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ORIGINAL RESEARCH PAPER

Developing a Pavement Condition Assessment Method for Unpaved Roads Using the Analytic Hierarchy Process (AHP)

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Abstract

Approximately 95% of the total road network in Uganda is unpaved, and this heavy reliance on unpaved roads is predominant in most developing countries in the world. Consistent monitoring and evaluation of the condition of these unpaved roads is crucial, given the high risk of sudden pavement deterioration due to traffic and environmental factors. Current condition assessment methods are subjective, labor-intensive, and time-consuming, leading to inconsistent evaluations. This study proposes an enhanced approach for assessing the condition of unpaved roads in Uganda. The novel Gravel Road Condition Index (GRCI) was developed using the Analytic Hierarchy Process (AHP) to convert subjective questionnaire survey results into objective mathematical data. The AHP theory provided a quantitative method for weighting and ranking the nine key road surface distresses for unpaved roads in the Country. The weightings obtained for the nine distresses were a maximum of $w1 = 0.311$ for inadequate drainage and a minimum of $w9 = 0.103$ for rutting. The index was tested through an application on a case study road. The GRCI was then compared to the existing condition assessment method in Uganda. The findings indicated that the new method provides a fast, streamlined, and user-friendly procedure for assessing unpaved roads, utilizing objective weightings, and demonstrating consistency in its evaluations.

Keywords Analytic Hierarchy Process · Gravel Road Condition Index · Unpaved roads · Road surface distresses · Road maintenance · Pavement condition assessment

1 Introduction

A significant portion of transportation infrastructure across numerous regions consists of unpaved roads. These roads are essential in rural and remote areas, providing vital links for communities. They facilitate the transport of goods, services, and people, which drives economic activity and improves the overall quality of life. In Uganda, for example, unpaved roads constitute 95% of the road network [1]. These roads are, however, often characterized by poor conditions and inadequate funding for maintenance, posing challenges to transportation efficiency, safety, and accessibility. Effectively addressing these challenges necessitates robust pavement condition assessment methods to enable prioritization of the maintenance and rehabilitation needs. While significant advancements have been made in assessing the condition of paved roads, evaluating unpaved road conditions remains challenging due to the inherent complexity and variability of these unpaved surfaces [2, 3].

The pavement condition assessment for unpaved roads has traditionally been conducted through subjective visual inspections, which can be labor-intensive, time-consuming, and may lead to inconsistent evaluations [4]. To address these limitations, there is a growing interest in developing more objective and systematic approaches for assessing the condition of unpaved roads [5]. This study has developed a new method for assessing the condition of unpaved roads by deploying the Analytic Hierarchy Process (AHP). According to Saaty [6], Haque [7], Musfigur [8], and Brunelli [9], the Analytic Hierarchy Process is a quantitative decision-making method that employs pairwise comparison matrices to derive relative weights of each factor influencing the decision. Developing a new condition assessment method for unpaved roads using the AHP theory had several advantages. First, the AHP-based model provided a more systematic and standardized approach to assessing pavement

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conditions than the existing subjective methods. Second, by assigning weights to each road surface distress, the pairwise comparison matrices allowed a more comprehensive evaluation of the relevant distresses influencing the condition of unpaved roads. Third, using AHP ensured that the developed method was an objective model for relative mathematical measurement, leading to accurate and reliable condition assessments.

Most of Uganda's road network consists of unpaved roads, which often suffer from poor maintenance due to the lack of efficient pavement condition assessment methods and insufficient funding for maintenance and rehabilitation activities. This poses a significant challenge because unpaved roads make up the majority of the total road network in the Country. Moreover, the unpredictable nature of unpaved road surfaces, characterized by loose gravel and uneven crossfall, increases the risk of accidents, particularly at higher speeds. Consistent monitoring and evaluation of the condition of these unpaved roads is crucial, given the high risk of accidents and sudden pavement deterioration caused by traffic and environmental factors. The current condition assessment methods are subjective, labor-intensive, and time-consuming, leading to inconsistent evaluations. This study, therefore, proposes an enhanced method for assessing the condition of unpaved roads in Uganda, aiming to address these challenges and improve the overall management of the Country's road infrastructure.

This study aimed to develop an objective and systematic method for assessing the condition of unpaved roads in Uganda. The research focused exclusively on the Ugandan unpaved road network and sought to accomplish the following objectives:

i. Comprehensively review literature and deliver a detailed analysis highlighting the limitations and challenges of the current road condition assessment methods.
ii. Identify, prioritize, and produce a list of the high-impact road surface distresses for unpaved roads in Uganda obtained through stakeholder input and empirical data.
iii. Develop a standardized and objective pavement condition assessment method using the Analytic Hierarchy Process (AHP), incorporating weighted distress parameters to generate consistent condition ratings for unpaved roads.
iv. Validate the developed method for reliability and applicability through case study testing on an unpaved road, including comparative analysis with traditional methods in Uganda.

The first section of this paper summarizes the current pavement condition assessment methods and reviews studies utilizing AHP theory in road condition assessments. The second section describes the methodology applied to achieve the study's objectives and details the development of the novel index. The third section discusses the procedural field-based application of the GRCI. The results of the field-based condition assessment on the case study road are discussed in the fourth section. The last section highlights the study's contribution to the body of knowledge, research limitations and recommendations for future work.

1.1 Background Information

Various techniques have been developed to evaluate the condition of unpaved roads and assess their maintenance needs. In reviewing the literature, it was noted that for unpaved roads, these methods are grouped into manual or automated assessments [10, 11].

1.1.1 Manual Condition Assessments

Manual condition assessments are subdivided into two main categories, i.e., visual *"windshield"* evaluations and measured condition surveys [12, 13]. Visual *"windshield"* evaluations are subjective, on-site assessments of the road's condition typically carried out from a moving vehicle [13]. In contrast, measured condition surveys involve objective field measurements to quantitatively evaluate the pavement characteristics, such as the extent and severity of the surface distress [12]. The advantages and disadvantages of the manual condition assessments discussed hereafter are summarized in Table 1.

The Gravel PASER *(Pavement Surface Evaluation and Rating)* method is a visual windshield survey used widely in the U.S. by local road agencies to evaluate the condition of gravel roads from the decision makers' point of view [13]. According to Walker [14], the Gravel PASER assesses three major distresses, i.e., camber, gravel thickness, and drainage, on a road condition scale of 1 (Failed) to 5 (Excellent). Additionally, Walker [14] contends that road surface distresses like potholes, rutting, corrugations, and dust are considered secondary and do not influence the primary evaluation of the gravel road condition. This method uses example photographs and verbal descriptions of the distresses for the ratings and is carried out by an assessor traveling in a vehicle at an average speed of 40 km/hr [10]. Being a visual windshield assessment, the Gravel PASER is criticized for being a subjective rating that heavily relies on the assessor's ability to estimate the severity and extent of distress rather than focusing on objective distress measurements. Because of this, Huntington and Ksaibati [10] compared the Ride Quality Rating Guide (RQRG) and the Gravel Roads Rating System (GRRS) that had been developed by the Wyoming Technology Transfer Centre against the Gravel

Table 1 Summary of the advantages and disadvantages of each manual condition assessment method

Manual Condition assessment method	Advantages	Disadvantages
Gravel PASER	− Simple method that rates road condition on a 5-point rating scale of 1 (Failed) to 5 (Excellent). − Quick visual windshield survey. − Assesses three major distresses i.e., camber, drainage, and gravel thickness.	− Subjective rating. − Heavily relies on assessor's experience in distress identification.
Standard Visual Assessment Manual for Unsealed Roads (TMH12)	− Visual assessment with 5-point rating scale of 1 (Very Good) to 5 (Failed). − Assesses distresses like potholes, corrugations, rutting, erosion, stoniness, dust, drainage, gravel profile and riding quality based on their severity.	− Requires considerably more effort and training of the assessors.
Ride Quality Rating Guide (RQRG)	− Visual method that assesses unpaved roads on a rating scale of 1 (Failed) to 10 (Excellent). − Combines the use of photographs to illustrate seven identified distresses. − Reduced error level of repeatability.	− Subjective rating.
Unsurfaced Road Condition Index (URCI)	− Field survey measurements of seven distresses i.e., Improper cross section, Inadequate roadside drainage, Corrugations, Dust, Potholes, Ruts and Loose aggregate. − Observed distresses are rated according to a 3-point severity level of low, medium, or high. − Classifies unpaved roads according to traffic volume, construction history, and road rank.	− Rigorous and time-consuming because each of the seven distresses must be quantified and recorded for every kilometer.
Bedömning av grusväglag (Gravel road assessment)	− Pavement condition rated according to a 3-point rating scale i.e., Class 1 (good) to Class 3 (poor). − Condition assessments are carried out every 3 months. − Collects condition data on potholes, ruts, roughness, loose gravel, and dust. − Objectively measures roughness.	− It is only suitable for agencies with nomadic climates.

PASER. Both the RQRG and GRRS assess unpaved roads on a rating scale of 1 (Failed) to 10 (Excellent) and use photographs to illustrate the distress severity of seven identified distresses [10]. Findings from the Huntington and Ksaibati [10] study indicated that increasing the rating scale from 5 (Gravel PASER) to 10 (RQRG) decreased the repeatability error levels, leading to a more accurate rating of the gravel road condition.

In South Africa, road agencies classify road sections into five condition categories based on the Standard Visual Assessment Manual for Unsealed Roads (TMH12) developed by the Council for Scientific and Industrial Research [15]. These five unpaved road condition categories are 1 (Very Good), 2 (Good), 3 (Fair), 4 (Poor) and 5 (Failed). According to Brooks et al. [16], TMH12 deploys a severity scale of 0 (distress not present) to 5 (high level of distress) to assess corrugations, potholes, erosion, rutting, dust, stoniness, drainage, gravel profile, and riding quality. Huntington and Ksaibati [10] assert that the South African TMH12 method requires more man-hours to train assessors than the U.S. Gravel PASER. Another key distinction between TMH12 and PASER is that South Africa has a higher road smoothness expectation than the U.S. for unpaved roads. This difference in smoothness expectations is attributed to unpaved roads in South Africa carrying higher traffic volumes than roads in the U.S [10].

In Sweden, the *Bedömning av grusväglag* (Gravel road assessment) developed by the Swedish National Road and Transport Research Institute is used to assess the condition of unpaved roads. This method classifies the condition of unpaved roads into three categories, i.e., Class 1 (good), Class 2 (acceptable), and Class 3 (poor) [12]. Assessors collect condition data on roughness, ruts, potholes, dust, and loose gravel every 3 months. Saeed et al. [12] add that this assessment only suits road agencies with nomadic climates. Saeed et al. [12] also state that this assessment method is similar to Gravel PASER because both methods subjectively measure distresses based on written descriptions and photographs illustrating the various levels of distress severity. Contrary to this, Alzubaidi [17] argues that the Swedish gravel road assessment method is objective and uses equipment such as road meters and profilometers to measure the roughness of unpaved roads.

The Unsurfaced Road Condition Index (URCI), developed by the Army Corps of Engineers, is a measured condition assessment used in the U.S. and Canada [10]. The URCI measures the condition of unpaved roads on a 0 (Failed) to 100 (Excellent) scale calculated from physical measurements of seven distresses [18]. These distresses, namely, potholes, ruts, corrugations, loose aggregate, dust, improper cross-section, and inadequate roadside drainage, are measured either linearly or by area and recorded according to a 3-point severity level of low, medium, or high [10, 18]. Saeed et al. [12] contend that because the URCI was one of the earliest objective condition assessment methods for unpaved roads, its use should be widespread and popular. However, this is not the case because being a field measurement-based method makes the URCI rigorous, slow, and time-consuming. It is for this reason that road agencies prefer the Gravel PASER to the URCI [12].

In contrast to the visual condition assessment methods discussed, such as Gravel PASER, TMH12, and RQRG, the novel Gravel Road Condition Index (GRCI) was developed by converting subjective survey findings into quantitative mathematical data. This advantage with the GRCI of utilizing objective weightings for the identified road surface distresses translated into improved consistency and objectivity in condition evaluations, as opposed to the more subjective nature of the other assessment methods.

1.1.2 Automated Condition Assessments

Automated condition assessments use special data collection equipment such as Unmanned Aerial Vehicles (UAVs), Smartphone applications, Satellite imagery, DashCams, and sophisticated survey vehicles to rapidly carry out objective road condition assessments [19]. Kans et al. [20] argue that while manual condition assessments can be subjective, lack repeatability, and are time-consuming, they are still preferred over automated condition assessments by road agencies for unpaved roads. This is because the special vehicles and/or equipment required to carry out automated condition assessments are expensive and easily damaged by dust and water commonly associated with unpaved roads [20]. However, some road agencies are slowly adopting automated condition assessments for use on their unpaved roads.

The use of Unmanned Aerial Vehicles (UAVs) to collect road condition data was developed by Zhang [21]. The system included a low-cost helicopter mounted with a camera, GPS, geomagnetic sensor, and a navigator. The UAV captured images with the camera, which were used to generate 3-D models of the unpaved road surface. The model surface was then used to identify surface distresses such as potholes, corrugations, and ruts to a ground resolution of up to 5 mm [21]. Using computer-aided techniques, the UAV-based digital models were used to measure the extent of distress accurately. The UAV system can enable road agencies to conduct condition assessments with an unmanned helicopter, ensuring the data collection process is rapid, safe, and efficient. More recently, Khilji et al. [22] presented a low-cost Unmanned Aerial System (UAS) utilizing a vision-based approach for the automated identification of distresses on unpaved road images captured by a UAS. However, this method is limited in providing depth information for the identified distresses and, therefore, cannot be directly employed in objective road condition assessment techniques, such as the International Roughness Index.

Smartphones have increasingly been used to measure the roughness condition of unpaved roads by estimating the International Roughness Index (IRI). These measurements are made by the smartphone accelerometer, which records the vertical vibrations of a vehicle driving on unpaved roads [13]. The accelerometer readings provide information on the riding quality of the unpaved road surface. Saeed et al. [12] add that smartphone applications such as Roadroid, RoadBounce, and RoadLab objectively measure the IRI values of an unpaved road section. These applications use the accelerometer and GPS built within the smartphone to measure the IRI by correlating them to the phone vibrations.

In Canada, the Forest Engineering Research Institute collects roughness data on unpaved roads within the forests by using accelerometers mounted onto logging trucks. The Opti-Grade System enables road agencies to collect accurate and reliable real-time roughness data at a reduced cost because the system relies on the accelerometers installed into the large number of logging trucks using the Canadian unpaved road network [16]. However, Kans et al. [20] note that accelerometer-based devices cannot convey information on the nature and extent of road surface distress since the devices are only limited to measuring road roughness. Another disadvantage of accelerometer-based devices is the continuous occurrence of *"false positives"* brought about by sudden braking and gear changes of the vehicle during condition assessments. These errors within the collected data reduce the accuracy of the objective measurements associated with accelerometer-based devices [12].

Sophisticated survey vehicles mounted with cameras, road profilers, scanners, GPS, and accelerometers can be used to assess the condition of unpaved roads. These vehicles have high operation and maintenance costs and are very expensive to purchase, which makes them uneconomical for small road agencies with limited budgets [23]. While these vehicles are very effective for assessing the condition of paved roads, distresses such as dust and loose gravel associated with unpaved roads make using these vehicles uneconomical due to high maintenance costs.

1.2 Use of AHP in Road Condition Assessments

Pavement performance researchers have used the AHP method to develop mathematical models for assessing the condition of road pavements. According to Mardani et al. [24], pavement performance researchers prefer AHP over other multi-criteria decision-making methods. This is because AHP provides a consistent framework for the use of pairwise comparison matrices, which reduces biases and ensures transparency in the decision-making process.

Salman et al. [25] developed a condition assessment model for a residential road network in Dammam City (Saudi Arabia) using the AHP method. AHP was utilized to calculate the relative weight factors of the road pavement distresses that informed the overall weighting of the condition assessment model. It was noted that although the AHP relied on expert opinions, checking the consistencies of the developed matrices as part of the AHP process ensured objectivity within the weight factors. The model developed through the AHP process was tested, and results showed that the model was a more economical and efficient condition assessment method.

Milad et al. [26] applied AHP to determine the weights and ranking of distresses observed in flexible road pavements in Malaysia. The study observed that AHP could be used to create a hierarchical framework for objective evaluation of the various distresses. The study concluded that the AHP-based model could aid decision-makers in justifying road condition assessments characterized by limited expertise and minimum funding.

Ahmed et al. [27] used the AHP method to prioritize pavement maintenance sections in Mumbai City (India). The study proposed an objective method that obtained pairwise comparison values based on field data collected from the road network. The pairwise priority ratings from the AHP method were compared with the values from the existing road condition index. Results showed that the AHP was more suitable for prioritizing pavement maintenance of roads in Mumbai City. The study further reinforced that the AHP method provides a more simplified and objective evaluation for pavement condition assessments.

Alfar [28] applied the AHP pairwise comparison methodology to analyze responses from a questionnaire survey to determine the maintenance priorities of roads in Surrey County (UK). The Alfar study is relevant to this research study because it demonstrated a connection between subjective data from a questionnaire survey and the development of AHP pairwise comparison matrices.

2 Methodology of the Study

The research methodology used in this study comprised five stages, which were (1) research formulation, (2) investigation; (3) AHP application, (4) model development, and (5) model testing and validation, as shown in Fig. 1. At the first stage, the research problem, goal and objectives were identified. The second stage used a questionnaire survey to identify and rank the high-impacting road surface distresses that affect the condition rating of unpaved roads in Uganda. In the third stage, the distress weighting was analyzed using the AHP method for each of the nine (09) identified distresses. The fourth stage involved using the AHP weighting to develop a new condition assessment model. At the final stage, the developed unpaved road condition assessment model was tested and initially validated on a case study.

2.1 Research Formulation

The research problem, goal, and objectives were determined following a review of the existing literature on unpaved road condition assessments, with a particular focus on applying AHP to road condition assessments. A review of the current state of unpaved road condition assessments in Uganda enabled the establishment of a clear definition of the research problem. The core of the research problem was the lack of an objective, user-friendly, and streamlined method for assessing the condition of unpaved roads in Uganda, which was identified as a critical issue given that 95% of the Country's road network is unpaved and susceptible to rapid deterioration.

2.2 Investigation

After conducting an extant literature review [14–16, 18, 29], nine road surface distresses were identified that are predominant on unpaved roads. These distresses are (1) inadequate drainage, (2) inadequate gravel thickness, (3) camber loss, (4) corrugations, (5) loose gravel, (6) stoniness, (7) potholes, (8) erosion gullies, and (9) rutting. Distresses such as dust and visibility associated with unpaved roads were not considered for assessment because dust is minimized by applying dust palliative. However, this, in practice, is expensive and usually not done in developing countries. A questionnaire survey was designed to rank and weigh the high-impacting road surface distresses that affect the condition rating of unpaved roads in Uganda. The questionnaire was distributed to 70 experts (engineering professionals) in road maintenance management. These engineering professionals, i.e., road maintenance engineers, road asset managers, and road inspectors, were carefully selected from a sample size of 23 districts to represent the 136 districts in the entire Country. The participant selection process also ensured that all six regions of the Country were considered, and the selected sample districts represented 17% of Uganda's entire road network. The survey attained a response rate of 36 participants (51%), which was considered adequate. The results from the questionnaire survey shown in Table 2 indicated the total score of each distress and showed the rank and weight of the distresses in terms of having the highest impact on the condition rating of unpaved roads in Uganda. The research questionnaire demonstrated high internal consistency and reliability, as evidenced by Cronbach's Alpha coefficient of 0.845 obtained through analysis using IBM SPSS Statistics version 27.

The mean weight factors of the distresses were calculated using the *"mean weight method"* in descriptive statistics. However, these weight factors were not suitable for developing the GRCI model. This was because the weight factors

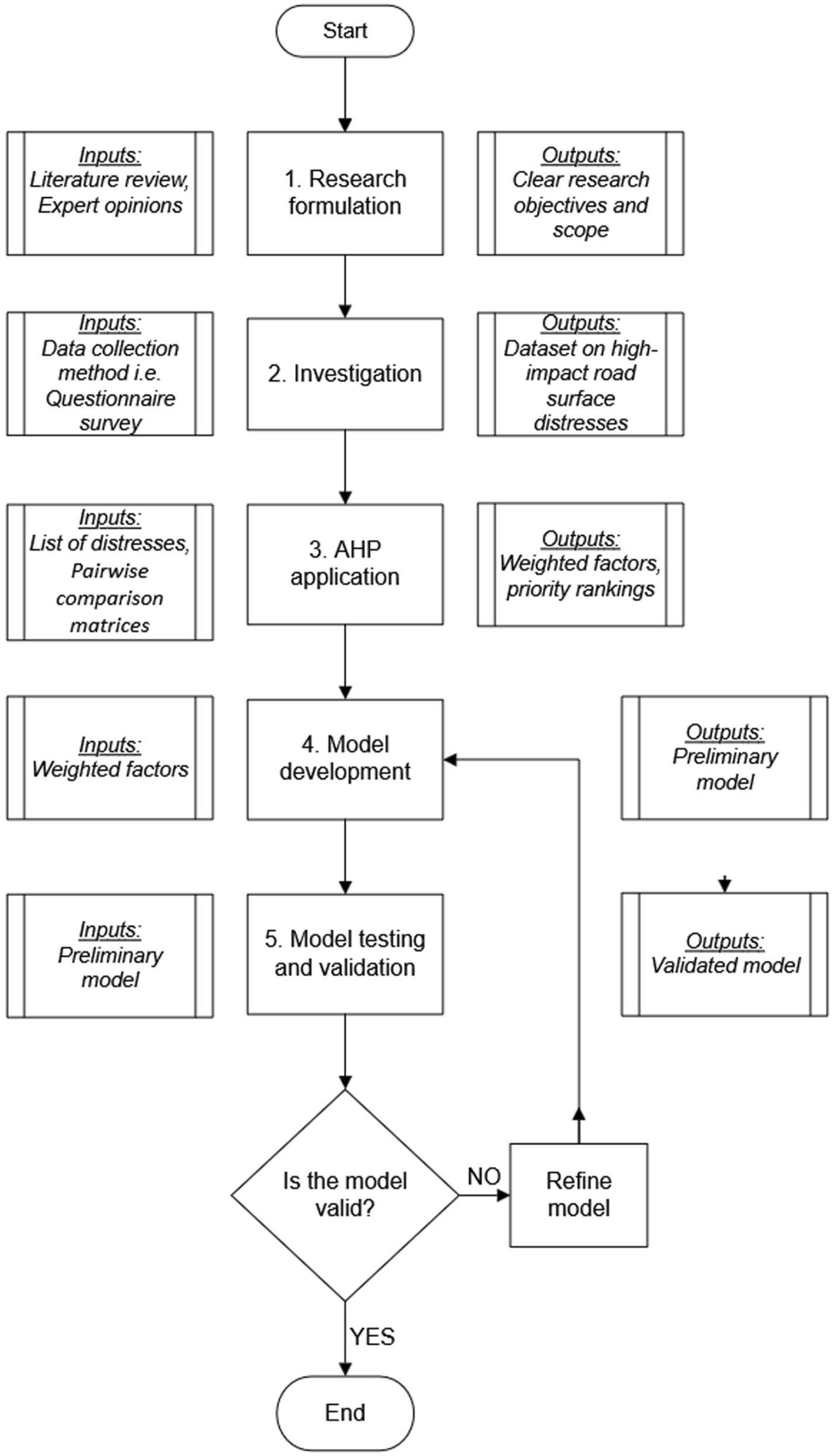

Fig. 1 Research methodology flowchart

Table 2 Summary of results from the questionnaire survey

Distresses	Impact Rating					Total Responses (N)	Total Score	Weight Factor	Rank
	1	2	3	4	5				
Inadequate drainage	1	0	2	6	27	36	**166**	0.137	**1**
Inadequate gravel thickness	1	1	17	11	6	36	**128**	0.106	**6**
Camber loss	0	5	10	13	8	36	**132**	0.109	**5**
Corrugations	3	3	15	11	4	36	**118**	0.098	**8**
Loose gravel	1	2	17	8	8	36	**128**	0.106	**7**
Stoniness	2	6	21	4	3	36	**108**	0.089	**9**
Potholes	1	2	7	9	17	36	**147**	0.121	**3**
Erosion gullies	1	2	4	13	16	36	**149**	0.123	**2**
Rutting	1	3	8	17	7	36	**134**	0.111	**4**

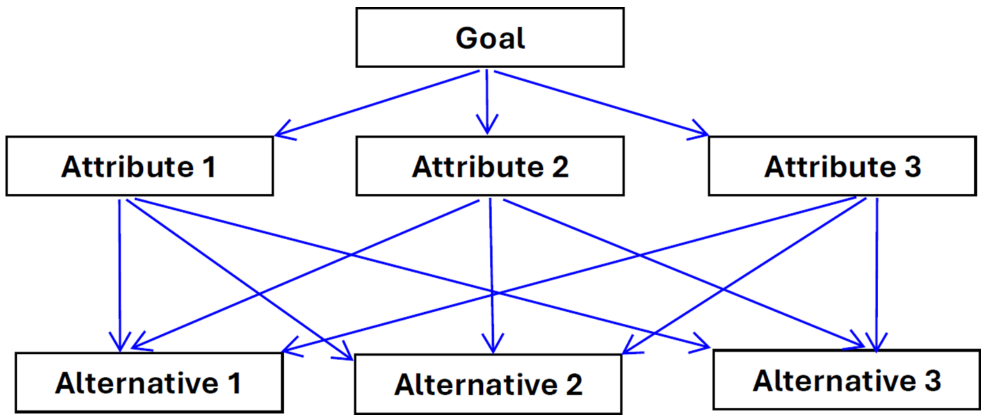

Fig. 2 AHP hierarchy structure

derived from the survey data were normally distributed, and no comparison had been made to determine the impact of one distress over another. In contrast, the AHP method was found more appropriate as it provided a means to objectively carry out relative mathematical measurements of the distress weights.

2.3 AHP Application

Distress weighting using the AHP method was determined by following the steps outlined by Saaty [6]. This involved (1) defining the goal and AHP hierarchical structure, (2) constructing a pairwise comparison matrix to facilitate relative measurement, (3) normalizing the matrix to establish the appropriate weight factors, and (4) testing for consistency of the derived weight factors.

2.3.1 Defining the Goal and AHP Hierarchical Structure

The initial step was to define the goal of the AHP. The goal of the study was to establish weight factors for each of the road surface distresses affecting the condition rating of unpaved roads in Uganda. The hierarchical structure proposed by Saaty [6] had three levels, with the goal located at the topmost level then, followed by attributes and alternatives at levels two and three, respectively, as shown in Fig. 2. It should, however, be noted that this study comprised only two levels, i.e., the goal and the attributes or elements (the nine road surface distress attributes). In this study, the AHP method was employed solely to determine the weight factors of the road surface distresses using pairwise comparison matrices, and there was no need to formulate decision alternatives.

2.3.2 Constructing a Pairwise Comparison Matrix

The next step in the AHP method was to construct a pairwise comparison matrix using Eq. 1, as proposed by Saaty [6]. The matrix rows and columns consisted of the road surface distress attributes, which were compared against one another using Saaty's 9-point scale of relative importance to derive the attribute judgment values, as shown in Table 3.

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \quad (1)$$

Where $\boldsymbol{a}$ = attribute and $\boldsymbol{n}$ = number of attributes

The AHP pairwise comparison matrix shown in Table 3 was used to analyze the nine road surface distresses, denoted D1 to D9. This was done by comparing two distresses at a time using a 9-by-9 matrix. For example, comparing inadequate drainage (D1) to stoniness (D6) using Saaty's

Table 3 AHP pairwise comparison matrix for the road surface distresses

	Inadequate drainage	Inadequate gravel thickness	Camber loss	Corrugations	Loose gravel	Stoniness	Potholes	Erosion gullies	Rutting
	D1	D2	D3	D4	D5	D6	D7	D8	D9
D1	**1.000**	5.000	4.000	6.000	5.000	7.000	3.000	3.000	4.000
D2	0.200	**1.000**	0.500	2.000	1.000	3.000	0.333	0.333	0.500
D3	0.250	2.000	**1.000**	3.000	2.000	3.000	0.333	0.333	0.500
D4	0.167	0.500	0.333	**1.000**	0.500	2.000	0.250	0.250	0.333
D5	0.200	1.000	0.500	2.000	**1.000**	3.000	0.333	0.333	0.500
D6	0.143	0.333	0.333	0.500	0.333	**1.000**	0.200	0.167	0.333
D7	0.333	3.000	3.000	4.000	3.000	5.000	**1.000**	0.500	2.000
D8	0.333	3.000	3.000	4.000	3.000	6.000	2.000	**1.000**	3.000
D9	0.250	2.000	2.000	3.000	2.000	6.000	0.500	0.333	**1.000**

Table 4 Normalized matrix for the road surface distresses

	Inadequate drainage	Inadequate gravel thickness	Camber loss	Corrugations	Loose gravel	Stoniness	Potholes	Erosion gullies	Rutting	Weight (W)	Rank
	D1	D2	D3	D4	D5	D6	D7	D8	D9		
D1	0.348	0.280	0.273	0.235	0.280	0.194	0.377	0.480	0.329	**0.311**	**1**
D2	0.070	0.056	0.034	0.078	0.056	0.083	0.042	0.053	0.041	**0.057**	**6**
D3	0.087	0.112	0.068	0.118	0.112	0.083	0.042	0.053	0.041	**0.080**	**5**
D4	0.058	0.028	0.023	0.039	0.028	0.056	0.031	0.040	0.027	**0.037**	**8**
D5	0.070	0.056	0.034	0.078	0.056	0.083	0.042	0.053	0.041	**0.057**	**7**
D6	0.050	0.019	0.023	0.020	0.019	0.028	0.025	0.027	0.027	**0.026**	**9**
D7	0.116	0.168	0.205	0.157	0.168	0.139	0.126	0.080	0.164	**0.147**	**3**
D8	0.116	0.168	0.205	0.157	0.168	0.167	0.252	0.160	0.247	**0.182**	**2**
D9	0.087	0.112	0.136	0.118	0.112	0.167	0.063	0.053	0.082	**0.103**	**4**
	1.000	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	

9-point scale determined that inadequate drainage was *'very strongly more important'* than stoniness, with a Saaty-scale value of 7.000. Conversely, the reciprocal value of 0.143 represented the relative superiority of inadequate drainage over stoniness. For the D1 over D6 example stated above, the AHP scale or attribute judgment value for inadequate drainage (D1) over stoniness (D6) was calculated from the variance between the total scores of the distresses obtained from the questionnaire survey.

2.3.3 Normalizing the Matrix to Establish Weight Factors

The third step of the AHP method was to normalize the pairwise comparison matrix. This was done by calculating the column totals of the Saaty-scale values assigned to each road distress in the matrix. Then, each individual judgment value was divided by its respective column total to produce a normalized matrix, as shown in Table 4. The weight *(W)* of each road surface distress was then calculated by obtaining the arithmetic mean of each row in the normalized matrix. The derived weights were: w1 = 0.311, w2 = 0.057, w3 = 0.080, w4 = 0.037, w5 = 0.057, w6 = 0.026, w7 = 0.147, w8 = 0.182 and w9 = 0.103.

2.3.4 Testing for Consistency of the Derived Weight Factors

After determining the weight factors of each road surface distress from the normalized matrix, the final step of the AHP method was to test the consistency of the results. Saaty [6] contends that the consistency of the matrix can be evaluated by first calculating the largest Eigen value denoted as λ_{max}, using Eq. 2.

$$\lambda_{max} = \sum_{j=1}^{m} \frac{(S.V)j}{m.v_j} \tag{2}$$

Where; m = the number of rows in the normalized matrix
S = the pairwise comparison matrix
v = the matrix eigenvector

The Consistency Index (CI) was then derived from the Eigenvalue (λ_{max}) using Eq. 3 as proposed by Saaty [6]. A CI value of 0.055 was obtained, as indicated in Table 5. MATLAB computation software was deployed to compare the Eigenvalue. The MS Excel calculation resulted in a λ_{max} value of 9.4361, while the MATLAB software computed a value of 9.4347. Since the values obtained from both computational approaches were comparable, it was possible to accurately ascertain the validity of the largest Eigenvalue (λ_{max}).

Table 5 Consistency test calculations

	D1	D2	D3	D4	D5	D6	D7	D8	D9	Weighted Sum Value	Weight (W)	Ratio
D1	0.311	0.285	0.319	0.220	0.285	0.184	0.441	0.546	0.413	3.005	0.3108	9.669
D2	0.062	0.057	0.040	0.073	0.057	0.079	0.049	0.061	0.052	0.530	0.0571	9.278
D3	0.078	0.114	0.080	0.110	0.114	0.079	0.049	0.061	0.052	0.736	0.0796	9.242
D4	0.052	0.029	0.027	0.037	0.029	0.053	0.037	0.046	0.034	0.341	0.0367	9.301
D5	0.062	0.057	0.040	0.073	0.057	0.079	0.049	0.061	0.052	0.530	0.0571	9.278
D6	0.044	0.019	0.027	0.018	0.019	0.026	0.029	0.030	0.034	0.248	0.0263	9.435
D7	0.104	0.171	0.239	0.147	0.171	0.131	0.147	0.091	0.207	1.408	0.1470	9.580
D8	0.104	0.171	0.239	0.147	0.171	0.158	0.294	0.182	0.310	1.776	0.1821	9.753
D9	0.078	0.114	0.159	0.110	0.114	0.158	0.073	0.061	0.103	0.971	0.1034	9.390
											λ max =	**9.436**
											CI =	0.055
											RI =	1.45
											CR =	**0.0376**

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{3}$$

Where; n = the number of elements or attributes

λ_{max} = the largest eigenvalue

The next step was calculating the Consistency Ratio (CR), which Saaty [6] describes as the degree of compatibility for data analyzed by the AHP method. The Consistency Ratio indicates any potential incompatibility by determining whether the inconsistency in the pairwise comparison matrix is acceptable or not [28]. If the CR is less than or equal to 0.1, the inconsistency is deemed acceptable; however, a CR greater than 0.1 would suggest that the pairwise comparison matrix should be re-examined to improve consistency. The Consistency Ratio was calculated as shown in Eq. 4.

$$CR = \frac{CI}{RI} \tag{4}$$

Where; CI=the Consistency Index

RI=the Random Index

The Random Index (RI) value was extracted from the Random Inconsistency Index table developed by Saaty [6] for fifteen (15) elements with different matrix orders, as shown in Table 6. The study used a 9-by-9 matrix to assess the nine road surface distresses. Applying the appropriate RI value of 1.45 for a 9-by-9 matrix, the Consistency Ratio (CR) was calculated as 0.0376 using the formula in Eq. 4. Since this CR value is less than the acceptable threshold of 0.1, it was determined that the weight factors derived from the AHP method were reliable, and the pairwise comparison matrix had acceptable consistency.

2.4 Model Development

The Gravel Road Condition Index (GRCI) was developed as a mathematical model to assess the nine identified distresses affecting unpaved roads in Uganda. The GRCI utilized a 5-point rating scale (values 1 to 5) and considered three key distress attributes: type, severity, and weight factor. The GRCI was formulated as a function of the weighting factor and severity combination for the nine distresses, employing a weighted sums approach to derive condition indices. This study developed the GRCI based on the methodology outlined in the South African Standard Visual Assessment Manual for Unsealed Roads (TMH12), which calculated a condition index value for each assessed road section by combining the severity rating and weight factor of each distress type [15].

This approach of aggregating pavement distresses into a single index to evaluate the functional performance of pavement was employed by Ndume et al. [30] in developing

Table 6 Random inconsistency index by Saaty [6]

N	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59

an enhanced road condition index for Tanzania. Similarly, Tawalare and Vasudeva Raju [31] constructed a pavement performance index as the product of the rating and weighting of each deteriorating parameter for rural roads in India. Likewise, Attoh-Okine and Adarkwa [32] observed that an overall pavement index could be formulated by integrating the weighting factor of each distress and the rating of the individual distress for roads in Pennsylvania (U.S.). This study, therefore, developed a GRCI mathematical model based on the weighted sums method, as shown in Eq. 5.

$$GRCI = \sum_{i=1}^{9} (W_i \, x \, S_i) \tag{5}$$

Where; W_i = Weight of Distress

S_i = Distress Severity (Scale of 1 to 5)

i = Distress Type (1 to 9)

The general mathematical model shown in Eq. 5 was further expanded as represented in Eq. 6.

$$GRCI = W_1S_1 + W_2S_2 + W_3S_3 + \ldots\ldots + W_9S_9 \tag{6}$$

The mathematical model shown in Eq. 7 for the nine road surface distresses represented the Gravel Road Condition Index (GRCI).

$$\begin{aligned} GRCI =& 0.31S_1 + 0.06S_2 + 0.08S_3 \\ &+ 0.04S_4 + 0.06S_5 + 0.02S_6 \\ &+ 0.15S_7 + 0.18S_8 + 0.1S_9 \end{aligned} \tag{7}$$

Where; S_i = Distress Severity (Scale of 1 to 5)

3 Model Testing and Validation

The developed GRCI model shown in Eq. 7 was tested and validated through a field-based application on an unpaved road case study. A condition assessment form was developed to record the severity of the weighted distresses, assessing a maximum of 1 km per road section. The results were then verified through a comparison with the pre-existing condition assessment method.

3.1 The Case-Study Unpaved Road

The Misindye-Kiyunga Road is an 11-kilometer-long national gravel road located in Mukono District in the central region of Uganda, as shown in Fig. 3. The GRCI model was tested on the Misindye-Kiyunga Road because (1) the road exhibited all nine identified distresses across its 11 sections; (2) the road carries low to medium traffic with dual functionality; (3) the existing road is over 6 m wide in all 11 sections; (4) existing road condition data was readily available; and (5) the road connects locally significant traffic generators with their rural hinterland.

3.2 Procedural Application of the GRCI

An assessment of the condition of the Misindye-Kiyunga Road was carried out using the developed GRCI model. The procedural application of the GRCI involved four steps, namely; (1) hold a pre-assessment meeting with the assessors and vehicle drivers; (2) prepare the data collection forms and tools prior to the assessment; (3) conduct the condition assessment and provide a condition rating for each section of the assessed road length; (4) determined the overall condition rating and condition category of the entire road length. It should be noted that the assessors carried out these steps in the field before conducting the condition assessment of the unpaved road in the case study.

3.2.1 Pre-Assessment Meeting

The first step of the field-based condition assessment involved holding a pre-assessment meeting on the case-study road with the assessors and vehicle drivers, as shown in Fig. 4. During this meeting, the two assessors discussed and familiarized themselves with the GRCI condition assessment form, which was used to record the severity values of each of the nine identified distresses. Additionally, the 1 to 5 severity scale and the distress severity classification were reviewed to ensure that the assessors clearly understood the 5-point distress rating procedure indicated on the assessment forms. The vehicle drivers were also provided information on the assessment procedure, emphasizing maintaining a maximum traveling speed of 20 km/hr.

3.2.2 Preparation of the Data Collection Forms and Tools

The second step entailed preparing the data collection forms and tools. Each assessor was issued ten GRCI condition assessment forms, which were deemed adequate as each form could record data for two road sections. Additionally, the assessors were furnished with clipboards, pens, and calculators to facilitate recording the distress severity values and computing the standardized model values.

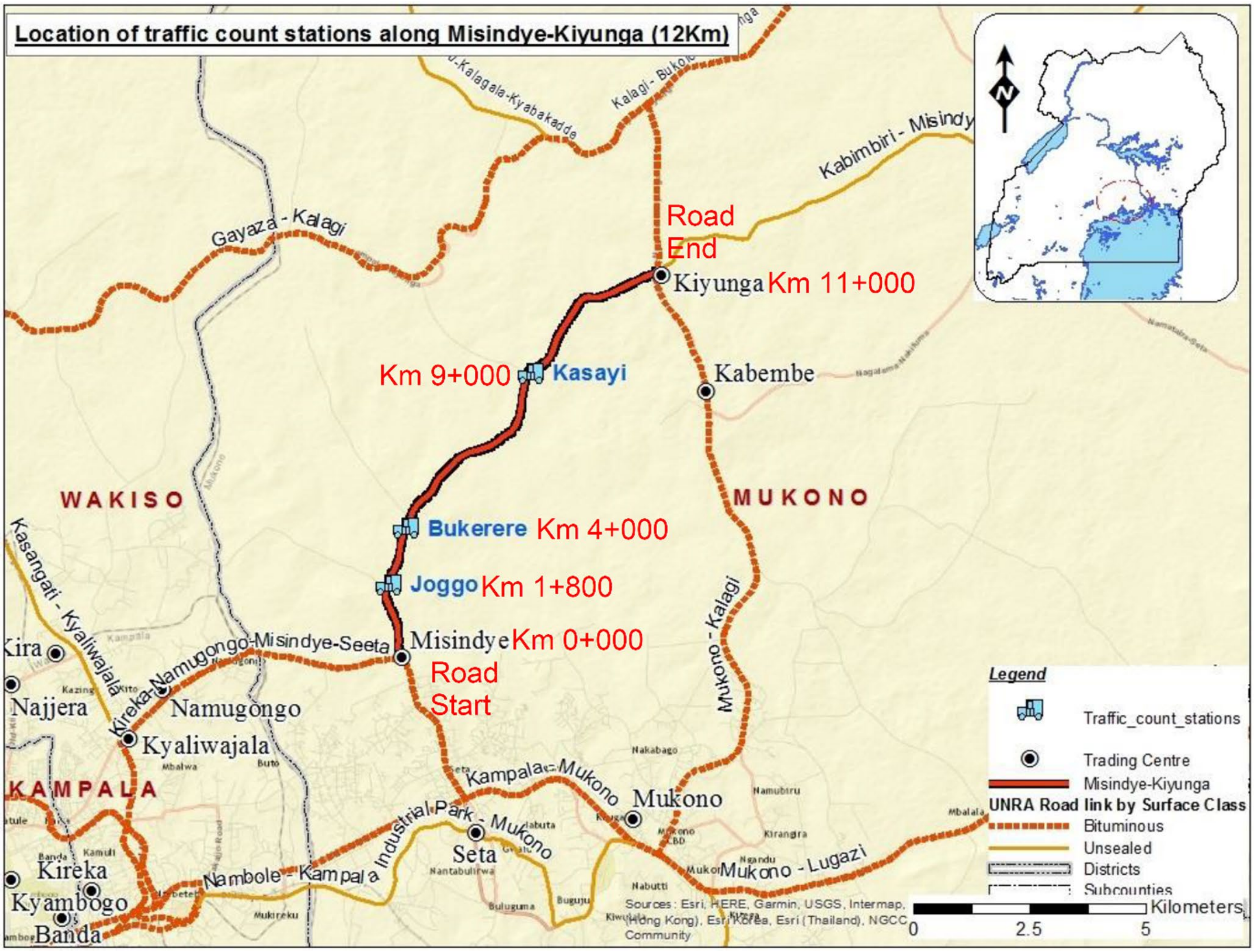

Fig. 3 Location of the Misindye-Kiyunga Road in Mukono District (Central Uganda)

Fig. 4 Pre-assessment meeting on the Misindye-Kiyunga Road

3.2.3 Carry Out the Condition Assessment

The third step of the condition assessment process involved a visual windshield survey, where two assessors traveled in separate vehicles to inspect the road. Each 1 km section was visually assessed, and the assessors then stopped to determine the GRCI rating for that section using the GRCI condition assessment forms before moving on to the next section. This approach of deploying two assessors enabled a comparative analysis of the results, ensuring that the GRCI ratings had no concerns regarding repeatability. Each assessor recorded the road name, inspection date, their name, the form code, and the distress severity values ranging from 1 to 5. These severity values were then used to calculate the GRCI rating, which defined the condition category of the assessed road sections. Both Assessor No.1 and Assessor No.2 documented the GRCI ratings and condition categories for all 11 sections of the case-study road.

Table 7 Results of the condition assessment on the Misindye-Kiyunga Road

Assessor No.1				Assessor No.2			
Gravel Road Condition Index (GRCI)				Gravel Road Condition Index (GRCI)			
Misindye-Kiyunga Road (11 km)				Misindye-Kiyunga Road (11 km)			
Road Section	Standardized Model Value	GRCI Rating	GRCI Condition Category	Road Section	Standardized Model Value	GRCI Rating	GRCI Condition Category
1	3.22	3	Fair	1	2.99	3	Fair
2	3.54	4	Poor	2	2.90	3	Fair
3	2.51	3	Fair	3	3.00	3	Fair
4	3.02	3	Fair	4	2.47	3	Fair
5	3.12	3	Fair	5	2.85	3	Fair
6	3.13	3	Fair	6	3.00	3	Fair
7	3.02	3	Fair	7	2.88	3	Fair
8	2.22	2	Good	8	2.67	3	Fair
9	3.00	3	Fair	9	3.02	3	Fair
10	2.69	3	Fair	10	2.89	3	Fair
11	2.94	3	Fair	11	3.26	3	Fair
Overall Condition		**3**	**Fair**	**Overall Condition**		**3**	**Fair**

4 Results and Discussion

4.1 Results of the Field-Based Condition Assessment

The final step involved calculating the overall condition rating and category for the Misindye-Kiyunga Road. This was achieved by computing the weighted average of the GRCI ratings obtained for the 11 sections of the case-study road. The condition assessment results for both assessors are summarized in Table 7. A comparison of the overall condition rating and category between Assessor No.1 and No.2 indicated that the case-study road was in a *"Fair"* condition. Notably, both assessors recorded the same overall rating, suggesting that the GRCI method had no repeatability concerns. It was observed that there were discrepancies in some individual section ratings, where Assessor No.1 rated Sect. 2 as *"Poor"* while Assessor No.2 rated it as *"Fair*," and Assessor No.1 rated Sect. 8 as *"Good"* while Assessor No.2 rated it as *"Fair*." However, these differences in section-level ratings did not impact the overall condition rating and category, which remained consistent between the two assessors. Additional testing on a more extensive gravel road network is necessary to ascertain that the GRCI method lacks repeatability issues.

4.2 Comparison Between GRCI and the Existing Condition Assessment Method

The GRCI was verified through a comparative analysis with Uganda's existing condition assessment method. The Visual Condition Index (VCI) rates the road condition on a scale of Very Good (100) to Very Poor (0) and is calculated for every 1 km section of unpaved road. The condition data for the Misindye-Kiyunga Road, with Road Code 678 and Road Name C045, was obtained from UNRA [33] as summarized in Table 8. Given that the VCI also has five condition categories, it was possible to conduct a direct comparison between the GRCI and VCI, as shown in Fig. 5. The overall condition category of the Misindye-Kiyunga Road was determined to be *"Fair*," with a VCI rating of 61.89. The comparative analysis undertaken demonstrated that the results from both the GRCI and VCI condition assessment methods were similar, with both indicating a *"Fair"* condition for the case-study road. Consequently, the results from the GRCI were verified and found to be consistent with the existing condition assessment method.

Table 8 VCI rating and condition category of the Misindye-Kiyunga Road [33]

Road Code	Road Name	Link	Segment	Weighted VCI	VCI Condition Category
678	C045	C04501	1	59.00	Fair
678	C045	C04501	2	60.25	Fair
678	C045	C04501	3	60.50	Fair
678	C045	C04501	4	64.25	Fair
678	C045	C04501	5	61.75	Fair
678	C045	C04501	6	64.25	Fair
678	C045	C04501	7	60.25	Fair
678	C045	C04501	8	64.25	Fair
678	C045	C04501	9	57.75	Fair
678	C045	C04501	10	64.25	Fair
678	C045	C04501	11	64.25	Fair
			Overall Condition	**61.89**	**Fair**

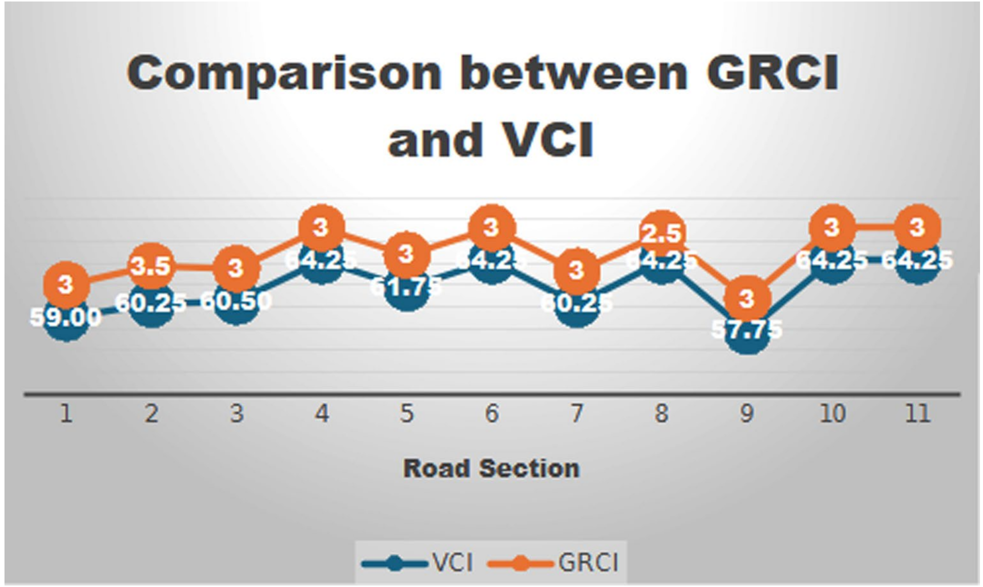

Fig. 5 Comparison between GRCI and VCI

4.3 Summary of Results

This study developed a new condition assessment model based on objective weightings of road surface distresses. The weightings obtained for the distresses were: inadequate drainage (w1 = 0.311), inadequate gravel thickness (w2 = 0.057), camber loss (w3 = 0.080), corrugations (w4 = 0.037), loose gravel (w5 = 0.057), stoniness (w6 = 0.026), potholes (w7 = 0.147), erosion gullies (w8 = 0.182), and rutting (w9 = 0.103). The use of AHP pairwise comparison matrices allowed a more comparative evaluation of the relevant distresses influencing the condition of unpaved roads. The AHP method also provided a means to quantitatively check the pairwise matrices for consistency. Having obtained a Consistency Ratio of 0.0376 *(less than 0.1)*, it was determined that the weight factors derived from the AHP method were reliable and that the pairwise comparison matrix had acceptable consistency. The GRCI model developed in this study was applied to an unpaved road case study, and the results showed that the overall condition rating of both assessors indicated a "Fair" condition. It was further noted that since both assessors recorded the same overall rating, the GRCI had no repeatability concerns. The results from the case study application of the new index were verified and found to be consistent with the existing condition assessment method in the Country. Overall, this study developed a method that provided a fast, inexpensive, streamlined, user-friendly procedure for assessing the condition of unpaved roads.

5 Conclusion

This study successfully developed a novel method for assessing the condition of unpaved roads in Uganda, addressing the critical need for an objective, systematic, and user-friendly approach to evaluating unpaved road surfaces. By leveraging the Analytic Hierarchy Process (AHP), the research established a robust framework for weighting and prioritizing high-impact road surface distresses, resulting in the creation of the Gravel Road Condition Index (GRCI). The GRCI model integrates objective weightings of nine key distresses into a mathematical model that provides a standardized and consistent approach to condition assessment. The AHP-based methodology ensured transparency and reliability, as evidenced by the Consistency Ratio (CR) of 0.0376, which confirmed the validity of the derived weight factors.

Applying the GRCI model to the Misindye-Kiyunga Road case study demonstrated its practicality and effectiveness. The results indicated a "Fair" overall condition rating, consistent with Uganda's existing condition assessment method. This validation underscores the GRCI's potential as a reliable alternative to traditional subjective assessment methods. Furthermore, the study highlighted the GRCI's advantages, including its streamlined data collection process, cost-effectiveness, and ability to minimize repeatability concerns, as demonstrated by the consistent ratings provided by two independent assessors.

The research contributes significantly to the body of knowledge by introducing an innovative condition assessment method tailored to unpaved roads, constituting a substantial portion of road networks in developing countries. The GRCI model not only enhances the understanding of high-impact distresses but also provides a foundation for future studies and practical applications in pavement management. However, the study acknowledges limitations, such as the reliance on a single case study and the need for broader testing across more extensive road networks to further validate the method's repeatability and generalizability. Overall, this study provides a valuable tool for road maintenance engineers and policymakers, offering a practical solution to unpaved road condition assessment and management challenges.

5.1 Contribution to the Body of Knowledge

The study sought to address the lack of information regarding pavement condition assessment techniques for unpaved roads by proposing an enhanced method known as the Gravel Road Condition Index. This innovative approach provided a more comprehensive understanding of the high-impact surface distresses that influence the condition ratings of unpaved roads. Furthermore, developing the GRCI method generated valuable references for future studies aiming to minimize subjectivity in the condition assessments of unpaved roads. In practice, the study devised a method that employs objective weightings and demonstrated consistency in its evaluations.

5.2 Research Limitations

This research study encountered certain limitations. Using a questionnaire survey for data collection posed constraints regarding participants' number and response rates. Although a reasonable response rate of 51.4% was obtained, the generalization assumptions could have been enhanced with an even higher response rate. Additionally, the GRCI method was applied to a case study road of only 11 km due to limited resources and funding. Therefore, further testing on a more extensive gravel road network is necessary to comprehensively ascertain that the GRCI method lacks repeatability issues. Furthermore, alternative methods such as Principal Component Analysis, Mazziotta-Pareto Index, Structural Equation Modeling, or Statistical Regression could not corroborate the Analytic Hierarchy Process results. Lastly, the study did not explicitly address statistical validation using paired t-tests to compare the GRCI model's ratings with the VCI or between multiple assessors. While the study validated consistency via AHP's Consistency Ratio (CR) and field-testing, a paired t-test would have strengthened the statistical rigor by quantifying the significant differences between GRCI and VCI ratings and by testing inter-assessor reliability.

5.3 Recommended Future Work

Future research could expand the survey coverage to include other countries within Sub-Saharan Africa, enabling the development of a generalized condition assessment model applicable to road agencies operating in tropical climates. Furthermore, additional research could be conducted to establish an appropriate Pavement Management System, utilizing the GRCI values as inputs for the condition information. This study's scope did not encompass the development of a Pavement Management System, which would be essential in assisting road maintenance engineers in Uganda in having a centralized and functional platform for planning and monitoring the performance of the unpaved road network in the Country. Finally, future studies could further validate the GRCI model by incorporating paired t-tests that would statistically compare the GRCI and VCI ratings and evaluate inter-assessor reliability using quantitative significance testing.

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Authors' Contributions The study's conception and methodological design were collaboratively developed by all authors. Richard Musiime, PhD, Juan Ferriz-Papi, PhD, and Amanda Marshall-Ponting, PhD, were responsible for the preparation of the survey, as well as the collection and analysis of the data. Richard Musiime, PhD, authored the initial draft of the manuscript, which was subsequently reviewed and revised by all authors. Each author has read and approved the final version of the manuscript.

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Code Availability Not applicable.

Declarations

Ethics Approval Not applicable.

Consent to Participate Not applicable.

Consent for Publication Not applicable.

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