December 2024

Report No. 25-068

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Development of a Visualization, Sharing, and Processing Platform for Large-Scale Highway Point Cloud Data

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U.S. Department of Transportation
Federal Highway Administration

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Technical Report Document Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
25-068		

4. Title and Subtitle	5. Report Date
Development of a Visualization, Sharing, and Processing Platform for Large-Scale Highway Point Cloud Data	December 2024
	6. Performing Organization Code
7. Author(s) Bryan Remache-Patino, Simos Gerasimidis, and Chengbo Ai	8. Performing Organization Report No.
9. Performing Organization Name and Address University of Massachusetts Amherst 130 Natural Resources Way, Amherst, MA 01003	10. Work Unit No. (TRAIS)
	11. Contract or Grant No.
12. Sponsoring Agency Name and Address Massachusetts Department of Transportation Office of Transportation Planning Ten Park Plaza, Suite 4150, Boston, MA 02116	13. Type of Report and Period Covered Final Report - December 2024 (March 2023 -December 2024)
	14. Sponsoring Agency Code n/a

15. Supplementary Notes
Project Manager - Neil Boudreau, MassDOT

16. Abstract

This study presents the development and validation of a web-based platform designed for the visualization, sharing, and processing of large-scale LiDAR point cloud data tailored to the operational needs of MassDOT. Leveraging open-source technologies, particularly Potree, the platform addresses key challenges associated with the management of high-resolution 3D spatial data, including data size, format complexity, and limited accessibility. Major contributions include enhancements to Potree's architecture for efficient data loading, modular input control, and expanded compatibility with diverse LiDAR formats. Crucially, the platform integrates external GIS data using GeoJSON as an intermediate format, enabling bidirectional workflows between Potree and existing spatial analysis systems. The platform demonstrates its effectiveness in supporting infrastructure assessment, decision-making, and multi-agency collaboration through five detailed case studies, including bridge inspection, asset management, project estimation, horizontal curve safety analysis, and statewide data management. This work establishes a scalable and extensible framework for modernizing LiDAR data utilization in transportation applications.

17. Key Word	18. Distribution Statement
LiDAR, Visualization, GIS, Platform, Potree, Network	

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
unclassified	unclassified	58	n/a

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

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Massachusetts Department of Transportation (MassDOT)
and
University of Massachusetts Amherst

Development of a Visualization, Sharing, and Processing Platform for Large-Scale Highway Point Cloud Data

Final Report

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Acknowledgments

Prepared in cooperation with the Massachusetts Department of Transportation, Office of Transportation Planning, and the United States Department of Transportation, Federal Highway Administration.

The Project Team would like to acknowledge the efforts of Mr. Neil Boudreau, Mr. James Danila, Mr. Corey O'Connor from the Highway Division at MassDOT for providing technical support and oversight into this project, and Dr. Hao Yin, Mr. Patrick McMahon from the Office of Transportation Planning at MassDOT, for providing necessary data and constructive suggestions for this project.

The Project Team would also like to acknowledge the efforts of Mr. Matt Mann and Ms. Kimberley Foster from the University of Massachusetts Transportation Center for their administrative support.

Disclaimer

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Executive Summary

This study of Development of a Visualization, Sharing, and Processing Platform for Large-Scale Highway Point Cloud Data was undertaken as part of the Massachusetts Department of Transportation Research Program. This program is funded with Federal Highway Administration (FHWA) State Planning and Research (SPR) funds. Through this program, applied research is conducted on topics.

This research study presents the development and application of light detection and ranging (LiDAR) data visualization and geographic information system (GIS) integration platform built on Potree, designed to serve the evolving needs of transportation agencies, particularly the Massachusetts Department of Transportation (MassDOT). The effort addresses the challenges of managing massive 3D point cloud datasets while providing intuitive, web-accessible tools for infrastructure evaluation, asset management, and project planning. The study is organized into three major methodological components:

- *Literature Review*: A comprehensive assessment of LiDAR technology, data characteristics, and existing visualization tools. The review highlights the growing utility of LiDAR for infrastructure management and identifies gaps in current visualization systems, especially in handling large-scale datasets and integrating them with geospatial systems. The literature review assessed both open-source and commercial tools for LiDAR visualization. Potree emerged as the preferred platform due to its:
    - WebGL-based rendering, supporting billions of points directly in browsers.
    - Open-source architecture, enabling full customization without licensing constraints.
    - Interactive tools, including measurement, slicing, classification-based visualization, and multi-format data support.
    - Scalability, allowing deployment on local machines or cloud environments with content delivery network (CDN) acceleration for distributed users. In this study, the CDN is established through a local network.
- *Prototype Development*: Enhancements to the open-source Potree viewer to improve performance, flexibility, and usability. The customized platform introduces advanced rendering, optimized data handling, and user-centric interaction tools.
    - The research team engineered key improvements to Potree to address limitations and meet DOT requirements:
    - Data Loading Optimization: Implemented a viewport-based scheduler for loading only relevant tiles, reducing system overhead.
    - GPU Acceleration: Enabled streaming of vertex buffer objects (VBOs) and parallel decoding using Web Workers.

- Level-of-detail (LOD) Management: The adaptive subdivision of octree structures ensures fine detail where needed while conserving memory elsewhere.
- Input Customization: Created a centralized input manager to support hotkeys and mouse gestures for streamlined workflows.
- File Format Support: Integrated LASTools and enhanced PotreeConverter usage to support LAS, LAZ, E57, XYZ, and other 3D formats.

- *GIS Data Integration*: A robust workflow using JavaScript Object Notation (JSON) and Geographic JavaScript Object Notation (GeoJSON) as a bidirectional exchange format between Potree and GIS environments. This integration supports simultaneous visualization and interaction with vector-based GIS data and 3D LiDAR scenes.
    - GeoJSON was adopted as the primary format for linking Potree with GIS databases:
    - Visualization: Users can overlay GeoJSON features (e.g., roadways, utilities) in 3D space, supporting interaction and attribute display.
    - Measurement Tools: Snapping and profile extraction were extended to interact with GeoJSON geometries, such as LineStrings and Points.
    - Network Modeling: Developed new modules (e.g., `GeoJSONLoader.js`, `NetworkAnalyzer.js`, `GeoStyler.js`) to support topological queries, attribute-based rendering, and infrastructure-level analysis.
    - Bidirectional Workflow: 1) GIS to Potree: Agencies export layers to GeoJSON, which Potree renders using `Three.js` primitives; 2) Potree to GIS: Annotations and measurements are exported as GeoJSON for reintegration into enterprise GIS systems.

To validate and demonstrate platform capabilities, five detailed case studies were conducted:

- *Bridge Inspection*: Potree was used to assess geometric conditions (e.g., cross slope, curb height) and surface deterioration (e.g., deck cracking) from mobile and high-resolution terrestrial LiDAR scans. GeoJSON overlays inspection results with MassDOT's asset data.
- *Roadway Asset* Management: The platform processed and visualized 26GB of mobile LiDAR along Route 126. Assets such as signs, sidewalks, and vegetation were classified and reviewed through custom color schemes, annotation tools, and GIS-linked metadata, streamlining quality control and asset tracking.
- *Project Estimation*: Using 74GB of LiDAR from Route 6, Potree supported quantity takeoff for guardrails, drainage, curbs, and vegetation removal. Interactive tools allow field teams to measure dimensions, validate object locations, and cross-reference with administrative boundaries via GIS overlays.
- *Horizontal Curve Safety*: Analyzing Route 113, Potree enabled curve radius and superelevation extraction for advisory speed calculation. The viewer supported line-of-

sight verification and ideal signage placement per Manual on Uniform Traffic Control Devices (MUTCD) standards. Outputs were shared across teams using synchronized bookmarks and annotations.

- *Statewide Data Management*: A scalable solution was created for over 16TB of point cloud data and video logs. Using Potree for visualization and Leaflet for GIS-based indexing, users could query and access segments by route, location, or metadata. A PostGIS and GeoServer backend ensured responsive performance and integration with MassDOT's enterprise systems.

This study establishes a scalable, extensible, and GIS-integrated framework for LiDAR data visualization using Potree. The customized platform empowers transportation agencies with real-time, 3D spatial awareness and analysis capabilities, enabling direct interoperability with GIS systems. Potree's transformation from a viewer to a comprehensive geospatial tool offers a new paradigm for infrastructure inspection, asset management, and project planning—bridging the gap between high-resolution reality capture and actionable decision-making across the transportation sector.

- Performance and Usability: The enhanced Potree platform deliverThisTUns responsive, browser-based access to massive 3D datasets, supporting analysis on mobile field tablets.
- Data Interoperability: Full compatibility with vector GIS formats via GeoJSON enables seamless workflows between Potree and agency GIS tools.
- Flexibility and Customization: Modular architecture and hotkey configuration empowers practitioners to tailor the tool to varied workflows across inspection, design, and maintenance teams.
- Infrastructure Readiness: Proven ability to manage statewide-scale data for asset visualization, collaborative inspection, and decision support.

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List of Acronyms

Acronym	Expansion
3DEP	3D Elevation Program
AASHTO	American Association of State Highway and Transportation Officials
ADA	Americans with Disabilities Act
API	Application Programming Interface
CAD	Computer-Aided Design
CDN	Content Delivery Network
COPC	Cloud Optimized Point Cloud
CRS	Coordinate Reference System
DSM	Digital Surface Model
EPT	Entwine Point Tile
FHWA	Federal Highway Administration
GeoJSON	Geographic JavaScript Object Notation
GIS	Geographic Information System
GLSL	OpenGL Shading Language
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GPU	Graphics Processing Unit
IMU	Inertial Measurement Unit
JSON	JavaScript Object Notation
LiDAR	Light Detection and Ranging
LOD	Level of Detail
LRU	Least Recently Used
MassDOT	Massachusetts Department of Transportation
MUTCD	Manual on Uniform Traffic Control Devices
PDAL	Point Data Abstraction Library
QGIS	Quantum Geographic Information System
QTM	Quick Terrain Modeler
REST	Representational State Transfer
RGB	Red Green Blue
SLAM	Simultaneous Localization and Mapping
SPR	State Planning and Research
UAV	Unoccupied Aerial Vehicle
UI	User Interface
USDOT	United States Department of Transportation
USGS	United States Geological Survey
VBO	Vertex Buffer Object

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1.0 Introduction

This study of Development of a Visualization, Sharing, and Processing Platform for Large-Scale Highway Point Cloud Data was undertaken as part of the Massachusetts Department of Transportation (MassDOT) Research Program. This program is funded by the Federal Highway Administration (FHWA) and State Planning and Research (SPR) funds. Through this program, applied research is conducted on topics of importance to the Commonwealth of Massachusetts transportation agencies.

1.1 Background

With the advancement of remote sensing technologies, light detection and ranging (LiDAR) point cloud data has become widely available and accessible with better quality. High-resolution scans have been leveraged efficiently and effectively in many critical transportation applications. MassDOT recognizes the power of this data source and has procured a powerful mobile LiDAR unit that will be installed in the Pavement Management van. The collected LiDAR point cloud will provide rich data and support several critical tasks for MassDOT. Unfortunately, due to the large size and the complex format, the utilization of the point cloud data has been burdened with expensive hardware, proprietary software, extensive training, and inflexible workflow. The point cloud data will only benefit if MassDOT can extract, process, access, and visualize the information. There is a great need for a convenient software platform to maximize the utilization of valuable point cloud data through efficient visualization, sharing, processing, and management. While some efforts were made in previous studies, none were tailored toward network-level data management or focused on critical highway applications, e.g., bridge inspection, asset management, and safety analysis.

The platform proposed in this study will help MassDOT establish a versatile infrastructure for point cloud data visualization, sharing, and processing, and significantly improve the utilization of various point cloud data in which MassDOT is continuously investing. The web-based platform will provide much broader and more convenient access to the point cloud data in different offices of MassDOT, which was previously limited due to the data's hardware/software and technical constraints. With more and routinely collected point cloud data using the new Pavement Management van, the developed tool will establish the critical platform for MassDOT to better access and utilize the data. The goal of this effort is to provide the entire MassDOT with a convenient, flexible, and effective tool to maximize the utilization and benefits of the point cloud data.

1.2 Objectives and Detailed Work Tasks

The objectives of this study include 1) to develop a convenient data platform with functionalities of visualization, sharing, and processing for large-scale LiDAR point cloud data; 2) to integrate the platform with the typical data sources and spatial analysis tools in MassDOT; and 3) to customize processing pipelines using the platform for several MassDOT's critical highway applications, e.g., asset management, safety analysis, bridge management, etc., and demonstrate the feasibility and benefits of the platform.

This study aims at delivering two products, including 1) a prototype, web-based platform for point cloud data visualization, sharing, and processing; the platform should accommodate the typical data sources and interface with the existing spatial analysis tools at MassDOT; 2) cases studies that demonstrate the utilization of the customized point cloud data processing pipeline in the platform for critical highway applications. The detailed tasks completed in this study are listed as follows:

- *Task 1 - Review of Existing Efforts in LiDAR Data Visualization and Sharing*: The research team conducted a detailed literature review of available and ongoing research and implementation efforts for point cloud data processing, visualization, and sharing. The available point cloud dataset in MassDOT and its potential applications will also be identified through communication with MassDOT.
- *Task 2 - Development of the Prototype Point Cloud Data Platform*: The research team developed a web-based, GIS-enabled point cloud data visualization platform based on the octree data structure for better visualization efficiency without compromising the granularity of the point cloud data. The research team also designed the platform in such a way that it can be adaptive to different point cloud sources (e.g., mobile LiDAR, airborne LiDAR, unoccupied aerial vehicle (UAV) imagery, etc.), can support different visualization modes (e.g., intensity, color texture, elevation, etc.), and can facilitate basic point cloud processing (e.g., feature selection, geometry measurement, etc.). The platform included flexible interfaces to facilitate the subsequent customization of the processing functions in the case studies. The research team also evaluated the performance of the developed prototype platform using data collected from different LiDAR models that are hosted by the research team, e.g., Riegl VMZ2000, Inertial Labs RESEPI, etc., and by MassDOT, e.g., Riegl VMX450, Z+F 9020, etc.
- *Task 3 - Prototype GIS Integration*: The research team developed integration plans, prototype geodatabases, and the corresponding programs to integrate the existing, relevant spatial database (e.g., RIF) with the point cloud data. The research team also developed automated tools for GIS-cloud and cloud-cloud data integration.

- *Task 4 - Customization of Processing Tools and Case Studies*: The research team communicated with MassDOT to identify representative use cases for point cloud data and developed the corresponding case studies to demonstrate the feasibility and efficiency of the developed data visualization/processing/sharing platform. The processing tool will be tailored individually for different use cases. Example case studies include infrastructure monitoring (e.g., bridge inspection), safety analysis (e.g., horizontal curve safety), asset management (e.g., pavement marking management), etc.
- *Task 5 - Reporting of Results:* The research team prepared the final report and the corresponding PowerPoint-based project presentation with all the technical details.

1.3 Organization of this Report

This report is organized as follows. Section 1 introduces the background, research needs, objectives, and the detailed work tasks of this research project. Section 2 presents the proposed method, including the literature review, the developed prototype platform, and the integration mechanism for the geographic information system (GIS) data. Section 3 presents the use cases of the prototype platform. Section 4 summarizes the findings and results of this project and recommendations for future studies.

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2.0 Research Methodology

The research methodology for this study consisted of three main parts: a review of existing data and technologies, the development of the prototype platform, and the integration of the external GIS data. Section 2.1 reviews the literature on the existing efforts for point cloud data visualization and sharing. Section 2.2 presents the prototype platform's architecture, design, and development, followed by Section 2.3, which presents the method for integrating external GIS data.

2.1 Literature Review

2.1.1. LiDAR Data Overview

LiDAR (Light Detection and Ranging) technology enables the acquisition of high-resolution 3D spatial data surrounding a sensor's environment. A range of LiDAR systems exists with varying capabilities and costs, yet most operate on similar principles. A typical LiDAR unit emits laser pulses at known angular intervals. It measures the time-of-flight of the reflected signals to calculate distances based on the known speed of light. Each return provides a spatial point characterized by its distance and the intensity of the returned signal, producing a dense collection of 3D points, commonly referred to as a point cloud. These points are generally accurate relative to the sensor's position (1, 2).

When the LiDAR system is mobile, additional data processing is required to georeference the point cloud. Mobile LiDAR platforms often integrate global positioning system (GPS) or global navigation satellite system (GNSS) receivers with Inertial measurement units (IMUs) to estimate the sensor's trajectory and orientation during data collection (3). Alternatively, simultaneous localization and mapping (SLAM) techniques can be employed, leveraging identifiable features across overlapping scans to infer the system's motion and align point clouds accordingly (4, 5).

Raw point clouds include spatial coordinates and intensity values for each point. These datasets may be further enhanced by integrating additional sensor modalities. For example, co-registered cameras can capture RGB imagery that, when calibrated with the LiDAR sensor's perspective, enables the colorization of point clouds (6, 7). While intensity-based coloring is common, it is influenced by factors such as range, material reflectivity, and incidence angle and, therefore, does not represent actual surface color (8). Colorization using RGB imagery, on the other hand, provides more intuitive visualizations of the real-world appearances. Colorization using optical imagery may be less practical at larger scales, such as with airborne LiDAR. Alternative visualization schemes, such as elevation-based or classification-based coloring, support applications like terrain analysis or thematic mapping (9). In specialized use cases, LiDAR can be integrated with non-visible spectrum sensors, such as thermal infrared cameras, to visualize additional environmental attributes in 3D, such as surface temperature variations (10).

LiDAR point clouds are applicable at multiple scales and have significantly reduced the labor intensity of traditional field surveys. One notable example is the U.S. Geological Survey (USGS)'s 3D Elevation Program (3DEP), which aims to create a high-resolution elevation map of the United States. With approximately 89.5% of the country surveyed, many states have contributed data through airborne LiDAR campaigns (12). These datasets support a wide range of applications, from mineral resource exploration under the Earth Mapping Resource Initiative (13) to hydrological modeling (14, 15) and geohazard assessments such as landslide risk mapping (16). Beyond infrastructure geometry, LiDAR intensity data can be used to assess surface characteristics. For instance, pavement markings can be identified and condition-scored using a combination of geometry and intensity signatures. In a study on roadway markings, longitudinal stripes were segmented into points, each assigned a degradation score, and visualized through color mapping, highlighting areas in need of maintenance (26). However, this approach is more practical at the corridor-level due to the data volume involved.

LiDAR applications also extend to rail infrastructure. Mounting LiDAR on hi-rail or track geometry cars supports clearance assessments and infrastructure monitoring (31). In such cases, point cloud data may be abstracted into tabular summaries due to the fixed alignment of rail systems. In structural health monitoring, repeated LiDAR scans can detect temporal changes, such as wall deformations or landfill volume fluctuations, by comparing aligned datasets over time (32).

2.1.2. Existing LiDAR Visualization Tools

Visualizing LiDAR point cloud data is critical for effective interpretation, quality assessment, and integration into downstream applications. Various software tools support this task, from open-source utilities to commercial-grade platforms. These tools differ in processing capabilities, supported formats, rendering performance, and suitability for specific use cases such as GIS integration, web-based sharing, and 3D modeling.

The following list describes some open-source tools:

- *CloudCompare*: CloudCompare is a standalone, open-source 3D point cloud processing tool widely used for visual inspection, point cloud registration, segmentation, and surface reconstruction. It supports large datasets and includes tools for computing distances, volume changes, and statistical analysis. (https://www.cloudcompare.org).

- *PDAL (Point Data Abstraction Library)*: PDAL is a C++ library and application for manipulating point cloud data. While not a direct visualization tool, it is critical in preprocessing and filtering LiDAR data before visualization. https://pdal.io
- *Potree*: Potree is a WebGL-based open-source renderer for massive point clouds. It allows for efficient web-based visualization and supports interactive tools for measuring, filtering, and classifying data directly within a browser. (https://potree.org).
- *Plas.io*: Plas.io is a lightweight, browser-based point cloud viewer that enables users to visualize LAS/LAZ files without requiring installation. It is especially useful for quick previews and sharing visualizations online. (https://plas.io).
- *MeshLab*: MeshLab is a standalone, open-source tool for mesh reconstruction and point cloud visualization. It is particularly effective for creating surface models from LiDAR data. (http://www.meshlab.net).
- *LAStools*: LAStools is a robust set of tools for fast and efficient processing of LAS/LAZ files. It includes utilities for filtering, tiling, classification, and format conversion, and is widely used for preprocessing point clouds. (https://rapidlasso.com/lastools/).
- LidarView: LidarView, built on ParaView, is tailored to visualize LiDAR data in autonomous vehicle applications. It supports synchronized playback of LiDAR with camera and GPS data. (https://www.paraview.org/LidarView).

These are some readily available commercial tools:

- *Bentley Pointools*: Designed for high-performance visualization, Bentley Pointools supports editing, animation, and modeling of point clouds within civil engineering workflows. (https://www.bentley.com).
- *Leica Cyclone*: Leica Cyclone provides tools for point cloud registration, editing, and feature extraction. It is often used with Leica hardware and integrates with Leica TruView for cloud sharing. (https://leica-geosystems.com).
- *Trimble RealWorks:* Trimble RealWorks supports processing, modeling, and analysis of 3D scan data. It is optimized for survey, civil, and construction applications. (https://geospatial.trimble.com).
- *FARO SCENE*: FARO SCENE is optimized for data from FARO scanners and includes features such as automatic object recognition, VR support, and cloud-based sharing. (https://www.faro.com).
- Pix4D Mapper: Although primarily a photogrammetry tool, Pix4D Mapper can process LiDAR and RGB data to generate colorized point clouds, orthomosaics, and digital surface models (DSMs). (https://www.pix4d.com).
- Esri ArcGIS Pro: ArcGIS Pro supports the import and analysis of LAS datasets and other point cloud formats. It is particularly suited for GIS-based workflows and can handle classification, visualization, and conversion to raster or vector data. (https://www.esri.com).

- *Quick Terrain Modeler (QTM)*: QTM is a powerful software suite developed by Applied Imagery that visualizes and analyzes LiDAR and terrain data. It is particularly well-suited for defense, engineering, and geospatial applications, supporting fast rendering and elevation analysis. (https://www.appliedimagery.com).
- *LP360*: LP360 is a powerful LiDAR processing tool that integrates directly into ArcGIS and offers a standalone viewer. It supports classification, feature extraction, and advanced QA/QC workflows. (https://lp360.com).

LiDAR visualization tools vary significantly in their capabilities, from lightweight web-based viewers like Potree to comprehensive processing suites such as Esri ArcGIS Pro and Leica Cyclone. The application's scale often determines the choice of tool, the required level of analysis, integration with other datasets, and the technical proficiency of users. Open-source options offer flexibility and cost-effectiveness for research and prototyping, whereas commercial platforms are often preferred for enterprise-level deployment and standardized workflows. Table 2.1 lists the pros and cons of the existing tools.

Table 2.1 Available LiDAR data visualization and processing tools

Tool	Pros	Cons
CloudCompare	Open-source, cross-platform, rich tools, handles large datasets.	Not ideal for real-time use, limited scripting, and complex operation.
Potree	Web-based, efficient for large data, interactive filter and measure.	Preprocessing required, lacks editing features, and limited mobile support.
PDAL	Scriptable, integrates with Python, and powerful for preprocessing.	No GUI, requires scripting knowledge, not a visual tool.
MeshLab	Free, supports mesh reconstruction, good visualization options.	Not optimized for large datasets, older interface, limited tools.
LAStools	High-speed processing, versatile toolset, good ArcGIS integration.	Not fully open-source, command-line driven, visualization limited.
Plas.io	Browser-based, lightweight, easy sharing, open-source.	Limited features, not for large datasets, no editing capabilities.
Bentley Pointools	High-performance rendering, good animation support.	Costly, proprietary formats, limited ecosystem flexibility.
Leica Cyclone	Industry-standard, comprehensive features, integrates with Leica.	High cost, proprietary system, complex UI.
Trimble RealWorks	Strong modeling, suited for surveying, good analysis tools.	Expensive, resource intensive, less community support.
FARO SCENE	Excellent for FARO data, VR support, robust automation.	High licensing cost, hardware-tied, limited cross-compatibility.
Pix4D Mapper	Photogrammetry/LiDAR integration, intuitive UI, drone friendly.	Subscription model, limited LiDAR tools, not ideal for huge data sets.
ArcGIS Pro	Comprehensive GIS integration, spatial tools, strong documentation.	Licensing cost, high learning curve, intensive on system resources.
QTM	Excellent for terrain and elevation analysis, fast rendering	Windows-only, costly, limited public awareness.
LP360	ArcGIS integration, standalone mode, supports QA/QC and extraction.	Commercial license, Windows-only, complex for new users.

2.1.3. Existing Efforts from State DOTs and Agencies

Due to their large file sizes, LiDAR datasets are commonly divided into tiles and converted into raster formats for more efficient storage and analysis (17, 18). This facilitates integration into GIS, where derived products can be layered with other spatial datasets. For instance, the U.S. Department of Transportation (USDOT) leverages GIS to disseminate Justice40 data, identifying disadvantaged communities based on geographic analysis (19). State-level DOTs similarly maintain GIS platforms with public access to spatial data and employ specialists to manage and interpret this information (20).

Several state agencies have undertaken LiDAR-based asset management initiatives. For example, Idaho's Statewide Asset Attribute Inventory uses LiDAR to extract transportation infrastructure features, such as sidewalks and curb ramps, and presents them as shapefiles in ArcGIS Viewer (21, 22). These shapefiles include feature geometries (points, lines, or polygons) and attribute data, such as compliance with the Americans with Disabilities Act (ADA) (23). Web-based GIS applications allow users to filter for non-compliant assets, streamlining accessibility assessments. Similar projects in other states demonstrate the scalability of LiDAR-enabled asset inventories and the value of interactive visualization tools (24, 25).

Custom visualization tools have also been developed for specific use cases. For instance, Greenman-Pedersen, Inc. created a viewer to streamline traffic sign extraction from LiDAR data in collaboration with MassDOT. This application facilitated sign identification and post-collection retroreflectivity assessments (30).

2.1.4. Summary

By reviewing different available tools, Potree stands out as a strong foundational platform for further development into a user-friendly, web-based visualization tool tailored for state DOTs. Its core advantages, including its open-source architecture, efficient rendering of massive point cloud datasets, and lightweight browser-based interface, make it well-suited for public sector applications that demand accessibility, scalability, and cost-effectiveness. Potree's ability to stream large LiDAR datasets directly in the browser eliminates the need for specialized desktop software or high-performance computing infrastructure, enabling broad access across DOT divisions, field personnel, and external contractors.

Moreover, Potree supports interactive tools such as spatial measurement, slicing, point filtering, and basic classification display, which are essential for infrastructure condition assessment, asset inventory, and QA/QC workflows. Its flexibility allows integration with auxiliary data sources such as orthophotos, shapefiles, and attribute tables, providing a multimodal visualization environment that aligns with DOT asset management systems.

Unlike many commercial tools, Potree’s open framework encourages customization, enabling developers to build extensions that address DOT-specific requirements, such as ADA compliance review, right-of-way inspection, or pavement marking condition analysis. Given its extensibility and alignment with modern web standards, Potree offers an ideal foundation for developing a centralized, browser-based platform that democratizes access to LiDAR data while supporting advanced infrastructure management capabilities.

2.2 Prototype Development

2.2.1 Potree Architecture

As identified in the literature review, Potree is a WebGL-based point cloud renderer designed for visualizing massive 3D point cloud datasets directly in web browsers. It enables users to efficiently render billions of points from LiDAR scans, photogrammetry, or other 3D scanning techniques without requiring specialized desktop software. This section provides a high-level overview of Potree's architecture, functions, and core components. Figure 2.1 shows the overall architecture of Potree.

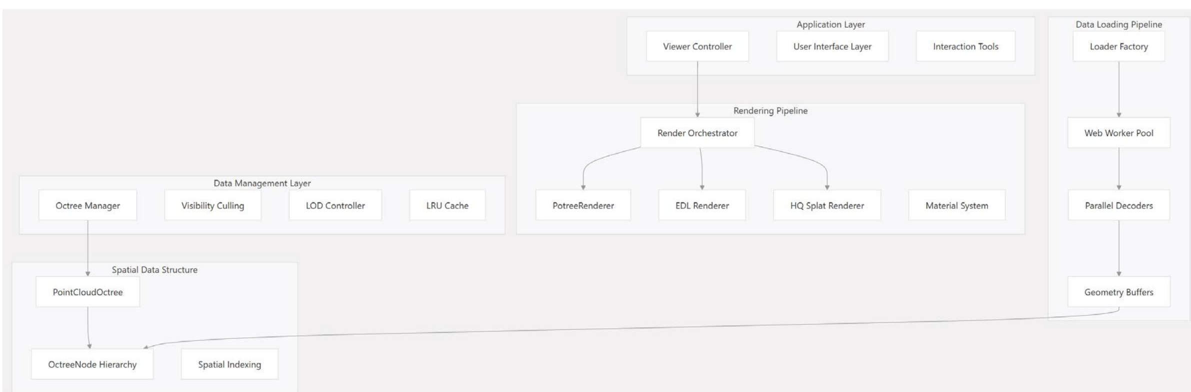

Figure 2.1 Overall architecture of the original Potree

The following are Potree's core architectural components:

- *Viewer Controller Framework*: The Viewer class serves as the central orchestrator, implementing an event-driven architecture that coordinates all subsystems. It manages the complete application lifecycle, from initialization through rendering and user interaction handling.
- *Hierarchical Spatial Data Structure*: The system employs a sophisticated octree-based spatial partitioning scheme through the PointCloudOctree class. Each PointCloudOctreeNode represents a spatial subdivision containing geometric data and maintains parent-child relationships for efficient hierarchical traversal.
- *Multi-Pipeline Rendering Architecture*: The rendering subsystem implements multiple specialized pipelines through distinct renderer classes: standard point cloud rendering, Eye-Dome Lighting (EDL) for enhanced depth perception, and high-quality splatting for superior visual fidelity. The rendering orchestrator dynamically selects appropriate pipelines based on performance requirements and quality settings.
- *Asynchronous Data Loading Infrastructure*: A robust parallel processing architecture utilizes Web Workers for non-blocking data decoding and geometry preparation. The system supports multiple data formats through a unified loader factory pattern, abstracting format-specific implementations.

Potree has an advanced rendering pipeline:

- *Level-of-Detail (LOD) Management*: An adaptive LOD system dynamically adjusts point cloud resolution based on viewing distance, screen-space error metrics, and performance constraints. This enables real-time visualization of datasets containing billions of points.
- *Shader-Based Material System*: The PointCloudMaterial implements a flexible attribute-based rendering system using OpenGL Shading Language (GLSL) shaders. The material system supports multiple visualization modes, including RGB, elevation, intensity, and classification-based coloring schemes.
- *Frustum and Occlusion Culling*: Sophisticated visibility determination algorithms eliminate non-visible geometry before rendering, significantly improving performance for large datasets.

Potree's memory management and performance optimization consists of these elements:

- *LRU Cache Management*: The system implements intelligent memory management through least recently used (LRU) caching strategies, ensuring optimal memory utilization while maintaining interactive performance.
- *Point Budget System*: A configurable point budget mechanism dynamically adjusts rendering quality to maintain target frame rates. The system automatically balances visual quality against performance requirements.

Modular component architecture: The codebase demonstrates exemplary modular design through ES6 module exports covering distinct functional domains: core data structures, material systems, data loaders, utility functions, navigation controls, and visualization tools. This architecture facilitates maintainability, extensibility, and selective feature loading. Tool System Architecture: Interactive tools are implemented as pluggable components that integrate seamlessly with the viewer framework. Each tool maintains its state management and event handling while leveraging shared infrastructure for scene interaction.

Data format abstraction layer: The system implements a sophisticated data format abstraction layer supporting multiple point cloud formats, including Entwine point tiles (EPT), cloud-optimized point clouds (COPC), and legacy point cloud formats. Format-specific loaders handle data parsing and conversion to the internal octree representation, ensuring consistent behavior regardless of source format. This architecture demonstrates advanced software engineering principles, including separation of concerns, dependency inversion, and plugin-based extensibility, resulting in a robust and scalable point cloud visualization platform.

2.2.2 Potree Library Customization

To optimize the Potree platform for large-scale point cloud visualization, the research team introduced several key enhancements to its core architecture:

- *Accelerated Octree Structure*: Implemented a customized octree initialization logic and extended its functionality for more efficient hierarchical data access.
- *Rendering Optimization via Resampling*: Integrated both random and Poisson resampling strategies within the `PointCloudLoader()` module to enhance rendering performance and reduce visual redundancy.
- *GPU-Based Rendering Enhancements*: Applied GPU-level optimizations within the `renderScene()` function to support smooth and responsive visualization of dense point cloud datasets.
- *Customizable Input Controls*: Developed a flexible user input system through `inputHandler()`, enabling users to define custom hotkeys and navigation schemes for improved interaction.
- *Flexible Data Format Support*: Extended compatibility with diverse data sources by designing modular formatting and parsing mechanisms.
- *Native GIS Integration*: Incorporated direct support for JSON and GeoJSON formats to enable seamless integration with GIS workflows.

These enhancements collectively improved Potree's scalability, efficiency, and adaptability for infrastructure visualization and geospatial analysis. The following sections provide more details on these customizations.

Data loading optimization: The increasing scale and complexity of point cloud datasets, often reaching terabytes, demand the continuous refinement of visualization platforms like Potree.

To address this, the research team has identified the most impactful and practical strategies for optimizing the data structure and the loading architecture of the Potree platform. The most effective enhancement centers on incremental data loading based on viewport relevance, prioritizing point cloud tiles based on the user's view and interaction context. Instead of uniformly loading all visible tiles, this approach uses screen-space relevance and spatial proximity to decide which nodes should be rendered first. This significantly reduces unnecessary data transmission and memory usage while improving the user's perception of speed and responsiveness. Complementing this are several condensed strategies that offer additional performance improvements:

- *Parallel Node Decoding with Web Workers*: Enables simultaneous decoding of multiple nodes using a dynamic background thread pool, reducing CPU bottlenecks and improving throughput during large dataset transitions.
- *Adaptive Octree Subdivision*: Enhances spatial indexing by dynamically adjusting the granularity of octree nodes based on local point density. This yields finer resolution in detailed regions while conserving memory in sparse areas.
- *GPU Buffer Streaming*: Replaces monolithic buffer uploads with incremental vertex buffer object (VBO) streaming, allowing point batches to be processed and rendered in real-time without stalling the rendering pipeline.
- P*rogressive Voxel-Based Refinement*: Employs a coarse voxelized LOD as a placeholder immediately after loading, progressively refined with high-fidelity data. This ensures a responsive initial load experience, even for extremely large scenes.

Together, these strategies establish a scalable foundation for rendering massive point cloud datasets in real-time, ensuring Potree remains an effective solution for infrastructure visualization and national-scale asset monitoring. Table 2.1 lists all the relevant files and functions with the corresponding optimizations.

Table 2.2 Detailed functions and files customized for data loading optimization

File	Functions Modified/Added	Description
`OctreeLoader.js`	`loadHierarchy()` `getVisibleNodes()`	Adapt hierarchy loading to account for viewport-based prioritization
`PointCloudOctree.js`	`updatePointClouds()`	Update logic to support adaptive LOD and dynamic octree subdivision
`PotreeRenderer.js`	`render()`	Integrate GPU buffer streaming and progressive voxel LOD rendering
`PointCloudOctreeGeometryNode.js`	`load()`	Implement partial VBO uploads and chunk-based GPU data transfer
`PointCloudOctreeGeometry.js`	`parse()`	Optimize for parallel decoding and attribute-specific data loading
`WorkerPool.js`	`schedule()`	Enable decoding thread parallelism with dynamic worker allocation
`viewer.js`	`update()`	Monitor camera state and feed viewport relevance to loader and scheduler
`OrbitControls.js`	`update()`	Extract camera velocity/direction for predictive node prefetching
`PointAttributes.js`	`construct()`	Support selective attribute loading configuration
`SmartQueueManager.js` *(new)*	`prioritizeQueue()` `dispatchTasks()`	Implement intelligent loading based on screen-space, distance, and semantic relevance

User input control customization: To enhance the flexibility and usability of the Potree platform, a modular input control system was developed to allow users to define custom interaction schemes. This enhancement has proven particularly valuable for infrastructure, GIS, and digital twin environments professionals who require tailored workflows. The system assigned actions, such as toggling measurement tools, clipping planes, or navigation modes, to custom key and mouse input combinations. The core of this system involved the implementation of a centralized module named `InputControlManager.js`. This module tracked real-time keyboard and mouse states and mapped them to user-defined actions. By providing a clean application programming interface (API) to register, unregister, and update input bindings, the system allowed full customization of control schemes without requiring modifications to the core logic.

The input manager was initialized in `viewer.js`, where users registered control mappings. For instance, hotkeys like "M" activated a measurement tool, while a combination such as `Ctrl+LeftClick` triggered a clipping box. All bindings were managed internally to prevent conflicts and ensure consistent execution. Users defined their input mappings via a structured configuration file, i.e., `inputBindings.json`. This enabled the system to read, parse, and apply preferences at runtime. For example, the JSON file maps keys like "m" to `toggleMeasurement` or "control+MouseLeft" to `activateClipping`, creating a consistent and user-driven interaction model.

To support broader usability, real-time feedback, and override capabilities were implemented. The system notified users of unrecognized or conflicting bindings and allowed them to enable, disable, or override mappings as needed. These features were exposed through a dedicated user interface panel, `InputSettingsPanel.js`, which provided a graphic user interface- (GUI)-based customization for non-technical users. Table 2.2 lists all the relevant files and functions with the corresponding hotkey control, and Table 2.3 lists all the recommended hotkeys and combinations.

Table 2.3 Detailed functions and files customized for user input control

File	Functions Modified/Added	Purpose
`InputControlManager.js`	`registerBinding()`, `handleKeyDown()/MouseDown()` `executeBinding()`	Core logic for binding input combinations to commands
`viewer.js`	`initInputControls()` `applyUserBindings()`	Initialization and application of user-defined input configurations
`OrbitControls.js`	`bindCustomInputs()`	Optional override of navigation behavior for customized input support
`InputSettingsPanel.js` (new)	`loadBindingsUI()` `saveBindings()`	Interface for GUI-based input customization and preference management

Table 2.4 Recommended hotkeys and combinations for typical operations

Action	Recommended Hotkey or Combination
Toggle Measurement Tool	`M`
Measure Point Coordinate	`Shift + P`
Measure Distance Between Points	`D`
Activate Clipping Box	`Ctrl + Left Mouse Click`
Zoom to Full Extent	`Z`
Toggle Annotation Tool	`A`
Enable/Disable EDL Renderer	`E`
Reset View	`R`
Rotate View Mode	`Space`
Navigate (Orbit Mode)	`Right Mouse Click + Drag`
Move Camera (Pan Mode)	`Shift + Left Mouse Click + Drag`
Select Point	`Ctrl + Shift + Left Mouse Click`

Data compatibility improvement: In addition to user input configuration, Potree relies on preprocessing tools like `PotreeConverter` to structure point cloud data for web visualization. PotreeConverter supports various formats used in 3D scanning, photogrammetry, and LiDAR. Table 2.4 summarizes the supported formats and their typical use cases and limitations:

Table 2.5 Detailed data format included in the data compatibility improvement

Format	Description	Notes
LAS	Standard uncompressed LiDAR format	Full attribute support
LAZ	Compressed LAS format (via LASzip)	Most efficient and preferred for large datasets
PLY	Polygon file format for point clouds	Less consistent attribute support
XYZ/TXT/CSV	Delimited text file with XYZ	Requires manual attribute declaration
E57	Rich format for 3D scanning data	May need external libraries
PTX	Structured point cloud grid format	Less common, slower to process

Despite this broad support, PotreeConverter has several limitations regarding data compatibility. GeoJSON, shapefile, and other vector formats are not supported as input, and any semantic or tabular metadata must be stripped or preprocessed before use. Custom attributes (e.g., material type, reflectivity beyond intensity) are ignored unless mapped to known Potree attributes during conversion. In addition, formats like `.e57` are not fully supported across all builds due to their dependency on external libraries such as `libE57Format`, which may cause compatibility issues on some systems. When using simple text-based formats like `.xyz`, users must explicitly define attribute mappings (e.g., to include RGB or intensity), or the converter may discard unrecognized columns. Lastly, all datasets must be converted to a supported spatial reference system before conversion, as Potree does not reproject input data. Careful preparation and validation of input formats are essential to ensure reliable visualization output.

In this study, the research team adopted the script of `LAS2LAS`, `LAS2TXT`, and `TXT2LAS` from the LASTools and integrated it with the Potree utility of PotreeConverter, which enables the customized Potree platform to support all types of 3D point cloud formats with necessary attributes.

2.3 GIS Data Integration

In this study, one of the key objectives is to develop a prototype platform that can natively support GIS data integration (including from GIS to Potree and Potree to GIS) so that the subsequent data analysis and decision-making for MassDOT is possible. While Potree performs well in displaying high-resolution 3D environments, its capabilities in handling traditional geospatial vector data formats remain limited. In particular, GeoJSON, a widely adopted open standard for encoding various geographic data structures, has not been fully integrated into the Potree framework at a native level. To advance Potree's applicability in infrastructure planning, spatial analytics, and asset management, particularly for state departments of transportation, this report outlines a technical workflow that enables full GIS integration using GeoJSON. The integration covers three progressive levels of complexity: data-level overlays, measurement-based analytical support, and network-level modeling and interaction.

- *GIS Data Integration Using GeoJSON:* The most basic level of GIS integration has involved the ability to visualize GeoJSON-encoded geographic features, points, lines, and polygons alongside 3D point cloud data within Potree's rendering environment. Currently, Potree does not support direct parsing or the rendering of GeoJSON files. Users have relied on manual scripting using `Three.js` to convert GeoJSON objects into renderable geometries. This workaround has limited scalability and integration potential. To enable native support, a new module, provisionally named `GeoJSONLoader.js`, has been implemented. This module has been designed to load GeoJSON files, interpret their geometry, and generate the appropriate visual elements for display in the Potree viewer. The system has also required the addition of support for coordinate transformation. Since GeoJSON data typically uses WGS84 (EPSG:4326) and many point clouds employ local or projected systems, a projection utility such as `proj4.js` needs to be integrated and managed through an enhanced version of `Projection.js`. Feature layers have also required visibility management and interaction support. The `Viewer.js` and `Sidebar.js` modules have been extended to allow users to toggle vector layers, adjust rendering styles, and control visibility. Furthermore, the display of feature attributes stored in the `properties` field of GeoJSON has been made accessible through interactive UI elements managed by the updated `AttributesPanel.js`. These developments have allowed users to view and interact directly with geospatial metadata linked to infrastructure elements within the 3D scene.
- *Measurement Integration with GeoJSON Features:* The second integration level has involved enhancing Potree's measurement tools to interact with GeoJSON-derived features. In its existing form, Potree has allowed users to measure distances and profiles only within the point cloud data, with no capacity to reference vector data. This limitation has made it challenging to compare real-world spatial measurements with design or inventory data encoded in GIS formats. The measurement module `MeasuringTool.js` has been modified to support snapping behavior to overcome this. This functionality has allowed users to anchor measurement points onto the nearest feature in a loaded GeoJSON layer, such as a road centerline, property boundary, or utility alignment. This has significantly improved the precision of user-driven measurements. Additionally, it has been necessary to extract elevation profiles along GeoJSON-defined paths, such as

roadways or pipelines. `ProfileTool.js` has been updated to accept a LineString geometry from a GeoJSON feature and to sample the underlying point cloud along that path. Projection utilities in `GeoUtils.js` have facilitated accurate alignment between 2D vector data and 3D surface points. To support contextual analysis, the system has also displayed feature attributes dynamically during measurement. For instance, when measuring from a pole to a utility line, the viewer has shown the selected asset's installation year, material type, or maintenance status. This contextual linkage between geometry and metadata has been critical for engineering review, inspection planning, and regulatory assessment.

- *Full Network-Level Integration and Spatial Analysis:* The most advanced level of integration has focused on representing and interacting with large-scale infrastructure networks encoded in GeoJSON, including transportation systems, drainage networks, and utility corridors. Potree has not previously included mechanisms for managing or analyzing topological relationships in vector data. To address this gap, the system has required several significant architectural enhancements. A hierarchical layer manager has been introduced by expanding `LayerManager.js` and `Viewer.js`. This enhancement has allowed infrastructure layers, such as roads, bridges, water lines, and power cables, to be organized into structured groups. Users have been able to control the visibility and styling of each group independently. Additionally, the system has supported dynamic styling based on feature attributes. A dedicated module named `GeoStyler.js` has been introduced to evaluate attribute queries and apply visual encodings, such as color gradients based on age, thickness, or traffic volume. To support network-level analysis, a new module named `NetworkAnalyzer.js` has been developed. This module has interpreted connected LineString geometries and enabled topological analysis such as downstream tracing, connectivity validation, and service area detection. These functions have been particularly useful in applications involving water systems, electrical grids, or pavement management networks. Backend data integration has also been introduced through a module named `DataFetcher.js`, which has allowed Potree to retrieve external data records based on feature IDs. For example, when a user clicks on a bridge, the system retrieves associated maintenance reports or condition assessments from an external asset management database via representational state transfer-ful (RESTful) APIs.
- *User Interaction and Hotkey Mapping:* To facilitate efficient GIS interaction within Potree, enhancements have been made to the input handling system. The `InputHandler.js` module has been updated to support keyboard shortcuts and interactive gestures tailored to GIS workflows. Users can press the `G` key to toggle GeoJSON layer visibility, use `Ctrl + Click` to snap a measurement to a vector feature, or press `Shift + G` to cycle through thematic layers. Additionally, holding the `Alt` key while hovering over a feature has triggered the display of detailed attribute data. These interactions have increased the user experience's intuitiveness and allowed domain

professionals, such as engineers and inspectors, to conduct complex spatial evaluations more efficiently within the Potree environment.

Transportation agencies typically maintain extensive spatial databases, road centerlines, bridges, signage, pavement condition, and drainage infrastructure, stored in formats such as Esri File Geodatabases (.gdb), shapefiles (.shp), and enterprise geospatial databases. These formats, while powerful, are not natively compatible with Potree. To support visualization and interaction with such data in Potree, agencies can export GIS layers to GeoJSON, which Potree can ingest and render as vector overlays aligned with 3D point clouds. Conversely, annotations, measurements, or inspection updates generated within Potree can be exported as GeoJSON and re-imported into the agency's GIS, where they can be re-integrated into enterprise databases or used to trigger workflow actions (e.g., maintenance scheduling). The research team investigated the following workflows using GeoJSON as the intermediate data structure and demonstrated the tight cross-platform integration between Potree and MassDOT's GIS. The following workflows are recommended for future implementation of the Potree platform in MassDOT.

Going from GIS to Potree (data import) involves the following steps:

- *Step 1: Export GIS Layers to GeoJSON.* MassDOT can begin by exporting specific spatial layers of interest (e.g., curb lines, sign locations, road edges) from their GIS software (such as ArcGIS Pro or QGIS). Most GIS tools provide built-in functionality to export layers as GeoJSON. Care should be taken to include relevant attributes (e.g., asset ID, material type, condition status, inspection date) during export.
- *Step 2: Coordinate System Alignment.* Most GIS data will be stored in local state plane or UTM projections. GeoJSON, by default, uses WGS84 (EPSG:4326). Since Potree often uses projected coordinates aligned with the point cloud's CRS, the exported GeoJSON should either (a) be reprojected to match the point cloud CRS using GIS tools before export or (b) be dynamically transformed within Potree using integrated libraries like `proj4.js`.
- *Step 3: Load GeoJSON into Potree***.** The GeoJSON files are loaded into Potree using a custom or native `GeoJSONLoader`. Each geometry (Point, LineString, Polygon) is rendered using `Three.js` primitives. Attribute data from the `properties` field is accessible via hover or click in the Potree UI. The loaded layers can be styled (e.g., by type or condition) and toggled interactively for review alongside the point cloud data.

The workflow From Potree to GIS (data export) involves the following steps:

- *Step 1: Create Annotations or Edits in Potree.* Users performing inspections or validations in Potree can create annotations (e.g., marking utility pole locations or measuring offset to road centerlines) using Potree's measurement tools or custom editing interfaces. These actions result in geometry (points, lines) paired with user-entered or system-generated attributes (e.g., `status: "needs repair,"` `distance: 0.75m`).
- *Step 2: Export as GeoJSON.* These newly created features are serialized into GeoJSON format. Each feature contains a geometry (in 3D coordinates where needed) and a `properties` object that may include fields like `user`, `timestamp`, `observation`, or `priority`.
- *Step 3: Re-import into the GIS Environment.* The exported GeoJSON is then imported back into the agency's GIS environment. Both ArcGIS and QGIS support GeoJSON import directly. During import, attributes can be mapped to database fields in the destination geodatabase or shapefile. Features can also be spatially joined to existing layers using unique IDs or proximity to existing assets.

2.4 Summary

This section presents a comprehensive methodology for developing a web-based LiDAR visualization platform tailored for transportation agencies like MassDOT. The research was structured into three main components: a literature review, developing a customized Potree platform, and integrating external GIS data. The literature review evaluated LiDAR technologies, data characteristics, and various existing visualization tools. Potree emerged as the most suitable foundation due to its open-source framework, browser-based rendering capabilities, and scalability for massive datasets. Prototype development focused on enhancing Potree's performance, usability, and compatibility, optimizing data loading using viewport-aware prioritization, and GPU streaming.

- Improved level-of-detail rendering and parallel node decoding.
- A modular hotkey-based input control system allowing user-defined interactions.
- Extended data format support through integration with LASTools and PotreeConverter.

GIS integration was implemented across three levels:

- Basic visualization of GeoJSON layers using a custom `GeoJSONLoader.js` module and coordinate transformation via `proj4.js`.
- Measurement integration enables snapping to vector features and extracting elevation profiles from point clouds.

- Network-level analysis using hierarchical layer management, attribute-based styling, and topological tracing via new modules like `NetworkAnalyzer.js`.

Bidirectional workflows were established between Potree and GIS platforms. GIS layers (e.g., shapefiles, geodatabases) can be exported as GeoJSON for display in Potree. Conversely, Potree annotations and measurements can be exported back as GeoJSON for reintegration into GIS systems. These developments significantly advance Potree's capabilities as a geospatial analysis tool, providing transportation agencies with a powerful, extensible platform for infrastructure visualization, inspection, and asset management.

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3.0 Case Studies

To demonstrate the capabilities and versatility of the Potree-based visualization platform, five representative case studies were conducted across key areas of transportation infrastructure management and presented in this section. These case studies included bridge inspection, roadway asset management, project estimation, horizontal curve safety analysis, and statewide LiDAR data management. Each case study showcased how Potree could be applied to visualize, measure, and interpret large-scale point cloud datasets while supporting GIS integration, interactive analysis, and cross-team collaboration. They highlight the platform's potential to enhance decision-making, streamline workflows, and support data-driven practices for transportation agencies like MassDOT.

3.1 Use Case 1—Bridge Inspection

Bridge infrastructure requires continual inspection and evaluation to ensure safety and longevity. In this case study, the research team demonstrates the application of Potree as a foundational platform for performing interactive bridge inspections using LiDAR data. The inspection workflow focused on two primary objectives: (1) bridge geometry assessment using mobile LiDAR and (2) bridge deck condition evaluation for cracking analysis.

3.1.1 Bridge Geometry Inspection with Mobile LiDAR

The geometric evaluation focused on a 4GB dataset collected using a mobile LiDAR scanning system. This dataset captured essential roadway and bridge deck features, including cross slopes, curb heights, and lane widths. Potree processed and rendered this data within a web environment, offering real-time, interactive visualization. This setup enabled fast, intuitive interpretation of spatial relationships and roadway characteristics, improving the accuracy and accessibility of bridge geometric evaluations. Figure 3.1 shows an example of the processed and visualized data for the bridge geometry inspection use case.

- *Data Preparation*: The raw LiDAR point cloud was converted into Potree format using PotreeConverter, enabling efficient web-based rendering.
- *Geometric Analysis*: Practitioners conducted simple operations such as distance, slope, and angle measurements directly within the Potree viewer.
- *Flexible Access*: Both offline and online versions of Potree were deployed to support field and office use.
- *GIS Integration*: Using external GeoJSON overlays, the extracted geometry was linked with statewide GIS datasets to enhance data usability across DOT systems.

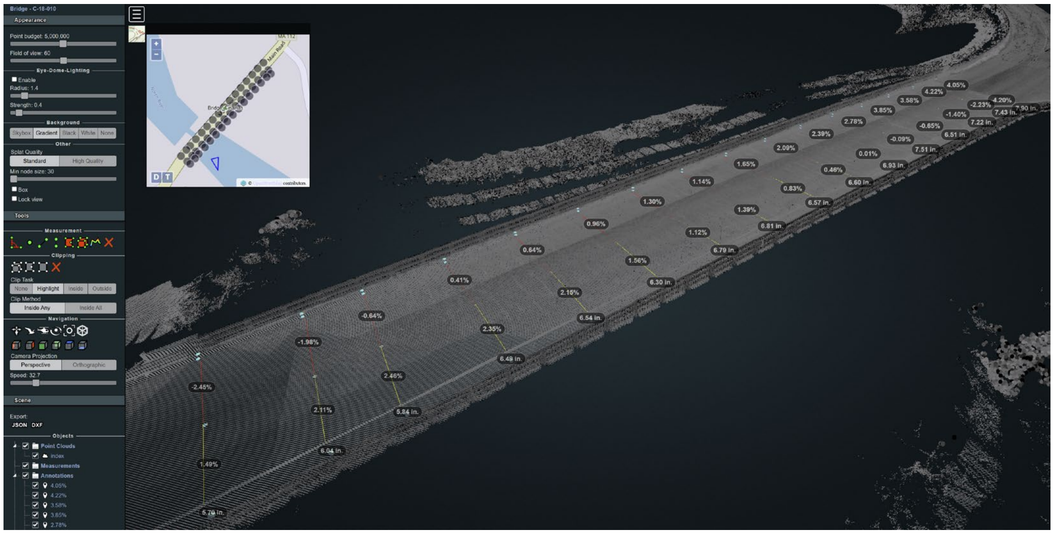

Figure 3.1 Bridge geometry inspection case using the customized prototype platform

3.1.2 Bridge Deck Surface Condition Evaluation Using High-Resolution LiDAR

For the second objective, Potree was applied to a 400GB dataset representing high-resolution scans (i.e., Artec Leo scanner) of bridge deck surfaces. The objective was to identify and evaluate surface cracking through detailed raw point cloud data inspection. Figure 3.2 shows an example of the processed and visualized data for the bridge deck condition evaluation use case.

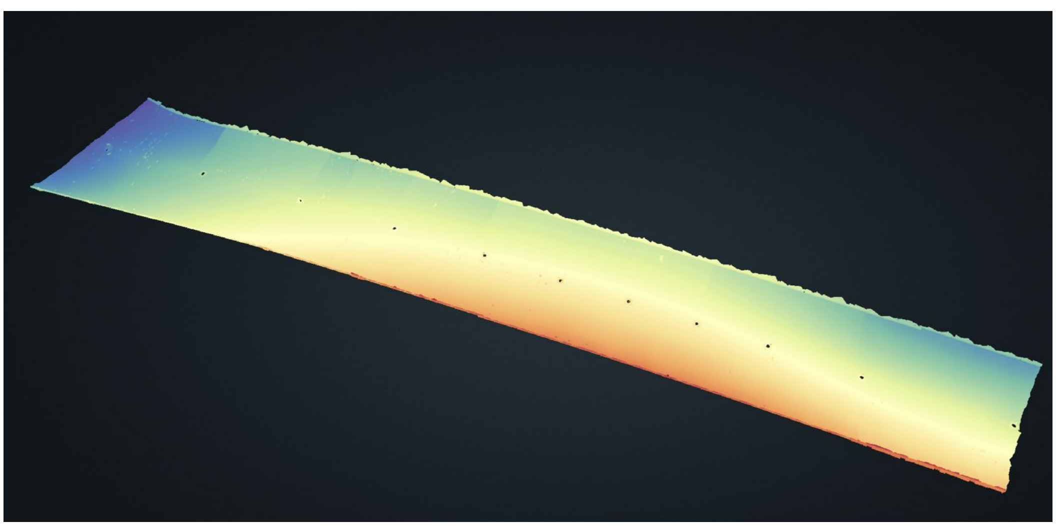

Figure 3.2 Bridge deck surface condition evaluation use case using the customized prototype platform

- *Data Volume Management*: Given the large data size, the dataset was tiled and optimized using customized PotreeConverter settings to maintain fidelity while enabling browser-based navigation.
- *Crack Detection Workflow*: Offline algorithms were used to preprocess the point cloud and extract crack patterns rendered in Potree with color mapping to highlight severity and extent.
- *Multi-Layered Visualization*: Users could toggle between the raw point cloud and annotated crack layers within Potree, facilitating better diagnostics and cross-validation.
- *GIS Pipeline*: Detected surface defects were encoded in GeoJSON and shared with transportation GIS systems to support condition rating and maintenance prioritization.

This case confirmed Potree's capability to manage and present large-scale point cloud datasets while preserving the resolution required for micro-level defect detection. Table 3.1 lists the detailed features and benefits of using the customized bridge geometry and condition evaluation platform.

Table 3.1 Customized features and benefits for bridge geometry and condition evaluation

Capability	Bridge Geometry	Deck Surface Evaluation
Web-Based Visualization	Enabled remote geometry review	Allowed inspection of 400GB point cloud in browser
Real-Time Measurements	Distance, slope, and elevation tools	Used to confirm the depth of cracks and surface depressions
Layered Views	Compared extracted geometry to design baselines	Switched between raw, processed, and crack-highlight layers
GeoJSON Integration	Linked extracted features with GIS	Geolocated cracks and surface defects in spatial databases
Scalability	Efficient for mobile LiDAR datasets	Maintained performance even with massive terrestrial scanning data

3.2 Use Case 2—Asset Management

Effective roadway asset management requires detailed inventory, classification, and condition evaluation of roadside elements such as pavement markings, signs, poles, sidewalks, parking features, and vegetation. In this case study, Potree managed and interpreted a large-scale mobile LiDAR dataset for Route 126, integrating object extraction workflows with GIS systems to support intelligent asset tracking and decision-making with over 26GB of mobile LiDAR data. The developed prototype Potree platform was used as the core visualization platform due to its ability to support interactive inspection and GIS integration at scale. The implementation followed a three-staged flow: data conversion and tiling, interactive asset review, and GIS export and integration. Figure 3.3 shows an example of the processed and visualized data for the asset management use case. Figure 3.3 shows the original point cloud data (left), the segmented results (middle), and the exported GIS results in ArcGIS Pro (right).

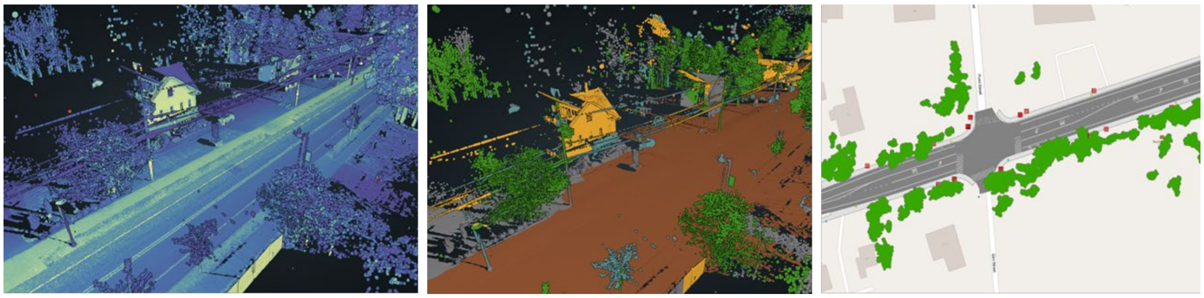

Figure 3.3 Asset management use case using the customized prototype platform

The first step in the Potree workflow involved preparing the raw LiDAR data. These files, originally in LAS format, were processed using PotreeConverter. Specific parameters were carefully selected to balance resolution fidelity with performance. A point spacing of 0.01 meters was configured to ensure that small yet significant roadway features, such as curb lips, thin pavement markings, or pole bases, would be preserved during downsampling. The converter was instructed to retain key point attributes, including intensity, classification labels, and RGB values, allowing for multi-dimensional filtering and visualization downstream. The material rendering was also configured with Eye Dome Lighting to improve depth perception in dense urban scenes. Once processed, the output was structured as a standalone Potree project and deployed initially on a local server. It was later transitioned to cloud storage behind a CDN to support distributed access across multiple stakeholder offices and field teams.

With the Potree scene prepared, the project team shifted focus to configuring the viewer interface and embedding thematic intelligence. The classified point cloud was visually encoded with a custom color mapping scheme that assigned distinct hues to different asset classes: sidewalks appeared in cyan, vegetation in green, traffic poles in red, and signage in yellow. This color encoding was overlaid dynamically using the classification attributes preserved during conversion. Such visual segmentation enabled rapid visual parsing of the corridor, allowing users to isolate and examine individual asset types easily.

Beyond color coding, Potree was extended through JavaScript interface enhancements. A custom control panel was added to the sidebar, allowing users to toggle individual asset layers on and off. This interactivity proved especially useful when overlapping features, such as trees near utility poles or road markings beneath parked vehicles, required isolation for accurate classification review. The built-in measurement tools were also customized with preset values commonly used in transportation design, allowing for quick verification of standard features such as lane widths, sidewalk offsets, and pole clearances. A live data panel was developed to display positional coordinates, classification IDs, and intensity values under the user's cursor, streamlining error detection and quality control to support on-the-fly update of point attributes.

For object validation, Potree was instrumental in supporting both manual and semi-automated review processes. Analysts and field inspectors accessed the scene through browsers on desktops and tablets, where they performed targeted quality assurance on previously classified features. Misclassifications, such as a tree labeled as a signpost or a light pole missed by automated routines, were flagged using Potree's built-in annotation tools. These annotations were spatially anchored and preserved across sessions, allowing for collaborative validation. Analysts also used bookmarks and camera path tools to document specific locations, ensuring continuity between field and office assessments. Annotated sessions were exported in JSON format and re-imported for centralized reconciliation or QA/QC logs integration.

The corrected and validated features were prepared for integration into GIS systems after the verification phase. Asset layers, identified initially within the point cloud, were extracted and saved as GeoJSON or Shapefile outputs. Each object carried structured metadata, including its object type, geospatial coordinates, height, and reference IDs used in DOT inventory systems. These data layers were imported into enterprise GIS platforms and joined with existing asset registries. The Potree viewer was configured to display additional spatial overlays, including parcel boundaries, right-of-way lines, and roadway centerlines, using shapefile plugins to enhance contextual understanding. This provided a powerful visual reference for checking spatial consistency between newly extracted assets and legacy map layers.

To support broad accessibility and maintain responsive performance, Potree was deployed with scalability in mind. The web viewer dynamically loads data tiles based on the user's zoom level and viewport, leveraging adaptive LOD rendering to balance fidelity and frame rate. Point clouds were culled outside the view frustum, reducing system overhead on lower-performance field tablets. Using CDN further ensured that scene tiles loaded rapidly over limited bandwidth connections.

Altogether, Potree's implementation in the Route 126 project facilitated the visualization of large-scale point cloud data and transformed it into a fully interactive, GIS-compatible, and quality-controlled asset management tool. It allowed analysts to validate classification accuracy visually, empowered inspectors to validate roadway features in 3D, and provided a scalable means to bridge LiDAR data with statewide transportation infrastructure databases. Through this carefully tailored deployment, Potree enabled a new digital, decentralized, and data-rich roadway asset management paradigm. Table 3.2 lists the detailed features and benefits of using the customized platform for transportation asset management.

Table 3.2 Customized features and benefits for transportation asset management

Capability	Description
Scalable Visualization	Enabled responsive handling of 26GB mobile LiDAR data through multiscale LOD rendering.
Rich Scene Interpretation	Allowed interpretation of mixed-use urban corridors with complex visual environments.
Cross-Platform Accessibility	Supported browser-based access on desktops and mobile devices, ideal for field teams.
Layered and Colored Views	Helped classify, isolate, and verify roadway asset types with customized symbology.
Interactive Measurement and Annotation	Allowed precise object size, spacing, and offset measurements to support data validation.
GIS Pipeline Compatibility	Extracted objects were easily converted into geospatial formats for integration with ArcGIS or QGIS.

3.3 Use Case 3—Project Estimation

Infrastructure improvement projects require comprehensive, data-driven estimation of work quantities, ranging from curb replacements and guardrail upgrades to drainage improvements and vegetation removal. Traditional estimation methods are often manual, labor-intensive, and spatially disconnected from reality. Potree was employed as a centralized visualization and measurement platform in this case study to streamline project estimation along Route 6 using 74GB of mobile LiDAR data. By offering interactive 3D exploration, geometric verification, object quantification, and GIS interoperability, Potree helped engineers produce more accurate, defensible, and visually validated quantity estimates.

The initial step in the implementation involved preprocessing the point cloud data using PotreeConverter. The converter was configured to preserve classification and intensity attributes essential for distinguishing between different feature types, such as curbs, drainage structures, vegetation, and signage. The conversion process employed a refined tiling strategy and a multi-resolution LOD structure, ensuring that small-scale features such as reflector poles and catch basin inlets were clearly rendered even at full zoom. Eye Dome Lighting was enabled during conversion to improve object edge contrast, a vital enhancement for distinguishing hardscape boundaries in cluttered roadside scenes.

Once the dataset was transformed into a Potree-compatible format, a dedicated web viewer instance was created and hosted on a project-specific server. This deployment allowed engineers, designers, and inspectors to access the 3D scene using standard web browsers without plug-ins or software installations. The Potree interface was heavily customized for the project, with feature-specific color mappings that differentiated asset classes. Curb edges were rendered in white or light gray, drainage structures in blue, guardrails in metallic tones, vegetation in green, and signage in vivid hues. These distinctions provided immediate visual feedback about the corridor's asset type and spatial distribution.

The interface also integrated advanced interactive controls to support detailed estimation tasks. Potree’s measurement tools were enhanced with user presets aligned to standard transportation design units. This allowed practitioners to quickly measure curb lengths, offset distances, drainage slopes, and vegetation encroachments with minimal manual input. For instance, when estimating tree removal zones, users could delineate the horizontal buffer from the pavement edge and visually assess which tree trunks fell within the work limits. Likewise, when evaluating drainage upgrades, Potree’s vertical measurement tools were employed to confirm the inlet depth relative to adjacent grade or to assess sag point elevations.

The platform incorporated classified point cloud layers generated from offline processing tools to support asset-level estimation. These layers identified features such as signs, poles, utility boxes, and guardrails using shape-based segmentation and spatial filtering. Within Potree, these classified features were overlaid as distinct, selectable elements. Users could isolate them by class, visually validate their locations, and manually adjust the counts. For instance, signposts identified by automatic routines were reviewed in Potree to confirm their presence and orientation. Engineers could annotate misclassified features directly within the viewer, attach notes, and export the annotations as JSON or GeoJSON files for integration with estimation sheets.

In critical asset counts, such as the number of catch basins to be replaced or linear footage of guardrails to be upgraded, Potree served as both a measurement engine and a visual audit tool. Engineers used the scene to tally feature instances while simultaneously validating their spatial accuracy. Potree’s bookmarking and camera view tools made these tasks more effective, allowing users to document key locations, intersections, or problematic conditions. Bookmarked views were then shared among team members for discussion and resolution, streamlining communication between GIS analysts, designers, and cost estimators.

GIS integration played a central role in this implementation. Potree was configured to load external shapefiles and GeoJSON overlays, including parcel boundaries, zoning layers, and utility locations. This enabled simultaneous review of extracted features and their administrative context. For example, when estimating sidewalk reconstruction near private property lines, Potree provided the 3D scan and the cadastral map in the same interface. This hybrid visualization was critical for determining right-of-way conflicts, utility relocation needs, and the extent of necessary grading or tree clearing.

To ensure system performance despite the large dataset, the Potree instance was optimized with server-side tile caching and view frustum culling. The viewer automatically adjusted point density based on zoom level and field of view, enabling smooth interaction even when accessed on standard field tablets. For distributed collaboration, the system supported secure access through user authentication and was backed by a cloud-hosted CDN, ensuring fast load times and seamless navigation for remote users.

Throughout the implementation, Potree became more than just a visualization engine; it served as an estimation control center. It allowed project engineers to transition from static design files and flat maps to immersive, data-rich scenes where every roadside object could be examined, measured, annotated, and validated. From quantifying how many feet of curbing needed to be realigned to measuring the vertical clearance under tree canopies to identifying outdated signage for replacement, Potree provided a versatile and intuitive environment that accelerated project planning and improved estimation accuracy. Figure 3.4 shows an example of the processed and visualized data for the project estimation use case: the original point cloud data (left), and exported GIS results with all types of assets and roadway geometry in ArcGIS Pro (right).

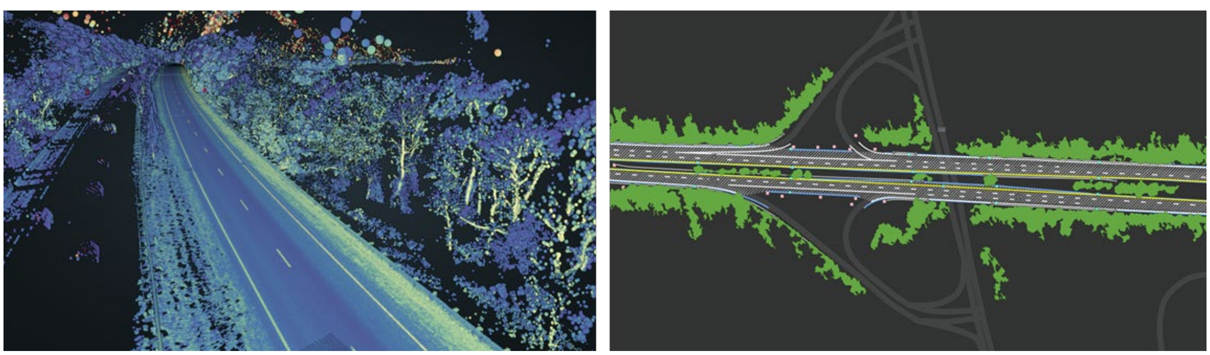

Figure 3.4 Project estimation use case using the customized prototype platform

Ultimately, Potree enabled a more precise and collaborative estimation process. It brought geometric reality into the estimation workflow, reduced reliance on field revisits, minimized overestimation risks, and allowed agency teams to anchor their cost projections in spatially and visually verifiable data. This implementation demonstrated Potree’s capacity to manage massive datasets and positioned it as an essential tool for data-driven infrastructure planning. Table 3.3 lists the detailed features and benefits of using the customized bridge geometry and condition evaluation platform.

Table 3.3 Customized features and benefits for transportation asset management

Features	Description
3D Feature Validation	Allowed visual confirmation of each asset slated for improvement, minimizing overestimation.
Interactive Quantity Takeoff	Enabled direct counting and measuring signs, guardrails, curb lengths, and tree encroachments.
Slope and Elevation Analysis	Used for verifying compliance of ramps, drainage slopes, and longitudinal grades.
Layer Isolation and Filtering	Streamlined analysis of drainage, pavement markings, and vegetation in isolation.
Collaborative Web Review	Facilitated shared estimation work among geographically dispersed teams.
Integration with GIS	Linked feature locations to maintenance zones and funding boundaries, improving prioritization.

A similar application of the developed platform for asset management has also been seamlessly expanded and deployed in other network-level efforts. Figure 3.5 shows an example of the visualization and the GIS integration of the network-level sidewalk inventory with detailed geometry and condition information: the original point cloud data with extracted sidewalk boundary (left) and the exported GIS results for District 4 in ArcGIS Pro (right).

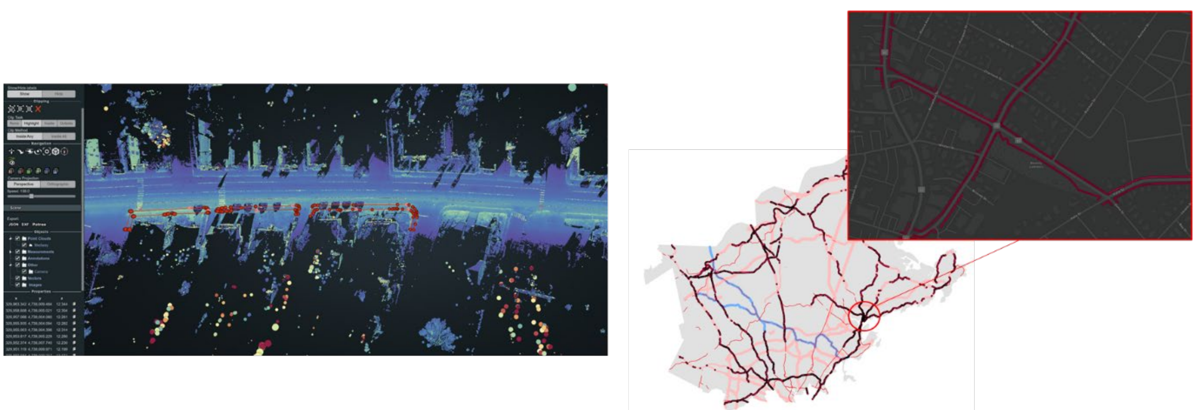

Figure 3.5 Project estimation use case using the customized prototype platform

3.4 Use Case 4—Horizontal Curve Safety

Horizontal curves on rural and suburban roadways are often the locations of reduced visibility, increased lateral force, and higher crash risk. Determining appropriate advisory speed limits and identifying optimal signage placement are essential components of proactive roadway safety management. In this case study, Potree was applied to the analysis of Route 113, using 17GB of mobile LiDAR data to assess curve geometry, extract superelevation profiles, and recommend advisory speeds, all through an interactive 3D visualization and measurement framework. Figure 3.6 shows an example of the visualization of the horizontal curve LiDAR data with detailed geometry and condition information.

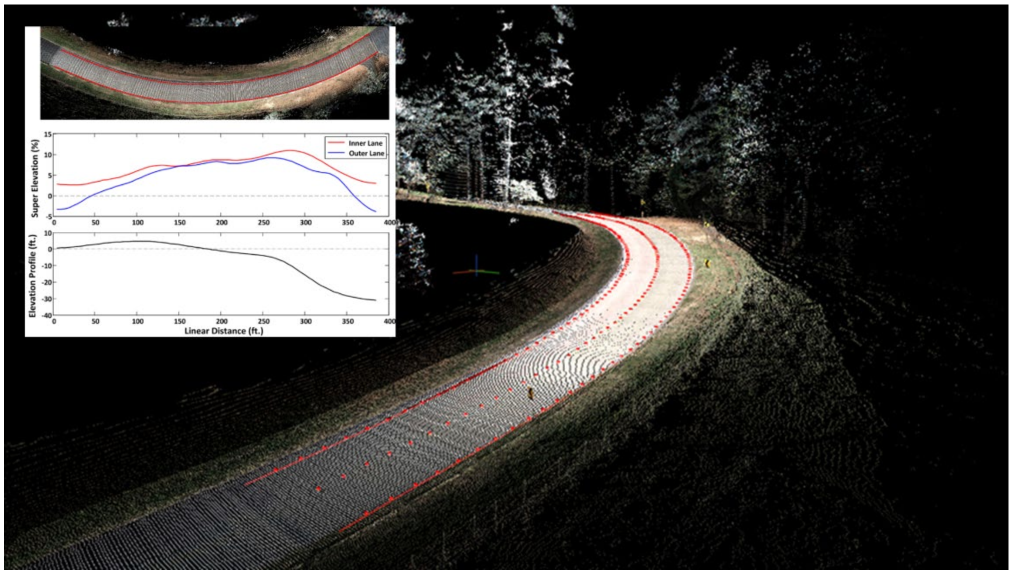

Figure 3.6 Project estimation use case using the customized prototype platform

The LiDAR data was first processed through PotreeConverter to support this analysis and create a web-compatible point cloud visualization. The converted dataset retained classification information (e.g., ground, road markings, trees), intensity values for feature discrimination, and RGB attributes to support visual fidelity. High-density tiling allowed curve segments to be examined at centimeter-level precision while maintaining smooth user interaction in the web browser.

Once the data was loaded into Potree, the analysis team configured the viewer to highlight road-related features essential to horizontal alignment analysis. Edge-of-pavement and centerline features were isolated using classification filters and color-coded within the viewer. In curved segments, the visual arc of the road was discernible due to the differentiation between travel lanes, shoulder edges, and roadside vegetation. Analysts used Potree’s measurement tools to extract horizontal chord lengths, curve radii, and transition lengths. These values were manually verified using annotations and polylines drawn directly within the scene.

Potree proved especially useful in calculating superelevation, which is critical for advisory speed determination. Users could extract elevation differences between the inner and outer travel lanes by using cross-section measurements perpendicular to the curve alignment.

Potree's slope and height tools were applied regularly along the curve to quantify lateral grade changes. These measurements were then exported and used as inputs to the calculation of the recommended advisory speed, according to the AASHTO Green Book formula:

$$V = 15(R(e + f))$$

where V is advisory speed (mph), R is the radius of curve (ft), e is the superelevation (ft/ft), and f is the side friction factor.

With the advisory speeds calculated, Potree was used to determine candidate locations for warning sign placement. The 3D scene allowed users to verify line-of-sight distances for each curve and check that advisory signs would be visible to approaching drivers. Analysts used measurement tools and the profile view to ensure that sign placement met the MUTCD-specified minimum visibility distance and conformed to vertical alignment constraints. In wooded or topographically constrained areas, users explored alternative placements and annotated them directly in Potree for later field validation.

With these measurements, Potree supported the overlay of existing signage data in GeoJSON format, enabling comparison of current and recommended advisory signage locations. Where discrepancies were identified, such as missing or incorrectly placed signs, annotations were added to flag corrective actions. These annotations were then exported for integration into MassDOT's statewide traffic sign inventory and capital improvement planning tools. Beyond engineering analysis, Potree also served as a communication platform. Safety analysts and regional traffic engineers shared bookmarks and camera views that captured specific curve segments. These links enabled rapid discussion of advisory speed recommendations and signage strategies without requiring the physical presence of the reviewing team or access to desktop-based CAD software. Table 3.4 lists the detailed features and benefits of using the customized platform for horizontal curve safety assessment.

Table 3.4 Customized features and benefits for horizontal curve safety

Feature	Application
High-Resolution Geometry Visualization	Enabled detailed curve geometry inspection for radius and chord length analysis.
Superelevation Measurement Tools	Supported cross-slope measurements essential for computing recommended advisory speeds.
3D Visibility Assessment	Allowed evaluation of signage visibility and placement under real-world terrain conditions.
Interactive Annotations and Profiles	Facilitated collaborative decision-making and data validation between safety teams.
GIS Data Integration	Provided context through an overlay of existing signage inventory and roadway asset layers.

3.5 Use Case 5—Network-Level Point Cloud Data Management

As transportation agencies like MassDOT adopt high-volume mobile LiDAR scanning across entire state networks, the challenge of storing, organizing, and accessing these vast spatial datasets becomes paramount. This case study presents a statewide LiDAR data management solution that combines Potree's scalable 3D web visualization platform with a Leaflet-based map indexing portal. Together, they provide a seamless system for browsing, locating, and accessing over 16TB of point cloud data and 16TB of synchronized video log imagery, enabling effective statewide asset management and data-driven decision-making. The point cloud data and the synchronized video log images were collected in 2023-2024 through the Pavement Management group at MassDOT. The goal of this use case was to enable efficient querying, visualization, and GIS integration of raw point cloud files by route, region, or segment.

The foundation of the data management system is centered on the use of Potree to enable interactive 3D visualization of large-scale LiDAR data in a browser environment. Given the scale of the dataset, 16 terabytes distributed across thousands of tiles, the implementation began with a statewide data tiling and indexing procedure. Each roadway segment was processed individually through PotreeConverter, generating multiresolution scene files with embedded classification, intensity, and RGB attributes. The point spacing and resolution were configured dynamically based on the road class, with higher-fidelity output reserved for urban arterials and complex interchanges. Once converted, the scene tiles were hosted in a cloud storage environment with CDN-backed delivery to ensure low-latency access from multiple state agencies. Each segment was packaged with a self-contained Potree viewer and associated metadata file, allowing users to have modular access without needing to load the entire dataset.

Potree's built-in tools were customized to suit a network-level inspection context. The viewer supported dynamic loading of shapefiles and GeoJSON overlays corresponding to road ownership boundaries, traffic volume categories, and maintenance districts. Users could load both point cloud data and tabular GIS attributes, enabling them to inspect LiDAR data alongside official asset inventories. For example, within a single Potree session, a user could explore a section of Route 2, measure roadway slope and lane width, overlay signs and drainage locations, and extract asset geometry directly from the point cloud.

The system also leveraged Potree's annotation capabilities to enable collaborative reviews. Users could tag known issues, such as sign misplacement, pavement rutting, or obstructions, and export these notes for integration with asset management systems or maintenance work orders. These annotations, linked to global coordinates, became valuable references for DOT planners and asset engineers during scoping and prioritization. Potree also served as a visualization endpoint for processed analytics results. Feature extraction pipelines that identified curb lines, lane edges, signs, and poles populated GeoJSON layers that were dynamically loaded into Potree. In this way, Potree displayed raw LiDAR data and acted as the delivery interface for advanced AI-based asset extraction workflows.

A GIS-based indexing portal was developed using `Leaflet.js`, an open-source JavaScript mapping library, to support navigation and access across the vast dataset. This map-centric interface provided users with a statewide overview of all LiDAR data segments and allowed interactive querying and retrieval of 3D scenes. Each segment of the state roadway network was represented as a polyline feature in a spatial database, linked to its corresponding Potree viewer and metadata through a unique identifier. Users could zoom and pan across the Leaflet interface, click on any segment, and open the associated Potree viewer in a new browser tab. Metadata filters and search tools enabled users to locate segments by route ID, municipality, collection date, or data provider. For instance, a user could request all LiDAR segments collected along Route 3 in Barnstable County and be presented with a filtered set of map features, each linking to its corresponding Potree scene. Figure 3.7 shows the leaflet-based index portal (left), and the LiDAR data integrated in the Potree platform (right).

Figure 3.7 Network-level data management examples of all the point cloud data along the state highway system in the Commonwealth

The portal also included synchronized access to video log frames. By selecting a segment on the map, users were able to open both the Potree point cloud viewer and a browser-based video log viewer side-by-side, synchronized by time and GPS. This dual-mode exploration supported a more comprehensive inspection and estimation process. To ensure system scalability and multi-user support, the Leaflet portal was backed by a spatially indexed PostGIS database, exposed via GeoServer and RESTful APIs. These services deliver high-performance map rendering and query response even under concurrent use by multiple district engineers, consultants, and planners. Table 3.5 lists the detailed features and benefits of using the customized platform for network-level, large-scale data management.

Table 3.5 Customized features and benefits for network-level, large-scale data management

Feature	Description
Modular 3D Viewer Deployment	Enabled route-specific access to Potree scenes, avoiding full dataset loads.
Multi-Attribute Rendering	Allowed simultaneous viewing of classification, RGB, and intensity to support visual interpretation.
GIS Overlays and Metadata Filters	Supported side-by-side inspection of point cloud data and official asset inventories.
Scalable Access	Delivered high-performance visualization to users statewide via CDN and tile-based rendering.
Annotation and Collaboration Tools	Facilitated network-wide defect tagging and condition logging.

4.0 Conclusion

This research presents a comprehensive methodology and platform development for LiDAR data visualization tailored to the operational needs of transportation agencies such as the Massachusetts Department of Transportation (MassDOT). The study is structured into three primary components: a literature review of LiDAR and visualization technologies, the development of a customized Potree-based web platform, and full integration of external GIS data for infrastructure inspection, asset management, and project planning.

The literature review analyzed current LiDAR technologies, emphasizing their application in transportation infrastructure. Various visualization tools were evaluated, with Potree identified as the most suitable platform due to its open-source framework, browser-based interface, and high efficiency in rendering massive point cloud datasets. Potree's flexibility allows for real-time measurements, slicing, classification-based rendering, and integration of orthophotos and GIS attributes. It stands out as a scalable, cost-effective solution, particularly aligned with DOT requirements.

The prototype platform was developed by significantly enhancing Potree's architecture. Improvements included viewport-aware data loading, adaptive level-of-detail rendering, GPU-based streaming, and parallel node decoding for performance scalability. A custom input control system was also created, enabling users to define hotkeys and interaction schemes tailored to specific engineering workflows. Potree's compatibility was extended through integration with LASTools and PotreeConverter, allowing support for various point cloud formats while ensuring efficient data rendering in constrained computing environments.

A critical advancement was made in integrating GIS data, particularly through adopting GeoJSON as the intermediate format. This enabled Potree to support importing GIS layers (e.g., road centerlines, sign inventories) and exporting annotations and measurements back into agency GIS systems. The integration was implemented at three levels: basic overlay of GeoJSON features, measurement interaction with GIS-defined geometries, and full network-level modeling with topological analysis using new modules like `GeoJSONLoader.js` and `NetworkAnalyzer.js`.

To validate the platform, five detailed case studies were conducted:

- Bridge Inspection – Demonstrated Potree's capability to visualize bridge geometry and surface defects using mobile and high-resolution LiDAR, facilitating GIS-linked asset assessments.
- Asset Management – Showcased Potree's effectiveness in visualizing, classifying, and validating roadside assets across a 26GB dataset, with seamless GIS export for statewide asset tracking.
- Project Estimation – Highlighted how Potree enabled detailed, data-driven estimation of roadside features and infrastructure conditions, supporting defensible cost projections and spatial validation.
- Horizontal Curve Safety – Applied Potree for superelevation analysis, advisory speed calculations, and sign placement verification using AASHTO guidelines and MUTCD visibility standards.
- Network-Level Management – Developed a statewide point cloud data system integrating Potree and Leaflet for modular visualization and GIS-driven segment access across 16TB of LiDAR and video logs.

The research demonstrates how Potree can evolve from a point cloud viewer into a comprehensive, GIS-integrated platform that supports real-time inspection, data-driven decision-making, and cross-departmental collaboration. The proposed workflows and platform enhancements provide a robust foundation for MassDOT and similar agencies to manage, interpret, and act on LiDAR data at project and network scales.

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