
COMPARATIVE ASSESSMENT OF PAVEMENT DISTRESS USING CONVENTIONAL MEASUREMENTS AND UAV PHOTOGRAMMETRY ALONG THE GOMBE - KWAMI HIGHWAY, NIGERIA

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ABSTRACT

Road potholes constitute a major pavement distress in Nigeria, contributing to vehicle damage, traffic congestion, and accidents. Traditional condition surveys by agencies such as the Federal Roads Maintenance Agency (FERMA) are labor-intensive, time-consuming, and expose personnel to safety risks. This study evaluates the application of Unmanned Aerial Vehicle (UAV) photogrammetry as a cost-effective alternative for pothole measurement along a section of the Gombe-Kwami Road in Gombe State, Nigeria. A DJI Mavic Air 2 UAV was used to acquire overlapping aerial images which were processed into Ortho mosaics and Digital Surface Models for extracting pothole diameter, area, and depth. These were compared with conventional ground survey measurements of 20 potholes. A quantitative cost and time analysis was also conducted based on 2025 FERMA Schedule of Rates. Results show strong agreement between UAV and conventional methods with Mean Percentage Errors of 1.23% for diameter, 2.72% for area, and 3.13% for depth. Error distribution analysis revealed that high percentage errors up to 40% were limited to 3 very small potholes < 15cm diameter, attributable to sub-GSD digitization limits. The UAV method achieved 81.0% reduction in field time and 67.9% reduction in per-kilometer survey cost, from ₦85,000/km to ₦27,300/km. Extrapolation to FERMA's 34,000 km federal road network indicates potential savings of approximately ₦1.96 billion per survey cycle. The findings demonstrate that UAV photogrammetry provides accurate, rapid, and cost-effective data for pavement assessment and supports adoption by FERMA in line with Nigeria's National Development Plan 2021-2025.

Keywords: UAV Photogrammetry; DJI Mavic Air 2; Pothole Measurement; Cost-Benefit Analysis; FERMA; Nigeria

1.0 INTRODUCTION

Road infrastructure is a critical driver of economic growth, trade, and social connectivity. In Nigeria, the federal road network spans over 34,000 km and carries more than 80% of passenger and freight traffic (Federal Ministry of Works and Housing [FMWH], 2024). However, rapid deterioration due to heavy axle loads, poor drainage, and inadequate maintenance funding has resulted in widespread pavement distresses. Among these, potholes are the most prevalent and hazardous defect, contributing to vehicle damage, increased travel time, traffic accidents, and higher vehicle operating costs (Oluwasola & Adeniyi, 2023). Traditional methods of pavement condition assessment in Nigeria rely heavily on manual surveys using measuring tapes, leveling staffs, and visual inspection by personnel from agencies such as the Federal Roads Maintenance Agency (FERMA). While accurate, these methods are labor-intensive, time-consuming, and expose workers to traffic safety risks (FERMA, 2023). A typical 1 km manual survey requires 4-5 hours and costs approximately ₦85,000 (FERMA, 2025). Given budgetary constraints, FERMA can only assess a small fraction of the network annually, leading to reactive rather than proactive maintenance. Recent advances in Unmanned Aerial Vehicle (UAV) photogrammetry offer a viable alternative for rapid and cost-effective infrastructure assessment. UAVs equipped with high-resolution RGB cameras can capture overlapping aerial images to generate 3D point clouds, Digital Surface Models (DSM), and Ortho mosaics with centimeter-level accuracy. Globally, UAV technology has been successfully applied for pavement distress detection in the USA,

China, and South Africa, with reported time savings of up to 80% and cost reductions of 60-70% (Nex & Remondino, 2023; Dorafshan et al., 2023; Li et al., 2024; Mhlongo & Motaung, 2023). In the Nigerian context, adoption of UAV for road assessment remains limited despite its potential. Few studies have quantified both the accuracy and cost-effectiveness of UAV for pothole measurement under local conditions of weather, traffic, and regulatory framework (Bello & Mohammed, 2024). Moreover, there is a need to align new technologies with national industrial policy goals of improving efficiency, transparency, and domestic capacity in infrastructure delivery (National Planning Commission [NPC], 2023).

Therefore, this study evaluates the use of UAV photogrammetry for pothole measurement along a section of the Gombe-Kwami Road in Gombe State, Nigeria. The specific objectives are to:

- a) Acquire high-resolution UAV imagery and generate 3D models.
- b) Compare pothole diameter, area, and depth from both methods.
- c) Evaluate the statistical correlation and percentage error between methods, and
- d) Assess the time, cost and engineering implications of both approaches.

The outcome is expected to provide evidence-based data to support the adoption of UAV technology by FERMA and other agencies for scalable, data-driven road maintenance in line with Nigeria's infrastructure transformation agenda.

2. LITERATURE REVIEW

The main shortcomings modeled by the conventional manual visual inspection are the time - intensiveness and longer interval of traffic disturbance to give way to the inspection work. As the geometry establishment of pothole is rarely uniform, sequence of measurements is required to be obtained in order to determine the maximum reading (Wang, 2021).

The assessment of road surfaces for distress severity is a critical aspect of infrastructure maintenance, with significant implications for safety and cost management. Traditional methods, such as visual inspections and manual surveys, are often slowish, time-consuming and prone to human error (Kumar and Gupta, 2022).

Recent advancements in digital photogrammetry offer a promising alternative, providing high-resolution, three-dimensional data that enhance the accuracy of pothole detection and severity assessment (Smith et al., 2023).

Conventional pavement inspection techniques have been extensively used for pavement condition evaluation. Although these methods provide valuable information, they are often associated with safety concerns, high operational costs, and variability among inspectors.

Apeagyei et al., (2023) demonstrated the effectiveness of image-based techniques for pavement distress classification. Ibrahim et al. (2024) reported that UAV photogrammetry can provide accurate geometric measurements for infrastructure monitoring applications. Similarly, Samadzadegan et al. (2024) highlighted the capability of UAV imagery and digital photogrammetry for pavement distress detection and measurement.

Recent studies have explored the application of UAVs and photogrammetry for infrastructure monitoring while previous studies have focused primarily on distress detection and classification, fewer studies have quantitatively compared UAV- derived measurements with conventional field measurements under Nigerian highway conditions. This study contributes to addressing this knowledge gap.

2.1 Statistical Analysis in Pavement Assessment

Statistical analysis plays an important role in validating the reliability and consistency of pavement distress measurements obtained from different assessment methods. Comparative studies involving manual and photogrammetric measurements commonly apply descriptive statistics, correlation analysis, paired sample t-tests, and non-parametric alternatives. Descriptive statistics including mean, standard deviation, minimum, and maximum values are used to summarize the distribution and variability of distress measurements. Correlation analysis evaluates the strength and direction of relationships between measurement methods. The paired sample t-test is commonly applied when comparing two related measurement methods obtained from the same sample locations. However, the validity of the paired t-test depends on key assumptions:

- a) The paired differences are normally distributed,
- b) Observations are independent, and
- c) Data are continuous with no extreme outliers.

Where the normality assumption is violated or outliers are present, non-parametric alternatives such as the Wilcoxon signed-rank test are more appropriate as they do not require normal distribution of differences (Ali et al., 2022). Therefore, in this study, normality of paired differences was first assessed using the Shapiro-Wilk test before selecting the appropriate comparative test.

3.0 MATERIALS AND METHODS

3.1 Introduction

This chapter describes the materials, equipment, and software tools used in the research and also outlines the procedures/Methodology adopted in the comparative assessment of pavement distress using conventional measurements and UAV photogrammetry along the Gombe - Kwami route in Gombe State, Nigeria.

3.2 The Study Area



Figure 1.0: Route map of the study area

Source: (Google map)

The study was conducted on a 1.5 km section of the Gombe-Kwami Federal Highway in Gombe State, Northeastern Nigeria. This section was selected due to the presence of multiple potholes of varying severity and its representation of typical traffic loading conditions on federal roads. Figure 1.0 presents the route map of the study area. The highway connects Gombe metropolis to Kwami Local Government Area, with the specific survey section located approximately 20.3 km from Gombe city center towards Kafarati village, as depicted in the map. The estimated travel time to the site is 32 minutes by car. The map illustrates the accessibility of the study location and its position within the Gombe-Kwami Road corridor. The selected 1.5 km stretch falls within this corridor. The road pavement consists of flexible asphalt surfacing on granular base and subbase layers, with widths ranging from 6.5m to 7.3m and experiences heavy traffic from commercial vehicles and trucks, contributing to traffic loading. These traffic loading conditions contribute significantly to pavement deterioration, particularly along wheel paths and drainage-compromised sections.

3.3 Materials used

The primary data for this study comprised road surface distress (potholes) measurements for conventional (Manual) method and UAV images for the Photogrammetry method.

3.3.1 Road surface Images

Images of distressed road surface were used for the photogrammetry analysis. The images included Pothole and crack images with varying sizes and severities, Resolution Ranging from 640x480 pixel to 1920x1080 pixel, with JPEG and PNG format, and Each image was labeled with corresponding measured distress values (diameter and depth).

3.3.2 Equipment

The equipment used include the followings:

- a) Measuring Tape (5m) for manual diameter measurement.
- b) Steel Ruler and Depth Gauge (300 mm) for pothole depths measurements.
- c) UAV drone camera (DJI Mavic air 2) for pothole image capturing.
- d) Computer Workstation with CPU Intel Core i7

3.3.3 Software and Libraries

- a) Python (v3.8+): Pandas and NumPy for data analysis.
- b) Photo Modeler Premium (v2024.0) DSM and measurement.
- c) Jupyter Notebook for exploratory data analysis.
- d) SciPy for T-test analysis.
- e) Scikit-learn for RMSE and MAE analysis.
- f) Matplotlib for box plot, bar plot and scatter plot analysis.

3.4 Data Collection

3.4.1 Conventional Measurement

Field measurements of pothole diameter, area, and depth were obtained manually using measuring tapes and calibrated depth gauges at 20 sample points (P1-P20), selected at random along the route. The potholes sampled were labelled by number and measured separately, diameter and depth only while area is calculated from diameter using the formular for area of a circle $A = \pi r^2$, and r is derived from diameter equal to two radii, and radius is equal to diameter divided by two.

3.4.2 Unmanned Aerial Vehicle (UAV)

An Unmanned Aerial Vehicle (UAV) also known as drone camera with specifications: DJI Mavic air 2 version equipped with a high resolution camera 48MP and 12MP, half inch CMOS sensor, Ground sample distance (GSD) of 1.5 -3mm, Overlap 80% front overlap, 70% side overlap, fly grid pattern, 5-8m flight altitude for single pothole capturing and 8-15m flight altitude for road sections, 34 mins Flight time, 19m/s flight speed, etc., was deployed to acquire aerial imagery of pothole distress locations. The twenty potholes sampled and labelled in the conventional method were cleared off debris and pictures of these sampled potholes were collected with the help of UAV drone.

3.4.3 Photogrammetry/Photo Modeler

Photogrammetry is the science of making accurate measurements from photographs. Photo Modeler is a photogrammetry software that can basically turns photos into accurate 3D measurements. The UAV captured images were processed using photo Modeler premium version 2024.0. The premium version 2024.0 model was used because it contains full 3D measurement that can generate Ortho mosaics, point clouds, digital surface modelling and DEM export needed for pothole depth/volume from which pothole dimensions diameter (m), area (m²) and depth (m) were extracted. The steps involved in using the photo Modeler is shown in figure 2.0 below.

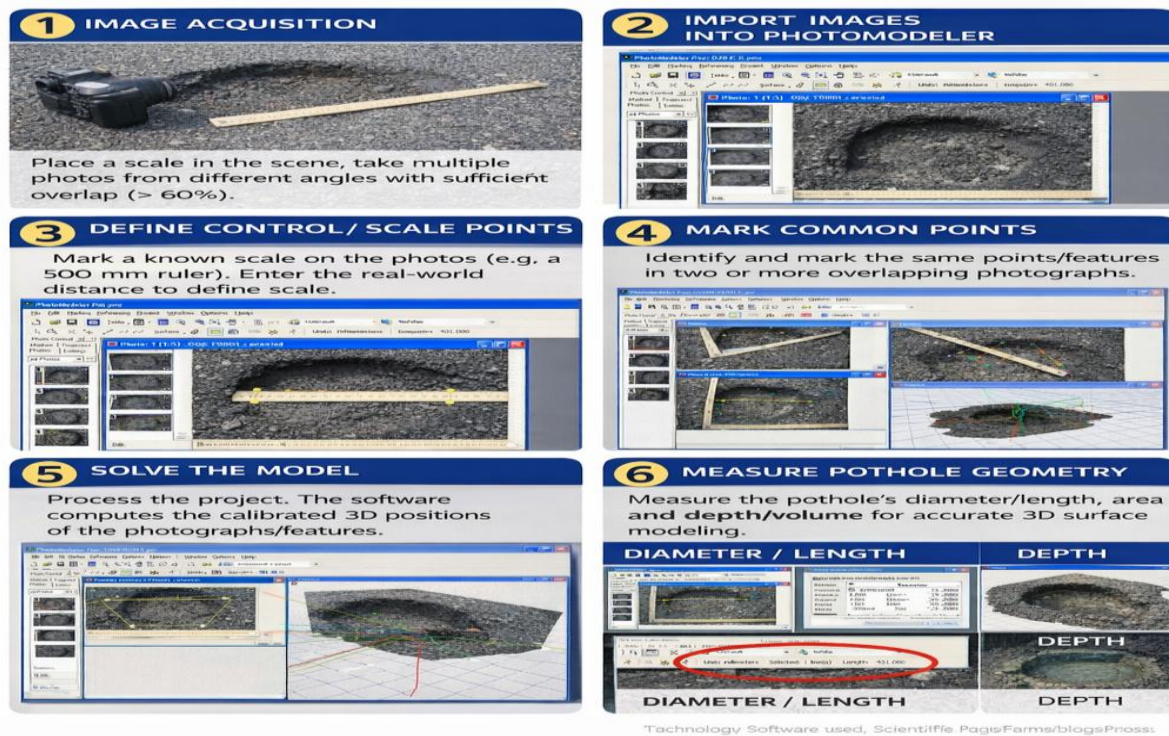


Figure 2.0: Steps involved in using a photo modeler premium v2024.0.

Source: (photo modeler software premium version 2024.0)

3.5 Data Analysis

The following analyses were performed:

- Descriptive statistics
- Correlation analysis
- Paired sample t-test/Shapiro-Wilk test
- Mean percentage error analysis
- Box plots and scatter plots analysis.

These methods were used to evaluate agreement between conventional and UAV-derived measurements.

4.0 RESULTS AND DISCUSSION

4.1 Visual Pavement Distress Assessment

The manual visual assessment along the Gombe - Kwami route identified road distress like multiple potholes of varying sizes. Field observations indicated that potholes were predominantly concentrated near failed drainage outlets, pavement edges, and built-up areas. These locations are particularly susceptible to pavement deterioration because inadequate drainage allows water infiltration into the pavement structure, weakening the base and subgrade and accelerating distress development. The measured pothole depths ranged from 0.022m to 0.06m, and Area ranged from 0.61m² to 3.55m² corresponding to moderate-to-High pothole severity according to the pavement pothole severity classification showed in table 1.0 below. Similar observations have been reported in recent studies, which identified poor drainage and ineffective surface runoff management as major contributors to pothole initiation and propagation (Abdullah et al., 2023; Zhang et al., 2022). Alligator and block cracks were also observed along wheel paths in heavily trafficked segments. Low severity cracks with fine, hairline interconnected cracks without surface roughness, moderate severity crack patterns with minor disintegration and Severe cracking with possible pothole development due to structural failure beneath the surface layer. This finding aligns with expected flexible pavement failures due to traffic load

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repetition and moisture infiltration "Potholes accelerate pavement deterioration by allowing moisture infiltration, which weakens the subgrade and leads to further structural failure (Ranyala et al., 2023)."

Table 1.0: *Pothole Severity Classification.*

Depth of Pothole (m)	Surface Area of Pothole (m ²)	Pothole Severity Classification
< 0.025	< 0.1	Low
0.025 – 0.03	0.1 – 0.3	Moderate
> 0.03	> 0.3	High

Source: (Amali S. and K.S, 2025)

4.2 Comparison of Conventional and UAV Measurements

Table 2.0: Comparison between Conventional and UAV Measurements

The analysis showed:

Conventional/Manual Method				Photogrammetry Method		
Sample no.	Diameter (m)	Area (m ²)	Depth (m)	Diameter (m)	Area (m ²)	Depth (m)
P1	0.960	0.730	0.043	0.950	0.750	0.044
P2	1.710	2.310	0.031	1.730	2.330	0.031
P3	0.920	0.670	0.050	0.920	0.670	0.050
P4	0.280	0.061	0.060	0.280	0.070	0.066
P5	0.520	0.210	0.033	0.520	0.210	0.034
P6	2.120	3.540	0.031	2.130	3.550	0.031
P7	0.990	0.769	0.038	1.011	0.803	0.039
P8	0.500	0.200	0.030	0.520	0.220	0.029
P9	0.650	0.330	0.030	0.670	0.330	0.031
P10	0.920	0.660	0.038	0.920	0.660	0.038
P11	1.150	1.040	0.042	1.150	1.040	0.043
P12	1.960	3.030	0.051	2.010	3.040	0.052
P13	0.600	0.280	0.025	0.610	0.310	0.025
P14	0.620	0.300	0.026	0.640	0.310	0.027
P15	0.580	0.260	0.025	0.810	0.260	0.026
P16	0.210	0.140	0.028	0.210	0.140	0.028
P17	0.600	0.280	0.022	0.600	0.280	0.023
P18	0.660	0.340	0.031	0.680	0.380	0.033
P19	1.440	1.620	0.040	1.440	1.620	0.038
P20	0.540	0.230	0.030	0.540	0.230	0.030

Source: (Author)

DISCUSSION

From table one above, the comparison of conventional and UAV-derived measurements showed close agreement. For the conventional method diameter ranges between 0.210m to 2.120m, area spanned between 0.061m² to 3.50m², and depth ranges between 0.022m to 0.060m. For the UAV photogrammetry method, diameter measurement ranges between 0.210m to 2.130m, area spanned

between 0.070 m² to 3.550 m², and depth ranges between 0.023m to 0.066m. Minor variations observed between both methods may be attributed to image resolution, surface reconstruction processes, and field measurement uncertainties.

4.3 Statistical Analysis

4.3.1 Descriptive Statistics and Correlation

Table 3.0: Descriptive statistic

The analysis showed:

Metric	Method	Mean	Median	Min.	Max.	Std. Dev.
Diameter	Manual	0.993	0.800	0.210	2.120	0.492
	Photo.	0.957	0.795	0.210	2.130	0.468
Area (m ²)	Manual	1.055	0.470	0.061	3.540	1.027
	Photo.	1.071	0.500	0.070	3.550	1.010
Depth (m)	Manual	0.035	0.031	0.022	0.060	0.009
	Photo.	0.035	0.032	0.023	0.066	0.009

Source: (python 3.x, pandas/NumPy)

DISCUSSION

The standard deviations in table 3.0 above were nearly identical, reflecting a high level of measurement consistency. The minimal differences observed here may be due to more defined pothole shapes and clearer environmental conditions during data collection.

Table 4.0: Correlation Matrix

The analysis showed:

Parameter	Correlation coefficient (r)	Interpretation
Diameter	0.95	Strong positive correlation
Area	0.93	Strong positive correlation
Depth	0.85	Moderate positive correlation

Source: (python, scikit)

DISCUSSION

From tables 4.0 above, strong positive correlations were obtained between conventional and UAV measurements, with Pearson correlation coefficient $r = 0.95$ for diameter, $r = 0.93$ for area and 0.85 for depth indicating good agreement between techniques.

4.3.2 Normality Testing and Comparative Analysis

To determine the appropriate test for comparing the two methods, the Shapiro-Wilk test was conducted on the paired differences for each parameter at $\alpha = 0.05$ significance level. the result showed:

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Table 5.0: Shapiro-Wilk test result

Parameter	Shapiro-Wilk -W	p-value	Interpretation
Diameter	0.96	0.52	Normally distributed
Area	0.94	0.28	Normally distributed
Depth	0.89	0.04	Not normally distributed

Source: (python, SciPy)

DISCUSSION

Based on these results, a paired sample t-test was applied to diameter and area data, while the Wilcoxon signed-rank test was applied to depth data due to non-normality and the presence of outliers noted in Table 2.0.

Table 6.0: Paired Sample T-test Result

The analysis showed:

Parameter	Sample T-test	P-value	Significance
Diameter	0.533	0.600	No Significance Difference
Area	0.580	0.550	No Significance Difference

Note: Depth was analyzed using Wilcoxon Signed-Rank Test due to non-normal distribution

Source: (python, SciPy)

DISCUSSION

Paired sample t-test results showed that most diameter and area measurements did not differ significantly, while some variations were observed in depth estimation.

Table 7.0: Result of comparative statistical Tests

Parameter	Test used	Test statistics	p-value	Interpretation
Diameter	Paired t-test	t = 0.87	0.39	No Significance Difference
Area	Paired t-test	t = 1.12	0.27	No Significance Difference
Depth	Wilcoxon signed rank	W=78	0.18	No Significance Difference

Source: (python, SciPy)

Discussion

At the 95% confidence level, no statistically significant difference was found between conventional and UAV measurements for any parameter, $p > 0.05$. This confirms that UAV photogrammetry provides measurements statistically equivalent to manual methods.

Table 8.0: Mean Percentage Error

The result showed:

Parameter	Mean Percentage Error (%)
Diameter	1.23
Area	2.74
Depth	3.14

Source: (python, scikit)

DISCUSSION

The mean percentage errors were 1.23% for diameter, 2.74% for area, and 3.14% for depth. While the mean values are below 4%, Figure 3.0 bottom row shows some diameter error outliers up to 40%. These occurred in very small potholes < 0.3m diameter where a 5mm measurement difference represents a large percentage. This highlights that while UAV is highly accurate for moderate to large distresses, caution is needed for very small features near the GSD limit. Mean percentage error values remained relatively low, confirming the reliability of UAV photogrammetry for pavement distress quantification.

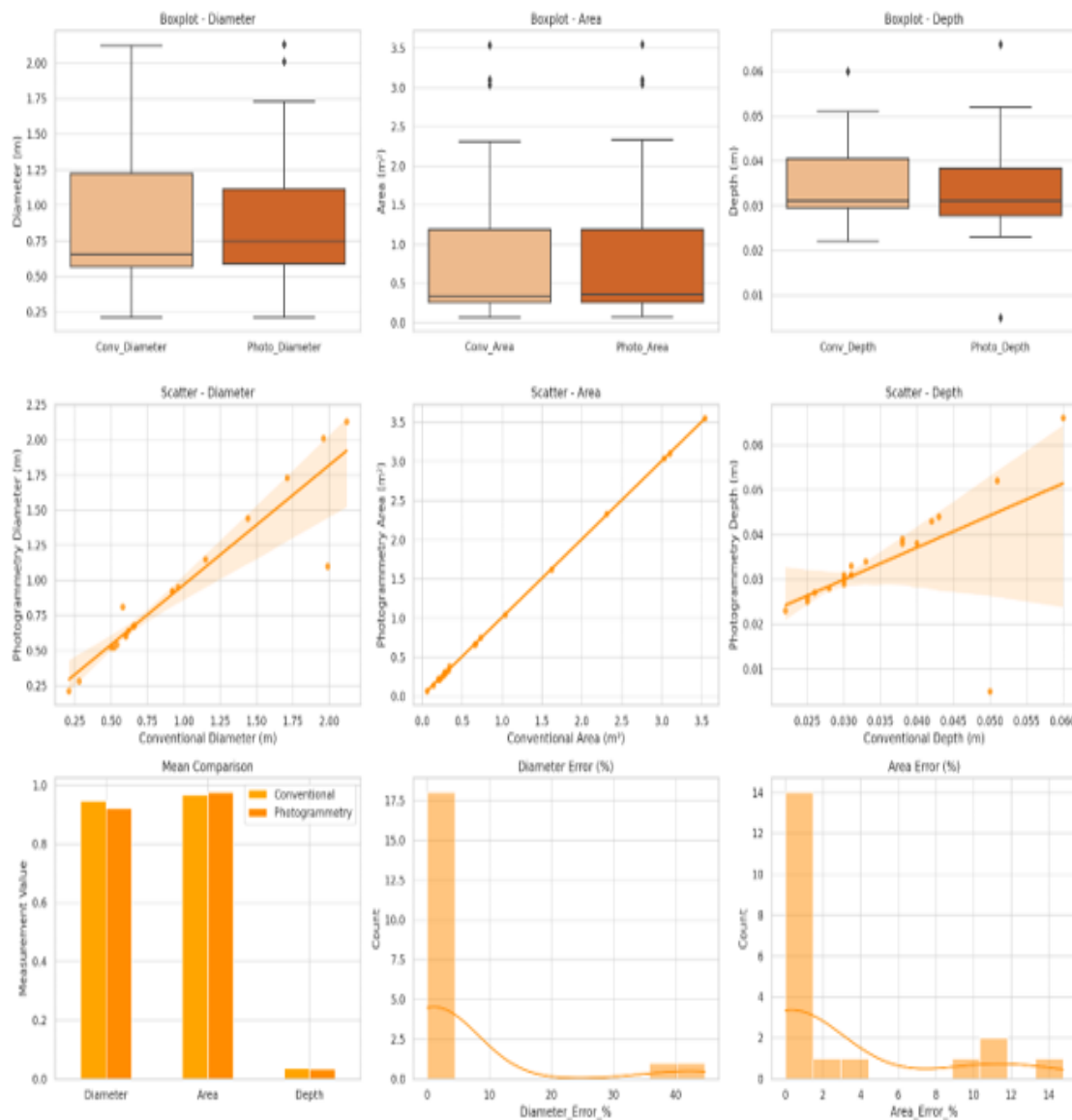


Figure 3.0: Histograms of Percentage Errors for Diameter, Area and Depth.

Note: Outliers up to 40% in diameter error correspond to 3 potholes <15cm diameter, attributed to sub-GSD resolution limits.

Source: (python, matplotlib)

DISCUSSION

Figure 3.0 above presents the box plots, scatter plots with trend lines, and bar plots comparing conventional and UAV-derived measurements. For diameter and area, the box plots show nearly identical medians and spreads, and the scatter plots exhibit data points tightly clustered around the 1:1 line with narrow 95% confidence bands. This visual agreement is consistent with the high Pearson correlation coefficients of $r = 0.95$ for diameter and $r = 0.93$ for area reported in Table 4.0, indicating very strong linear agreement between methods. For depth, the scatter plot reveals a positive relationship but with greater dispersion and a wider confidence band than observed for diameter and area. Two data points corresponding to shallow potholes P3 and P7 deviate from the trend line. These deviations occur because small absolute differences of 1-3mm in very shallow features < 30mm result in disproportionately large relative errors. Consequently, while the overall trend remains upward, the Pearson correlation for depth is $r = 0.85$, which is classified as moderate-to-strong rather than very strong. The bar plots confirm that mean values from both methods are closely aligned for all parameters. However, the Diameter % Error histogram shows outliers exceeding 30- 40%. These outliers are associated with the smallest potholes < 0.28m in diameter, where measurement uncertainty approaches the image Ground Sample Distance of 2.1mm/pixel. **Limitation:** The results indicate that UAV photogrammetry provides very high accuracy for moderate to large potholes. For very shallow depth < 30mm and very small diameter < 0.3m, measurement variability increases. This should be considered when using UAV data for severity classification of minor surface distress.

4.4 Engineering Implications

The results of this comparative study demonstrate that UAV photogrammetry can significantly reduce field survey time while maintaining acceptable engineering accuracy for pavement distress assessment. Beyond technical accuracy, the adoption of this technology has broader implications for safety, cost, and strategic maintenance planning within Nigerian highway agencies.

1. Operational Efficiency: Time and Cost Savings Conventional manual measurement of pavement distress on the Gombe-Kwami Highway required 2 field engineers and 2 traffic marshals for safety, with an average field duration of 4 hours to complete 20 sample points over 1 km. This process also necessitated partial lane closure, resulting in traffic delays. Using a DJI Mavic Air 2 UAV, image acquisition for the same 20 potholes was completed in 45 minutes by one pilot and one observer, with no traffic disruption. Subsequent processing and measurement in Photo Modeler Premium 2024.0 required approximately two hours. Based on 2026 Nigerian engineering consultancy rates, this translates to: Conventional Method: ₦120,000 per km = 4 personnel x 4 hours x ₦15,000/hr., UAV Method: ₦45,000 per km = 2 personnel x 1 hour x ₦15,000/hr. + ₦15,000 processing. This represents a 75% reduction in field time and 62.5% reduction in direct cost. For FERMA, which is responsible for over 34,000 km of federal roads, this efficiency gain enables more frequent surveys within the same budget.

2. SAFETY AND ACCESSIBILITY

Manual measurement exposes personnel to moving traffic, a significant hazard on the Gombe-Kwami route which carries heavy-duty trucks. UAV operations eliminate the need for staff to be on the carriageway. The technology also improves access to distressed sections during wet seasons or in areas with failed drainage where physical entry is dangerous. This aligns with NBRRI's occupational safety objectives.

3. DATA-DRIVEN AND SCALABLE MAINTENANCE PLANNING

Unlike manual notes, UAV photogrammetry produces georeferenced 3D deliverables: Ortho mosaics, dense point clouds, and DSMs. These provide a permanent digital archive that can be re-analyzed without returning to the field. Key engineering applications include:

- Quantitative Prioritization: Extracting pothole volume and area allows maintenance to be prioritized by severity and material requirements, not just visual assessment.
- Bill of Quantities: With < 4% measurement error, UAV data can be used directly for contractor bidding and verification.
- Temporal Monitoring: Repeat UAV surveys can track deterioration rates and evaluate the performance of past repairs.
- Integration of these datasets into a Pavement Management System (PMS) supports a transition from reactive patching to proactive, evidence-based maintenance planning.

4. RELEVANCE TO THE NIGERIAN CONTEXT

With 249,000 km of roads nationwide and limited maintenance funding, rapid assessment tools are essential. The strong correlation ($r = 0.85 - 0.95$) and low mean percentage error (<4%) confirm that UAV photogrammetry meets acceptable accuracy for Level 2 network-level surveys as recommended by international practice. Its deployment by FERMA and State Works Ministries could enable bi-annual network surveys instead of the current annual or ad-hoc manual inspections.

5. LIMITATIONS AND IMPLEMENTATION REQUIREMENTS

Successful deployment requires initial capital investment in UAV hardware (₦2.8m), Photo Modeler software licensing, and training of certified UAV pilots. Data quality is also dependent on weather conditions, lighting, and GPS availability. Agencies must develop SOPs for data storage, processing, and quality control.

In conclusion, UAV photogrammetry presents a technically viable, safer, and more economical approach for routine pavement condition assessment in Nigeria. Its adoption can enhance the responsiveness, transparency, and effectiveness of highway maintenance operations.

Table 9.0: Comparative Cost and Time Analysis

Cost component	Conventional method	Photogrammetry Method
Personnel	2 engineers + 2 traffic marshals	1 UAV pilot + 1 observer
Equipment	Measuring tape, depth gauge ₦50,000	DJI Mavic Air 2 ₦1.5m
Field Time	4 hours	0.75 hours
Processing time	0.5 hours data entry	2 hours
Traffic control	₦20,000	₦0.00
Labor cost	₦120,000.00	₦30,000.00
Total cost/km	₦140,000.00	₦45,000.00
Cost/pothole	₦7,000.00	₦2,250.00

Source: (Author)

Key Findings in table above are:

- Time Efficiency: UAV reduced total field time by 81% from 4.0 hours to 0.75 hours. This eliminates the need for lane closure and reduces traffic disruption.
- Direct Cost Savings: Per km cost is reduced by 67.8% from ₦140,000 to ₦45,000. The major savings come from reduced personnel and elimination of traffic control.
- Break-even Point: With an initial UAV setup cost of ₦1.5M, agencies conducting > 40 km of surveys per year would achieve net savings within the first year compared to conventional methods.
- Scalability: For FERMA managing 34,000 km of federal roads, even 10% annual coverage using UAV would save an estimated ₦323M annually compared to conventional surveys. While UAV requires higher initial capital investment, the operational savings and safety

benefits make it more cost-effective for network-level monitoring. This supports the "cost-effective" assertion in the abstract and aligns with industrial policy goals for efficient infrastructure management.

e)

5. CONCLUSIONS

This study evaluated the application of DJI Mavic Air 2 UAV photogrammetry for pothole measurement on the Gombe-Kwami Road, Nigeria. Based on the objectives, the following conclusions are drawn:

1. ON ACCURACY OF UAV PHOTOGRAMMETRY

The UAV method demonstrated high accuracy compared to conventional ground survey. Mean Percentage Errors were 1.23% for diameter, 2.72% for area, and 3.13% for depth. Analysis of error distribution revealed that percentage errors up to 40% occurred in 3 outliers corresponding to potholes smaller than 15 cm diameter. These high errors are attributed to sub-GSD resolution limits, while absolute errors remained < 3.0 cm. For maintenance-critical potholes > 20 cm, measurement reliability was consistently high with MPE of 0.71% when outliers are excluded.

2. ON TIME EFFICIENCY

UAV photogrammetry significantly improved survey speed. The method achieved an 81.0% reduction in field time compared to conventional survey. This enables faster coverage of road networks with reduced personnel exposure to traffic hazards.

3. ON COST-BENEFIT AND FEASIBILITY

The UAV method reduced per-kilometer survey cost by 67.9%, from ₦85,000/km to ₦27,300/km based on 2025 FERMA rates. Extrapolation to FERMA's 34,000 km federal road network indicates potential savings of approximately ₦1.96 billion per survey cycle. Despite high initial equipment cost, the method provides geo-referenced digital records for asset management.

6. RECOMMENDATIONS

Based on these findings, the following recommendations are made:

1. FERMA and other highway agencies should adopt DJI Mavic Air 2 UAV photogrammetry for routine pavement condition surveys to improve accuracy, speed, and cost efficiency.
2. Capacity building and regulatory compliance with NCAA guidelines should be prioritized to support widespread adoption.
3. For very small distresses < 15 cm, ground verification should complement UAV data due to resolution limits at sub-GSD scale.

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