Revolutionizing Toll Road Maintenance: High-Accuracy Solutions for Monitoring Toll Road Settlements

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Key words: toll road, road settlement, mobile mapping systems

SUMMARY

PT Hutama Karya (Persero) (HK), as a toll road operating entity, faces the challenge of managing approximately 848 kilometres of toll roads. Ensuring compliance with Minimum Service Standards is HK's responsibility to maintain the quality of toll roads and provide optimal service for road users. One of these responsibilities includes monitoring road settlements to detect changes in road surface elevation, which serves as a mitigation measure against accidents caused by uneven surfaces, as well as predicting damage for road repair or reconstruction purposes.

A comprehensive analysis of road settlements must be conducted across the entire toll road network, requiring data of the highest accuracy and precision to detect elevation changes at a centimetre-scale resolution. To meet this demand, the use of Mobile Mapping System (MMS) with LiDAR technology becomes essential. This technology facilitates periodic acquisition of topographic data along the toll road, enabling effective analysis of road settlement.

This study focused on measuring and scanning a 10 km segment of the Palembang–Indralaya toll road in Sumatra, Indonesia, over two separate data acquisition periods. The data collection epochs were conducted within a short time frame of a few days, assuming no significant elevation changes occurred between the two periods.

A critical factor in utilizing Mobile Mapping System (MMS) technology for road settlement analysis in extended corridor areas is ensuring the consistency of topographic data across periodic measurements. This consistency can be influenced by both random and systematic errors. To minimize these errors, the scanning process was structured into segments with a maximum trajectory length of 5 km, an overlap of 1 km between data segments, a base station (BM) radius of 5 km, and Ground Control Points (GCP) placed every 500 meters. Additionally, the quality of each parameter during both data acquisition and processing was carefully controlled, maintaining an accuracy of approximately 1 cm.

The study results reveal that the deviation between the two data acquisition periods is significant, indicating no deformation, as confirmed by a t-student test. The data distribution falls within the normal range, with a relatively low occurrence of random errors. This highlights the high accuracy and precision of the data, achieving an LE90 value of 0.012 m. Furthermore, 95% of the elevation variations between the two periods are within the range of 0 to 1.5 cm.

Consequently, any elevation values exceeding 1.5 cm can be interpreted as evidence of road settlement.

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1. BACKGROUND

Based on Presidential Regulation Number 117 of 2015, PT Hutama Karya (Persero) received an assignment in accelerating the construction of the Trans Sumatra toll road, the assignment consists of funding, technical planning, construction implementation, operation, and maintenance.

The total length of the Trans Sumatra toll road is ± 2770 km. Until 2025, Hutama Karya has operate 848 km of Trans Sumatera toll road. Ensuring compliance with Minimum Service Standards is HK's responsibility to maintain the quality of toll roads and provide optimal service for road users. One of these responsibilities includes monitoring road settlements to detect changes in road surface elevation, which serves as a mitigation measure against accidents caused by uneven surfaces, as well as predicting damage for road repair or reconstruction purposes.

A comprehensive analysis of road settlements must be conducted across the entire toll road network, requiring data of the highest accuracy and precision to detect elevation changes at a centimetre-scale resolution. To meet this demand, the use of Mobile Mapping System (MMS) with LiDAR technology becomes essential. This technology facilitates periodic acquisition of topographic data along the toll road, enabling effective analysis of road settlement.

2. DATA AND METHODOLOGY

The location is on the Palembang - Indralaya Toll Road KM 0+800 - KM 9+800 in South Sumatra Province. The analysis was carried out using data from the acquisition of Mobile Laser Scanner for 2 periods, point clouds adjusment against GCP, and accuracy checking against ICP values and statistical testing was carried out to obtain the data analysis.

The implementation of data collection was carried out by optimizing the Mobile Laser Scanner mission length to 5 km with an overlap between missions along 1 km. GCPs were installed with a distribution of 500m crosswise on lane A and lane B of the toll road. and for testing the accuracy of point clouds data, Independent Check Point (ICP) with a random distribution representing various toll road conditions such as embankment excavation conditions, structures, and soil improvement conditions (such as vacuum and preloading).

2.1 Workflow

The flowchart below presents the process of the study conducted

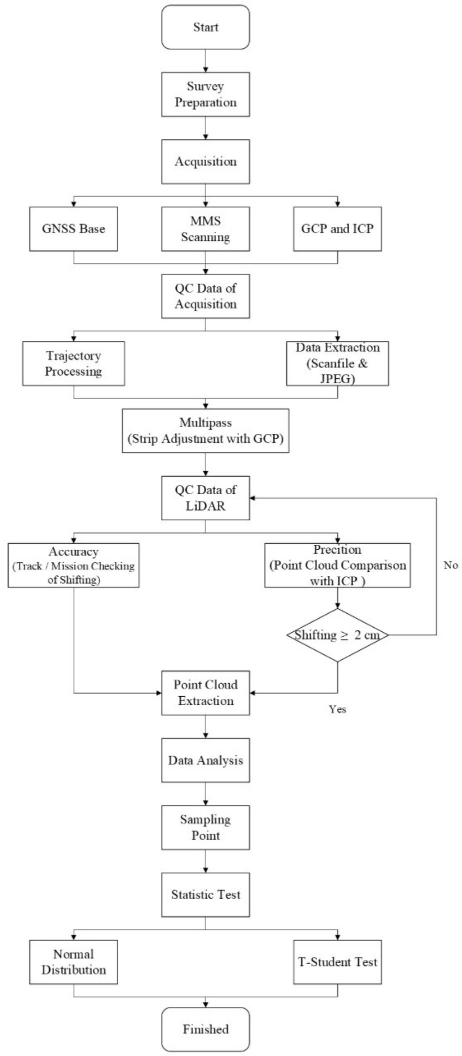


Figure 1 Workflow of Work

2.2 Data Acquisition Methods

The data acquisition method is divided into two main sub-activities, namely Static GNSS acquisition and Mobile Laser Scanner.

2.2.1 Acquisition GNSS Data

2.2.1.1 GNSS Data Acquisition for Benchmark

Observation of GNSS network method at benchmark by considering the distance between points, observation time and the angle formed is the same in each triangle or network, the quality of benchmark coordinates is one of the keys in determining the quality of the final MLS data results.

2.2.1.2 GNSS Data Acquisition for GCP dan ICP

Observation of GCP and ICP reference points using the differential static method. The observation time of each GCP and ICP point was kept consistent for 1 hour by considering variations in the distance of the observation point from the Base Station. GCP points were placed every 500 m on the right and left sides of the roadway in a crosswise manner to reduce random and systematic errors in the MMS data. ICPs were randomly placed at specific locations along the acquisition site.

2.2.2 Mobile Laser Scanner Data Acquisition

The mobile laser scanner data acquisition process includes per-mission data acquisition activities along 5km for 2 periods. Data acquisition activities include parallel recording of the Base Station and Laser Scanner to obtain the results in the form of a precise 3D point cloud in each period. The data acquisition process was carried out under the condition that Premark GCP and ICP were fully installed in the field, with the aim of recording Premark objects in the point cloud. With the point cloud data in each period, it will be used to identify whether there are elevation changes in the 2 data periods. The assumption is that there is no change in elevation in the 2 periods, because the epochs are only different days apart. The breakdown of the data acquisition scheme is organized in the following table.

Table 1 Mobile Laser Scanner Acquisition Scheme

Misi	Periode	Trajectory (km)	KM Awal	KM Akhir	Lintasan	Base	Overlap Misi (km)	GCP
Misi 1	1	5	0+800	5+800	2	BM 3+300A	1	500 m
Misi 2	1	5	4+800	9+800	2	BM 7+300A		
Misi 1	2	5	0+800	5+800	2	BM 3+300A	1	
Misi 2	2	5	4+800	9+800	2	BM 7+300A		

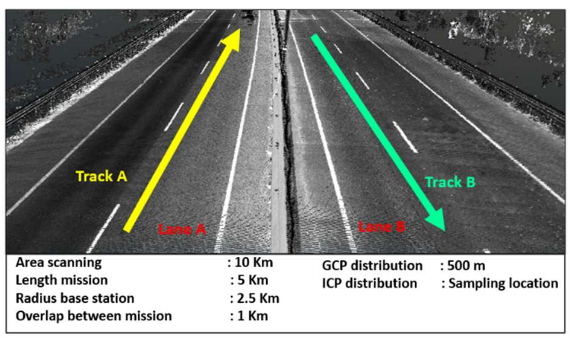


Figure 2 Mobile Laser Scanner Acquisition Scheme

2.3 Data Processing Methods

In the MLS data processing, the base station coordinates will be used as a reference to the MLS trajectory. MLS data processing includes trajectory processing, image and scan file extraction, georeferencing, and 3D Point Cloud data extraction. To get a better accuracy value, after 3D

Point Cloud data extraction, a data matching process is carried out using GCP as a tie point whose position is known in the field. The GCP detection scheme is carried out with Ground Target Recognition will detect automatically based on Premark templates installed in the field and GCP coordinates.

2.4 Metode Analisa Data

Data analysis was carried out using sampling points per 25 meters. This sampling point is used to detect the elevation value of the 3D Point Cloud in each data period. Furthermore, each point will be compared to the elevation between periods. The scope of data analysis includes making sample points, calculating elevation differences, eliminating data with the outlier method, statistical testing with the Z test, and conclusion.

3 RESULT

3.1 GNSS Data

3.1.1 Network Adjusment

The network adjusment results for the 4 Base Station BM reference points used in MLS acquisition are shown in the following table

Table 2 Accuracy of Base Station Network Processing

No	Station	SD		
		WGS 84 Lat	WGS 84 Long	Height
1	BM 10+800 A	0.00658	0.00658	0.00718
2	BM 5+800 A	0.0052	0.0052	0.00549
3	BM 7+300 A	0.00569	0.0057	0.00602
4	BM LJ 01	0.00593	0.00594	0.0074

From the observation and processing results, the accuracy of GNSS processing for all control net reference points shows an accuracy below 1 cm for position and elevation values.

3.1.2 Independent Check Point (ICP)

GNSS observations for ICP were carried out with static diffrential or radial methods at 7 points placed at locations with special characteristics on toll roads such as bridge structure areas. The results of the ICP observations are shown in the table below

Tabel 3 Accuracy of ICP Processing

No	Point	3D CQ (m)	2D CQ (m)	1D CQ (m)
1	ICP 1+350 A	0.00018	0.0001	0.00016
2	ICP 2+400 B	0.00021	0.00011	0.00018
3	ICP 4+780 A	0.00025	0.00013	0.00022
4	ICP 5+600 B	0.0004	0.00014	0.00037
5	ICP 6+050 A	0.00017	0.00009	0.00015
6	ICP 9+300 B	0.00032	0.00013	0.00029
7	ICP 10+200 A	0.00017	0.00009	0.00015

The quality of the processing results of 7 ICP points shows accuracy of less than 1 mm for all three parameters 3D, 2D and 1D CQ.

3.1.3 Ground Control Point (GCP)

The results of GNSS observations of the static diffrential method for GCPs as many as 20 points placed on lanes A and B of the toll road every 500 m in a spread manner are shown in the table below.

Table 4 Accuracy of GCP Processing

No	Point	3D CQ (m)	2D CQ (m)	1D CQ (m)
1	GCP 0+800A	0.0009	0.00031	0.00084
2	GCP 1+300B	0.00042	0.00017	0.00038
3	GCP 1+800A	0.00022	0.0001	0.00019
4	GCP 2+300B	0.00033	0.00012	0.00031
5	GCP 3+200A	0.00016	0.00008	0.00013
6	GCP 3+300B	0.00016	0.00008	0.00014
7	GCP 3+800A	0.00019	0.0001	0.00016
8	GCP 4+300B	0.00016	0.00008	0.00014
9	GCP 4+800A	0.00039	0.00014	0.00036
10	GCP 5+300B	0.0005	0.00022	0.00045
11	GCP 6+300B	0.00014	0.00006	0.00012
12	GCP 6+800A	0.0001	0.00005	0.00009
13	GCP 7+300B	0.00006	0.00003	0.00005
14	GCP 7+800A	0.00011	0.00005	0.0001
15	GCP 8+300B	0.00011	0.00005	0.0001
16	GCP 8+800A	0.00024	0.0001	0.00022
17	GCP 9+300B	0.00024	0.00012	0.0002
18	GCP 9+800A	0.00028	0.00015	0.00024
19	GCP 10+300B	0.00035	0.00016	0.00031
20	GCP 10+800A	0.00007	0.00003	0.00006

The results of processing and analysis of GCP points radially show good results with an accuracy level below 1 mm for all points of the 3 coordinate quality parameters.

3.2 Trajectory

to ensure the quality of the trajectory, the following variables are checked

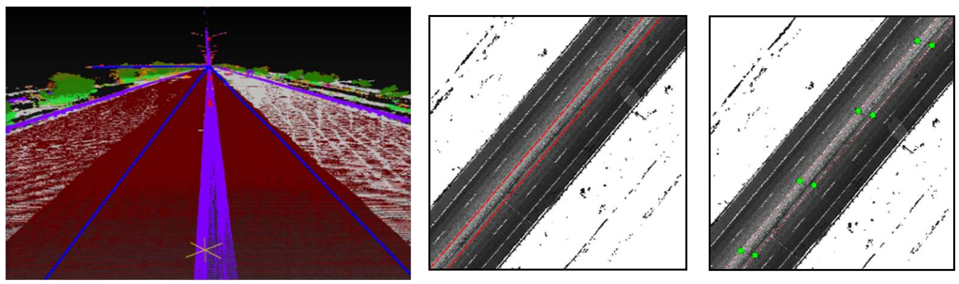
Table 5 The Result Parameters of MLS Trajectory

Parameter Pengecekan	Kriteria	Periode 1		Periode 2	
		Misi 1	Misi 2	Misi 1	Misi 2
File Data Coverage GNSS	Covel All Remote & IMU	√	√	√	√
Skema Forward Backward	No Error	√	√	√	√
Satelite Type	GPS, Glonass, Beidou	√	√	√	√
Minimum Satelite	Min 20	√	√	√	√
PDOP	Max 4	√	√	√	√
Ambiguity Phase	Fixed on Acquisition Area	√	√	√	√
Combined Separations	Max 0.15	√	√	√	√

The trajectory quality results show that all missions in 2 periods meet all the criteria of the checking parameters, so that the trajectory of the Mobile Laser Scanner acquisition has good data quality.

3.3 3D Point Clouds and Sampling Point

The point cloud results are automatically digitized on the shoulder of the toll road with TopoDOT as a reference for sampling points per 25m. Then the elevation extraction of the point cloud or LiDAR data is carried out for 2 data periods.



(a) (b) (c)

Figure 3 (a) The result of Point Cloud Extraction (b) Sampling Lines (c) Sampling Points

3.4 Accuracy Test

Accuracy testing was carried out by comparing the elevation value of the LiDAR results with the elevation value of the ICP. This is done to eliminate data that has a large deviation value to maintain good data quality accuracy.

Table 6 Outlier Test of ICP at Period 1

Mission Period	ICP	Z ICP	Z LiDAR	Dz	Abs Dz	Dz^2
Period 1	ICP 2+400 B	6.510	6.510	0.000	0.000	0.00000
	ICP 4+700 A	4.909	4.905	0.004	0.004	0.00002
	ICP 5+600 B	10.460	10.640	0.000	0.000	0.00000
	ICP 6+050 A	5.253	5.250	0.003	0.003	0.00001
	ICP 9+300 B	5.906	5.890	0.016	0.016	0.00025
	ICP 10+200 A	4.826	not coverage by LiDAR			
				Data		5
				Average		0.005
				RMSE		0.007
				LE90		0.012
				STDEV		0.007

Table 7 Test of Period 2

Outlier ICP at

Mission Period	ICP	Z ICP	Z LiDAR	Dz	Abs Dz	Dz^2
Periode2	ICP 2+400 B	6.510	6.500	0.010	0.010	0.00009
	ICP 4+700 A	4.909	4.900	0.009	0.009	0.00008
	ICP 5+600 B	10.460	10.640	0.000	0.000	0.00000
	ICP 6+050 A	5.253	5.255	0.002	0.002	0.00000
	ICP 9+300 B	5.906	5.900	0.006	0.006	0.00003
	ICP 10+200 A	4.826	tidak tercover LiDAR			
				Data		5
				Average		0.005
				RMSE		0.007
				LE90		0.011
				STDEV		0.005

the LE90 value of period 1 is 0.012, while the LE90 of period 2 is 0.011

3.5 Statistical Tests

3.5.1 Elimination of Outliers

Outlier data analysis was performed with Z-Score for each sampling point per-25m. The results of data tolerance are considered outliers if the Z value is more than 2, assuming a data confidence level of 95%.

$$z = (x - \mu)/\sigma \qquad (1)$$

From the results of the analysis there are 350 data from the results of sampling points carried out along the acquisition track in lanes A and B. On track A there are 42 outlier data and 40 data on track B. Data that includes outlier data or has a Z value of more than 2, is not used in further analysis.

3.5.2 Normal Distribution

Normal distribution results are performed on the comparison of 2 periods of lane A and lane B

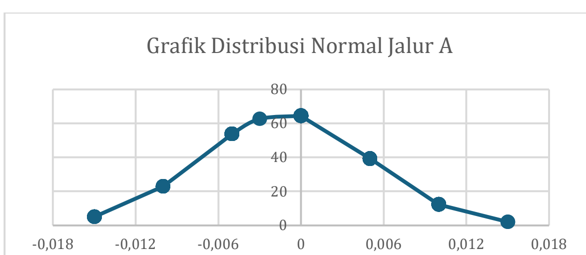


Figure 4 Normal Distribution Graphic at Lane A

Line A there are 308 data with a mean of 0.004571, standard deviation of 0.004 and degrees of freedom of 307 data. Of the total 308 data 91.883% or as much as 283 data is in the accuracy category range of 0 - 1 cm and the rest is in the category range of 1 - 2 cm.

Figure 5 Comparison of Lane A Profile

From the results of the comparison of the 2 profiles for 2 periods in Lane A, it shows that the profiles have aligned and it is assumed that the results are good.

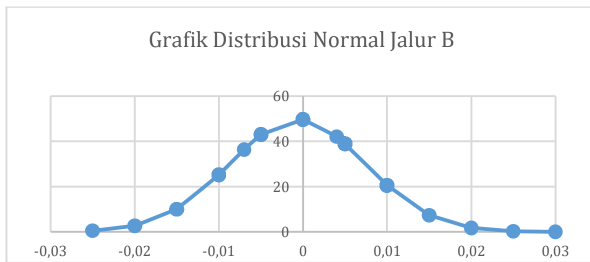


Figure 6 Normal Distribution Graphic at Lane B

Periods 1 and 2 in lane B have a total data of 310 data with a standard deviation of 0.005 and a mean value of 0.006 and a total number of degrees of freedom of 309. Of the total data, 86.774% have an accuracy category of 0 - 1cm, 9.355% are in the 1 - 2 cm category and the rest are more than 2 cm.

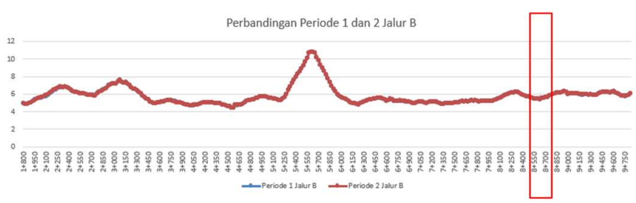


Figure 7 Comparison of Lane A Profile

The results of the comparison of 2 profiles for 2 periods in Line B coincide so it can be concluded that the results are good.

3.5.3 Uji T-Student

The significance test is conducted to see the change in sample elevation (segmentation) against population deviation (overall data). Testing is done one-tailed because the rejection criteria are on one side, where the t value is rejected if > 1.96 (large amount of data/∞ at 95% confidence level).

$$t = (y - \mu)/(S / \sqrt{n}) \quad (2)$$

Significance Test:

H0 = If t < tα, then there is no significant difference, so no deformation occurs.

HA = If t > tα, then there is a significant difference, so deformation occurs

Significance tests were conducted on a sample of highway conditions for the Mainroad location of the excavated embankment and bridge structure.

Table 8 Significance Test Lane A

Location (KM)	Type	Average (S)	Total (N)	T Hitung	T Table	Result
1+800-5+550	Mainroad Cut & Fill	0.005	139	0.003	1.96	Significant
5+575-5+650	Underbrige	0.001	4	0.045	1.96	Significant
5+675-9+825	Mainroad Cut & Fill	0.004	165	0.001	1.96	Significant

Table 9

Significance Test Lane B

Lokasi (KM)	Jenis	Average (S)	Total (N)	T Hitung	T Tabel	Result
1+800-5+550	Mainroad Cut & Fill	0.006	139	0.003	1.96	Significant
5+575-5+650	Struktur Jembatan	0.005	4	0.010	1.96	Significant
5+675-9+825	Mainroad Cut & Fill	0.006	161	0.003	1.96	Significant

From the results of the analysis carried out on lanes A and B at the segmentation location, the results show that they are not statistically different or significant, so it can be concluded that there is no deformation of the road on lane A and lane B.

4 CONCLUSION

The quality of GNSS data processing results (BM MLS, GCP and ICP) shows good accuracy with an accuracy level of less than 1 cm.

The use of GCPs every 500m in the data processing or strip adjustment process increases the accuracy of the 3D point cloud and reduces random errors.

Based on the method that has been carried out, it is concluded that the level of accuracy and precision of the data achieved is very good, namely LE90 0.012 and the variation value of the 2-period data elevation deviation of 95% is in the range of 0 - 1.5 cm, so that for data deviations of more than 1.5 cm it can be said that road settlement occurs.

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