An Evaluation of IFC-CityGML Unidirectional Conversion for Road and Transportation Models

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Keywords: IFC Road Model, CityGML Transportation Model, BIM-GIS Integration, Transportation Ontology, GeoBIM Interoperability.

Abstract

The integration of Building Information Modeling (BIM) and Geographic Information Systems (GIS) is increasingly critical for infrastructure planning, asset management, and smart city applications. While prior efforts have largely focused on buildings, the need for semantically rich, interoperable models for roads and transportation networks is becoming more prominent. This paper investigates the potential for unidirectional conversion between IFC 4.3-based road models and the Transportation model of CityGML 3.0. Through manual schema matching, the study classifies correspondences into full, partial, or no match categories and assesses the potential for semantic and geometric translation between the two domains. Findings reveal that while basic spatial and geometric entities can be mapped with partial fidelity, significant semantic details such as alignment geometry, layered road structures, and road furniture remain unmapped. The paper concludes by recommending the development of a unified road ontology or mediation layer to support lossless integration. These insights contribute to ongoing efforts in GeoBIM interoperability, such as those led by buildingSMART International and the OGC's CityGML working groups.

1. Introduction

The integration of Building Information Modeling (BIM) and Geographic Information Systems (GIS) is increasingly vital for smart cities, infrastructure asset management, and digital twin development (Tan, 2023). BIM provides semantically rich representations of built assets, particularly through standards like IFC. GIS platforms, especially those based on CityGML, offer scalable, spatially contextualized models for urban analysis and planning. The convergence of these technologies is now essential for connecting detailed engineering design with large-scale city reasoning (Shkundalov and Vilutienė, 2021; Xia et al., 2022).

Research on BIM-GIS integration has predominantly focused on buildings, with extensive work on schema alignment, semantic mapping, and geometry transformation (e.g., El Mekawy et al., 2012; Biljecki et al., 2021; Stouffs et al., 2018; Zhu et al., 2019). However, road infrastructure presents unique challenges, including linear and distributed geometry, alignment-based representations, and complex multiscale semantics. Recent schema enhancements in IFC 4.3 and CityGML 3.0 now provide native support for infrastructure models. Although these developments lay the groundwork for integration, the practical realization remains difficult (Kolbe and Donaubauer, 2021).

Bridging BIM and GIS road models is critical for applications such as traffic simulation, construction planning, and environmental analysis. Yet, without a shared semantic framework, interdisciplinary workflows are hindered by fragmented data. As noted in recent work (Beil and Kolbe, 2024; Cepa et al., 2024), unified infrastructure modeling is essential to fully enable integrated digital twin and urban systems.

1.1 Problem Statement

Despite their complementarity, integrating IFC and CityGML for road modeling remains technically challenging and semantically fragile. A key difficulty lies in semantic misalignment: BIM standards describe roads through engineering concepts like material layers and design tolerances, whereas GIS models abstract them as spatial features organized by function or location (Noardo et al., 2020; Şenol & Gökgöz, 2024). This makes translation across domains problematic.

A second challenge lies in geometric representation. IFC uses parametric and high-precision volumetric geometry tailored to simulation and construction processes. In contrast, CityGML emphasizes explicit surface and curve-based geometry aligned with ISO 19107 concepts, optimized for visualization and geospatial analysis. Converting IFC solids into surface-based GIS geometries often results in data loss. On the other hand, reverse translation can introduce geometry that is inferred or artificially constructed, leading to inconsistency and potential inaccuracies (D'Amico et al., 2020; Zhu et al., 2021). Additionally, issues related to georeferencing, projection distortions, and curvature of the Earth are especially relevant for elongated infrastructure such as roads and must be considered in any conversion strategy (Jaud et al., 2020).

Most current workflows result in lossy conversions. Important data such as alignment curves, construction phases, or road markings are often omitted due to lack of equivalent concepts in the target schema. Existing tools mainly focus on buildings and are not well-suited for linear infrastructure. The emergence of newer standards like InfraGML and CityJSON adds complexity, as tool support is fragmented and implementation maturity varies (Han et al., 2020; Pedó et al., 2023). This study evaluates schema compatibility between IFC 4.3 and CityGML 3.0's Transportation model. It applies a structured classification to identify fully, partially, or non-transferable features and to highlight technical gaps. The findings support the introduction of a semantic mediation layer, such as a Unified Road Model (URM), to enable low-loss integration. This aligns with current standardization initiatives by buildingSMART, ISO/TC 59/SC 13, and the OGC GeoBIM group.

2. Overview of IFC and CityGML Road Models

This section outlines the road modeling capabilities of IFC 4.3 and the Transportation model in CityGML 3.0. These two standards form the conceptual basis for the schema mapping and compatibility assessment conducted in this study.

2.1 IFC Road Model (IFC 4.3)

The IFC Road Model, part of the IFC schema developed by buildingSMART International (IFC, 2025), enhances data exchange and interoperability for road infrastructure projects. It follows object-oriented modeling principles and supports the full lifecycle of road assets, from planning to design, construction, and maintenance (Niestroj et al., 2018; Ait-Lamallam et al., 2021). The structure is defined in UML under IFC 4.3 and conforms to ISO 6707-1, including road-specific extensions (IFC, 2025).

https://doi.org/10.5194/isprs-archives-XLVIII-4-W15-2025-63-2025

IFC has traditionally served as the core schema for Building Information Modeling in architecture, engineering, and construction (AEC). With the release of IFC 4.3, the schema was expanded to accommodate linear infrastructure domains such as roads, railways, tunnels, and bridges. The introduction of entities like IfcRoad and its associated classes enables comprehensive modeling across multiple project phases. The primary class, IfcRoad, defines the road facility and connects to broader project hierarchies using IfcProject and IfcSite. Roads can be subdivided into logical components through IfcRoadPart, which enables decomposition into lanes, intersections, sidewalks, and shoulders. These components are hierarchically organized using IfcRelAggregates (see Figure 1).

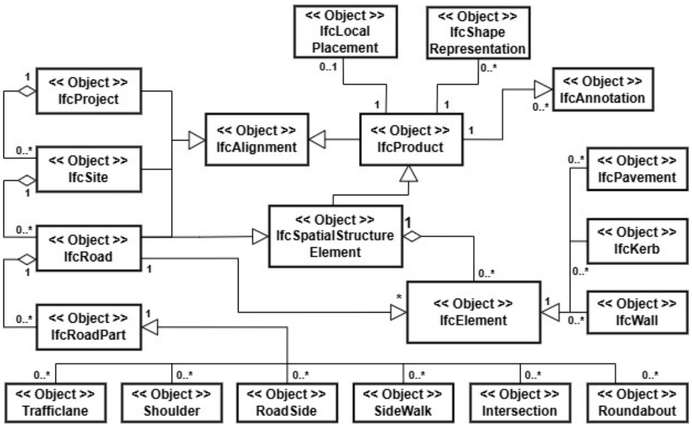

Figure 1. Proposed IFC Road Model.

A key feature of IFC 4.3 is its support for parametric alignment geometry through the IfcAlignment entity. This enables precise modeling of horizontal, vertical, and Cant alignments using 2D and 3D curves. It allows engineers to define complex geometries such as variable-width lanes or curved intersections.

Road parts like IfcTrafficLane and IfcShoulder are modeled as subtypes of IfcFacilityPart and include semantic attributes such as material composition, structural function, and intended use. Their geometry is defined using IfcShapeRepresentation, which supports various modeling types including boundary representation (B-rep), swept solids, extrusions, and constructive solid geometry (CSG), ensuring high accuracy. Additional entities such as IfcRoadFurniture, IfcAnnotation, and IfcRoadMarking support the inclusion of features like signs, markings, and furnishings. These enrich the model both semantically and visually, allowing for more realistic and informative representations. While IFC offers high geometric fidelity and detailed semantics, it has limited native support for geospatial referencing, multi-scale representation, and topological relationships across spatial hierarchies. These aspects are more directly addressed in CityGML 3.0.

2.2 CityGML Transportation Model (CityGML 3.0)

CityGML is an open standard developed by the OGC to support 3D city models and infrastructure representations (OGC, 2025; ISO TC211, 2025). While it includes an XML-based encoding, CityGML 3.0 is primarily defined through a UML-based conceptual schema that is format-independent. Unlike IFC, which originates from the construction sector, CityGML is rooted in the geospatial domain and is optimized for urban planning, spatial analysis, navigation, and visualization. The release of CityGML 3.0 introduced significant enhancements that align more closely with BIM workflows and extend its application scope. The Transportation model, shown in simplified form in Figure 2, is based on ISO standards (ISO, 19107; ISO, 19109) and uses UML class diagrams to ensure semantic and structural consistency.

CityGML's Transportation model provides a structured representation of roads, railways, squares, and related features. The central class, TransportationComplex, serves as a container for transportation entities, most commonly instantiated as Road, which can be subdivided into thematic surface features. Two subclasses support this breakdown:

- TrafficArea for drivable zones (e.g., lanes, ramps, roundabouts)
- AuxiliaryTrafficArea for non-drivable areas (e.g., sidewalks, medians, verges)

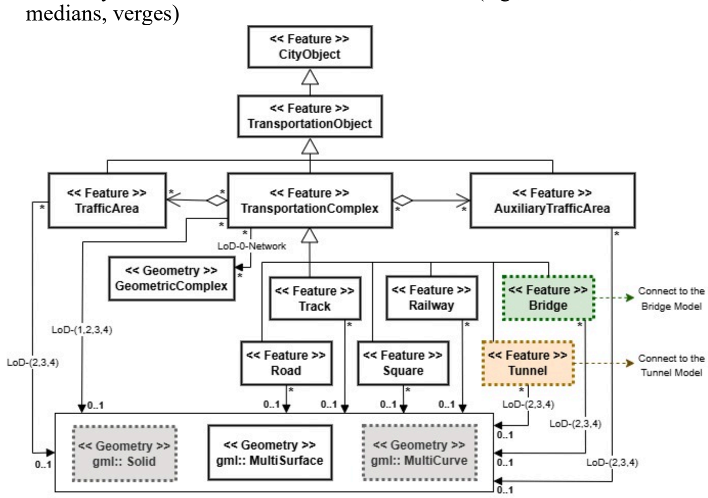

Figure 2. CityGML Transportation Model.

These classifications support thematic modeling and are designed for contextual integration within the broader urban environment. In addition to that, a defining strength of CityGML is its support for multiple Levels of Detail (LoD):

- LoD0: Network-level centerlines for routing
- LoD1-LoD2: Surface geometry with functional differentiation
- LoD3: High-detail surfaces with furniture and markings
- LoD4: Rarely used in roads; reserved for interiors (mostly buildings)

CityGML represents geometry using constructs from GML. These include gml:MultiSurface and gml:MultiCurve, which are considered geometric collections rather than primitives. Although gml:Solid is part of the schema, it is rarely used for modeling roads.

From a semantic perspective, CityGML focuses on the functional and spatial context of infrastructure. It models how elements interact with the urban environment, but does not capture structural or material-level detail. This makes it highly suitable for large-scale planning but limits its utility for detailed engineering tasks. CityGML supports Application Domain Extensions (ADEs), which allow users to define custom classes or attributes beyond the core schema. Tools such as FME, 3DCityDB, and CityGML4j provide partial support for ADEs. However, most standard implementations rely on the core modules, which may not fully represent the construction-level semantics available in IFC.

3. Schema Matching and Mapping Approach

This section describes the methodological steps used to analyze schema compatibility between IFC 4.3 and CityGML 3.0. The approach draws on established practices in semantic mapping and model transformation and is adapted to the specific challenges of road infrastructure modeling.

3.1 Objectives and Scope of the Mapping

The primary objective is to identify and classify correspondences between the IFC 4.3 Road schema and the CityGML 3.0 Transportation model. The goal is to support consistent and meaningful transformation of data across the two domains.

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Achieving this requires a deep understanding of how each standard conceptualizes roads, represents geometry, encodes semantics, and structures spatial relationships. While earlier research has focused on buildings, road modeling introduces additional complexities such as alignment-based geometry, linear topologies, and domain-specific entities like lanes, shoulders, and intersections. Both IFC and CityGML have recently expanded to include road infrastructure, though their support in this area remains under active development.

To maintain precision, the mapping is limited to:

- Core road elements, including spatial structure and alignment definitions
- Functional surfaces, such as lanes and sidewalks
- Geometric representations and LoD abstractions
- Annotations and furniture, such as signage and markings

Bridges, tunnels, and railways are excluded due to their domain-specific requirements. These features are supported by both standards but will be addressed in future studies.

3.2 Methodology for Schema Mapping

A structured manual approach was applied, using expert evaluation and reference to published schema specifications. The process involved iterative comparison to identify semantic and geometric alignment, as well as gaps that could lead to data loss or ambiguity.

Step 1: Concept Identification and Extraction:

We began by reviewing the formal specifications of both IFC 4.3 and CityGML 3.0, focusing on the classes, attributes, and geometry types relevant to road infrastructure.

These concepts were documented in parallel, allowing side-by-side comparison of their semantics, role in the model hierarchy, and geometry definitions.

Step 2: Conceptual Comparison and Matching:

Each IFC concept was evaluated against its potential CityGML counterpart using the following criteria:

- Semantic equivalence: Does the role and function align?
- Geometric compatibility: Can the IFC geometry be approximated in CityGML?
- Model hierarchy: Is the entity a core or auxiliary part?
- LoD adaptability: Can the concept be expressed meaningfully at a supported LoD?

Clear cases where a one-to-one mapping was possible (e.g., IfcTrafficLane → TrafficArea) were distinguished from partial correspondences (e.g., IfcAlignment → GeometricComplex) or cases where no meaningful mapping could be established (e.g., IFC's layered pavement structures). Whenever conceptual ambiguity arose, such as whether a single IFC entity maps to multiple CityGML elements or whether multiple IFC classes map to a single CityGML class - we documented the rationale for the classification and included explanatory notes in the mapping summary.

Step 3: Classification of Correspondences:

To bring consistency to the mapping analysis, all IFC-to-CityGML mappings were categorized into one of three groups:

- **Full Match:** The IFC concept has a direct equivalent in CityGML. Both semantic meaning and geometry can be preserved without significant loss or reinterpretation.
- **Partial Match:** There is a conceptual or geometric approximation, but either semantics are simplified (e.g., detailed materials not supported), or geometry must be abstracted (e.g., solids converted to surfaces).
- **No Match:** No viable mapping exists within the CityGML schema. These cases often involve engineering-specific details or volumetric components that CityGML cannot accommodate without extensions (e.g., through an ADE).

This classification system enables readers and tool developers to prioritize which entities can be safely converted and which ones require manual intervention or extended modeling support.

3.3 Considerations in Mapping: Semantics, Geometry, LoD

Due to the different modeling paradigms, a successful conversion must take into account multiple dimensions of data representation. In this study, we identified three primary dimensions of concern:

Semantic Alignment: IFC, as an engineering standard, provides rich semantic definitions tailored to the construction and operation of physical assets. For example, entities like IfcPavement or IfcShoulder not only define physical parts but also embed properties such as material composition, thickness, load-bearing, and intended use. CityGML, by contrast, organizes entities around functional and spatial roles within the urban context. While a TrafficArea may represent a lane or intersection, it lacks engineering semantics such as material properties or structural behavior. As a result, apparent mappings often lose deeper domain-specific information. Where possible, we attempt to align functional semantics, such as drivable vs. non-drivable surfaces, but construction-level semantics remain generally beyond the scope of CityGML.

Geometric Representation: IFC geometry centers on volumetric solids, parametric shapes, and precise B-reps, often derived from alignments and swept profiles, crucial for construction, simulation, and analysis.

In contrast, CityGML primarily uses surface-based geometries like gml:MultiSurface, with limited support for gml:Solid or gml:Curve at certain LoDs. Converting from IFC often requires flattening solids, abstracting alignments, and omitting subsurface detail, resulting in geometric simplification that may or may not suit the intended application.

Level of Detail (LoD) Mapping: CityGML uniquely supports multiple LoDs, from network-level (LoD0) to detailed models (LoD4). Converting IFC data requires selecting a target LoD and adjusting the transformation accordingly.

For example, IFC alignments can map to gml:Curve at LoD0, while road surfaces may appear as TrafficArea or AuxiliaryTrafficArea at LoD2. Detailed solids, like layered pavements, rarely transfer without ADEs, and LoD4 support for roads remains limited. Thus, LoD strongly influences what can be mapped and how much detail is retained.

4. Evaluation of Mapping

This section presents the results of the schema mapping process described in the previous chapter. The analysis is organized thematically to evaluate the correspondence between the concepts of the two models. Each subsection focuses on a specific domain of the road and assesses the degree of compatibility between the two standards.

4.1 Spatial Structure and Hierarchy

4.1.1 IFC Spatial Structure for Roads: In IFC, roads are modeled using a facility-based spatial hierarchy. The root entity for road infrastructure is IfcRoad, a subclass of IfcFacility, which aggregates all relevant physical and logical components of the road. This object serves as the semantic and spatial container for the road system.

To enable modular modeling, IfcRoad can be decomposed into multiple IfcRoadPart instances, representing segments like lanes, intersections, or shoulders. As a subclass of IfcFacilityPart, each part includes a predefined type indicating its specific role (e.g., TrafficLane, Sidewalk, Intersection). This decomposition goes beyond geometry, reflecting how roads are structured in

https://doi.org/10.5194/isprs-archives-XLVIII-4-W15-2025-63-2025

engineering practice. Each part may have its own alignment, geometry, materials, and contextual relationships. Spatial arrangement is organized via IfcSpatialStructureElement classes like IfcSite and IfcAlignment, which support positioning within a broader geospatial framework, though georeferencing is managed separately.

From a data organization standpoint, this structure supports semantic richness, construction sequencing, and detailed lifecycle modeling. However, it lacks a global urban-scale topological context, which is where CityGML excels.

4.1.2 CityGML Transportation Hierarchy: CityGML organizes road data differently, using TransportationComplex as the top-level thematic feature. As a subclass of CityObject, it can represent either a single road or a network, depending on scale. Unlike IFC, roads are subdivided by functional surface areas rather than construction parts. Two main subclasses support this:

- TrafficArea: Represents drivable areas such as lanes, intersections, and roundabouts.
- AuxiliaryTrafficArea: Represents supportive areas like sidewalks, shoulders, verges, and medians.

These areas use surface geometries (e.g., gml:MultiSurface) and are classified by function rather than construction logic, with attributes like usage, classification, and network role. CityGML emphasizes functional context over strict hierarchies, i.e., a Road may connect to a Square, intersect a Railway, or link to a Bridge, with such relationships typically implied or managed via external models or ADEs..

Importantly, CityGML's transportation hierarchy is inherently LoD-aware, allowing users to selectively include or exclude spatial details depending on application needs.

4.1.3 Mapping and Evaluation: Comparison of the two structures reveals:

- IfcRoad and TransportationComplex serve similar roles as top-level containers, each capable of representing a full road or network.
- Below this level, the models diverge: IfcRoadPart enables detailed, engineering-based decomposition, while CityGML relies on functional surfaces like TrafficArea and AuxiliaryTrafficArea.
- CityGML has no direct counterpart to IfcRoadPart; features like intersections or sidewalks are inferred from surface types rather than explicitly modeled with semantic identifiers or construction logic.
- Conversely, IFC lacks an explicit concept of topological relationships between roads, such as those CityGML supports through connectivity modeling and geospatial context.

This leads to the following classification of concept mappings (Table 1):

IFC Entity	CityGML Entity	Matching Type	Notes
IfcRoad	Transportation Complex	Full Match	Both serve as top-level road containers; semantics and purpose align.
IfcRoad Part	*Not available*	No Match	No direct equivalent in CityGML; requires ADE or flattening via LoD2.
IfcSite	Transportation Object	Partial Match	CityGML's site context is broader and lacks engineering-specific roles.
IfcAlig nment	Geometric Complex (LoD0)	Partial Match	Can be represented as curve geometry, but loses parametric alignment data.

Table 1. Mapping of Spatial Structure and Hierarchy

4.1.4 Implications for Conversion: The mismatch in hierarchical structuring presents a challenge for unidirectional conversion from IFC to CityGML. While high-level road objects can be transferred without difficulty, the subdivision into road parts and functional assemblies cannot be directly mapped unless an ADE is introduced or information is simplified into surface classifications (e.g., by collapsing IfcTrafficLane into a TrafficArea).

As such, while a basic road network can be reconstructed in CityGML, much of the modular structure and semantic richness of IFC Road is lost. For use cases like visualization, simulation, or integration into 3D city models, this loss may be acceptable. However, for applications requiring traceability of design elements or maintenance scheduling, the lack of part-level hierarchy can be a significant limitation.

4.2 Alignment and Geometry

4.2.1 Alignment Modeling in IFC: IFC offers robust alignment modeling via the IfcAlignment class, which defines a road's centerline or reference axis that serve as the geometric basis for linear infrastructure. The IfcAlignment entity is structured hierarchically into three components:

- IfcAlignmentHorizontal: Defines the horizontal layout as a sequence of 2D curves (e.g., straights, arcs, clothoids).
- IfcAlignmentVertical: Specifies the elevation profile along the horizontal path, using vertical curves and grades.
- IfcAlignmentCant (optional): Used primarily in rail design for super-elevation (tilt), and may apply in certain road contexts.

Alignments in IFC act as **parametric references**, generating 3D geometry via offsetting and sweeping - enabling precise modeling of lanes, sidewalks, or barriers with control over slope and curvature, essential for grading, drainage, and pavement design. Resulting geometry is expressed using IfcShapeRepresentation with volumetric entities like IfcSweptAreaSolid, IfcSurface, or IfcAdvancedBrep, supporting high-detail modeling for fabrication, simulation, and planning.

4.2.2 Geometric Representation in CityGML: CityGML adopts a surface-based approach to modeling transportation geometry, using GML primitives like gml:Curve, gml:MultiSurface, and, less frequently, gml:Solid.

In LoD0, alignments are expressed as non-parametric gml:Curve centerlines, mainly for routing or topological use. These lines indicate general road direction but lack vertical curvature, grades, or Cant which limits engineering applicability.

At higher LoDs (LoD1+), CityGML shifts to surface modeling, using TrafficArea and AuxiliaryTrafficArea polygons with gml:MultiSurface, often draped over terrain. While suitable for visualization and spatial analysis, this lacks the parametric control found in IFC's alignment-based geometry.

Although CityGML 3.0 conceptually allows for more detailed alignment modeling via external references or future ADEs, native support remains limited, making accurate, lossless conversion from IFC difficult.

4.2.3 Mapping and Evaluation: The comparison reveals a significant disparity in how alignment and geometry are treated:

- IFC's IfcAlignment allows for a precise, multi-dimensional, parametric definition of road centerlines, which is deeply integrated with geometric representations.
- CityGML's alignment modeling is limited to linear features, with no built-in semantics for vertical or Cant alignments.

Volumetric geometry (e.g., IfcSolidModel, IfcSweptAreaSolid) are not directly represented in CityGML except in LoD4, which is rarely implemented for transportation features. Conversion workflows flatten/simplify solids into MultiSurface geometries, resulting in loss of thickness, layering, and subgrade detail.

This leads to the following mapping classification (Table 2):

IFC Entity	CityGML Entity	Matching Type	Notes
IfcAlignment	gml:Curve in LoD0	Partial Match	Horizontal trajectory can be preserved; vertical/Cant information lost.
IfcAlignment Horizontal	*None (implicit)*	No Match	No direct representation; geometry flattened into 2D.
IfcAlignment Vertical	*None (implicit)*	No Match	Elevation profiles cannot be modeled natively in CityGML.
IfcSolid Model	gml:Multi Surface	Partial Match	Volume to surface conversion required; internal structure lost.
IfcSweptArea Solid	gml:Multi Surface	Partial Match	Swept solids must be approximated as surface patches.

Table 2. Mapping of Alignment and Geometric Representation

4.2.4 Implications for Conversion: The disparity in geometric modeling approaches implies that any attempt to convert IFC alignment-based geometry to CityGML must rely on significant simplification:

- Only the horizontal path of the alignment can be transferred effectively to CityGML.
- Vertical geometry and derived properties (e.g., slope, grade, Cant) will be lost unless extended through ADEs.
- IFC solids must be flattened into surfaces, typically losing subcomponent integrity, volume, and structural semantics.

Despite these challenges, converting alignment data to gml:Curve and transforming IFC solids into LoD2 TrafficArea surfaces may be sufficient for visualization, general planning, and urban analytics. However, engineering applications requiring accuracy or continuity of alignment cannot rely on CityGML alone.

4.3 Road Surfaces and Functional Areas

4.3.1 Functional Surface Modeling in IFC: Road surface areas are primarily modeled through instances of IfcRoadPart, each defined with a PredefinedType enumeration that categorizes the part based on its functional or structural role. These predefined types include, among others:

- Trafficlane: Individual lanes for vehicle flow.
- Sidewalk: Pedestrian pathways adjacent to traffic lanes.
- Shoulder: Lateral support or emergency stopping space.
- Roadsidepart, Median, Roundabout: Specialized functional elements.

Each IfcRoadPart is associated with its own geometry, material composition, and position in the road's alignment structure. These elements are typically represented as volumetric solids, such as extruded or swept shapes, providing accurate dimensions and enabling simulations such as drainage modeling or safety analysis. Additional semantic detail can be applied using IfcMaterialLayerSet, IfcSurfaceFeature, and annotations, allowing a rich description of surface behavior, load-bearing capacity, friction characteristics, and more.

4.3.2 Surface Classification in CityGML: CityGML classifies road surface components based on functionality and models them as part of the Road object, which in turn belongs to a TransportationComplex. The decomposition includes two major classes:

- TrafficArea: Used to represent drivable areas, such as vehicle lanes, intersections, and roundabouts.
- AuxiliaryTrafficArea: Covers non-drivable areas, including sidewalks, shoulders, medians, verges, and green spaces.

These features are modeled using surface geometries (gml:MultiSurface) and are classified via function and usage attributes (e.g., "sidewalk", "bus lane", "crossing"). They can also be semantically linked to CityGML's LoD levels. For instance:

- In LoD2, roads are decomposed into TrafficArea and AuxiliaryTrafficArea surfaces with 3D geometry draped on terrain.
- In LoD3, finer geometric detail (e.g., curb heights, lane markings) may be included, although this depends on the implementation.

CityGML does not explicitly define road parts like IfcRoadPart. Instead, it emphasizes thematic and spatial roles rather than construction or assembly logic.

4.3.3 Mapping and Evaluation: There is a relatively strong conceptual alignment between IFC and CityGML in this domain - particularly for surface features. Functional components in IFC, though defined structurally and materially, often have clear thematic equivalents in CityGML. Table 3 below summarizes key mappings:

IFC Entity	CityGML Entity	Matching Type	Notes
IfcRoadPart (Trafficlane)	TrafficArea	Full Match	Semantic and geometric meaning align; geometry must be simplified.
IfcRoadPart (Sidewalk)	Auxiliary Traffic Area	Full Match	Equivalent thematic role; material and volume will be lost.
IfcRoadPart (Shoulder)	Auxiliary Traffic Area	Full Match	Functional match is strong; IFC provides more detail.
IfcRoadPart (Median)	Auxiliary Traffic Area	Full Match	Requires attribute mapping for clarity; LoD2 supports geometry.
IfcRoadPart (Roundabout)	Traffic Area	Partial Match	Structure can be modeled, but lacks internal logic like circulation path.
IfcMaterial LayerSet	*Not supported*	No Match	Material and layer info not representable in native CityGML.

Table 3. Mapping of Functional Surfaces and Road Parts

4.3.4 Implications for Conversion: The surface representation of roads is one of the most promising areas for IFC–CityGML integration, particularly at LoD2, where both standards allow for functionally differentiated surface areas. IFC's traffic lanes, sidewalks, and shoulders can be flattened and transferred to TrafficArea and AuxiliaryTrafficArea elements with reasonable fidelity. However, this conversion process will inevitably result in:

- Loss of volumetric geometry (thickness, material layers, subgrade data).
- Loss of engineering semantics, unless extended through metadata or ADEs.
- Loss of part-level identifiers, which may be needed for operations like maintenance planning.

Despite these losses, spatial extent and functional roles of surface features can be preserved accurately, making this one of the strongest candidate domains for successful unidirectional conversion between IFC and CityGML. For urban applications, such as traffic simulation, mobility planning, or city-scale visualization, this level of representation may be sufficient.

4.4 Road Markings, Signs, and Furniture

Beyond structural and functional surfaces, road models include auxiliary features such as lane markings, traffic signals, signage, lighting, and other furniture. These elements play essential roles in guiding vehicles and pedestrians, enforcing safety, and conveying information. Though often physically small, they are semantically rich and spatially relevant making them important for both engineering design and urban planning.

4.4.1 Annotation and Furniture Modeling in IFC: IFC includes an expanded set of entities to model road-related annotations and furniture. These include:

- IfcRoadMarking: Models surface-applied markings like lane dividers, arrows, crossings, and stop lines. These are typically represented via surface geometry (IfcCurve, Ifc-AnnotationFillArea) and linked spatially to the road surface.

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- IfcAnnotation: A general-purpose entity for 2D/3D symbolic content, such as text signs, hazard warnings, and visual guides, freely positioned and associated with road elements or structures.
- IfcRoadFurniture: A subclass of IfcFurnishingElement for physical roadside objects like guardrails, bollards, lights, signs, and benches. These include IfcProduct geometry and may carry attributes for material, mounting, and maintenance.

These components are tightly integrated into the IFC hierarchy, either within IfcRoadPart or linked to IfcRoad. Semantic detail is added via IfcClassificationReference, IfcLabel, and IfcPropertySet, defining usage, placement, and visibility. All elements use solid geometry, positioned relative to reference systems and linked via relationships like IfcRelAssigns or IfcRelConnects.

4.4.2 Representation in CityGML: Unlike IFC, CityGML offers limited native support for road annotations and furniture within its Transportation module:

- Road Markings: While CityGML 3.0 introduces the class *Marking* for representing road surface annotations, it is not included in this implementation. As a result, road markings may only appear as textures or visual overlays without semantic attributes.
- Road Furniture: Modeled using the CityFurniture module, objects like benches, streetlights, or signs can be embedded in scenes with basic geometry and attributes (e.g., function, usage). However, they are loosely connected to the transportation hierarchy and often managed externally.
- Annotations: Textual or symbolic annotations are not explicitly modeled. Such elements are typically omitted or handled through external metadata.

Extensions via ADEs can introduce specific annotation and road marking features, but such implementations are project- or domain-specific and lack standardization across CityGML tools and data platforms.

4.4.3 Mapping and Evaluation: Due to IFC's strong support for road annotations and furniture and CityGML's limited native representation, conversion in this domain is highly constrained. Most features require approximation, abstraction, or may be omitted entirely, unless extended through a custom ADE. Table 4 below outlines key mappings:

IFC Entity	CityGML Entity	Matching Type	Notes
IfcRoad Marking	*Not supported*	No Match	No direct representation; may require ADE or texture mapping.
Ifc Annotation	*Not supported*	No Match	Symbolic/textual signs not modeled in CityGML Transportation model.
IfcRoad Furniture	City Furniture	Partial Match	Geometry and location transferrable; lacks integration into road model.
Ifc Furnishing Element	City Furniture	Partial Match	Function may be approximated via attributes, but semantics simplified.

Table 4. Mapping of Road Annotations and Furniture

4.4.4 Implications for Conversion: The inability to transfer road markings, signs, and annotations from IFC to CityGML without semantic loss is a major interoperability limitation, especially for use cases like:

- Traffic regulation modeling (e.g., stop lines, lane restrictions).
- Safety simulations (e.g., visibility, signage compliance).
- Asset management of small-scale infrastructure (e.g., traffic signs, streetlights).

Partial conversion via CityFurniture is possible but:

- Disconnects objects from their functional context,
- Falls short for analytical workflows (e.g., rule checking),
- And requires custom enrichment to restore semantic meaning.

Therefore, unless extended through project-specific ADEs or semantic annotation layers, the unidirectional transfer of these elements is largely lossy, limiting the usefulness of converted models in domains beyond basic visualization.

4.5 Pavement Layers and Substructure

While BIM and GIS often focus on surface-level infrastructure, subsurface and layered components, such as pavement layers, base courses, drainage, and soil stabilization, are vital for road performance, safety, and lifecycle cost. A model's ability to represent these elements is crucial to its engineering applicability.

4.5.1 Pavement Layer Modeling in IFC: IFC supports detailed modeling of road composition through entities such as:

- IfcPavement: Represents the full pavement system, which can be decomposed into layers through aggregation.
- IfcMaterialLayerSetUsage and IfcMaterialLayer: Define the vertical structure of the pavement, specifying material, thickness, position, and role (e.g., surface, base).
- IfcBuiltElement, IfcSlab: Used for more generic structural zones, such as rigid pavements or composite sections.
- Geometry is volumetric, expressed via swept solids, extrusions, or profiles, allowing precise control over thickness and taper.

These layers are semantically rich, supporting properties like compaction, drainage, and thermal resistance, critical for simulation, structural assessment, and maintenance. They're typically aligned to IfcAlignment, ensuring spatial consistency.

4.5.2 Representation in CityGML: Does not natively support subsurface or multi-layer pavement modeling. Roads are typically represented at the surface level using TrafficArea or AuxiliaryTrafficArea, modeled as gml:MultiSurface.

Even at LoD3, the focus remains on visible, functional features. Though gml:Solid could, in theory, represent thickness, it is rarely used and lacks the semantic structure needed for layered construction. Additionally, CityGML does not support:

- Material-specific modeling for pavement layers.
- Structural composition or sequencing of layers.
- Geotechnical or underground information relevant to road construction.

In some ADE-based implementations or hybrid models (e.g., with InfraGML or CityGML+IFC integrations), extended support for substructure may be introduced, but this lies outside the scope of standard CityGML capabilities.

4.5.3 Mapping and Evaluation: The differences between IFC and CityGML in this domain are substantial and structural, not merely stylistic. IFC treats subsurface and layered road components as first-class modeling objects, while CityGML omits them entirely from its core transportation ontology. Table 5 below summarizes the evaluation:

IFC Entity	CityGML Entity	Matching Type	Notes
IfcPavement	*Not supported*	No Match	No CityGML class for representing entire pavement assemblies.
IfcMaterial LayerSet	*Not supported*	No Match	Layer composition cannot be represented in standard CityGML.
IfcMaterial Layer	*Not supported*	No Match	Layer thickness and material type lost in conversion.
IfcSlab (if used)	gml:Solid (LoD4 only)	Partial Match	Theoretical conversion to solids possible but not widely implemented.

Table 5. Mapping of Pavement Layers and Substructure

4.5.4 Implications for Conversion: From a conversion perspective, this domain suffers the highest level of semantic and geometric loss. While IFC offers detailed structural and material breakdowns, CityGML's transportation model is designed for surface-level abstraction and urban planning visualization, not engineering-grade modeling. Attempting to convert IFC pavement components to CityGML would:

- Lose all subsurface semantics, including materials, layering order, and performance properties.

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- Discard volumetric geometry, unless extended via custom ADEs or linked to an external BIM/GIS bridge.
- Break traceability for construction, compliance, and lifecycle modeling use cases.

Therefore, for any application requiring structural analysis, materials management, or asset degradation tracking, CityGML without extensions is not a suitable target model. At best, one could preserve top-level surface geometry (e.g., the top of pavement) and attach descriptive metadata externally - but this falls short of meaningful interoperability.

5. Discussion

This chapter reflects on the schema mapping results from Chapter 4, offering deeper insight into the interoperability gap between IFC and CityGML. It considers the implications for real-world use and how solutions like unified models or domain extensions might bridge this divide. Rather than a segmented summary, the discussion is framed around two core themes: interpreting the mapping results and identifying the semantic and structural mismatches that highlight the need for mediation.

5.1 Interpretation of Mapping Outcomes

The mapping results reveal the uneven landscape of BIM-GIS interoperability for road infrastructure. Some domains, especially functional surfaces like lanes and sidewalks, allow for relatively smooth conversion. At LoD2, IFC solids can often be flattened into CityGML surfaces, preserving core spatial and functional semantics for city-scale integration.

However, this is the exception. In most domains, particularly alignment geometry, annotations, structural layers, and road furniture, the models diverge sharply. IFC emphasizes engineering-grade semantics and volumetric precision, while CityGML favors generalized, surface-based abstractions for visualization and planning.

Thus, converting from IFC to CityGML is not just a structural task but one of semantic compression. Rich IFC content must often be simplified, approximated, or omitted, limiting its usefulness for workflows like construction planning, simulation, or asset management.

At a practical level, the mapping outcomes suggest a tiered model of conversion feasibility:

- Surface-level representation (lanes, sidewalks) is convertible and retains reasonable fidelity.
- Parametric and structural data (alignments, materials, layers) suffer major loss or require reinterpretation.
- Annotations and micro-elements (markings, signage) are effectively unsupported and fall outside CityGML’s standard capabilities.

Thus, while partial interoperability can support lightweight use cases, such as visualization or basic GIS integration, it falls short for high-fidelity, engineering-driven applications. This segmentation of use cases is a critical insight for practitioners who hope to unify BIM and GIS workflows using current standards.

5.2 Semantic Gaps, Engineering Constraints, and the Need for Mediation

The limitations encountered in this study are not just technical but conceptual, rooted in the distinct modeling philosophies of IFC and CityGML. IFC represents infrastructure from the perspective of construction logic, where hierarchy, material, and parametric geometry drive the model. CityGML, conversely, approaches infrastructure as part of a functional, spatial, and urban context, prioritizing thematic representation and integration across city-wide datasets.

This fundamental misalignment underscores the difficulty of direct schema-to-schema transformation. Even when names or structures appear similar, their intended semantics and expected behaviors often differ. For instance, a “lane” in IFC is a physical object with a material definition and alignment path; in CityGML, a TrafficArea is a polygon annotated with functional attributes, not linked to any construction details or layered semantics.

As such, attempts to directly map these models will always encounter friction. More importantly, forcing a direct translation risk undermining the integrity of the source model by stripping it of its core meaning. This raises a critical point: true interoperability is not achieved by translation alone, but through semantic mediation. This is precisely the rationale behind the development of a Unified Road Model (URM), a bridging ontology designed to identify shared concepts, resolve mismatches, and act as an intermediary for cross-domain integration. URM does not aim to replace IFC or CityGML, but rather to map between them with semantic awareness. It provides a space where alignment geometries, surface functions, and construction layers can coexist conceptually, even if they are implemented differently in their respective environments.

Additionally, the results point toward the need for semantic enrichment of CityGML, either through Application Domain Extensions (ADEs) or the integration of auxiliary ontologies. By extending CityGML to recognize road parts, layered structures, and annotated elements, a greater portion of IFC semantics could be retained in future conversions.

Finally, these findings highlight the value of developing tool-assisted transformation frameworks, which do not rely on hard-coded mappings but instead adapt intelligently to context, use case, and target LoD. Such tools could draw on ontologies, user-defined rules, or AI-supported inference to perform conversions that are purpose-driven rather than schema-bound.

In summary, the mapping results expose deep semantic and structural gaps, but they also illuminate the path forward. Interoperability, especially in the road domain, requires more than data reshaping; it demands conceptual alignment, enriched schemas, and intelligent mediation.

6. Conclusion and Future Work

This paper has presented a detailed evaluation of unidirectional conversion between the IFC 4.3 Road model and the CityGML 3.0 Transportation model, focusing on the feasibility of transferring semantic and geometric content from the engineering-centric BIM environment into the geospatially oriented GIS framework. Building upon established methods and enriched by insights from a unified schema perspective, the study explored the alignment between the two standards across five core domains: spatial structure, alignment geometry, functional surfaces, road furniture and markings, and subsurface pavement layers.

The results of the schema mapping demonstrate that partial interoperability is achievable, particularly for surface-level features such as traffic lanes, sidewalks, and medians, which can be transformed into CityGML's TrafficArea and AuxiliaryTrafficArea elements with reasonable fidelity. However, the evaluation also reveals substantial semantic and geometric gaps, especially in domains where IFC provides deep parametric or structural modeling, such as alignment definitions, multi-layer pavement composition, and road annotations or signage, which are either simplified or unsupported in CityGML’s core schema.

These gaps are not merely technical but conceptual, reflecting the fundamentally different purposes and modeling paradigms of the two standards. IFC focuses on detailed design, construction, and lifecycle management, while CityGML is optimized for city-scale representation, spatial integration, and thematic classification. As a result, direct schema-to-schema conversion inevitably involves information loss, limiting the usefulness of CityGML-converted models in high-precision, engineering-driven applications.

To address this, the paper reaffirms the value of semantic mediation frameworks, such as the Unified Road Model (URM), which abstract shared concepts across IFC and CityGML and provide a bridge for transformation that is both semantically aware and structurally consistent. Such frameworks offer the potential for loss-minimized, bidirectional interoperability, and provide a common foundation for tool development, data federation, and cross-domain querying. The domain-specific evaluations and conversion feasibility outlined in Tables 1–5 provide a structured reference for developers and researchers aiming to implement or extend cross-standard workflows

6.1 Future Outlook

To build on the findings of this study and address the identified limitations, several strategic directions are proposed:

1. Ontology-Based Mediation via the Unified Road Model (URM). The URM offers a semantically rich, conceptually aligned bridge between IFC and CityGML. Future work should focus on formalizing the URM as an ontology and using it to guide intelligent, loss-minimized transformation across standards.

2. CityGML Extension through Targeted ADEs. To capture essential IFC semantics, such as alignment profiles, road markings, and pavement layers, future efforts should develop CityGML Application Domain Extensions that reflect construction-specific needs while preserving GIS compatibility.

3. Deployment in Real-World Infrastructure Projects. Applying this mapping framework and URM to actual road projects will allow testing in real workflows (e.g., digital twins, maintenance platforms, traffic simulation), validating practical value and guiding refinement of both the model and tools.

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