Geomatics and open-source for road infrastructure management: standards, technologies, and future directions

Federica Gaspari, Daniela Carrion, Livio Pinto

Dept. of Civil and Environmental Engineering (DICA), Politecnico di Milano, Milan, Italy –
(federica.gaspari, daniela.carrion, livio.pinto)@polimi.it

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Abstract

The management of aging road infrastructure is increasingly challenged by climate change impacts, financial constraints, and the demand for digital transformation. While proprietary software dominates the sector, its limitations in interoperability and transparency have sparked interest in open-source alternatives. This study provides a state-of-the-art overview of open-source technologies, standards, and data for road asset management, focusing on documented applications within or in collaboration with Public Administrations. A systematic literature search across Google Scholar and Scopus identified case studies utilising tools such as QGIS and CloudCompare, and standards including IFC and CityGML. The findings are synthesised through a four-layer Digital Twin framework to assess current capabilities in data acquisition, modelling, analysis, and visualisation. Results indicate that while individual open-source tools offer robust solutions for specific tasks like bridge monitoring or traffic simulation, a lack of integrated workflows and standardised data pipelines remains a significant barrier. The study concludes that leveraging the collaborative nature of open-source ecosystems can enhance resilience and cost-effectiveness but requires concerted efforts to improve documentation, interoperability, and training for asset managers. Future directions include the development of seamless open-source toolchains and open educational resources to bridge the gap between technical potential and operational adoption.

1. Introduction

Following the introduction of guidelines for documenting road assets in Europe, infrastructure asset management is undergoing a new digital transformation. The reuse and transparency principles are fostering the adoption of open standards and open-source technologies (Sebastian et al., 2018). This paradigm shift toward digitising is evident in the monitoring and maintenance of critical infrastructure, such as bridges and road networks.

However, this transformation is driven by urgent and compounding challenges. Road networks are facing mounting pressures from aging materials and increasing traffic loads, leading to critical maintenance backlogs. These vulnerabilities are further exacerbated by the accelerating impacts of climate change, including extreme heat, flooding, and geohazards, which threaten structural integrity and service continuity (Werbińska-Wojciechowska et al., 2024). Managing these risks to prevent catastrophic structural failures is complex and requires robust, data-driven strategies capable of handling vast amounts of heterogeneous monitoring data (Yang et al., 2024).

New guidelines led to the proliferation of proprietary solutions, which, however, contributed to a fragmentation of data environments (Gaspari et al., 2025). Custom and licence-dependent formats limited the interoperability, scalability and transparency of infrastructure management workflows (Lee et al., 2018). In contrast, the open-source approach fosters collaboration, enhances accessibility to information, and supports more resilient, cost-effective and democratic decision-making processes. In order to develop operational solutions that address the guidelines, it is necessary to understand the state of open standards and technologies, as well as their potential and limitations in documented applications.

This contribution aims to provide an overview of the open-source and open-standard scenario in infrastructure management with case studies from literature. It offers a technical synthesis and a forward-looking perspective, with a particular focus on documented case studies that adopt Open Source Geospatial Foundation (OSGeo) projects (OSGeo, 2025), Open Geospatial Consortium (OGC) standards and open data. Leveraging the strengths of openness enables stakeholders to build more resilient infrastructure systems.

2. Methodology

This study conducts an overview to identify and analyse relevant literature on open-source solutions for road infrastructure management. To capture the current landscape of tools and standards, a search was conducted targeting academic literature and documented case studies within the timeframe of the last decade, with a particular emphasis on recent developments in Digital Twin and AI integration. The literature search was performed using the Scopus and Google Scholar databases, employing a multi-step query strategy designed to intersect three core domains: infrastructure type, management activity, and technological enabler. The primary search strings combined keywords using Boolean operators as follows:

- <u>Domain</u>: ("road infrastructure" OR "bridge" OR "highway" OR "pavement")
- <u>Activity</u>: AND ("asset management" OR "maintenance" OR "inspection" OR "monitoring" OR "condition assessment")
- Enabler: AND ("open source" OR "FOSS" OR "open data" OR "BIM" OR "GIS" OR "Digital Twin").

The retrieved records were screened according to three eligibility criteria: technological focus, application context, and asset scope. Studies were required to explicitly utilise or discuss open-source software, open standards, or open data. Priority was assigned to workflows relevant to Public Administrations, emphasising cost-effective, scalable, and interoperable solutions rather than proprietary commercial pipelines. Additionally, the selected research focused on the operation and maintenance phase of critical road assets, specifically bridges, road surfaces, and traffic signs, while excluding studies limited to the geometric design phase of new construction.

This approach allows for a flexible synthesis of diverse methodologies, from satellite-based monitoring to close-range photogrammetry, providing a holistic picture of the open geospatial ecosystem for infrastructure management.

The screening process yielded a final selection of 27 papers, which were categorised and synthesised using a four-layer framework adapted from recent definitions of digital twins (Mousavi et al., 2024; Wu et al., 2025). Insights from the literature were organised into Data, Model, Service, and Application Layers to examine technological trends, interoperability challenges, and the practical implementation of digital twin concepts in the public sector. This structured methodology enabled a thorough assessment of the current state of the art and facilitated the identification of gaps in existing workflows.

3. Results

The resulting case studies highlight the diverse solutions currently used for managing road infrastructure. To provide a structured analysis of these findings, the identified technologies and standards are categorised according to the four-layer Digital Twin framework defined in the methodology (Figure 1).

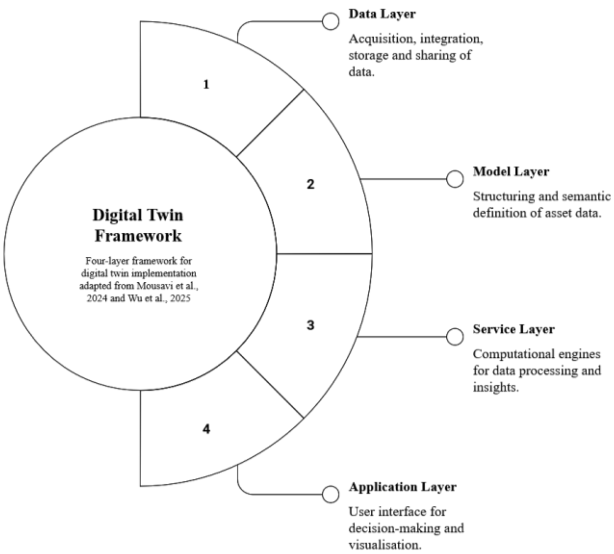

Figure 1. A conceptual four-layer Digital Twin framework for road infrastructure management, illustrating the hierarchy from data collection and storing (Data Layer) to decision-support visualization (Application Layer).

This section presents the main insights for each layer:

- Data Layer: This foundational layer encompasses the acquisition, integration, and storage of raw data. It includes open data sources, mobile collection workflows, and advanced sensing technologies, along with the database management systems required to archive geometry and monitoring records.
- Model Layer: This layer addresses the structuring and semantic definition of asset data. It focuses on open standards for interoperability across design, urban context, and linear alignment, as well as the use of ontologies to formalise domain knowledge.
- Service Layer: This layer covers the computational engines responsible for processing data to generate insights. It includes tools for safety assessment, simulation, and continuous structural health monitoring.
- Application Layer: The final layer represents the user interface for decision-making. It includes desktop and web-based visualisation platforms that allow stakeholders to interact with the digital twin, view 3D models, and access analytical dashboards.

3.1 Assets mapping and inventory

The foundation of any infrastructure management system lies in the accurate identification, geolocation, and cataloguing of physical assets. This phase corresponds to the Data Layer of the adopted framework, where the primary objective is to transition from fragmented, often analogue records to a cohesive, digital inventory. The literature highlights two main strategies for populating this layer using open resources: leveraging existing open data repositories and deploying open-source tools for new field data acquisition.

Before initiating costly field surveys, public administrations can exploit existing open geospatial data to build a preliminary inventory. OpenStreetMap (OSM) emerges as a critical resource in this domain. Far beyond a simple cartographic basemap, OSM provides a topological network that supports routing applications and serves as a collaborative asset database. Studies have demonstrated its utility in identifying and georeferencing critical structures, such as masonry bridges, by extracting specific tags and coordinates to populate initial GIS databases (Gandy et al., 2023; Dewadar and Pepe, 2024). Complementing this vector data, the Copernicus programme offers essential environmental context. Sentinel-2 satellite imagery allows for the monitoring of land use changes surrounding infrastructure, while digital elevation models (such as the Copernicus DEM) provide the morphological data necessary for flood risk assessment and terrain analysis (Loli et al., 2022). Furthermore, for structural health monitoring, the European Ground Motion Service (EGMS) provides open-access interferometric radar data (MT-DInSAR), enabling the detection of millimetre-scale deformation trends in bridges and road networks without the need for on-site instrumentation (Talledo and Saetta, 2025).

To validate and enrich these open datasets with granular, ground-truth information, the literature highlights a decisive shift towards open-source Mobile GIS solutions. Tools such as QField and MerginMaps act as field extensions of the QGIS desktop environment, allowing operators to view assets on a map interface and edit vector geometries directly in the field. These map-centric tools are particularly favoured for routine maintenance and inventory updates, with case studies reporting a reduction in geolocation errors to near zero compared to traditional paper-based methods (Gaspari et al., 2023). Alternatively, for non-expert operators, ODK Collect offers a form-centric approach. By guiding users through a structured sequence of questions (XLSForm standard), it simplifies data entry while ensuring consistent metadata collection, making it highly effective for large-scale, distributed data collection campaigns (Gharbi and Haddadi, 2020; Mazhindu and Madamombe, 2022).

For complex assets requiring detailed geometric characterization, such as bridges or tunnel intrados, simple GPS points are insufficient. Here, the integration of low-cost open hardware and photogrammetry becomes pivotal. Research has validated the use of Unmanned Aerial Systems (UAS) equipped with consumer-grade cameras (or even custom Raspberry Pi setups) to acquire high-resolution imagery of hazardous or inaccessible areas (Belcore et al., 2021). These images are

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processed using open-source photogrammetric suites like MicMac or COLMAP to generate dense point clouds and orthophotos with centimetre-level accuracy (Zhang et al., 2025). To manage these heterogeneous datasets—ranging from simple inventory tables to massive 3D point clouds—the open-source ecosystem relies heavily on PostgreSQL with its PostGIS extension. This combination serves as the robust, standards-compliant backend for the Data Layer, capable of handling complex spatial queries and large volumes of data (e.g., inspection photos) that would overwhelm file-based storage systems (Achuthan et al., 2021; Mangiameli et al., 2023). For applications requiring complex network topology and semantic analysis, such as optimising maintenance routes, graph databases like Neo4j are also emerging as powerful alternatives to traditional relational models (Zhang et al., 2023). Finally, to ensure interoperability and accessibility for downstream client applications, GeoServer is frequently employed as the middleware component, publishing spatial data from these backend databases via OGC-compliant web services (e.g. WMS, WFS) (Breytenbach et al., 2021).

3.2 Data models and standards

Once raw asset data is acquired and stored, it must be structured within a standardised framework to be interoperable and analytically useful. This corresponds to the Model Layer, where the challenge shifts from data collection to semantic definition. The literature indicates that no single standard can currently address the full complexity of road infrastructure management; rather, a complementary ecosystem of open standards is required to bridge the gap between detailed design and territorial context.

At the core of this ecosystem lies the distinction between prescriptive and descriptive modelling. For the detailed design and construction of individual assets, Industry Foundation Classes (IFC, ISO 16739) serves as the primary prescriptive standard. It supports high-fidelity parametric geometry and engineering-grade local coordinate systems, making it indispensable for modelling complex components like bridge girders or tunnel segments (Deng et al., 2025). By contrast, for urban-scale analysis and environmental context, CityGML (OGC) acts as the descriptive standard. Utilising Boundary Representation (B-Rep) and global geodetic coordinates, it defines assets not by how they are built, but by their semantic relationship to the urban environment through defined Levels of Detail (LOD) (Kumar et al., 2019, El Mekawy and Ismail, 2025). Bridging these two domains is LandInfra (and its encoding InfraGML), a more recent OGC standard specifically designed for civil engineering (Buuveibaatar et al., 2022). Unlike vertical building standards, LandInfra focuses on the linear alignment of infrastructure (roads and railways), providing a crucial semantic link that connects the detailed BIM geometry of a bridge to the topological network of the road it carries. However, difficulty and failure of direct translation persist between the standards, thereby leading to the adoption and testing of sophisticated bridging technologies.

Beyond geometry, the effective management of infrastructure requires a rigorous semantic layer to describe asset conditions and maintenance histories. The literature highlights the growing role of ontologies in formalising this domain knowledge. By using Web Ontology Language (OWL), researchers have developed specialised schemas such as the Bridge Maintenance Domain Ontology (BMDO), which model the complex relationships between structural elements, observed defects, and required maintenance actions (Zhang et al., 2023; Gao e al., 2024). Furthermore, classification standards like COBie (Construction Operations Building Information Exchange) are employed to tag geometric elements with standardised facility management data, ensuring that the "business logic" of asset management remains consistent across different software platforms (Niestroj et al., 2018).

A recurrent theme in the reviewed studies is the difficulty of integrating these disparate standards into a unified Digital Twin. The fundamental conflict arises from the mismatch between BIM's parametric, local-coordinate nature and GIS's surface-based, global-coordinate nature. Direct conversion (e.g., IFC to CityGML) often results in significant data loss or geometric degradation. To address this, the most promising open-source workflows are moving away from rigid file conversion towards a "federated" approach. Instead of forcing all data into a single format, these systems use Linked Data principles and graph databases to create references between datasets. In this model, a bridge in a CityGML city model might contain a unique identifier that links to a detailed IFC model stored separately, allowing users to access high-fidelity design data without compromising the performance of the geospatial environment.

3.3 Analysis and simulation

The Service Layer represents the analytical engine of the infrastructure management system, where raw data and structured models are processed to generate actionable insights. The overview of the literature reveals three primary domains where open-source technologies are driving innovation in the field summarised in Figure 2): automated safety assessment using computer vision, structural health monitoring via 3D analysis, and advanced network simulation for mobility planning.

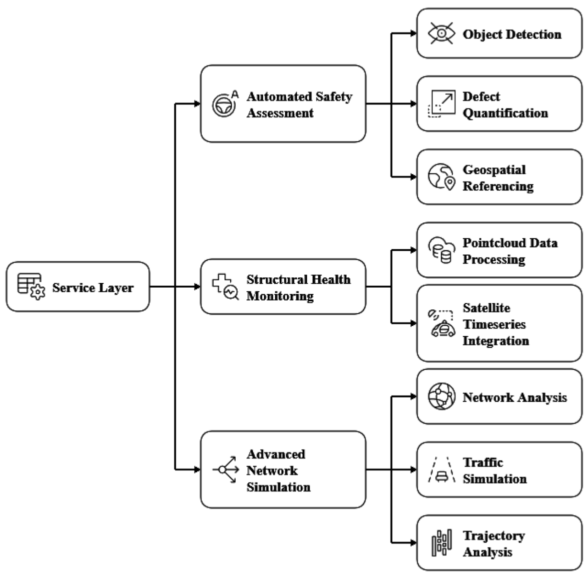

Figure 2. The open-source analysis categories for the road infrastructure management Service Layer as identified in the literature.

Traditional visual inspections are labour-intensive and subjective, but essential for most of the country-specific maintenance regulation. To address this, recent studies have extensively applied open-source deep learning frameworks to automate the quality assessment of road assets. For asset inventory, object detection models such as the You Only Look Once (YOLO) series have become a standard for identifying and classifying roadside components like traffic signs and safety barriers from video feeds in real-time (Sapkota et al., 2025; Santarsiero et al., 2025). Moving beyond simple detection to defect quantification, semantic segmentation algorithms (e.g., U-Net, Mask R-CNN) are employed to delineate pavement distresses (Ranyal et al., 2022) . More recently, foundation models like the Segment Anything Model (SAM) have been adapted via transfer learning to precisely segment road cracks and bridge components from diverse inspection images, demonstrating superior generalisation capabilities compared to traditional task-specific models (Zhou et al., 2024; Wang et al., 2025). These AI-driven workflows, often implemented using libraries like PyTorch or TensorFlow, allow for the rapid processing of massive datasets collected by mobile mapping systems. However, only few studies address the challenging of the geospatial referencing and/or registration in 2D or 3D spaces starting from the image local coordinates using libraries such as Geospatial Data Abstraction Library (GDAL) (Hu et al., 2024).

For the structural assessment of critical assets like bridges, analysis shifts from 2D images to 3D point clouds and satellite data. Open-source libraries such as Point Data Abstraction Library (PDAL) and CloudCompare are utilised to process dense LiDAR data, enabling the automated detection of geometric deformations and structural anomalies (Belcore et al., 2021). Furthermore, the integration of satellite-based interferometric synthetic aperture radar data allows for the continuous monitoring of ground and structure displacements. Methodologies leveraging open-source GIS tools to process Sentinel-1 data and timeseries have successfully identified millimetre-scale displacement trends in bridge decks and pavements, providing an early warning system for structural instability (Talledo et al., 2025).

Beyond the physical condition of individual assets, the Service Layer also encompasses the functional performance of the road network. Open-source simulation tools enable managers to move from descriptive analysis to predictive planning. For network analysis, Python libraries like OSMnx and the pgRouting extension for PostGIS allow for the calculation of optimal maintenance routes and emergency response paths based on the topological graph of the road network (Hosseini et al., 2025; Rezaei et al., 2025). To understand dynamic traffic behaviours, agent-based simulation platforms such as SUMO (Simulation of Urban MObility) and MATSim are employed (Lovelace, 2021). These tools facilitate the modelling of complex traffic flows and the assessment of how infrastructure interventions—such as road closures for maintenance—impact overall network capacity and user mobility. Additionally, libraries like MovingPandas enable the analysis of vehicle trajectory data to identify congestion hotspots and mobility patterns, further informing decision-making processes (Graser, and Dragaschnig, 2024).

3.4 End users' applications and visualisation

The final component of the framework is the Application Layer, which serves as the primary interface for decision-makers to interact with the digital infrastructure model. Effective visualisation is critical for translating complex datasets into actionable intelligence. The study highlights a bifurcation in open-source tools: desktop-based environments for technical experts and web-based dashboards for broader stakeholder engagement.

For technical personnel requiring deep analytical capabilities, desktop GIS software remains the standard. QGIS stands out as the predominant open-source platform, acting as a central hub where data from the lower layers converge. It allows for the simultaneous visualisation of vector inventories (e.g., from PostGIS), raster environmental data (e.g., from Copernicus). This environment supports the rigorous editing, querying, and spatial analysis tasks necessary for detailed asset management (Mangiameli et al., 2023, Christou et al., 2021). However, regarding the BIM adoption, proprietary desktop solutions are still the most adopted, with few documented case studies employing Blender and/or BlenderBIM for visualisation and rendering with limited applications in the road management domain.

To democratise access to infrastructure data, there is a strong trend towards web-based solutions that do not require specialised software installation. These applications leverage powerful open-source libraries to render complex environments directly in a browser. Geospatially-enabled frameworks such as Django or LizMap are well established for the development of WebGIS (Pascucci et al., 2025). For geospatial context, libraries such as LeafletJS, OpenLayersJS and CesiumJS are widely used to stream large-scale aerial images and terrain models essential for application for maintenance planning and monitoring (Bartczak et al., 2025). For the visualisation of specific structural assets, tools like the xeokit SDK allow for the high-performance rendering of IFC models on the web, enabling users to inspect individual bridge components and their associated maintenance records (Gao et al., 2024). Furthermore, point cloud data—often massive in size—can be efficiently streamed and visualised using the Potree library, which employs multi-resolution octree structures to ensure smooth interaction (Gaspari et al., 2025). By integrating these libraries into unified web dashboard, public administrations can provide asset managers with a holistic "Digital Twin" view, combining the macroscopic network context with microscopic asset details for informed decision-making.

4. Discussion

The overview of documented applications reveals that while open-source technologies have matured significantly, the implementation of comprehensive road infrastructure management systems still faces critical bottlenecks. A primary challenge lies in the lack of an integrated workflow spanning from data collection to the visualisation layer, with well-functioning but isolated tools for the data and service layers and with complex standards to reconcile in the model layer, often producing multiple formats that are hard to visualise through a single library or tool for the application layer. Indeed, most ongoing studies address isolated components of the asset lifecycle, such as specific traffic management algorithms or isolated structural health monitoring tools, rather than holistic systems. This results in data segregation, where high-quality inspection data (e.g., from UAS or mobile mapping) often requires manual, error-prone conversion before it can be utilised in decision-support environments. Consequently, the seamless integration of Digital Twin systems across transportation infrastructure remains a critical yet underdeveloped challenge, with many proposed solutions functioning as "islands of excellence" rather than interconnected pipelines.

Even within established web-based visualisation tools, significant interoperability challenges persist. While platforms like CesiumJS and xeokit offer powerful rendering capabilities, seamlessly integrating heterogeneous data sources—combining massive point clouds, detailed BIM geometry, and GIS vector layers into a single, unified web viewer—is rarely straightforward. It often necessitates complex data conversion pipelines (e.g., converting IFC to glTF or 3D Tiles) and rigorous optimisation strategies to ensure performance, which can be a barrier for smaller administrations lacking specialised IT resources.

Furthermore, technical barriers related to code accessibility and documentation significantly inhibit scalability and reproducibility. Despite the "open" label, many combined toolchains lack shared code repositories or sufficient documentation to be easily adapted to different national contexts or regulatory frameworks. This issue is compounded by a human capital gap; the literature highlights a stark lack of tailored training for decision-makers and asset managers.

This training gap directly impacts User Experience and adoption. For digital tools to be effectively embraced by non-technical stakeholders—such as municipal asset managers or policymakers—interfaces must be intuitive and user-friendly. The current landscape often prioritises technical functionality over usability, creating a steep learning curve that discourages widespread adoption. Bridging the gap between sophisticated backend analysis and accessible frontend presentation is crucial for empowering decision-makers to trust and utilise these digital systems.

Another significant gap identified in the literature concerns participatory data collection and IoT standards. While several studies leverage crowdsourced data (e.g., OpenStreetMap) as a static inventory source, there is a notable absence of documented case studies involving active, participatory data collection or reporting by citizens. This suggests that the potential for inclusive, community-driven monitoring remains largely untapped in the road infrastructure domain. Similarly, despite the proliferation of IoT sensors for structural health monitoring, the adoption of open interoperability standards for sensor data, such as the OGC SensorThings API, appears limited. Unlike in urban-scale Smart City or Digital Twin projects where SensorThings is widely adopted, road asset monitoring applications often rely on custom or proprietary data streams, hindering the seamless integration of real-time sensor feeds into broader management platforms.

Looking forward, future trends point towards increasingly immersive visualisation technologies. While currently less common in standard open-source workflows, the integration of Augmented Reality and Virtual Reality holds immense potential for pre-inspection technical training, on-site inspection and remote collaboration (Buuveibaatar et al., 2025). These technologies could allow field crews to overlay digital twin data directly onto physical assets, visualising hidden infrastructure or historical defect data in real-time, further enhancing the link between the digital model and physical reality.

5. Conclusions

This work provided an overview of the current landscape of geomatics and open-source solutions for road infrastructure management, categorised through a four-layer framework (Data, Model, Service, Application). The analysis demonstrates that a robust ecosystem of open tools—from OpenStreetMap and Copernicus data to QGIS and IFC standards—already exists to support public administrations in moving away from proprietary, siloed workflows. These technologies offer a viable pathway to enhance transparency, reduce long-term costs, and improve the resilience of critical infrastructure against aging and climate risks.

However, realising the full potential of this open ecosystem requires shifting focus from developing individual tools to creating integrated, reproducible workflows. Future directions must prioritise the development of standardised data pipelines that seamlessly link field acquisition with digital twins, reducing the friction of data conversion. Moreover, bridging the gap between technology and practice is essential; this demands investment in open educational resources and training programs that empower asset managers to not just use, but trust and govern these digital systems. Ultimately, the goal is to move towards a unified vision where open standards and tools bind disparate data into a coherent, actionable Digital Twin for the public good.

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