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Road Condition Monitoring with Drones and LiDAR in Infrastructure Technology

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Abstract
Effective road condition monitoring is essential for ensuring transportation safety and efficient infrastructure management. Traditional methods are often labor-intensive, time-consuming, and costly. This study investigates the use of drones equipped with Light Detection and Ranging (LiDAR) technology to enhance the accuracy and efficiency of road assessments. The research was conducted in Karawang Regency, West Java, Indonesia, particularly along the Rengasdengklok Arterial Road, a location identified by the local Public Works Department (PUPR) as frequently experiencing damage. The methodology included field surveys, drone-based data acquisition, and post-processing using photogrammetry and LiDAR point clouds to create detailed 3D road surface models. Pavement conditions were then analyzed using the Pavement Condition Index (PCI). The results showed that the road segment was in Level 2 (fair condition), aligning with previous visual assessments by the PUPR. Validation against traditional survey methods indicated an accuracy rate of 93.7%. This study demonstrates that the integration of drone and LiDAR technologies enables faster, safer, and more comprehensive road monitoring, especially in hard-to-reach areas. The approach supports data-driven maintenance planning and provides a valuable tool for local governments to improve infrastructure monitoring practices. The results highlight the potential for adopting this innovative method in broader applications, including integration with AI for automated damage detection and predictive maintenance.

INTRODUCTION

Road condition monitoring is a crucial aspect of transportation infrastructure management aimed at ensuring the safety and operational efficiency of road networks. Poor road quality can lead to accidents, increased vehicle repair costs, and longer travel times (Wang et al., 2020). Therefore, regular road condition monitoring is necessary to detect and address damages early. Traditional road monitoring methods, such as visual inspections and the use of specialized monitoring vehicles, have several limitations, including high costs, long time requirements, and restricted accessibility to certain areas (Chang et al., 2018). Technological advancements have driven the development of more efficient and accurate solutions, one of which is the use of drones and Light Detection and Ranging (LiDAR) in road condition monitoring (Astor et al., 2023).

Drones, with their high flying and maneuvering capabilities, can reach hard-to-access areas and collect data in a relatively short time (Hammad et al., 2019). Meanwhile, LiDAR technology enables the collection of highly detailed data about road surface conditions, including the identification of cracks, surface subsidence, and structural deformations (Riveiro et al., 2016) (Nappo et al., 2021). The combination of these two technologies offers significant potential for improving the efficiency and accuracy of road monitoring.

This study aims to explore the application of drones equipped with LiDAR sensors in road condition monitoring. The main focus of this research is to assess the accuracy and efficiency of this technology in identifying road damage compared to traditional methods. Additionally, this study will discuss the potential cost savings and improved transportation safety that can be achieved through the adoption of this construction technology.

RESEARCH METHODS

Data Collection

The data collection stage commences with field surveys and documentation to record road conditions. The scope of this research was carried out in a city in Indonesia, especially in Karawang Regency, West Java Province, Indonesia. The location was determined by researchers based on recommendations from the government. The public works and public housing department (Dinas Pekerjaan Umum dan Perumahan Rakyat or PUPR Karawang) state that the road conditions that often experience damage are in coastal areas. The representative location points were determined Arterial Road Rengasdengklok St., South Dengklok, Karawang, Indonesia (-6.158086, 107.298547).

Road Condition Survey with Drone and LiDAR

A road condition survey using drones and LiDAR technology provides an efficient and accurate method for assessing road infrastructure (Ali et al., 2023). The approach involves capturing high-resolution data through drone flights equipped with cameras and LiDAR sensors, which generate detailed 3D maps of the road surface (Kerle et al., 2019). Pre-flight planning ensures optimal coverage, and data is collected via photogrammetry and LiDAR to assess cracks, potholes, and structural deformations (Tong & Kong, 2021). Post-processing integrates visual and depth data, aligning LiDAR point clouds with images to create comprehensive 3D models. These models enable analysis of pavement conditions, including wear and tear measurement, using indices like the Pavement Condition Index (PCI) (Shahin & Walther, 1990). Validation is done by comparing the results with traditional ground surveys to ensure accuracy. The collected georeferenced data is then used to create detailed road condition maps, supporting predictive maintenance models. This methodology offers a proactive approach to road maintenance and infrastructure management, and future work could involve AI integration for automated damage detection.

Classifying Damages

Classifying road damages involves identifying and categorizing various types of defects and damages present on the road surface, classification of road damage as stated in Table 1:

Table 1. Classification of Road Damages

Cracks	Potholes	Rutting	Surface Distress	Deformations	Other Damage
Longitudinal	Potholes	Wheel Path Rutting	Raveling	Depressions	Crushed Aggregate
Transverse		Shoving	Polishing	Bumps and Heaves	Joint or Crack Seal Failure
Alligator			Weathering		
Block			Bleeding		
Edge					

1. Pavement Condition Index

   The Pavement Condition Index (PCI) is a numerical system used to assess road pavement conditions based on damage type, severity, and extent (ASTM-D6433-99, 2007). Stages used to analyze PCI, First calculate the level of damage which is the percentage of the amount of a type of damage to the damage number of slabs in a sample unit:

$$D = \frac{A_d}{A_s} \quad (1)$$

Ad = total types of damage for each level of damage

As = number of slabs in the sample unit.

PCI analysis begins by calculating the damage level, which is the percentage of each distress type relative to the number of damaged slabs in a sample unit. This helps quantify the spread of each damage type. The Total Deduct Value (TDV) is the sum of all individual deduct values for each type and level of distress in a sample unit. It reflects the total observed damage. Before calculating the Corrected Deduct Value (CDV), each deduct value must be verified to ensure accuracy. The value of m can be calculated using the equation:

$$m=1+\frac{9}{98}(100-HDVi) \quad (2)$$

m = correction value for deduct value

HDVi = largest deduct value in one sample unit.

Based on the curve of the relationship between the TDV value and the CDV value with selection. The curve of the curve corresponds to the amount of the deduct value which has a value greater than 2 (also called the q value). If the CDV value is known, then the PCI value for each unit samples can be calculated using the equation:

$$PCI = 100 - CDV \quad (3)$$

CDV is subtracted from 100 to get the PCI, which reflects pavement condition. A higher CDV means a lower PCI, indicating more damage and greater repair needs. This method helps engineers plan repairs, manage resources, and extend pavement life.

2. Identifying the level of damage

   The process of determining how severe or extensive the damage is on an object or infrastructure. In the context of roads, it means evaluating how much damage the road surface or structure has sustained (Pinatt et al., 2020). This process involves observation and analysis of the road's physical condition to understand the extent of damage that has occurred (Gertler et al., 2024). Methods for identifying the level of road damage based on severity and extent, as stated in Table 2.

Table 2. Level of Road Damage

Level 1 Good Condition	**Level 2** Fair Condition	**Level 3** Minor Damage	**Level 4** Severe Damage
The road is in optimal condition, with a smooth surface free from significant cracks, potholes, or deformations. Drainage systems function effectively, and road markings and signs are clearly visible. The road offers a safe and comfortable driving experience at normal speeds.	The road remains safe for use but exhibits minor cracks, small potholes, or deformations that do not significantly impact driving comfort. Road markings may begin to fade, and drainage systems are still operational, though minor water pooling might occur.	The road shows more noticeable signs of wear, such as larger potholes, widening cracks, or surface deformations that could affect driving comfort and safety. Some sections may require repairs, but the road remains passable at reduced speeds.	The road is in a highly deteriorated state, with severe damage such as large potholes, extensive cracking, major deformations, or missing surface sections. The road is unsafe and difficult to traverse, requiring immediate repairs to restore its functionality.

3. Decision-making in maintenance and repair planning

   According to Minister of Public Works Regulation Permen PUPR 13/PRT/M/2011 (Menteri Pekerjaan Umum, 2011) concerning procedures for road maintenance and surveillance, road maintenance are divided into:

   a. Routine Repairs

      Routine maintenance is maintenance work on road assets carried out every year. Preventive work is defined as work done to limit the type, level, distribution damage, and delay further damage. Apart from that, reactive work is road maintenance work that is carried out to repair any damage that has occurred to the pavement the road is beyond the ability of observation so that the road conditions can be returned to the condition as planned.

   b. Backlog and Minor Works

      Which is work where the quantity of work exceeds the norm, the quantity of routine maintenance work specified and the funds required to repair both sections of the road pavement or non-pavement whose value is greater than the cost of routine road maintenance to maintain the condition of internal roads good and medium levels according to plan.

   c. Holding Treatment

      Road handling work on segments roads that are in a condition of light damage or heavy damage postponement of periodic maintenance or rehabilitation work.

   d. Periodic Maintenance

      Periodic Maintenance is a type of road maintenance conducted periodically to keep the road in good condition and prevent further deterioration. It involves routine maintenance actions carried out at regular intervals.

   e. Special Maintenance

      Type of road maintenance performed to address specific issues or extraordinary conditions that require extra attention beyond routine maintenance. These special repairs are usually carried out outside of the periodic maintenance schedule.

f. Rehabilitations

Rehabilitation is a more extensive and comprehensive type of road repair than routine maintenance. It involves the restoration or structural renewal of roads that have experienced significant damage or have reached the end of their service life.

RESULTS AND DISCUSSION

The main purpose of road condition surveys is to identify and record data on damage to pavement and non-pavement (road shoulders, channels, slopes and road equipment). To meet the objectives of the condition survey, The following is a list of data that needs to be recorded when carrying out a condition survey roads are: location of road segments, condition of asphalt road damage, condition damage to non-asphalt roads, condition of damage to concrete roads, condition left and right road equipment, slope conditions, channel conditions, conditions road shoulder, sidewalk condition. In road condition surveys, data recording is carried out at certain intervals, generally every 100 or 200 meters.

Road conditions in Indonesia often experience decline, one of which is caused by weather factors where Indonesia has two seasons, rainy and summer. During the summer, the pores of the road pavement will stretch, but during the rainy season, rainwater will enter the pores of the asphalt and cause a lot of damage. Meanwhile, the majority of existing road pavement is asphalt. Significant changes in temperature can cause the pavement layer to expand and contract, which can result in cracks on the road surface. This can also occur in types of damage to concrete pavement, or pavement that is a combination of asphalt and concrete.

Reciprocally the conditions on the roads in Karawang, so this results in continuous repairs and causes increased expenditure on the repair budget. When interviews were conducted with the government, a road condition survey was carried out but it could not be carried out on a massive scale due to their limited human resources. So one of the most sophisticated solutions is to use a combination of drones and LiDAR. Image processing techniques like segmentation and surface detection can be used to identify areas in need of repair.

Figure 1. Tool requirements for Drone and LiDAR surveys

Table 3. Specification of Drone LiDAR

Specification	
Product Name	Zenmuse L1
Dimensions	152×110×169 mm
Weight	930±10 g
Power	Typical: 30 W; Max: 60 W
Supported Aircraft	Matrice 300 RTK
Detection Range	450 m @ 80% reflectivity, 0 klx ; 190 m @ 10% reflectivity, 100 klx
Point Rate	Single return: max. 240,000 pts/s ; Multiple return: max. 480,000 pts/s
System Accuracy (RMS 1σ)1	Horizontal: 10 cm @ 50 m; Vertical: 5 cm @ 50 m
Real-time Point Cloud Coloring Modes	Reflectivity, Height, Distance, RGB
Lidar Ranging Accuracy (RMS 1σ)2	3 cm @ 100 m
Operating Temperature Range	-20° to 50° C (-4° to 122° F)
Raw Data Storage	Photo/IMU/Point cloud data storage/GNSS/Calibration files

Source: terra-drone.co.id

The implementation of a road inventory survey requires at least 4 personnel, consisting of one team leader and three co-pilot. In the operation of drones, the roles of the team leader and the co-pilot are crucial to ensure mission success and safety, their responsibilities:

1. Team Leader / Pilot
   The team leader or main pilot for LiDAR and mapping is the primary decision-maker and coordinator for drone operations. This role requires a combination of strategic thinking, technical knowledge, and leadership skills.
2. Co- Pilot
   The co-pilot supports the team leader and plays an essential role in the successful execution of drone missions. Furthermore, they assisting pilot, GPS measurement, observe the drone clearance, and maintain checklist for the whole operation.

Table 4. Survey Methods using LiDAR and Drones

Process	Activity	Task
Preparation and Planning	Preliminary Study	Collect data about the area to be surveyed, including topographic maps, weather data, and other information
	Licensing	Ensure all necessary permits and regulations have been met
	Flight Planning	Use mission planning software to determine flight path, altitude, speed, and survey area coverage
Equipment Calibration and Testing	Sensor Calibration	Ensures LiDAR sensors and RGB cameras are properly calibrated
	DRTK Testing	Ensure the Differential Real-Time Kinematic (DRTK) system functions properly to increase position accuracy
Flight and Data Retrieval	Field Setup	Set up a DRTK base station in a stable, unobstructed location
	Drone Flight	Operate the drone according to the created flight plan, ensuring that all flight paths are covered and data is recorded
	Monitoring	Monitor drone flights in real-time to ensure safety and data quality
	Data Transfer	Move data obtained from the drone to the workstation for further processing
Data Processing	Pre-Processing	Filtering raw data to remove noise and errors
	Georeferencing	Uses DRTK data to improve position accuracy from LiDAR data and images
Analysis and Interpretation	Classification and Segmentation	Classifies LiDAR data into categories such as land surface, vegetation, and buildings
	Model Creation	Create Digital Elevation Models (DEM), Digital Surface Models (DSM), and other 3D models based on classified data

In this study, drone LiDAR and drone imagery are employed to assess road damage conditions. The approach involves utilizing image recognition tools on raster orthophoto mosaics generated from drone imagery. These tools are designed to identify and classify coordinate points of road damage based on predefined categories, providing a detailed spatial representation of the damaged areas. Following the identification process, the digitization of these damage points is carried out to capture their geometric properties. This step converts the classified points into a digital format that accurately represents the location and shape of each damaged instance. This digitized data is crucial for understanding the extent and distribution of road damage.

The final stage integrates the digitized damage data with vector data from the digital terrain model produced by LiDAR. This combination provides vertical information for each damage point, allowing for a thorough analysis of both the spatial and elevation aspects of the road damage. The integrated data facilitates a detailed evaluation of the damage and supports effective planning for restoration and repair efforts. This study was conducted on a 1 km stretch of the Rengasdengklok highway in Karawang. Attached below is a map showing the location of the research area.

Data Analysis Results

The analysis of road conditions was carried out using data collected from the drone LiDAR and imagery surveys. The processed data provides a comprehensive assessment of the road surface, allowing for detailed identification of various types of damage. The following sections present the key findings from the feature extraction process and the Pavement Condition Index (PCI) analysis, which were used to evaluate the overall condition of the road segment.

Figure 2. Rengasdengklok St. (-6.158086, 107.298547)

Feature extraction was performed using visual digitization on the orthophoto mosaic data to classify road damage based on predefined categories. In this area, several classes were identified, including Crack, Potholes, Rutting, and Other Damages. Below are the results of the feature extraction process. Based on the feature extraction results, a total of 1200 instances of road damage were identified, with 1182 of these find.

Figure 3. Rengasdengklok St., The results of the feature extraction process

After knowing the types and amount of damage in each slab or segment from the feature extraction process. Then the Pavement Condition Index analysis was carried out using the equations in (1) to (3), the results obtained were:

Table 5. PCI Analysis Results and Damage Level

Station	Crack	Potholes	Rutting	Surface Distress	Other Damages	Total Damages	D	DV	Crack	Potholes	Rutting	Surface Distress	Other Damages	TDV	CDV	PCI	Level of Damage
0+000 - 0+025	29	0	0	0	1	30	2,54%	6,50	66,00	0,00	0,00	0,00	22,00	88	64,00	36	3
0+025 - 0+050	68	0	0	0	1	69	5,84%	14,94	38,00	0,00	0,00	0,00	15,00	53	40,00	60	1
0+050 - 0+075	86	1	0	0	0	87	7,36%	18,84	42,00	62,00	0,00	0,00	0,00	104	72,00	28	3
0+075 - 0+100	46	0	0	0	0	46	3,89%	9,96	43,00	0,00	0,00	0,00	0,00	43	33,00	67	1
0+100 - 0+125	77	2	0	0	0	79	6,68%	17,11	57,00	73,00	0,00	0,00	0,00	130	86,00	14	3
0+125 - 0+150	77	1	0	0	1	79	6,68%	17,11	56,00	35,00	0,00	0,00	19,00	110	79,00	21	3
0+150 - 0+175	96	0	0	0	0	96	8,12%	20,79	57,00	0,00	0,00	0,00	0,00	57	41,00	59	1
0+175 - 0+200	139	0	0	0	0	139	11,76%	30,10	58,00	0,00	0,00	0,00	0,00	58	42	58	1
0+200 - 0+225	209	4	0	0	0	213	18,02%	46,12	64,00	76,00	0,00	0,00	0,00	140	90	10	4
0+225 - 0+250	65	0	0	0	0	65	5,50%	14,08	54,00	0,00	0,00	0,00	0,00	54	40,00	60	1
0+250 - 0+275	77	12	0	0	1	90	7,61%	19,49	34,00	84,00	0,00	0,00	22,00	140	90,00	10	4
0+275 - 0+300	0	9	12	3	2	26	2,20%	5,63	0,00	65,00	50,00	23,00	28,00	166	97,00	3	4
0+300 - 0+325	0	7	6	2	1	16	1,35%	3,46	0,00	65,00	31,00	18,00	20,00	134	87,00	13	3
0+325 - 0+350	0	0	13	6	3	22	1,86%	4,76	0,00	0,00	46,00	30,00	23,00	99	69,00	31	3
0+350 - 0+375	0	0	0	2	2	4	0,34%	0,87	0,00	0,00	0,00	8,00	16,00	24	17,00	83	1
0+375 - 0+400	0	0	12	0	4	16	1,35%	3,46	0,00	0,00	37,00	0,00	21,00	58	43,00	57	1
0+400 - 0+425	0	0	7	0	0	7	0,59%	1,52	0,00	0,00	34,00	0,00	0,00	34	23,00	77	1
0+425 - 0+450	0	0	3	3	4	10	0,85%	2,17	0,00	0,00	18,00	12,00	22,00	52	40,00	60	1
0+450 - 0+475	0	0	16	3	1	20	1,69%	4,33	0,00	0,00	29,00	13,00	13,00	55	41,00	59	1
0+475 - 0+500	0	0	10	6	0	16	1,35%	3,46	0,00	0,00	35,00	20,00	0,00	55	41,00	59	1
0+500 - 0+525	0	0	3	4	0	7	0,59%	1,52	0,00	0,00	27,00	22,00	0,00	49	37,00	63	1
0+525 - 0+550	0	2	0	5	0	7	0,59%	1,52	0,00	33,00	0,00	16,00	0,00	49	37,00	63	1
0+550 - 0+575	0	0	5	3	0	8	0,68%	1,73	0,00	0,00	32,00	24,00	0,00	56	42,00	58	1
0+575 - 0+600	0	0	5	3	2	10	0,85%	2,17	0,00	0,00	26,00	9,00	18,00	53	41,00	59	1
0+600 - 0+625	0	1	3	3	1	8	0,68%	1,73	0,00	30,00	9,00	24,00	10,00	73	52,00	48	2
0+625 - 0+646	0	0	8	3	1	12	1,02%	2,60	0,00	0,00	38,00	24,00	5,00	67	50,00	50	2
Total	**969**	**39**	**103**	**46**	**25**	**1182**			**100,00**	**4,02**	**10,63**	**4,75**	**2,58**				

The results of the drone survey and feature extraction process are in accordance with the understanding that as the PCI value from the analysis results increases, the condition of the road pavement will get better, as depicted in figure 4.

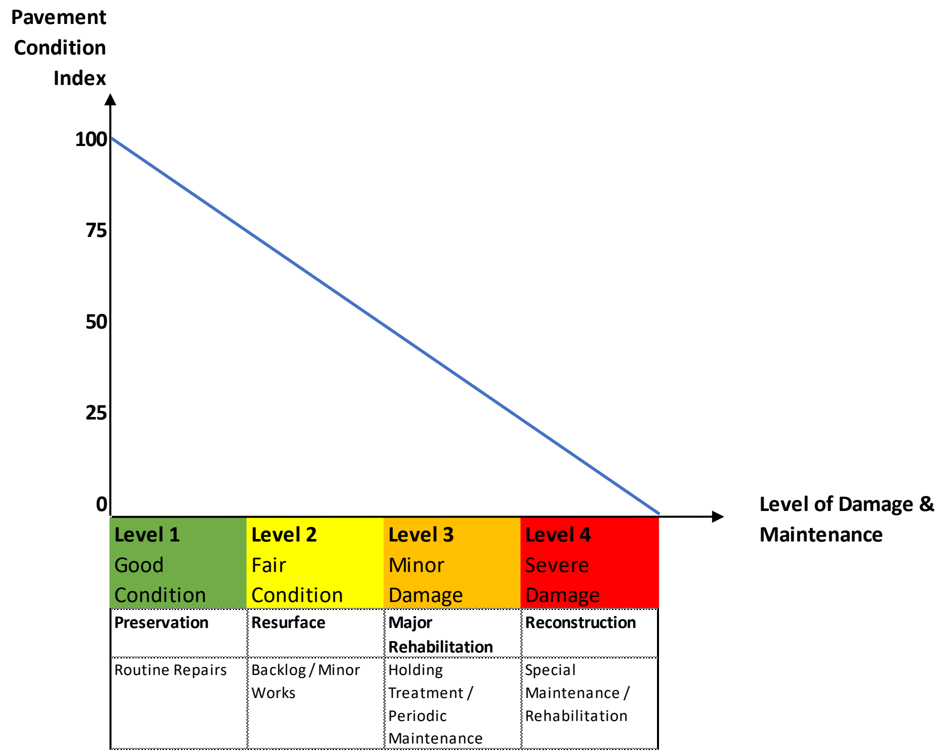

Figure 4. PCI Value with Level of Damage & Maintenance

Based on the results of the analysis, the results show that the Rengasdengklok road section has a road condition at Level 2, which means it is in fair condition. This is in accordance with the results of a survey conducted by the Karawang PUPR Road Department. The survey by the department was carried out using a visual method before the research survey activity, then using the same steps it was found that the Rengasdengklok Road section was at level 2 so it was necessary to repair the pavement layer or resurface. In this way, the use of Drone and LiDAR technology can be used as an option for monitoring road conditions.

CONCLUSION

The integration of drones and LiDAR technology represents a significant advancement in road condition monitoring, offering numerous benefits over traditional methods. By providing high-precision data, enhancing safety, and reducing costs, these technologies are set to play a crucial role in the future of road construction and maintenance:

1. The use of LiDAR installed on drones allows data collection with a high level of accuracy, identifies road damage to a detailed level and makes the classification process easier. This provides much more accurate results than visual methods.
2. Create an innovative solution for monitoring road conditions where the data obtained can easily be subjected to PCI analysis.
3. LiDAR drones are able to monitor road conditions in a shorter time than visual methods, which usually require more time and labor. By monitoring road conditions more effectively and efficiently, this technology has the potential to extend the life of road infrastructure, reduce long-term maintenance costs, and increase safety for road users.

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