Leveraging Mobile Mapping System for Pavement Condition Monitoring and GIS Asset Management

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Key words: Mobile Mapping System, Asset Management, GIS, Toll Road

SUMMARY

The government, through Presidential Regulation Number 100 of 2014 in conjunction with Presidential Regulation Number 42 of 2024, has assigned Hutama Karya the responsibility for developing and managing the Trans Sumatera Toll Road (JTTS) spanning 2,844 kilometers. This assignment encompasses financing, planning, construction, operation, and maintenance stages. In 2025 Hutama Karya will be operating ± 848 km of toll road. Maintaining and monitoring this toll roads is essential for comfort and safety of the toll road users. To maintain JTTS, Hutama Karya utilizes Mobile Mapping System (MMS) technology, to create and update as-built drawings, inspect road damage, detect settlement, and perform IRI testing.

This research focuses on leveraging MMS for pavement inspection by capturing the location and dimensions of the damage and visualizing the results through a spatial dashboard along 10 km of toll road. The study is limited to inspection pavement assets and also transforming point cloud data acquired by MMS into vector data to for toll road assets management, such as pavements, streetlights, CCTV, concrete barriers, guardrails, and road markings. Pavement of each lane and all line vector asset was segmented by 5m interval.

The inspection process uses two point cloud from LiDAR sensor and image from camera sensor. Point cloud inspection was done using LiDAR processing software. The software detect surface deformation by identifying uneven surfaces by analyzing point cloud elevation differences, detecting damage area based on pre-defined parameters. Image inspection was done using the MMS owned processing software, the software has manual digitization feature from 360 imagery that directly overlay the digitization to real world coordinate.

The inspection results show that the 4-lane road with inner and outer shoulders has 1,012 instances of rutting, 1,838 instances of bumps, 261 potholes, 5 instances of corrugation, 395 instances of depression, 1,371 instances of swelling, 2 instances of bleeding, and 5 cracks. The results consist of damage data in shapefile format with attributes classified by damage type, severity level, and inspection date. This information is spatially joined to the segmented vector data, producing shapefiles that indicate the condition of each pavement segment. These shapefiles are visualized in a GIS asset management dashboard, showcasing asset condition indices, counts of good and damaged assets, damage severity distributions, and an inventory of ongoing damage types. The dashboard reveals that a total of 64,023 asset segments are in good condition, while 8,995 asset segments are identified as being in bad condition, providing actionable insights for prioritizing maintenance and repairs.

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1. INTRODUCTION

The government, through Presidential Regulation Number 100 of 2014 in conjunction with Presidential Regulation Number 42 of 2024, has assigned Hutama Karya the responsibility for developing and managing the Trans Sumatera Toll Road (JTTS) spanning 2,844 kilometers. This assignment encompasses financing, planning, construction, operation, and maintenance stages. In 2025 Hutama Karya will be operating ± 848 km of toll road.

To maintain same service standards across all Indonesian Toll Road, Indonesian government through toll road regulatory body publish Toll Road Minimum Service Standard (SPM). This regulation consists of toll road condition, average travel speed, acesibility, mobility, safety, rescue and assistance services, environment and rest areas. Maintaining and monitoring this toll roads is essential for comfort and safety of the toll road users and also to comply with government regulations.

Hutama Karya utilizes various technology to maintain JTTS road condition one of it is mobile mapping system (MMS). MMS is an integrated system of surveying sensors mounted on a vehicle. It is considered as the most advanced technology for land surveying.[3] MMS consists of various sensor such as GNSS, IMU, camera (pavement, 360 and side camera) and laser scanner.

Figure 2 : Mobile mapping system

After data processing MMS will deliver two main output, it is point clouds and photos. With both of this data MMS has been implemented to asses road condition road international roughness inde (IRI), road damage detection such as crack, potholes and deformation and also road settlement [11]. MMS data can also be used for engineering drawing update such as as-built drawings and also feature extraction such as lane marking, road barrier, street lighting, etc.

Most of the data from MMS are spatial data. GIS is an excellent platform with which to integrate diferent data sources and provide convinient spatial data management functionalities. [18].

This research focuses on leveraging MMS for pavement inspection by capturing the location and dimensions of the damage and visualizing the results through a GIS spatial dashboard along 10 km of toll road. The study is limited to inspection pavement assets and also transforming point cloud data acquired by MMS into vector data to for toll road assets management, such as pavements, streetlights, CCTV, concrete barriers, guardrails, and road markings. Pavement of each lane and all line vector asset was segmented by 5m interval.

2. METHODOLOGY

The metodology begins with data collection using MMS technology captures point cloud and trajectory data, which is processed through GIS-based segmentation to define road sections. Damage detection is conducted via AI analysis and manual inspection, identifying issues based on severity and location. The data is then spatially linked to road assets and historical records, enabling predictive maintenance. A GIS dashboard visualizes road conditions, supporting real-time decision-making and optimized infrastructure management.

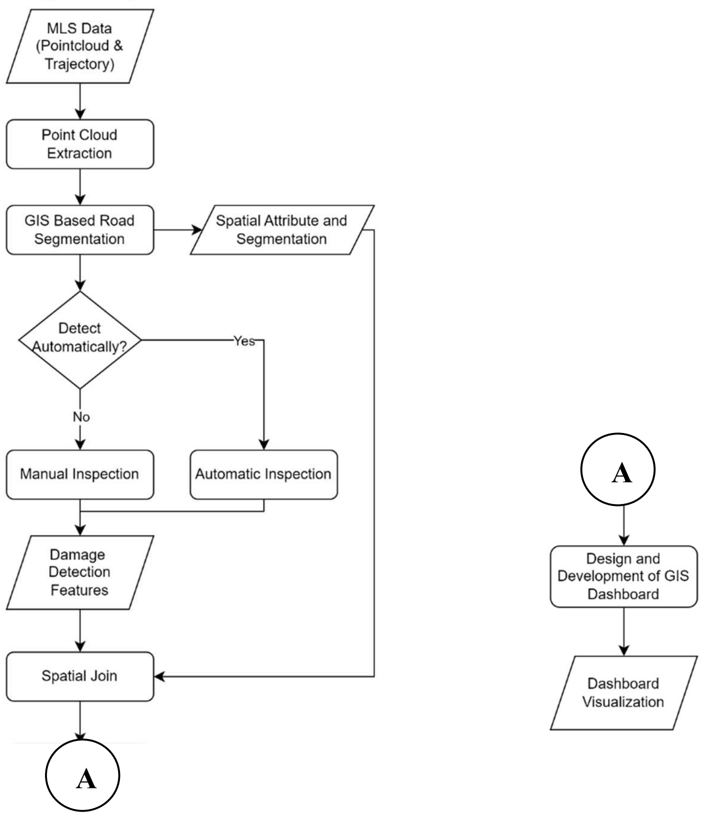

Figure 3 : Research Workflow

2.1. MMS Data

The process begins with the acquisition of spatial data using Mobile Mapping System (MMS). This technology is mounted on a vehicle to capture a dense point cloud and trajectory data along the roadway.

- Point Cloud Data: captures 3D pointcloud information about road surfaces, barrier, and other infrastructure.

– Panoramic Images: captures georeferenced panoramic images from 360 camera.
– Trajectory Data: provides precise location and orientation of the scanning system, ensuring accurate georeferencing of collected data.

By utilizing MMS, high-resolution road condition data can be obtained efficiently over long distances, offering a detailed digital representation of the road network[16].

2.2. Point Cloud Extraction

The point cloud extraction process involves transforming raw 3D point cloud data into structured 2D vectorized spatial data, which represents the exact locations of various toll road assets. This extraction ensures that road infrastructure such as pavement, lane markings, street lighting, CCTV cameras, median concrete barriers, and guardrails are precisely mapped and stored in a standardized Shapefile (SHP) format for use in Geographic Information Systems (GIS) as Digitalized Inventory Toll Road Asset and to be segmented for further data analysis[5]e che.

2.3. GIS Based Road Segmentation

To facilitate efficient analysis, monitoring, and maintenance, these extracted features are systematically segmented based on their functionality and spatial characteristics.

2.3.1. Segmentation of Extracted Point Cloud Data

Once extracted, the point cloud data undergoes segmentation to categorize different road elements into defined geometric representations. Each road asset is assigned a suitable spatial structure based on its size, shape, and role in the roadway system[14].

a) Road Pavement and Barrier Segmentation (Polygon-Based)

To effectively monitor and assess pavement conditions, road surfaces and barriers are divided into fixed-length segments measuring 5 meters in length and extending across the full width of the lane. This segmentation ensures[14]:

– A standardized approach to evaluating pavement conditions.
– Detailed asset tracking, allowing precise identification of damaged sections.
– Efficient repair scheduling, focusing on specific affected areas rather than entire road stretches.

The segmentation also applies to concrete barriers, medians, and retaining walls, ensuring that these critical safety elements are accurately mapped.

b) Lane Marking and Guardrail Segmentation (Line-Based)

Since lane markings and guardrails are linear features, they are segmented as continuous polyline data instead of fixed-area polygons. This structure allows for[20]:

– Accurate representation of lane boundaries across the road network.
– Tracking of worn-out or faded lane markings, aiding in maintenance efforts.
– Identification of gaps or damages in guardrails, ensuring road safety compliance.

c) Roadside Equipment Segmentation (Point-Based)

Vertical structures, including CCTV cameras, road lamps, and other tall roadside fixtures, are stored as point-based spatial features. These features are classified based on[20]:

– Their exact geospatial location using coordinate data.
– Their height and physical dimensions, ensuring proper classification within GIS systems.

– Their functional role, allowing easy differentiation between surveillance equipment, and lighting.

2.3.2. Standardized Asset Attribute of Extracted Point Cloud Data

Each segmented asset whether polygon-based (pavement and barriers), line-based (lane markings and guardrails), or point-based (CCTV, lighting) is enriched with a set of metadata attributes. These attributes serve as the digital identity of the asset, allowing for better organization, retrieval, and analysis of road infrastructure data[6].

The following categories of metadata are assigned to each segmented road asset:

a) Asset Identification and Location
Consist of asset ID, starting and ending station (chainage), coordinate and type of asset (pavement, guardrail, lane marking)
b) Asset Condition and Inspection Details
Consist of asset condition, damage category (structural, surface, etc), type of damage (pothole, rutting, etc), inspection date, inspector and damage documentation
c) Maintenance and Repair Records
Consist of maintaining agency name, repair status, repair date, repair priority, type of repair and repair documentation.
d) Spatial Referencing and Road Network Data
Consist of toll road segment code, road classification (toll, arterial, local, etc), segment, kilometer chainage, lane code (main lane or shoulder lane), construction code (rigid or flexible) and asset number

This structured metadata ensures that each asset segment is uniquely identifiable, accurately classified, and efficiently trackable within the GIS-based Asset Management System.

2.4. Automatic Digital Inspection

Point cloud data, captured by MMS-equipped survey, consists of millions of 3D coordinate points that represent the exact geometry and elevation of a roadway. Each point carries information about its X, Y, and Z coordinates, providing a high-resolution digital twin of the road surface. By analyzing variations in these data points, deformations and anomalies on the pavement surface can be detected[10][22].

The core principle of point cloud differentiation is the comparison of elevation data between scanned road sections to detect unexpected deviations[4].

The final output of automatic road damage detection is structured into GIS-compatible vector data, specifically in Shapefile (.shp) format, which is widely used for spatial data analysis and visualization. This file format allows detected road damages to be represented as polygon features, ensuring accurate geospatial referencing, classification, and visualization of pavement defects.

2.5. Manual Digital Inspection

While automatic detection using point cloud differentiation is highly effective for identifying elevation-based defects such as rutting, corrugation, depression, swelling and bumps, certain surface-level pavement defects cannot be reliably detected using LiDAR or MMS point cloud data alone. These defects include potholes, bleeding, and cracks, which require a different approach due to their low-profile, surface texture-based nature.

To ensure comprehensive road condition assessment, these defects must be manually digitized using GIS-based digital mapping tools. This process involves georeferencing high-resolution panoramic images captured alongside the point cloud, allowing inspectors to visually identify and mark defects that are otherwise undetectable through elevation analysis. The output of this manual process is a polygon-based shapefile dataset, where each defect is precisely mapped, and categorized within a GIS environment[13].

2.6. Spatial Join

The Spatial Join is a critical process in integrating and structuring the manual digital inspection output (from manual digitization of defects) and the automatic digital inspection output (from AI-based point cloud differentiation). This step ensures that all detected defects, regardless of how they were identified, are merged into a single, structured digital inventory of toll road assets [7][18].

This process involves overlaying the defect datasets onto the digital road asset inventory, allowing the system to determine which defects belong to which road segments.

2.7. Design of the Toll Road Asset Management Dashboard

The Toll Road Asset Management Dashboard is a GIS-based system that integrates spatial data from a published web map containing real-time asset conditions. The dashboard acts as an interactive decision-support tool, enabling users to visualize, analyze, and update road asset data efficiently[1] [2].

2.7.1. <u>Integration with the Published Web Map and Spatial Data Infrastructure</u>

At the core of this dashboard is its integration with a dynamically published web map, which serves as the primary data repository for all toll road asset information. The published web map is derived from the output of spatial join operations or processed shapefiles (SHP) of road conditions collected from various sources, such as mobile laser scanning (MMS), LiDAR, UAV imagery, and field inspections.

This integration of spatial datasets ensures that asset managers, engineers, and decision-makers have access to the most accurate and current representation of the toll road network at any given time.

2.7.2. <u>Data Storage, Retrieval, and Processing in the Dashboard</u>

The Toll Road Asset Management Dashboard functions as an advanced analytical interface built on big data and spatial database technologies. It connects with the published web map, retrieving various datasets stored within a centralized toll road asset database.

a) Data Structuring and Indexing

The database is designed to categorize road assets based on spatial location, type, and severity of deterioration. Spatial indexing techniques allow the dashboard to quickly retrieve and display relevant information based on a user's query.

b) Automated Data Synchronization with the Web Map:
The latest road condition datasets are published as a web map layer, ensuring automatic updates whenever a new inspection or analysis is completed. The dashboard synchronizes with the web map, so users always have access to the most recent asset condition reports.

The primary goal of this dashboard is to provide accurate and up-to-date asset information to support effective maintenance planning, and operational decision-making. By leveraging GIS technologies, and automated data retrieval, the dashboard enhances situational awareness and improves the overall road asset management process[2].

3. RESULTS

3.1. Point Cloud Extraction Result

The Point Cloud Extraction Result is a 3D geospatial representation of road assets, consisting of X, Y, and Z coordinates. The extracted data is processed into vector-based geometry, forming points, lines, or polygons that represent different road elements. The extraction process relies on sectional view similarity analysis, ensuring that road features are accurately digitized based on their geometric characteristics.

The extracted vectors maintain their georeferenced properties, meaning they are accurately positioned in relation to real-world coordinates. This allows the resulting vector data to precisely reflect the actual conditions of toll road assets in a digital format. The data is structured in Shapefile (SHP) format, making it suitable for GIS analysis and mapping applications.

Figure 1 demonstrates the transition from raw point cloud data to processed vectorized asset representation. The before-extraction stage consists of unstructured dense point clouds lacking attribute information. The after-extraction stage presents a cleaned, structured, and classified vector dataset, allowing for easier road asset visualization and analysis.

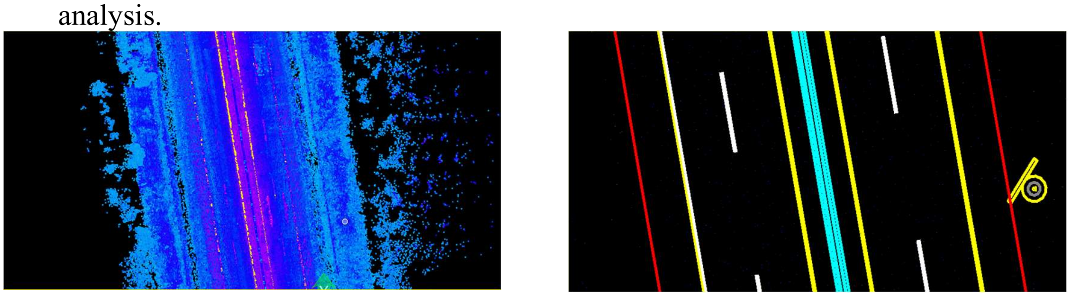

Figure 4 : Point cloud before extraction (left) and vector after extraction (right)

The extracted data can be visualized in GIS platforms and map viewers, providing a clear, interactive representation of road infrastructure[2]. The results are not limited to Shapefile (SHP) format—they can also be exported into other spatial formats such as KMZ (Google Earth format), DWG (Drawing file format for CAD-based applications), GeoJSON and other GIS-compatible formats Figure 2 illustrates how the extracted vector data appears within a GIS map viewer, where users can analyze, overlay, and interact with the dataset for further analysis.

Figure 5 : Feature extraction overlay with GIS platforms

3.2. Road Segmentation and Standardized Asset Attribute Result

This section discusses the results of road segmentation and standardized asset attributes as part of the digital asset management for toll roads. The segmentation process enables structured asset management by dividing the road into fixed-length sections and ensuring consistency in attribute recording.

3.2.1. Road Segmentation Result

Road segmentation refers to the division of toll road assets into standardized segments for better asset tracking, maintenance planning, and analysis. The segmentation process divides road sections into 5-meter longitudinal segments, ensuring each asset is properly recorded and managed.

The left side of Figure 6 displays a list of asset layers categorized based on asset type, such as CCTV, street lighting, directional signs, guardrails, and road markings. The right side of Figure 6 shows a spatial segmentation of toll road assets, where each asset is mapped into its respective section within the digital system.

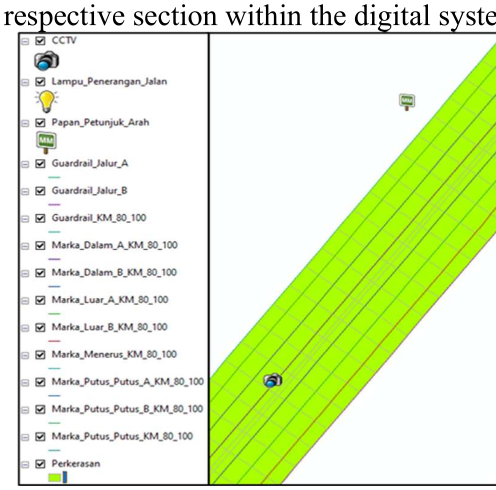

Figure 6 : Layer/Type of an Toll Road Asset (left) and Segmentation of an Spatial Shape of Toll Road Asset (right)

The segmentation result shown that (1) Pavement consist of 32,000 polygons, (2) CCTV consist of 19 points, Street Lighting consist of 92 points, (3) Guardrail consist of 8,000 line segments, (4) Dashed Line Markings consist of 8,000 line segments, (5) Continuous Line consist of 16,000 line segments.

3.2.2. Road Attribute Standarization Result

Standardized road asset attributes are critical for ensuring consistent data entry, structured asset tracking, and long-term historical recording. The attribute structure is designed based on the requirements of road inspection and asset management as shown in Table 1 Here is the Key Considerations in Standardization:

- Unique Asset ID (id_asset):
  Every asset is assigned a unique identification code. This ensures historical data can be stored, retrieved, and referenced efficiently.
- Standardized Data Fields:
  Asset data fields are predefined to include location, type, condition, damage category, and repair status. This ensures consistency in inspection and maintenance documentation.

Table 1 : Attribute Standardization

Field Name	Data Type	Example
OBJECTID	Object ID	1
id_asset	GUID /String	TS20/MR-L1-PVM/S1/000+000-000+200/B/RGD/01
sta_awal	String/Text	0+950
sta_akhir	String/Text	0+955
lokasi	String/Text	0+950 - 0+955
jenis_aset	String/Text	Perkerasan
kondisi_aset	String/Text	Rusak
kategori_kerusakan	String/Text	R2
jenis_kerusakan	String/Text	Ravelling
lajur	String/Text	Mainroad lajur B
jalur	String/Text	Jalur B
jenis_perkerasan	String/Text	Flexible Pavement
tanggal_inspeksi	Date	20/January/2023
inspektor	String/Text	Bitly
dokumentasi_inspeksi	Attachment (link)	https://portal.gis.com
jlo	String/Text	PT Swadaya Tol
status_penanganan	String/Text	Belum Ditangani
tanggal_penanganan	Date	Belum Ditangani
prioritas_perbaikan	String/Text	P1
jenis_penanganan	String/Text	Belum Ditangani
dokumentasi_penangana	Attachment (link)	Belum Ditangani
kode_ruas	String/Text	TS20
system	String/Text	MR-L1
segmen	String/Text	S1
km	String/Text	19+550-19+750
kode_jalur	String/Text	A
kode_type	String/Text	ASP
no_aset	String/Text	25

The Function of Standardized Attributes are to ensures consistency in recording and tracking road assets also to facilitates data analysis for maintenance planning and decision-making. Allows integration with GIS platforms for spatial analysis and visualization. Links asset data to historical inspection records to monitor asset deterioration trends[11].

3.3. Automatic Digital Inspection

The Automatic Digital Inspection process has identified a total of 11,914,521 defect polygons, categorized into various types of pavement damage. The breakdown of detected defects includes (1) 1,309,723 polygons representing rutting, (2) 5,414,448 polygons indicating bump defects, (3) 21,209 polygons for corrugation, (4) 403,720 polygons corresponding to depression, and (5) 4,574,560 polygons associated with swell formations.

An example of the defect polygons generated from the automated inspection process based on point cloud data is illustrated in Figure 7. The extracted defect data is fully georeferenced, meaning that each identified defect is spatially aligned with its real-world location and has a boundary that accurately matches the actual pavement distress.

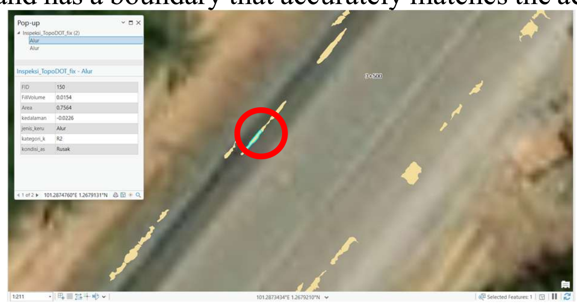

Figure 7 : Automatic inspection result

This finding confirms that the automatic digital inspection process can accurately interpret and detect actual pavement defects in the field, making it a reliable alternative to traditional manual inspections for road condition monitoring and asset management[8][19].

3.4. Manual Digital Inspection

The Manual Digital Inspection was conducted by digitizing defect areas based on parametric photographic data, where inspectors manually outlined the damaged sections. The results identified (1) 2 polygons representing bleeding, (2) 190,868 polygons representing potholes, and (3) 5 polygons representing cracks. An example of defect polygons derived from manual inspection process is illustrated in Figure 8

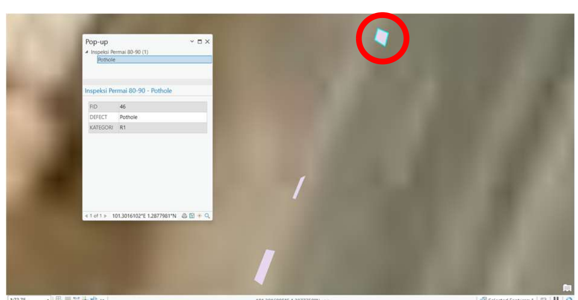

Figure 8 : Manual inspection result

Manual inspection serves as a complementary method to address limitations in automatic detection, particularly for defect types that rely on visual interpretation and do not exhibit significant elevation differences. However, this approach remains highly subjective, as it relies on the inspector's visual judgment, making it less precise in defining the exact boundaries of road damage[8].

3.5. Spatial Join Result

The spatial join process is specifically designed to enhance pavement condition visualization by integrating both automated and manual inspection results. This is achieved by intersecting defect polygons from the inspection process with pre-segmented asset polygons, ensuring that each road section accurately reflects its condition based on inspection data.

A total of 64,023 asset segments were classified as being in good condition. Meanwhile, 8,995 asset segments were identified as being in bad condition, requiring further analysis or maintenance intervention. As illustrated in Figure 1, the green-colored pavement asset areas represent road segments that remain in good condition with no detected damage. In contrast, the red-colored pavement asset areas indicate segments that have undergone deterioration and require maintenance. Each damaged segment contains linked attributes that, when selected, display detailed asset information, including : The type and severity of the detected damage, Photographic evidence from manual inspections, and Point cloud visualizations of the affected area.

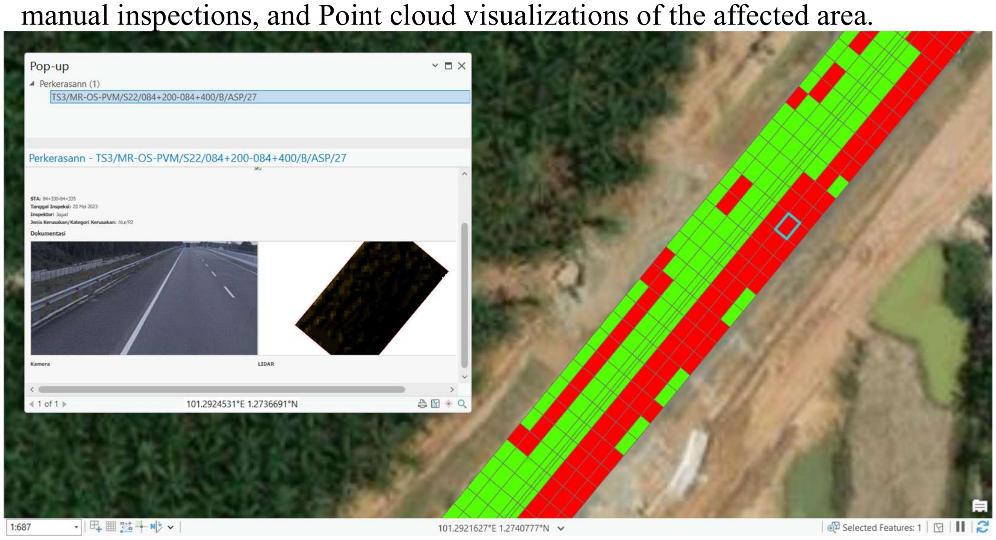

Figure 9 : Spatial join between segmented asset polygons and inspection results

By merging inspection data into pre-defined segmented road sections, the spatial join process significantly improves user accessibility and interpretation of pavement conditions. This structured approach simplifies the monitoring and decision-making process, enabling road asset managers to efficiently assess pavement health, prioritize maintenance needs, and plan preventive measures based on a comprehensive and spatially organized dataset[17].

3.6. Dashboard Visualization Result

The dashboard is designed to be fully integrated with a web map that contains a comprehensive dataset of layered spatial information, enabling dynamic visualization and interactive analysis of toll road assets. This integration ensures that users can efficiently access, interpret, and manage asset data in a single unified interface.

As illustrated in Figure 1, the developed dashboard consists of several key widgets and visual elements that provide an intuitive and structured representation of asset conditions:

1) Card Widget (Top Left): Displays the total length of the toll road section, offering a quick reference to the overall road network.
2) Donut Chart (Middle Left): Represents the asset condition index, visually indicating the proportion of assets in different condition categories.
3) Card Widget (Bottom Left): Summarizes the number of segmented assets classified as being in good or poor condition, providing a high-level overview of road health.
4) Interactive Map (Center): Serves as the primary spatial visualization tool, allowing users to analyze asset conditions based on geographical distribution.
5) Donut Chart (Top Right): Illustrates the severity levels of detected damage, assisting in prioritizing maintenance efforts.
6) Damage List Widget (Middle Right): Displays a detailed list of detected defects, including asset location, type, and severity classification.
7) Bar Chart (Bottom Right): Compares the frequency of different types of damage, enabling trend analysis for predictive maintenance planning.

By linking to the web map, the dashboard ensures real-time data synchronization, allowing stakeholders to interact with geospatially referenced road asset information. This system facilitates (1) efficient condition monitoring through spatial visualization, (2) Data-driven decision-making by highlighting critical asset conditions, (3) Predictive maintenance planning using trend analysis and severity indicators.

The dashboard's structured design and integration with GIS-based web maps significantly enhance the effectiveness of road asset management, enabling stakeholders to implement proactive maintenance strategies and optimize infrastructure planning based on real-time data insights[15].

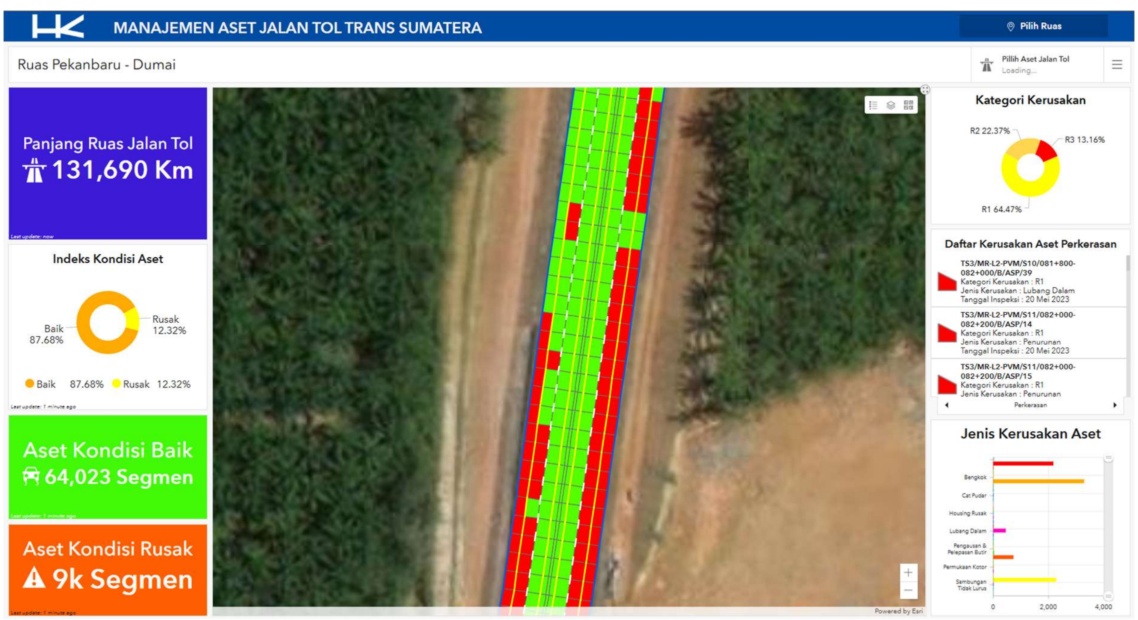

Figure 10 Toll Road Asset Management Dashboard

4. CONCLUSION

This study successfully demonstrates the utilization of Mobile Mapping System (MMS) technology for pavement condition monitoring and GIS-based asset management in toll road infrastructure. By integrating advanced LiDAR-based point cloud extraction, manual and automatic digital inspection, GIS spatial analysis, and dashboard visualization, the research provides a structured and efficient method for assessing toll road conditions.

While MMS provides a highly detailed and precise inspection method, its feasibility for rapid, daily inspections remains limited due to hardware and software constraints. The next step in MMS implementation should prioritize computational efficiency, ensuring that road condition assessments can be performed faster without sacrificing accuracy and data integrity.

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