7}$$

Where:

RI is the random index; the RI for 12 variables is 1.54 [52].

$CR = \frac{0.0709}{1.54} = 0.046$

Consistency ratio (CR) value of 0.046 is well within the acceptable threshold of 0.1 [52]. This result demonstrates that the Pairwise comparisons applied to balance safety and pavement distress are logically consistent.

The resulting weights (ranging from 0.16 for accidents to 0.04 for bleeding (fatting) implementing proactive framework that prioritises severe pavement distress while maintaining the safety aspect as the main decision- making driver. For instance, the weight of the rut depth was higher than the weight of the longitudinal crack or fatting, and thus due to the impact of rutting on traffic safety [48]. In the rainy weather, rutting impact will increase as rutting will gather rainwater in the vehicle path, reducing skid resistance of the road. In addition, the impact of rutting on safety will be much higher in curved roads as rutting becomes less identifiable and more dangerous [28, 29]. Potholes have a higher weight in the prioritization matrix because the existence of potholes in the road causes severe damage to the vehicle and may lead to traffic accidents [30]. It is worth noting that this model is designed to evaluate both flexible and rigid pavement conditions. Therefore, in the case of evaluating a rigid pavement, a fatting defect represents the texture conditions of the rigid pavement. While in the case of examining a flexible pavement, the score of longitudinal and transverse joints should be five if the road is in bad conditions to boost the total score, while the score should be one if the road is in good conditions, as the program is designed to accept values between 1 and 5.

To improve the applicability and accessibility of the proposed road management model (RMA), the scoring matrix is explained in Table 4. It can be converted into an application using the Python programming language. This program automated the process of entering data, calculating scores, producing results, and then saving the data in a CSV file format. Figure 3 showed the scoring results of the road scoring application saved as a CSV file format. In the image below, the Excel sheet is divided into two parts to show all the information entered for each road. The lines represent the survey results for roads evaluated during this research.

Table 4. Assessment matrix for road conditions model

Rank	Types of road defects & safety aspects	Weighting score
1	Accident rate	0.16
2	Safety concerns	0.13
3	Road importance	0.12
4	Rut depth	0.1
5	Pothole	0.1
6	Settlement	0.08
7	Transverse joint	0.07
8	Transverse cracks	0.06
9	Longitudinal joint	0.05
10	Longitudinal cracks	0.05
11	Surface damage	0.04
12	Bleeding (fatting)	0.04

Furthermore, the application removes the need for manual calculations, leading to fewer errors, lower costs, and greater efficiency. This application has a user-friendly interface where engineers select numbers from predefined scales, and the software instantly calculates the total score based on the weighted criteria. An example of a road condition scoring application created in this research is shown in Figure 4. This application makes prioritization, budget, and working planning more practical and objective for decision-makers, engineers, and inspectors, and allows consistent and efficient application on different road networks, mainly in routine surveys or large-scale assessments.

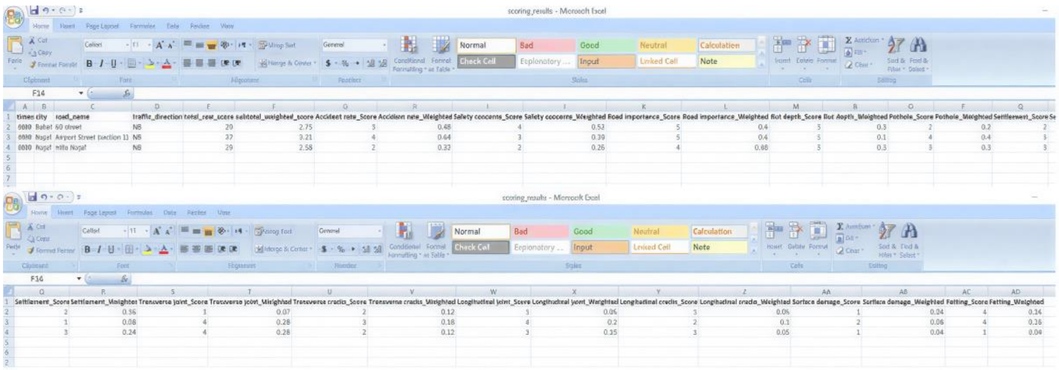

Figure 3. Example of road application results saved as a CSV file format

Moreover, based on the defect scores, engineers can identify the primary issue affecting a road segment; for example, as shown in the above figure, the main issue on 60 Street is fatigue cracking, which has the highest score (4) among all pavement defect types.

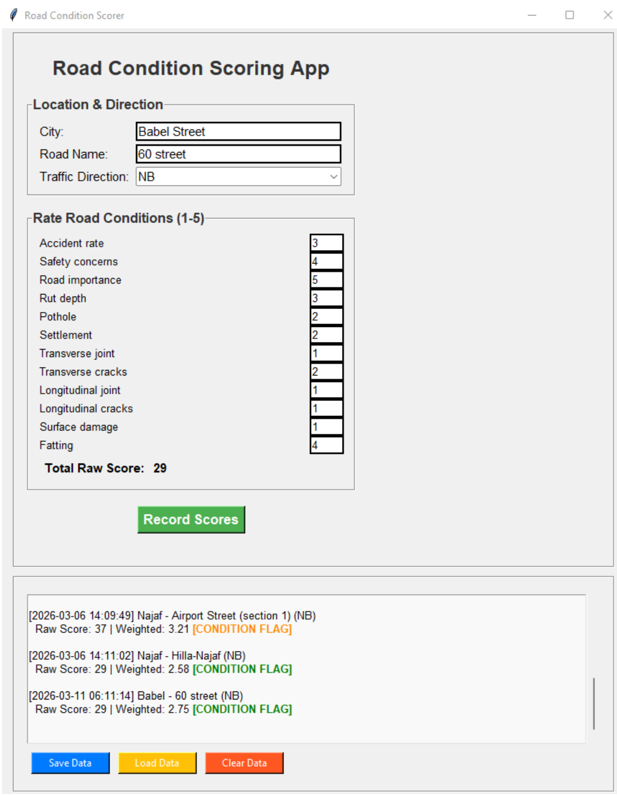

Figure 3. Example of a road condition scoring application front page built in this research

Application of the Proposed Road Management System Model (RMA)

To evaluate the usability and efficiency of the proposed road management model, a case study is conducted on an existing rigid-pavement road. This case study simulates the typical situation faced by a road agency without a road management model.

Testing the Developed Road Management Application (RMA) for Two Functionally Different Categories of Roads

To provide a broader and more diverse view of the roads, two functionally distinct routes were selected. The first is a main road within the city connecting the airport to residential areas, paved with concrete. The second is an external highway connecting the entrance to Najaf to the road leading towards Hilla, and considered an important route within the regional transportation network. This allows for a comparison of the different levels of exposure to safety hazards, their structural characteristics, and varying traffic volumes.

Case Study of Airport Street and Hilla-Najaf Street

Two streets were carefully selected for the study, examining the most important and high-traffic streets in the city. The first study area was Airport Street, a main urban street primarily used to connect Najaf airport with the city centre and the northern entrance to Najaf. It has three lanes in each direction. In some sections, the number of lanes is reduced to two, with each lane being 3.6 meters wide. The surface of this road is concrete. It was designed according to the specifications of the Iraqi Ministry of Transport, and the road speed limit does not exceed 80 km/h [50]. Figure 4and Figure 5 show the location of the Airport street section studied in this research.

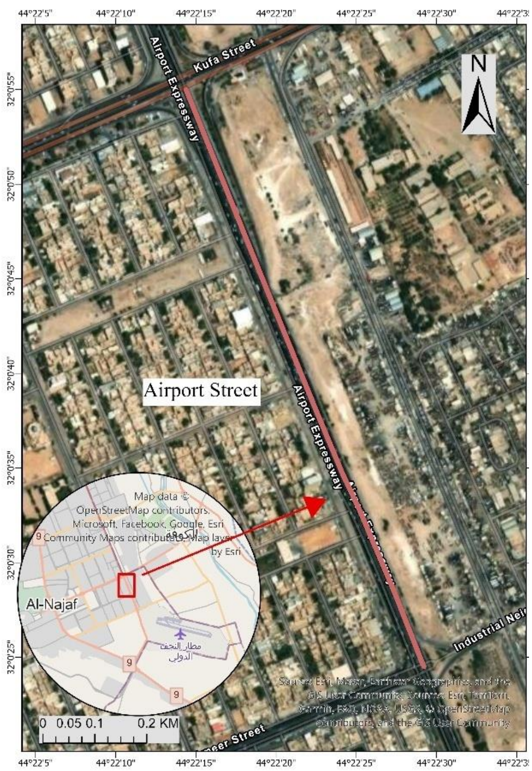

Figure 4.The Airport Street was identified using ArcGIS Pro

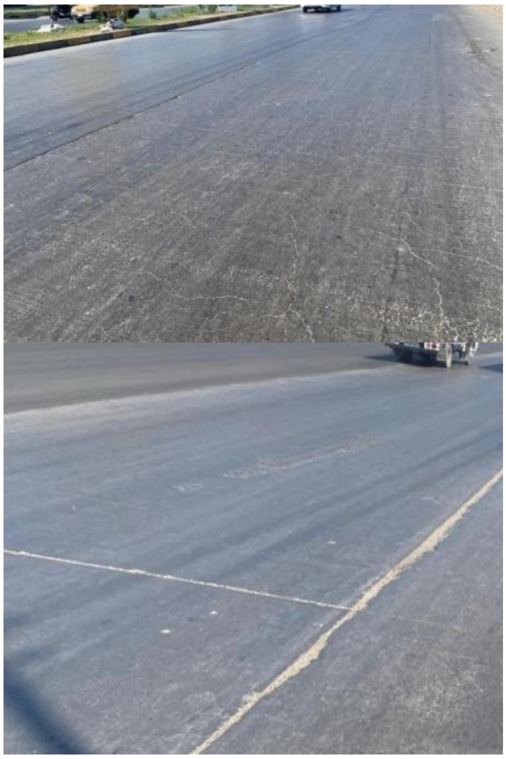

Figure 5. A field photograph of Airport Street taken by the author

The second study area is the first part of the Hilla-Najaf Road heading north. The Hilla-Najaf Road is a main rural road connecting the cities of Najaf and Babylon. It is a vital axis due to the proximity of the university and is one of the important gateways to the city. It has two lanes, 3.6-3.7 meters wide, in each direction, with a design speed of 80-100 km/h. It is characterized by mixed traffic flows, with small cars and most trucks entering the city via this road. Traffic flows are high during most of the year. Figure 6 and Figure 7 show the location of the Hilla-Najaf Road, which was included in this study.

In this research, a database was created for both roads using an integrated application designed in this study, as previously shown in Figure 2. Each road segment, including its construction and geometry data, was recorded based on available information. The location of each section in this study was identified, and the map was generated and processed using ArcGIS Pro, as shown in Figure 5 and 7.

A visual condition survey was implemented to evaluate the structural condition of both roads, Hilla-Najaf and Airport street, with the main objective of systematically examining their current structural conditions and safety concerns, and then assigning a quantitative condition score according to the scoring matrix developed in this study to each of them using the road condition scoring application software. The survey includes an on-site inspection, where engineers examine the entire length of the sections, carefully observing and scoring a range of pre-defined distress types in the road condition scoring application. The survey results of both road sections are shown in Figure 9. The number of accidents is taken from previous research [50]. The score value of road importance and safety concerns of Airport Street was higher than Hilla-Najaf Street following predefined criteria shown earlier in Table 3.

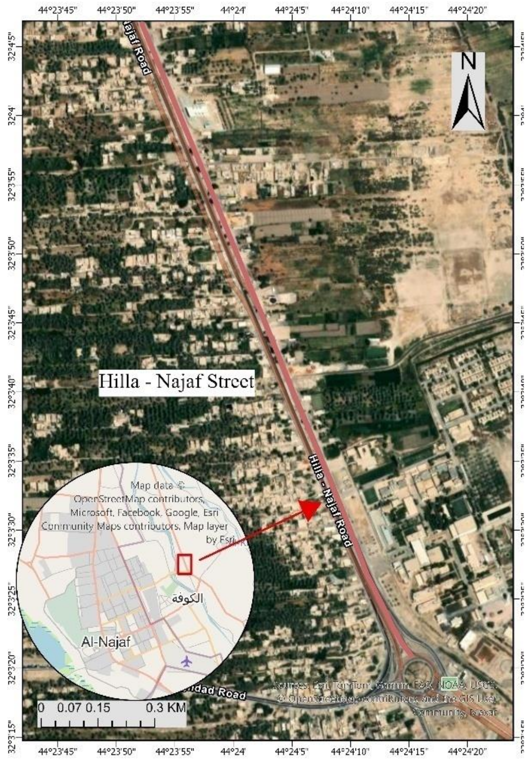

Figure 6. The Hilla-Najaf street location was identified using ArcGIS Pro

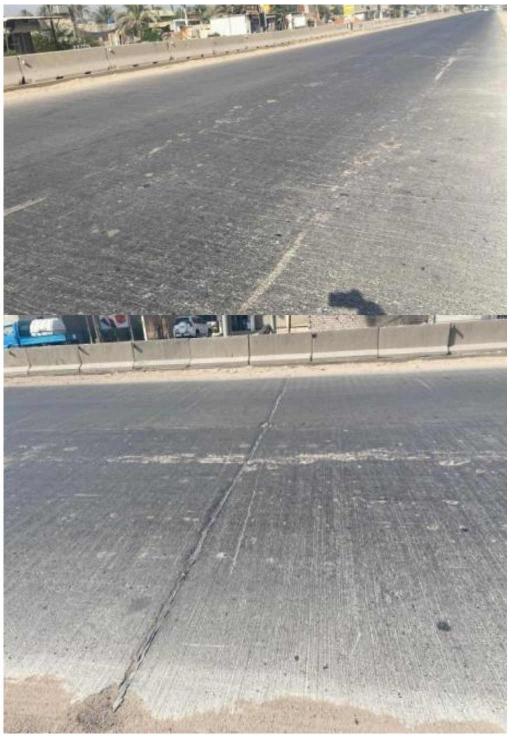

Figure 7. A field photograph of Hilla-Najaf Street, taken by the author

The results in Figur showed that Airport Street has a higher raw score and weighting score (37 and 3.21), respectively, compared to Hilla-Najaf Street with a total score of 29 and a weighted score of 2.58. It can be seen that the software displays an amber flag next to Airport Street, while a green flag displays next to Hilla-Najaf Street (see the red box in Figur). This feature does not exist in competing road management system model. Furthermore, this result is based on predefined criteria for severity, as shown in Table 3 and Table 4. If, only one project can be funded, Airport Street is ranked ahead of Hilla-Najaf Street. This is because Airport street's amber flag score represents a higher maintenance need than Hilla-Najaf's green-flagged rating.

Following a visual inspection, previous studies, and the author's knowledge of the area (utilizing ArcGIS Pro), the data collected for each road was uploaded into the road condition scoring application (RMA). All data will be stored in a CSV file and displayed at the bottom of the program window (highlighted in a red box), as shown in Figure 9. This application assigned weighted numerical values to each distress type, safety concern, and their corresponding severity, thus facilitating the combination of individual distress and safety issue scores into an integrated structural and safety condition index for Airport Street and Hilla-Najaf Street.

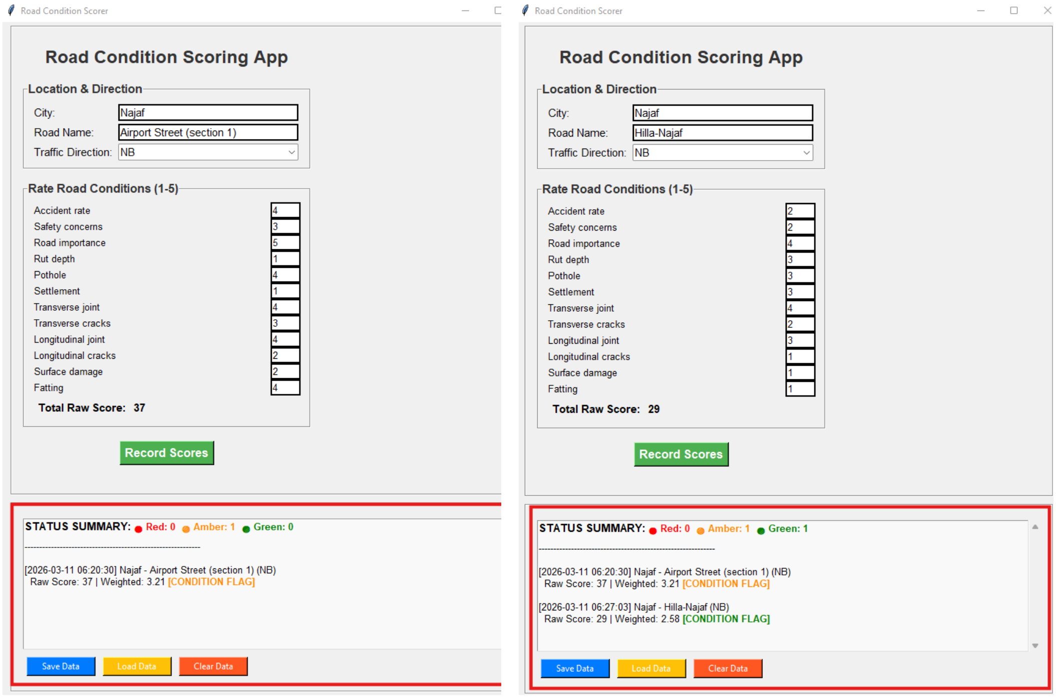

Figure 9. Road condition scoring application results for both Airport Street and Hilla-Najaf Street

The application approach (road condition scoring application) ensured an objective and consistent assessment, resulting in a clear, comparative numerical score that effectively communicates the overall structural condition and safety of each road. Therefore, this systematic approach enables informed decisions regarding maintenance and/or rehabilitation priorities. The road condition scoring application clarifies the main issues by displaying individual defect scores and stored in a CSV file. For instance, it can be seen from Figure 9. or from a CSV file that the main issues with Airport Street were the fatting, transverse and longitudinal joint conditions, which then led to potholes near joint locations (see Figure 9 highest scoring values). No other road management model discussed in this research offers this feature. Moreover, this approach could help monitor road performance over time by comparing scores every six months or annually.

To provide a standardized reference for these findings, the identical evaluation process was applied to the conventional pavement condition index (PCI) by using equation (8).

$$PCI = 100 - \text{Max } CDV \tag{8}$$

Where CDV is the corrected deduct value.

Tables 6 until 9 showing respectively the Hilla-Najaf street condition survey results, corrected deduct value (CDV) of Hilla-Najaf Street from ASTM adjustment chart, airport street condition survey results, and the corrected deduct value (CDV) of Airport Street from ASTM adjustment chart.

Table 6. Hilla-Najaf Street condition survey results

Distress Type	Severity	Slabs	Density	Deduct Value (DV)
Blowup / Buckling	M	1	5%	12
Corner Break	L	1	5%	7
Durability ('D') Cracking	M	3	15%	22
Faulting	L	5	25%	14
Joint Seal Damage	M	*N/A*	100%	7
Patching, Large & Utility Cuts	L	1	5%	3
Patching, Small	L	1	5%	2
Polished Aggregate	L	1	5%	1
Popouts	M	7	35%	4
Punchout *(Updated)*	L	3	15%	12
Scaling / Map Cracking	L	6	30%	6
Shrinkage Cracking	L	10	50%	0
Spalling, Joint	L	1	5%	2
Spalling, Corner	L	1	5%	4

Table 7. Corrected deduct value (CDV) of Hilla-Najaf Street from ASTM adjustment chart

Iteration	Deduct List	Total Deduct (TDV)	q	CDV
1	22, 14, 12, 12, 7, 7, 6, 4, 0.6	84.6	8	41
2	22, 14, 12, 12, 7, 7, 6, 2.0, 2.0	86	7	42
3	22, 14, 12, 12, 7, 7, 2.0, 2.0, 2.0	82	6	43
4	22, 14, 12, 12, 7, 2.0, 2.0, 2.0, 2.0	77	5	41

Table 8. Airport street condition survey results

Distress Type	Severity	Slabs	Density	Deduct Value (DV)
Blowup / Buckling	M	1	5%	12
Corner Break	L	1	5%	7
Durability ('D') Cracking	M	3	15%	22
Faulting	L	5	25%	14
Joint Seal Damage	M	*N/A*	100%	7
Patching, Large & Utility Cuts	L	1	5%	3
Patching, Small	L	1	5%	2
Polished Aggregate	M	16	80%	4
Popouts	M	7	35%	4
Punchout *(Updated)*	L	4	20%	15
Scaling / Map Cracking	L	6	30%	6
Shrinkage Cracking	L	10	50%	0
Spalling, Joint	L	1	5%	2
Spalling, Corner	L	1	5%	4

Table 9. Corrected deduct value (CDV) of Airport Street from ASTM adjustment chart

Iteration	Deduct List	Total Deduct (TDV)	q	CDV
1	22, 15, 14, 12, 7, 7, 6, 4, 0.6	87.6	8	42
2	22, 15, 14, 12, 7, 7, 6, 2.0, 2.0	87	7	44
3	22, 15, 14, 12, 7, 7, 2.0, 2.0, 2.0	83	6	45
4	22, 15, 14, 12, 7, 2.0, 2.0, 2.0, 2.0	78	5	43

The results showed that Hilla-Najaf Street has a higher PCI value compared to the airport street which is consistent with the RMA findings. This result indicated that Hilla-Najaf Street is in a better condition. However, PCI value of Airport Street showed that this section of the road falls under the poor condition category, with a PCI value of 55 slightly lower than Hilla-Najaf Street PCI value of 57. These results clearly demonstrate the importance of implementing safety and road importance aspects, this narrow margin (55 versus 57) would likely widen if those aspects were implemented. In addition, as mentioned earlier in state-of-the-art section, PCI value drops significantly even when the road faces a minor issue, such as hairline cracks near joints as shown in the case of Airport Street. Therefore, PCI method cannot distinguish whether the road requires a simple treatment, major maintenance or a full reconstruction. Furthermore, PCI value overlooks important safety issue such as polished aggregate surface as demonstrated in the case of Airport Street.

For a broader case study, the RCS was manually calculated using equation (2) for the first road, the Airport street, as shown in Figure 5, and the calculation results are in Table 10.

Table 10. RCS manually for Airport Street

Defect (Types)	**The severity rating of the defect S_i**	**The importance weight assigned to the defect W_i**	**The overall road condition scoring (RCS)= $S_i x W_i$**
Accident rate	4	0.16	0.64
Safety concerns	3	0.13	0.39
Road importance	5	0.12	0.60
Rut depth	1	0.10	0.10
Pothole	4	0.10	0.40
Settlement	1	0.08	0.08
Transverse joint	4	0.07	0.28
Transverse cracks	3	0.06	0.18
Longitudinal joint	4	0.05	0.20
Longitudinal cracks	2	0.05	0.10
Surface damage	2	0.04	0.08
Bleeding (fatting)	4	0.04	0.16

Road condition scoring value calculated manually as shown in Table 10 and the following equation.

$$RCS = 0.64 + 0.39 + 0.60 + 0.10 + 0.40 + 0.08 + 0.28 + 0.18 + 0.20 + 0.10 + 0.08 + 0.16 = 3.21$$

After performing manual calculations using the equation and matching them with the results of the RCS model for Airport Road, which yielded a value of 3.21, the results showed a reliable match, allowing the model to be smoothly applied to other roads while ensuring the accuracy of the input weights.

Implementation of the Proposed Road Management Model (RMA)

This model is expected to significantly improve the way Iraqi road agencies and any other road agencies plan, prioritize, and deliver maintenance operations based on the information shown earlier. The novelty of this research lies in two key contributions: first, the implementation of a new road management system that integrates both structural and safety aspects, and second, the consolidation of this data into a single semi-automated program, while systematically storing comprehensive road data (such as road classification, construction dates, surface materials, number of layers, layer thicknesses, lane width and lane number) in a single, centralized database. A centralized road database provides a clear picture of road conditions across the entire network and helps with strategic planning. Therefore, implementing such a system helps to improve pavement performance and road user satisfaction for several reasons. Firstly, systematic condition assessment and proactive maintenance reduce the rate of deterioration and extend pavement life. Secondly, maintenance actions are based on data-driven decisions rather than intuition or political influence. Thirdly, proactive maintenance reduces the need for costly rehabilitation or reconstruction in the long term. Additionally, improved road conditions increase road users' satisfaction and support for the road operating agency.

SUMMARY AND CONCLUSION

This study aims to address a critical gap in road maintenance management practices in developing regions, particularly Iraq, where digital and systematic pavement management systems remain limited. The proposed Road Management Application (RMA) is a structured, multi-component model that integrates construction data, pavement defects, road importance, safety concerns, prioritization, and performance monitoring within a single digital platform as demonstrated in this research. In addition, the system is suitable for both rigid and flexible roads. The defect database and scoring parameters were calibrated using local investigation data, however, the program structure allows straightforward adaptation to other regional conditions. Defect lists, weights, and classification rules can be modified without altering the core computational logic, supporting broader applicability.

This research developed road management system models (RMA) to provide a systematic, data-driven approach to managing road maintenance operations or monitoring and generating a data base across the network. These data gathered in this software (RMA) may serve as the foundation for building a predictive model for road deterioration. The study validated the model, as the observed field erosion patterns matched the calculated weights, confirming the model's internal reliability. However, some limitations should be noted. First, visual inspection may lead to small bias however it is controlled by standard measurement method. Second, model validation was limited to two sections of road, restricting the statistical generalizability of the results to the entire network.

The results demonstrated the possibility of establishing a digital database of the road network, which provides a clear picture of construction and safety aspect of the road network. The finding of this research demonstrated the applicability and effectiveness of the proposed road management system model (RMA). The RMA significantly reduced processing time and eliminated repetitive calculations, demonstrating its effectiveness as a decision-support tool for routine road condition assessments. Processing data in this research shows that the road management system model (RMA) does not accept any scoring values outside the defined range thereby eliminating human error compared to other management models.

This study shows that RMA is designed to be practical, user-friendly, and applicable for Iraqi road agencies and any other agencies with limited technology and budget, making it a good entry point for modernizing the maintenance management of the network with limited resources. The results of this research show that adopting such a model will improve road network performance, resulting in a more resilient and sustainable network, as the model can help prioritize network maintenance and objectively inform future road construction or expansion. Furthermore, it can easily track the main issue within the road section by examining the values in the distresses database as demonstrated in this research.

The results display an amber flag next to Airport Street, while a green flag displays next to Hilla-Najaf Street. Therefore, Airport Street is ranked ahead of Hilla-Najaf Street in maintenance during this study. The traditional PCI results confirmed these finding in terms of ranking only.

The finding of this research shows that RMA provides a more comprehensive and reliable assessment by implementing multiple evaluation parameters rather than relying on a single criterion. Consequently, RMA generates a more balance classification, avoiding the underestimation of performance that may occur in the PCI method when only one deficient parameter influences the final category as shown in this study.

Additionally, research bridges the gap between theoretical analytical hierarchy process (AHP) models and deployable, low-cost tools in Iraq. By implementing these models, the software enables management to transition from reactive maintenance to data driven prioritization, ensuring that tightening budgets are allocated toward the most critical infrastructure need.

NOMENCLATURE

RMA	Road management application
SORB	Standards and Specifications for Roads and Bridges
Wi	Weighting factors
RSA	Road Scoring Application
IRC	Indian Roads Congress
Rc	Critical Rate
NA	Not applicable
RCS	Overall road condition scoring

S_i	The severity rating of defect i
CSV	Comma separated values
(APH)	Analytical hierarchy process
$a_{i,j}$	Pairwise comparison value
w_i	Criterion weight
λ_{max}	Principal Eigenvalue
CI	Consistency index
CR	Consistency ratio
RI	Random index
ArcGIS Pro	Aeronautical Reconnaissance Coverage Information System Professional
PCI	Pavement condition index
DV	Deduct value
CDV	Corrected deduct value
TDV	Total deduct value
m	Maximum allowable number of deducts,
HDV	Highest deduct value

AUTHORS CONTRIBUTIONS

Conceptualization, M.M.; Methodology, M.M., and H.A.; Software and Computational Modelling, M.M. and A.W.A.; Validation, M.M., H.A., and A.W.A.; Formal Analysis, M.M., H.A., and A.W.A.; Investigation, M.M. and H.A.; Resources, M.M.; Data Curation, M.M. and H.A.; Writing Original Draft Preparation, M.M., H.A., and A.W.A.; Writing – Review & Editing, , M.M., H.A., and A.W.A.; Visualization, M.M., and H.A.; Supervision, M.M.

CONFLICT OF INTERESTS

The authors have no conflict of interest to declare.

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