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TLS IMPLEMENTATION FOR URBAN ROAD EVALUATION

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ABSTRACT: This study explores the use of Terrestrial Laser Scanning (TLS) technology, specifically the XGRIDS Lixel L2, for urban road evaluation. Traditional methods, such as manual surveys, and newer technologies, like drones, often face challenges in areas with dense vegetation or rough terrain. TLS, which combines LiDAR and SLAM technologies, offers a portable and precise solution for collecting 3D data, making it suitable for complex environments. In this study, both manual and TLS-based surveys were used to evaluate road gradient, width, and pavement condition. The findings confirm that TLS provides high accuracy, achieving 100% for Pavement Condition Index (PCI), 94.15% for road gradient, and 95.86% for road width. Notably, this study identifies ravelling damage, which was previously unreported, and demonstrates that TLS can detect small potholes, reinforcing the high quality of the generated 3D models. While TLS effectively overcomes UAV LiDAR's limitations in vegetated areas, tree shadows in real-color mode may obscure certain road damages, which can be mitigated by using RGB mode. Despite its higher cost compared to manual methods, TLS offers detailed and reliable road condition assessments, particularly in complex terrains. Future research should focus on optimizing TLS data acquisition, reducing costs, and integrating Machine Learning (ML) to enhance automatic damage detection and classification, further improving road evaluation processes.

Keywords: Terrestrial Laser Scanner, Road Evaluation, Pavement Condition Index, Road Geometry, Urban Road.

1. INTRODUCTION

Recent technological advancements have significantly influenced various fields, including civil engineering [1–4]. Innovations such as Building Information Modeling (BIM), renewable materials, and drone-based mapping have revolutionized infrastructure development and management [5–9]. In particular, the use of drones for geospatial data collection in road condition monitoring has proven beneficial, offering advantages such as reduced survey time, lower costs, and enhanced safety [10–16].

Despite these benefits, drone-based surveys face challenges such as limited penetration through roadside vegetation [17] and flight restrictions. These constraints become more pronounced in urban and hilly areas, where obstacles such as trees and high traffic interfere with shooting and flight safety.

To address this limitation, Terrestrial Laser Scanning (TLS) technology emerged as an alternative. TLS is a high-precision measurement tool that utilizes laser scanning to capture dense 3D point cloud data, enabling accurate representation of object conditions in short time [18–23]. TLS has been widely used in various fields, one of which is monitoring road conditions. As a result, the data produced is accurate and can represent the condition of the pavement [24–26]. Both TLS and UAV have almost the same accuracy under ideal conditions [27]. While previous studies have explored the use of TLS in road surface mapping, most have used static or tripod-based scanners. Furthermore, existing studies have limitations in detecting subtle surface defects.

Among the types of TLS, Handheld Terrestrial Laser Scanners (HTLS) have recently gained traction due to their portability and flexibility. Equipped with Simultaneous Localization and Mapping (SLAM) technology and LIDAR sensors, HTLS facilitates rapid and user-friendly data acquisition [28]. While SLAM-based scanners have been successfully employed in mining and bridge structure digitization [29,30], their application in monitoring road conditions remains underexplored.

HTLS shows strong potential for road condition evaluation, especially in areas where manual methods and UAV LiDAR are limited, such as roads with high traffic, dense vegetation, or complex geometry. Manual surveys in these conditions are time-consuming, less safe, and prone to subjective errors. In contrast, TLS offers objective, repeatable data and can be integrated with machine learning for automated damage detection.

This study aims to assess the condition of urban roads in hilly areas with low vegetation using HTLS XGRIDS Lixel L2 to enhance the efficiency and accuracy of road evaluations. Additionally, it compares the survey costs between TLS-based methods and traditional manual surveys. The results of this comparison are expected to serve as a basis for selecting the most appropriate method for road evaluation data collection. These findings will contribute to the development of a more effective road assessment methodology by facilitating more accurate decision-making while ensuring alignment with actual road conditions.

This paper will contain the research significance, the methods that explain the data collection process using HTLS and manual survey; the results and discussion that compares the accuracy, productivity, and cost between the two methods; and the conclusion that highlights the main findings and recommendations for future research and applications. This study contributes to the growing body of research by applying it specifically to urban hilly road conditions, which present unique geometric and accessibility challenges not commonly addressed in previous works.

2. RESEARCH SIGNIFICANCE

This study highlights a limitation of UAV-based road surveys, which cannot detect damage under dense vegetation. By examining how vegetation affects TLS performance, it aims to improve the accuracy of urban road assessments. The case study was conducted on a hilly urban road, where complex terrain and geometry posed additional challenges. The study also supports digital twin development by using high-resolution TLS data to create detailed 3D models for monitoring and maintenance. While TLS provides a more objective method than traditional surveys, its cost must be considered. These findings offer practical guidance for those considering TLS in urban road management.

3. MATERIALS

The data required for this study include road conditions, both geometric and pavement aspects, obtained through manual surveys, as well as road condition data gathered using HTLS (XGRIDS Lixel L2). XGRIDS Lixel L2 is integrated with LiDAR, visual and IMU moduls with AI. The point cloud thickness of this TLS is 0.5 cm and 1 mm spacing.

4. METHODS

4.1 Manual Road Evaluation Survey

The manual road evaluation survey contains road geometric survey and road pavement condition survey. Manual road geometric survey shows in Fig. 1. The method used to measure elevation differences in this study was the double stand method, which involves the use of a water pass and measuring signs placed at specific points along the road. This technique is commonly applied in road surveys to determine changes in elevation between two points. During the measurement process, the distance between the two points being measured, known as the slagh length, was set to vary between 20 to 50 meters, depending on the terrain and conditions found in the field. Subsequently, calculations are performed using Eq. (1) to determine the gradient value. The road gradient is expressed as a percentage. A positive gradient value indicates an uphill road, while a negative value indicates a downhill road.

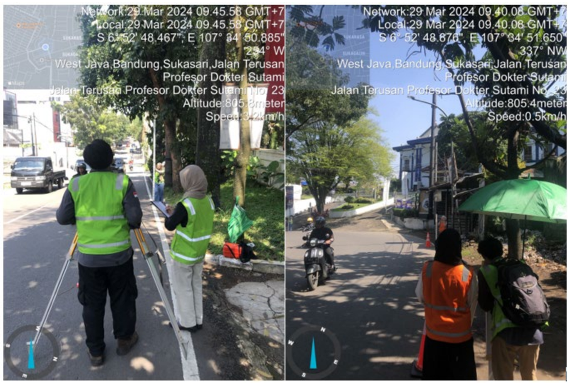


Fig. 1 Manual Road Geometry Survey

$$g\ (\%) = \frac{elevation\ difference}{slagh\ length}\ x\ 100 \qquad (1)$$

Explanation:

g (%)	: road gradient in percent.
elevation difference	: height difference two points.
slagh length	: inclined distance two points.

Manual road pavement conditions survey use the Pavement Condition Index (PCI) method according to the Pd-01-2016-B guidelines. Manual road pavement conditions survey needs assessment form, measuring tape, odometer, ruler, cell phone, and safety equipment (Traffic Cone Sign and Personal Protective Equipment).

To start the manual road condition survey, the road section was first divided into several sample units, each measuring 50 meters in length. According to the Pd-01-2016-B guidelines, the area of each sample unit should be around 225 ± 90 m². In this study, the road was divided into 14 sample units. The next step is to assess road damage. Any existing damage is identified and measured according to the type of damage. Manual pavement condition index (PCI) survey shows in Fig. 2.

Fig. 2 Manual Road Condition Survey

4.2 Road Evaluation Survey with TLS

Road evaluation survey using Handheld TLS is started with preparation Handheld TLS (Fig. 3). Determine a starting and ending point in data collection. Next, position the tool at that point and perform calibration. Make sure the surveyor is behind the tool so as not to obstruct the tool calibration process. Then, data collection can begin.

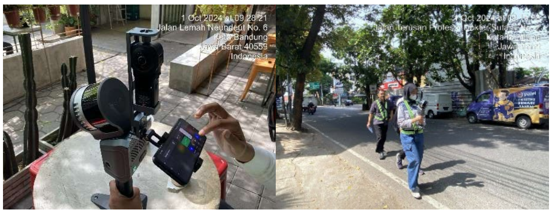
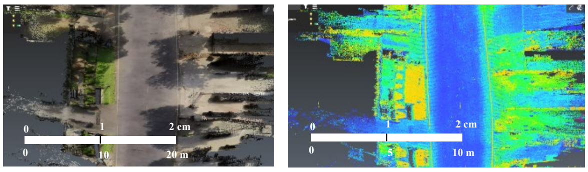


Fig. 3 Preparation and Data Collection using TLS

Data collection is done by tracing the location of the object forming a closed polygon. The data collection illustration can be seen in Fig. 4. The walking speed during data collection greatly determines the number of point clouds obtained. The slower the more point clouds are obtained. However, to save time, speed reduction can be done at certain locations only that requires more detailed results, namely at the location where the damage occurs.

After completing the data collection, the data will then be processed in the Lixel Studio software. This software has tools equipped with AI so that it can automatically delete moving objects such as vehicles passing through the surveyed road section. Furthermore, the data will be converted into LAS format. Fig. 5 is a road model in LAS format.



(a) (b)

Fig. 5 TLS result model view (a) Real Color (b) RGB

Next, road geometric and the condition of the road pavement can be carried out. Measurements are carried out using the ruler tools in the software for the width of the road and for the road gradient using z information from the two points whose distances are known so that the road gradient is known.

Fig. 6 and Fig. 7 show how to measure geometric roads. This measurement can be performed on all software that supports the LAS format, for example the free software, Cloud Compare and Cyclone 3D. The same thing applies to measuring road damage with the PCI method. An example of measuring road damage can be seen in Fig. 8, namely pothole.

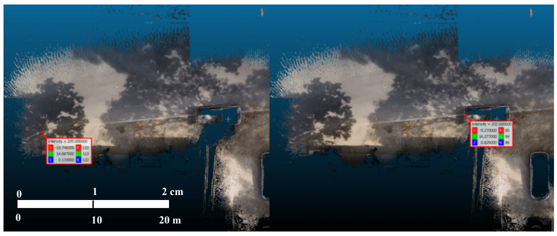


Fig. 6 Road Gradient using TLS

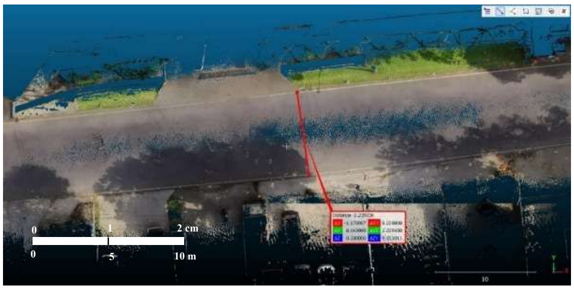


Fig. 7 Road Width using TLS

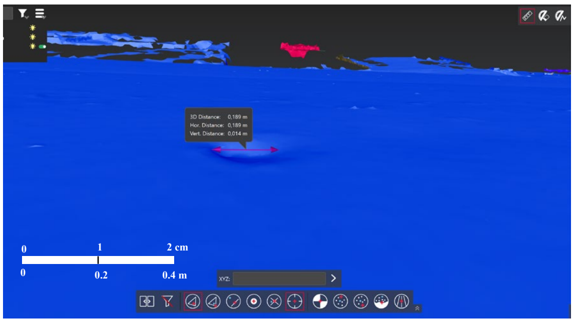


Fig. 8 Road Damage Measurement using TLS

After obtaining geometry and PCI data from both methods, the two data are then compared and their accuracy is calculated using Eq. (2).

$$Accuracy\ (\%) = (1 - \frac{Manual - TLS}{Manual})\ x\ 100 \qquad (2)$$

Explanation:
Accuracy (%) : accuracy in percent.
Manual : the value obtained manual survey.
TLS : the value obtained from TLS.

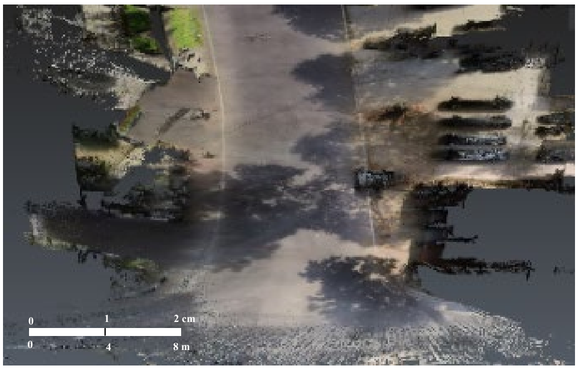
In addition to accuracy, both methods will be analyzed and compared for survey productivity and the costs required for each method. Furthermore, they will be compared to determine the most suitable method for urban road evaluation.

5. RESULTS AND DISCUSSION

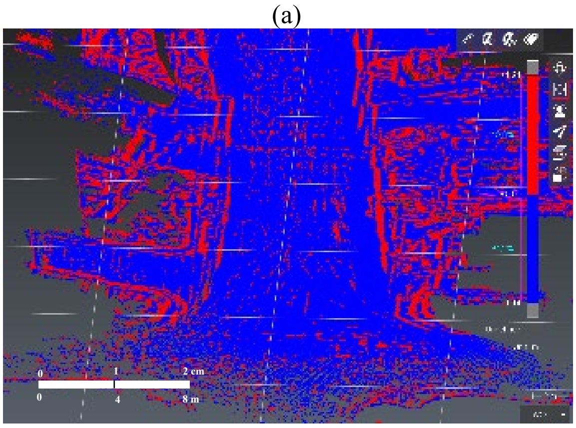
The 3D model produced using HTLS is quite good but has a drawback, namely that the shadows of road vegetation are still visible in the LAS (Real Color) format 3D model. After conducting an analysis based on the results of the manual survey data and using HTLS, the following comparison was produced between the two survey methods:

5.1 Comparison of PCI between manual and TLS

Based on the analysis carried out in this study, some types of damage found at the survey location, such as raveling and polished aggregate, were not visible in the TLS survey results when viewed using the real color display. However, these types of damage could still be seen when using the RGB view, as shown in Fig. 9.



(a)



(b)

Fig. 9 Ravelling, (a) Existing and (b) Model 3D

(a)

(b)

Fig. 10 Pothole Damage, (a) Existing and (b) Model 3D

This finding also confirms that the Handheld TLS is not only able to detect common types of damage such as alligator cracking, longitudinal cracking, patching, potholes, and pavement roughness on both flexible and rigid pavements, as reported in previous studies [31,32] but can identify other surface damage when viewed through different display modes. Fig. 9 and Fig. 10 present a comparison between the damage conditions in the field and 3D model from the TLS data.

Table 1. Manual PCI Value

No	STA		PCI Value	Manual A m2	PCI x A
1	0+000	0+050	100	225	22500
			100	225	22500
2	0+050	0+100	75	225	16875
			100	225	22500
3	0+100	0+150	100	225	22500
			100	225	22500
4	0+150	0+200	100	200	20000
			71	200	14200
5	0+200	0+250	91	200	18200
			100	200	20000
6	0+250	0+300	88	200	17600
			88	200	17600
7	0+300	0+350	100	200	20000
			89	200	17800
			Total	2950	274775
			Average PCI	93.1	

Table 2. TLS PCI Value

No	STA		PCI Value	TLS A m2	PCI x A
1	0+000	0+050	100	225	22500
			100	225	22500
2	0+050	0+100	75	225	16875
			100	225	22500
3	0+100	0+150	100	225	22500
			100	225	22500
4	0+150	0+200	100	200	20000
			71	200	14200
5	0+200	0+250	91	200	18200
			100	200	20000
6	0+250	0+300	88	200	17600
			88	200	17600
7	0+300	0+350	100	200	20000
			89	200	17800
			Total	2950	274775
			Average PCI	93.1	

Table 1 and Table 2 shows the comparison of Manual and TLS PCI from study location. Based on the results of the analysis that has been done, the accuracy of PCI measurement using TLS is 100%. Calculated using Eq. (2).

However, further research is needed at locations that have variations in vegetation density to see the effectiveness of TLS.

5.2 Comparison of Geometry Evaluation between manual and TLS

Based on the analysis that has been carried out, Table 3 and Table 4 show a comparison of Road

Gradient and Road Width measurements at the study location.

Table 3. Comparison of Manual and TLS Road Gradient

No.	STA	Gradient		Accuracy
		Manual	TLS	
1	0+000 - 0+100	-6.04%	-6.29%	95.95%
2	0+100 - 0+250	4.06%	4.54%	88.18%
3	0+250 - 0+350	-0.63%	-0.62%	98.41%
		Average Accuracy		94.15%

Table 4. Comparison of Manual and TLS Road Width

No.	STA	Road Width		Accuracy
		Manual	TLS	
1	0+000	9.00	8.23	91.44%
2	0+200	8.00	8.01	99.88%
3	0+350	8.00	8.30	96.25%
		Average Accuracy		95.86%

Table 5. T – Test Result

T - Test	t	df	Sig. (2-tailed)
Manual - TLS Gradient	-0.374	2	0.744
Manual - TLS Width	0.48	2	0.679

The accuracy of the TLS method in measuring road geometry reached 94.15% for gradient and 95.86% for road width, as calculated using Eq. (2). Furthermore, the results of the paired samples t-test indicated no statistically significant differences between the TLS and manual measurements for both parameters, gradient ($p = 0.744$) and road width ($p = 0.679$). These proves that the data generated by TLS is accurate and this technology can be used in road geometric evaluation. Based on this, it shows that TLS can represent existing conditions in the field and can identify ravelling damage that has not been identified in previous research.

5.3 Survey Cost Comparison

One of the main challenges in using TLS for road surveys is the high cost of the equipment. TLS devices, often require a large initial investment, making them less accessible for small-scale projects with limited budgets. Additional expenses include software licenses, data processing, and operator training. To provide a clearer picture of this issue, this section presents a comparison of survey costs and productivity between manual manual methods and TLS-based surveys. The comparison covers the total costs involved in equipment, labor, and time needed to complete the survey. Productivity in this study is measured based on the total area surveyed within one full workday, which is calculated as 7 working hours. This comparison aims to highlight the advantages and limitations of each method in terms of efficiency, cost-effectiveness, and practicality for road evaluation projects.

Table 5. shows the cost of conducting a road survey using TLS. The equipment rental must include an operator since the high price of the device makes it impractical to rent without one. The survey productivity using TLS is 4,550 meters per day, calculated from this study, where surveying a 350-meter road segment took 30 minutes, with an additional 30 minutes for initial setup. Based on this calculation, the cost per meter is approximately USD 0.10. Additionally, data processing requires a computer with specific minimum specifications (Intel Core i5, 8 GB RAM, 512 GB storage, and an NVIDIA GeForce GTX 1650 graphics card), costing around USD 726.83. The processing of TLS data also demands specialized skills, yet the availability of trained personnel remains limited. Therefore, software training is necessary to improve processing efficiency.

Table 5. TLS Survey Cost

No	Activity	Cost
1	TLS Rental per Day	$342
2	Operators	$ 85
3	Mobilization and Demobilization	$ 45
	Total	$472

For manual methods, the survey costs are divided into road damage assessment and geometric road surveys, as detailed in Table 6. that presents the cost of manual road condition surveys, while Table 7. shows productivity, which depends on several factors. As a result, the survey cost varies between USD 0.04 – 0.11 per meter, depending on the road conditions being assessed.

Table 6. Road Condition Survey Cost

No	Activity	Cost
1	Surveyors	$ 48.45
2	Data Collection Form	$ 6.06
3	Mobilization and Demobilization	$ 12.11
	Total	$ 66.63

Table 7. Road Condition Survey Productivity

Road Condition	Traffic Volume	Road Length (m)	Time (minutes)	Productivity (m/7 hours)
Good - Moderate	Moderate	350	90	1633,33
Moderate - Poor	Moderate	350	150	980
Moderate - Poor	High	350	240	612,5

The costs of manual geometry road surveys is the same as road condition survey (Table 6). The productivity of manual geometric surveys is 1,225 meters per day. This is based on the study's survey, where a 350-meter road section took 120 minutes using a round-trip data collection method. From this calculation, the survey cost is approximately USD 0.05 per meter.

Overall, the cost of a manual road condition survey ranges from USD 0.1 – 0.16 per meter. This is lower than TLS-based surveys due to the simpler data processing, which does not require specialized training or additional costs. In conclusion, road condition surveys using TLS are more expensive than manual methods. However, these costs are justified by the high-quality 3D road models produced, which serve as a valuable database for maintenance, repair, and road improvement planning. Furthermore, to optimize costs, TLS is most suitable for roads in hilly terrains with dense vegetation, high traffic volumes, severe damage, and lengths exceeding 1.6 km. This calculation is based on this study experiences.

5.4 Discussion

Both manual and TLS road surveys have their own limitations. Manual surveys are affected by weather, traffic, and road complexity. As road length or damage increases, they require more time and personnel. They are also subjective, relying on the surveyor's experience, which can lead to inconsistent results. In contrast, TLS provides objective, high-resolution data, but it also has drawbacks. TLS data collection is not feasible during rainfall, and the presence of stationary objects (e.g., parked vehicles) can obstruct full surface capture. High equipment costs and the need for specialized personnel and data processing tools also limit its wider adoption.

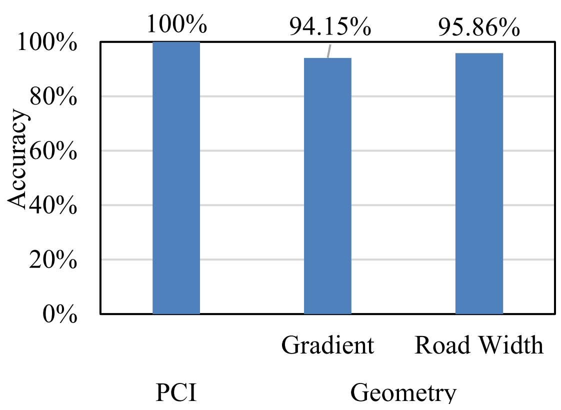


Fig. 11 Comparison of TLS Accuracy in Road Evaluation Aspects

The results of this study show that TLS has high accuracy in both PCI and road geometric evaluation (Fig. 12). This result indicates the use of TLS in this research successfully produced detailed and reliable data, which can be used to support road evaluation activities. Although this study was conducted on only one road segment, it involved a hilly urban area with complex geometry. Since TLS performed well in this challenging setting, it is likely also suitable for flat and mountainous roads. The main requirement for effective TLS use is the presence of a shoulder or sidewalk to allow safe and stable equipment setup.

One of the important findings in this study is the ability of TLS to identify ravelling damage, which has not been reported in several previous studies. This may due to the larger point clouds or lower point densities of the TLS instruments used, which prevented the laser from capturing the small cavities and surface texture changes. In contrast, the TLS device used in this study had a smaller (0.5 cm) and denser point cloud, allowing the detection of fine-scale surface damage that would otherwise have gone unnoticed. This result adds new information about the capabilities of TLS in detecting different types of surface damage. Potholes with small diameters were still clearly visible and could be measured accurately using the 3D model generated from TLS data. This proves that the quality of the model produced is very good and can represent the actual conditions in the field.

The use of TLS also successfully overcomes the limitations of UAV LiDAR in areas with vegetation. However, in real-color mode, tree shadows are still captured and visualized by TLS, which may reduce the visibility of damage beneath these shadows. To address this issue, alternative modes such as RGB can be used.

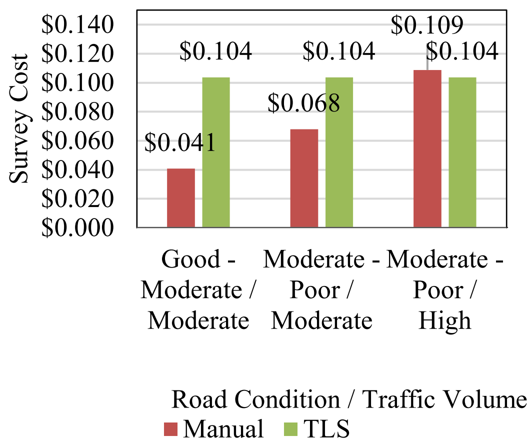


Fig. 12 Cost Comparison of TLS and Manual Survey

Besides data quality, survey costs and productivity were assessed. TLS costs more per meter than manual methods (Fig. 12) but delivers far greater daily productivity, making it more economical for projects over 1.6 km or in difficult conditions (hilly terrain, dense vegetation, heavy traffic). The TLS software used, Lixel Studio, employs AI-based filtering to remove moving vehicles and pedestrians in post-processing, minimizing obstructions and improving 3D model accuracy in urban areas.

Further research should focus on simplifying data acquisition and developing integrated machine learning (ML) models for automatic damage classification. Previous studies have shown that automated pavement inspection methods can achieve more than 90% compliance [32]. When paired with high-resolution TLS output, this method can further improve classification accuracy and reduce the time required for condition assessment.

6. CONCLUSION

This study confirms that TLS provides high accuracy in PCI and geometric evaluations, making it a reliable tool for urban road assessment. A key finding is the identification of ravelling damage, which was previously unreported, along with the detection of small-diameter potholes, demonstrating the high quality and accuracy of TLS models.

The comparison shows that TLS achieves 100% accuracy in PCI measurements and over 94% accuracy in road gradient and width assessments, effectively representing real field conditions. While TLS overcomes UAV LiDAR's limitations in vegetated areas, tree shadows in real-color mode can reduce damage visibility, which can be improved using RGB mode. Despite its higher cost compared to manual methods due to equipment, processing, and training needs, TLS offers high-quality 3D models that provide valuable data for road maintenance. Future research should focus on optimizing TLS data acquisition, reducing costs, and integrating Machine Learning (ML) to enhance automatic damage detection and classification.

TLS delivers high accuracy in PCI and road geometry assessments, effectively detecting fine surface damage. It is well suited for complex or long road segments.

7. ACKNOWLEDGMENTS

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