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Detailed streetspace modelling in the context of semantic 3D city and landscape models

Christof Beil

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Vorsitz:	Prof. Dr.-Ing. Christoph Holst
Prüfer der Dissertation:	1. Prof. Dr. rer. nat. Thomas H. Kolbe
	2. Prof. Dr.-Ing. Klaus Bogenberger
	3. Prof. Dr.-Ing. Jörg Blankenbach

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Abstract

Three-dimensional digital city models are increasingly utilized for analyzing urban areas. While buildings and the terrain are commonly represented, detailed streetspace models have played a minor role so far. However, this is currently changing due to three main reasons: First, advances in technologies such as mobile mapping systems allow an efficient process to automatically capture detailed data representing the streetspace in the form of point clouds or derived 3D models. Second, the semantically mostly unstructured data provided by these methods can be interpreted and enriched with semantic meaning through machine learning and other interpretation and model reconstruction techniques. These processes are also becoming increasingly automated. Third, new and emerging fields of application such as urban digital twins or automated driving require not only detailed (geo-referenced) geometric but also semantic, topological, temporal and visual information about the streetspace in a structured and standardized form.

Despite these advances, in the field of 3D city modelling there is little experience in how the streetspace can be meaningfully divided and structured into individual elements. It is also unclear which semantic classes, geometric and topological properties and relations are required in order to be able to serve the requirements of a large number of current and potential use cases. Thus, this work identifies and categorizes 36 use cases across four main application domains, namely (1) Infrastructure Planning, Construction and Management, (2) Automotive, Transportation and Navigation, (3) Environmental Simulations and Analyses and (4) Land Administration and Topographic Mapping. In order to achieve the goal of a specific use case, one or more required functionalities of software applications are identified. Then, a detailed analysis of requirements of these functionalities towards input data is conducted with regard to the aforementioned requirement aspects.

Additionally, this work evaluates relevant standards, conceptual models and guidelines in road and streetspace modelling to assess their ability to meet these identified requirements. This shows, that existing standards, conceptual models and data formats such as OpenDRIVE, GDF, OSM or IFC mostly focus on linear or parametric representations or lack clear definitions for non-redundant representations of roads and the streetspace as part of a consistent 3D city model. This includes version 2.0 of the international OGC standard CityGML, which has established itself as the most commonly used standard for semantic 3D city modelling but only provides limited concepts for modelling transportation infrastructure.

Based on the findings of this evaluation, revised and extended concepts of the CityGML Transportation module are developed. The resulting data model is adopted by the newest version 3.0 of CityGML. This includes concepts for geometric and semantic segmentation of transportation networks of roads (or railways) into sections and intersections further segmented in a hierarchical structure down to individual lanes. The introduction of representing each city object with spaces and space boundaries is transferred to the Transportation module. Additionally, three levels of granularity are introduced

in order to ensure possibilities for a clear semantic decomposition of road objects. Definitions for utilizing the revised Level of Detail (LOD) concepts for geometric representations of road objects are given. Geometric representations in a linear, areal or volumetric form or by using point clouds are presented and explained. Furthermore, examples for an integrated representation for multiple transportation infrastructure (e.g. roads and railways as level crossings or footpaths, bicycle paths and waterways, etc.) are given. Previously identified requirements of relevant software functionalities and use cases are evaluated with respect to this newly created concept of modelling roads and the streetspace within semantic 3D city models. It is shown, that most requirements are met, which allows models created according to the presented concepts to be used by a large number of use cases.
Corresponding datasets according to the presented concepts are created from various sources. This includes OpenDRIVE datasets mapped to concepts of CityGML 3.0 as well as upgraded datasets available according to CityGML 2.0 and city models generated from other geospatial data sources such as the Munich Lane Model or geospatial open data available for cities such as New York, Melbourne or Tokyo. The practicability of the data created according to the presented concepts is demonstrated by implementing selected use cases such as pavement rating and solar irradiation analysis, web-based visualizations of traffic simulation results, pedestrian simulations, multi-modal navigation or automatically evaluating the service quality of bicycle paths.

Zusammenfassung

Dreidimensionale digitale Stadtmodelle werden zunehmend für die Analyse von städtischen Gebieten genutzt. Während Gebäude und das Gelände häufig abgebildet sind, spielten detaillierte Straßenraummodelle bisher eine eher untergeordnete Rolle. Dies ändert sich derzeit aus drei Hauptgründen: Erstens ermöglichen Technologien wie Mobile Mapping Systeme eine effiziente und automatisierte Erfassung detaillierter Straßenraumdaten in Form von Punktwolken oder draus abgeleiteten 3D-Modellen. Zweitens können diese typischerweise semantisch unstrukturierten Daten beispielsweise mit Hilfe von Methoden des maschinellen Lernens sowie weiterer Auswerte- und Rekonstruktionsmethoden interpretiert und mit semantischer Bedeutung angereichert werden. Diese Prozesse können zunehmend automatisiert durchgeführt werden. Drittens erfordern neue und aufkommende Anwendungsfelder wie urbane digitale Zwillinge oder automatisiertes Fahren nicht nur detaillierte (georeferenzierte) geometrische, sondern insbesondere auch semantische, topologische, zeitliche und visuelle Informationen über den Straßenraum in strukturierter und standardisierter Form.
Im Bereich der 3D-Stadtmodellierung besteht bislang jedoch nur wenig Erfahrung darin, wie der Straßenraum sinnvoll in einzelne Elemente unterteilt und strukturiert werden kann. Unklar ist auch, welche semantischen Klassen, geometrischen und topologischen Eigenschaften sowie Beziehungen erforderlich sind, um eine Vielzahl aktueller und potentieller Anwendungsfälle bedienen zu können. Daher werden in dieser Arbeit 36 Anwendungsfälle identifiziert und nach vier Hauptanwendungsbereichen kategorisiert. Diese sind (1) Infrastrukturplanung, -bau und -management, (2) Automobilanwendungen, Transport und Navigation, (3) Umweltsimulationen und -analysen sowie (4) Landesverwaltung und topographische Karten. Um das Ziel eines bestimmten Anwendungsfalls zu erreichen, werden eine oder mehrere benötigte Funktionalitäten identifiziert, welche in der Regel durch Software Anwendungen bereitgestellt werden. Anschließend wird eine detaillierte Analyse der Anforderungen dieser Funktionalitäten an Datengrundlagen im Hinblick auf die zuvor genannten Anforderungsaspekte durchgeführt.
Des Weiteren werden einschlägige Standards, konzeptionelle Datenmodelle und Richtlinien im Zusammenhang mit der Modellierung von Straßen und Straßenräumen hinsichtlich ihrer Eignung zur Erfüllung der identifizierten Anforderungen evaluiert. Eine Erkenntnis dieser Evaluation ist, dass bestehende Standards, konzeptionelle Modelle und Datenformate wie OpenDRIVE, GDF, OSM oder IFC sich meist auf lineare oder parametrische Darstellungen von Straßen konzentrieren oder klare Definitionen für eine nicht-redundante Repräsentation von Straßen und des Straßenraums als Bestandteil eines konsistenten 3D-Stadtmodells fehlen. Dies gilt auch für Version 2.0 des internationalen OGC-Standards CityGML, der sich als der am häufigsten verwendete Standard für die semantische 3D-Stadtmodellierung etabliert hat, jedoch nur begrenzt Konzepte für die Modellierung von Verkehrsinfrastruktur bietet.
Basierend auf den Ergebnissen dieser Evaluation werden überarbeitete und erweiterte Konzepte des

CityGML Verkehrsmoduls (Transportation module) entwickelt. Die im Rahmen der Arbeit entwickelten Konzepte zur semantischen 3D-Straßenraummodellierung wurden in der neuesten Version 3.0 des internationalen OGC Standards CityGML übernommen. Dies beinhaltet Konzepte zur geometrischen und semantischen Segmentierung von Verkehrsnetzen aus Straßen (oder Schienen) in Abschnitte (Sections) und Kreuzungen (Intersections), die in einer hierarchischen Struktur bis hin zu einzelnen Fahrspuren weiter unterteilt werden. Die Einführung der Darstellung jedes Stadtobjekts durch Räume (Spaces) und Raumgrenzen (Space Boundaries) wird auf das Verkehrsmodul übertragen. Zusätzlich werden drei Granularitätsebenen eingeführt, um die Möglichkeit einer klaren semantischen Zerlegung von Straßenobjekten zu gewährleisten. Weiterhin werden Definitionen für die Verwendung der überarbeiteten Level of Detail (LOD)-Konzepte für geometrische Repräsentationen von Straßenobjekten gegeben. Geometrische Repräsentationen in linearer, flächenhafter oder volumetrischer Form oder unter Verwendung von Punktwolken werden vorgestellt und erläutert. Darüber hinaus werden Beispiele für eine integrierte Darstellung für mehrere Verkehrsinfrastrukturen, z.B. Straßen und Eisenbahnen in Form von Bahnübergängen oder Fußwegen, Radwegen und Wasserstraßen, etc. gegeben. Ermittelte Anforderungen an relevante Software Funktionalitäten und Anwendungsfälle werden im Hinblick auf dieses neu geschaffene Konzept zur Modellierung von Straßen und des Straßenraums in semantischen 3D-Stadtmodellen evaluiert. Es zeigt sich, dass die meisten Anforderungen erfüllt werden, sodass die nach den vorgestellten Konzepten erstellten Modelle für eine große Anzahl von Anwendungsfällen genutzt werden können.

Zur Demonstration der Praktikabilität der entwickelten Konzepte, werden CityGML 3.0-konforme Straßenraummodelle aus verschiedenen Datenquellen erstellt. Darunter OpenDRIVE-Datensätze und bestehende CityGML 2.0-Daten sowie Geodaten aus Städten wie München, New York, Melbourne und Tokio. Die erzeugten Daten werden für Anwendungsfälle aus unterschiedlichen Domänen genutzt. Diese sind Straßenzustandsanalysen, Sonneneinstrahlungsanalysen, Fußgängersimulationen, webbasierte Visualisierungen von Verkehrssimulationen, multimodale Navigationsanwendungen sowie die automatisierte Bewertung der Servicequalität von Radwegen.

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Chapter 1

Introduction

1.1 Motivation

In the context of smart cities and urban digital twins, three-dimensional semantic city models play a major role as an anchor point for integrating heterogeneous data, thus providing the foundation for a large range of applications and use cases (Biljecki et al., 2015). While the representation of buildings and the terrain has become standard for most digital city models, detailed spatio-semantic representations of roads and the streetspace (as well as other transportation infrastructure) have played a minor role so far. This is now changing for three main reasons as illustrated in figure 1.1.
First, with improved sensing technologies (including sensors and platforms) such as mobile mapping systems (MMS), the acquisition of detailed data of urban environments has become more accessible, affordable and time-efficient (Y. Xu and Stilla, 2021). These methods can (fully) automatically provide detailed geometric information on the streetspace down to individual curb stones. However, this data typically is semantically unstructured. Second, using improved data processing and interpretation methods based on machine learning techniques such as semantic classifications of point clouds, extracting information on road infrastructure from images and videos or lane-level road feature reconstruction, semantically unstructured information can be leveraged to derive semantically meaningful 3D models. However, the semantic structure of data generated by these processes often is not directly provided according to standardized conceptual models, which hinders the interoperable usage of this data required by a number of use cases and software functionalities. The third pillar for motivating this thesis are new and emerging fields of application such as urban digital twins, autonomous driving or three-dimensional digital landscape models, which require not only detailed geometric, topological and geo-referenced information of the streetspace but also especially benefit from spatio-semantic coherent information (Stadler and Kolbe, 2007).
These main reasons provide the motivation for the development of a coherent, integrated and standardized concept as well as a corresponding data model for the representation of roads and the streetspace in the context of semantic 3D city and landscape models as further discussed in the following subchapters. Semantic 3D city and landscape models are a suitable foundation for achieving this goal, since highly accurate geo-referenced, geometric and topological information as well as semantic capabilities are key strengths of these models (Kolbe and Donaubauer, 2021).

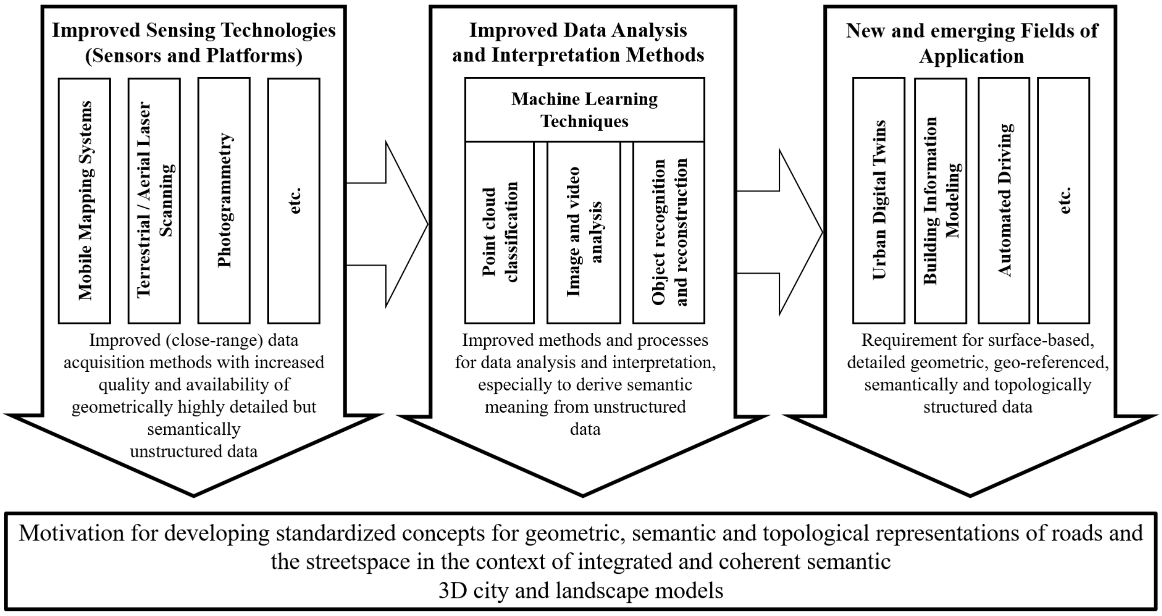


Figure 1.1: Motivation for developing standardized and coherent concepts for detailed 3D streetspace modelling in the context of semantic 3D city models.

1.1.1 Improved Technologies for gathering detailed Information on the Streetspace

The increased availability and detail of data representing roads and the streetspace from data sources such as laser scanning, mobile mapping systems or (close-range) photogrammetry improve the quality of geometrically highly-detailed information. There are different commonly used techniques utilized for gathering laser scanning data including terrestrial laser scanning (TLS), airborne laser scanning (ALS), handheld laser scanning (HLS) or mobile laser scanning (MLS). Each of these methods can be used to automatically produce highly-detailed point clouds representing road infrastructure with x-, y-, and z-coordinates as well as additional information on color, intensity or (basic) classification. Methods and technologies for gathering laser scanning data using mobile mapping systems exist for several decades (Puente et al., 2013). Modern MMS typically employ an integrated system of light detection and ranging (LiDAR) sensors in combination with cameras, positioning systems and inertial measuring units (IMU) for a highly accurate, quick and geo-referenced acquisition of point cloud data with (typically at least) centimeter accuracy (Elhashash et al., 2022). Y. Wang et al. (2019) present an overview on mobile laser scanning techniques and applications including mapping of road infrastructure and city furniture.

Recently, remote sensing technologies have improved significantly, with very-high-spatial-resolution (VHR) imagery typically providing a spatial resolution of 1-5 meters (Tong et al., 2023; Wen et al., 2021). H. Yao et al. (2019) give an overview on using unmanned aerial vehicles (UAVs) for gathering highly detailed imagery and discuss relevant applications. High-resolution imagery can be used for automatically reconstructing detailed point clouds and 3D surface models such as 3D meshes including road surfaces using image matching methods, which also increasingly improve due to deep learning approaches (Jiang et al., 2021). While the presented technologies, sensors and platforms allow a quick and fully automatic acquisition of geometrically highly detailed data, resulting datasets are typically unstructured in the sense, that they lack semantic meaning such as attributes or object hierarchies and relations. Thus, a further processing of this data is often required in order to generate semantically structured information and to reconstruct semantic 3D streetspace objects.

1.1.2 Improved Streetspace Data Interpretation and Model Reconstruction Methods

The increasing availability and detail of data such as point clouds or (aerial) imagery containing information on roads and the streetspace as well as sophisticated methods such as machine and deep learning techniques, allow the (increasingly automatic) interpretation and derivation of semantically enriched information from unstructured source data. In the context of point clouds, a first step towards creating semantically detailed 3D models typically involves the segmentation and classification of points into clusters.

J. Zhang et al. (2019) present a review on methods for semantic segmentation of point clouds. Recently, machine and deep learning methods have improved this process (Winiwarter et al., 2019; Kölle et al., 2021). While this classification often distinguishes between points belonging to buildings, vegetation or the ground, more detailed classifications concerning different types of grounds (e.g. based on surface materials) are increasingly available (Reichler et al., 2024). Behley et al. (2024) describe the creation of a semantically annotated point cloud including information on road surfaces, sidewalks and parking areas. The topic of road object detection and recognition from (laser scanning) point clouds or imaginary exists for some time (Oude Elberink, 2010), often focusing on traffic signs and other city furniture objects (Pu et al., 2011; Cabo et al., 2014) or road marking detection (Fischer et al., 2018). Balado et al. (2019) demonstrate the advantage of deep learning methods for the semantic segmentation of point clouds including the identification of road elements such as road surfaces, embankments or ditches. Gargoum and El-Basyouny (2017) give an overview on methods for automatically extracting road features such as road surfaces or lane markings from 3D point clouds. Großmann et al. (2023) present the automatic detection of road features including markings, traffic signs, streets or sidewalks from laser scanning data in combination with georeferenced street-level images using deep learning methods.

In the context of image and video analysis, machine learning methods have also improved possibilities for deriving information on road infrastructure from this data. Detecting information on roads from imaginary data can be done in multiple scales. Lian et al. (2020) present an overview on methods for extracting information on roads from high-resolution remote sensing imagery. While this resolution may be sufficient for detecting road networks with a similar accuracy, the extraction of more detailed information on roads can be achieved using close-range photogrammetry products (J. Chen et al., 2019). Constantin et al. (2018) and Wei and Ji (2022) describe the identification of roads from satellite images using deep learning methods. Similarly, roads can be detected from higher resolution imagery (e.g. gathered using UAVs) identifying more exact information on the extent of road surfaces (Rezaee and Y. Zhang, 2017). Similar to point cloud classification techniques, deep learning methods are increasingly utilized (Abdollahi et al., 2020).

A next step then is to (automatically) derive and reconstruct semantic 3D models of roads and the streetspace from the semantically classified and geometrically accurate data. L.-C. Chen and Lo (2009) present a workflow for deriving road centerlines from topographic 2D maps and then use this information in combination with LiDAR data for generating 3D road models. S. Chen et al. (2018) present a similar approach for extracting bridge deck surfaces from point cloud data (generated using low-cost UAVs). Details of the implemented region-growing algorithm can be found in Vo (2017). R. Wang et al. (2018) give an overview on different possibilities for reconstructing 3D models of urban environments such as roads and bridges using different strategies including point cloud information. Goebbels (2021) describes a method for reconstructing bridge decks from ALS and cadastral data. Javanmardi et al. (2017) describe the extraction of road features from mobile laser scanning data and aerial images. Ye et al. (2022) present a method for detecting individual lanes from point clouds for HD-map creation. Pan et al. (2024) present an approach for deriving lane-level components of highways from point clouds and creating a graph-based representation. Crampen et al. (2024a) present a method for generating spatio-semantic 3D models of roads from point cloud data. Rashidan et al. (2024) present a process for the semantic segmentation of 3D building models according to concepts of CityGML, which could be adapted for 3D road models.

While the presented 3D model reconstruction methods provide possibilities for the automatic creation of information on roads, processes of generating highly detailed (and surface-based) representations of road infrastructure in lane-level accuracy including additional information such as traffic logic typically remain a manually intensive task. With the further development of object recognition and reconstruction techniques, this process will become more automatic and thus less time-consuming and more affordable in the future. Nonetheless, an increasing number of cities, regions and countries are in the process of gathering geometrically detailed and semantically rich information on roads and the streetspace in order to serve a growing number of use cases within new and emerging fields of application (Uggla et al., 2023; Seto et al., 2023; Lehner et al., 2024).

1.1.3 New and emerging Fields of Application

One of the most significant fields of application in this context are *Urban Digital Twins (UDT)*. The term 'Digital Twin' originates from Industry 4.0, describing a digital counterpart of a real-world object over its entire life-cycle (Batty, 2018; Jones et al., 2020; Fuller et al., 2020). This concept recently was transferred to urban environments, thus creating the term 'Urban Digital Twin' representing a digital twin of cities and its components in the context of a smart city (Dembski et al., 2020; Shahat et al., 2021; Schonowski et al., 2024).

In addition to digital twins of buildings, transportation infrastructure such as roads play a significant role within a city ecosystem, which is reflected by aspects such as urban mobility, quality of living or environmental challenges. In this context, semantic 3D city models including roads and the streetspace can serve as an anchor point for a growing number of use cases such as mobility planning, traffic simulations, air quality analysis or asset management (Knezevic et al., 2022; Biljecki et al., 2015). Semantic 3D city models in higher levels of detail (e.g. LOD 3) are also increasingly available but still mainly focus on representations of buildings (Harshit et al., 2024). The increasing availability of the previously mentioned data sources would also allow the generation of highly detailed models for

transportation infrastructure, which could be useful for a number of use cases.
While semantic 3D city models usually are created on a city-wide scale, *Building Information Modeling (BIM)* typically focuses on individual (construction) sites (Kolbe and Donaubauer, 2021). While the focus of BIM has mostly been on buildings, recently, concepts for representing and modelling transportation infrastructure gained increased attention. Several countries already legally require the implementation of digital representations of building and infrastructure projects during planning, construction and operating phases for public contracts in order to increase time and cost efficiency (Borrmann et al., 2020; Borrmann et al., 2021).
Another relevant field of application in the context of digital representations of roads are emerging transportation systems such as *Automated Driving* (Richter et al., 2020). Depending on the specific concept, detailed HD-maps are required for implementing automated driving functions. Additionally, digital models of roads and the streetspace can be used for virtually testing automated driving functions before they are actually implemented in order to transfer testing-kilometers required for the approval of autonomous vehicles into these virtual environments (Schwab and Kolbe, 2019). Use cases from the presented and further fields of applications typically not only require detailed geometric and geo-referenced data but also topological as well as semantically structured information including attributes, relations and object hierarchies, ideally in a standardized form. Thus, coherent and integrated concepts for representing roads and the streetspace as part of a standardized 3D city and landscape model are required.

1.2 Problem Statement

The international standard City Geography Markup Language (CityGML) issued by the Open Geospatial Consortium (OGC) has established itself as the most widely used specification for storing, modelling and exchanging semantic 3D city models. Especially models of buildings in Level of Detail (LOD) 1 and 2 are available for a large number of cities and regions world-wide[1]. Some cities and regions also provide selected building models in LOD 3 (Wysocki et al., 2024). While version 2.0 of the standard already contains a *Transportation* module for representing infrastructure such as roads or railways (Gröger et al., 2012), these concepts are not expressive enough to fulfill modelling requirements of emerging use cases, such as virtually testing autonomous driving systems (Schwab and Kolbe, 2019). Thus, concepts of CityGML need to be revised and extended by taking into account requirements of existing and potential applications and use cases as well as relevant standards in the field of street(space) modelling for ensuring interoperability.
There are several reasons why examining related standards is relevant. First, there are software products and datasets that already exist for widely used data models, such as Geographic Data Files (GDF) and OpenDRIVE. Available data sources should be interoperable with newly created concepts. Second, established standards also provide know-how on how to fulfill the requirements of use cases within their intended domain. Third, potential limitations of currently available standards can be identified and addressed accordingly. The streetspace includes different components such as individual lanes, pedestrian paths and crosswalks, bicycle lanes, parking areas, raised traffic islands, markings or

[1] https://github.com/OloOcki/awesome-citygml

3D objects such as traffic lights or traffic signs. Additionally, 3D elevations and cross-profiles as well as roads on multiple levels, e.g. on bridges, in tunnels or as part of complex motorway interchanges present some challenges for modelling these scenarios in a standardized and consistent way. Using the standard CityGML, complex city features can be hierarchically structured into smaller components with clear geometric and semantic representations. Buildings for example are decomposed into individual parts such as roof-, wall- or ground-surfaces. Transportation infrastructure, such as large street or railway networks, also need to be segmented into smaller objects in order to follow this hierarchical concept. However, in the context of 3D city modelling, there is not much experience in how to subdivide and structure transportation network elements in a similar and most useful way. Also, required object classes, relations and attributes are unclear.

Transportation systems in large cities not only include roads used by cars but also various other transportation infrastructure, such as railways, footpaths, bicycle lanes. These different modes of transportation often intersect and, in some cases, even occupy the same spaces within a city. Level crossings of roads and railways or tramways within a road, for example, share identical areas of the streetspace. Therefore, creating non-redundant and consistent models for multimodal transportation relations within 3D city models is challenging. However, it is crucial to achieve this to accurately depict real-world scenarios suitable for a variety of use cases. Depending on the specific purpose, various geometric representations, such as linear graph networks, areal surface models, or volumetric spaces, should be possible and consistent (Gröger and Plümer, 2011). In this context, Stadler and Kolbe (2007) describe the importance of spatial and semantic coherence of city models and highlight respective capabilities of CityGML. This requires concepts as well as corresponding data models to segment complex real-world scenarios into individual streetspace objects.

Creating concepts for modelling the streetspace and overcoming the presented challenges is not sufficient. In order for these concepts to be usable for different software functionalities and use cases, the ability to acquire and generate data according to the CityGML standard is vital. There are some companies, that are able to generate highly detailed information of the streetspace (more or less automatically using complex derivation methods) and provide resulting data in the OpenDRIVE format. However, the parametric representation of geometries of OpenDRIVE exclude the use of this data for applications that need explicit geometries with surface-based models of the streetspace. Furthermore, while there are tools available for converting OpenDRIVE data to CityGML, existing OpenDRIVE datasets are mostly limited to regional and spatially limited extents. Several cities (such as New York City, Melbourne, Munich or Singapore) have detailed data on roads and the streetspace available, usually within an ArcGIS or QGIS environment. However, this data is often structured in different non-standardized ways (semantically and geometrically). Modelling this data within a common representation framework allows the immediate usage of the data with the same tools for a number of use cases. Thus, methods for transferring existing data to the presented concepts need to be developed and implemented, demonstrating the usability of the created data for various use cases.

1.3 Research Questions and Hypotheses

The main objective of this thesis is to extend the capabilities of semantic 3D city and landscape models by detailed representations of transportation infrastructure while focusing on the streetspace. This includes developing modelling concepts, implementing these concepts and subsequently using the created models for several use cases. In this context, the following research questions and hypotheses are derived:

Question 1.1: What geometric, semantic, topological, temporal and visual requirements do existing and potential applications and use cases impose upon digital models of the streetspace?

Question 1.2: How are roads and the streetspace represented in relevant standards, conceptual data models and data formats and do these concepts adequately address the determined requirements?

Question 1.3: How should the streetspace be modelled in the context of semantic 3D city models in order to meet requirements of intended applications and use cases?

Question 1.4: How should urban spaces (including roads, railways and other transportation infrastructure) be segmented into well-defined 3D objects in order to achieve non-redundant geometric and semantic representations?

Hypothesis 1.5: The international OGC standard CityGML version 2.0 can be extended and revised in order to be suitable for representing the streetspace in such a way, that requirements imposed by most use cases are met.

Hypothesis 1.6: Interoperability of CityGML with other existing standards for road modelling can be improved by extending and revising modelling concepts.

Question 1.7: What data sources are available and suitable for generating streetspace models according to the developed concepts and which levels of model granularity can be achieved?

Question 1.8: How can selected use cases from different application domains be implemented in order to benefit from the newly available concepts?

1.4 Structure of the Thesis

The contents of this thesis are based on research that was published in several scientific publications including journal and conference articles as well as technical guidelines, which are listed in the 'Original publications' section at the end of this thesis. The general structure of this thesis is illustrated in figure 1.2.

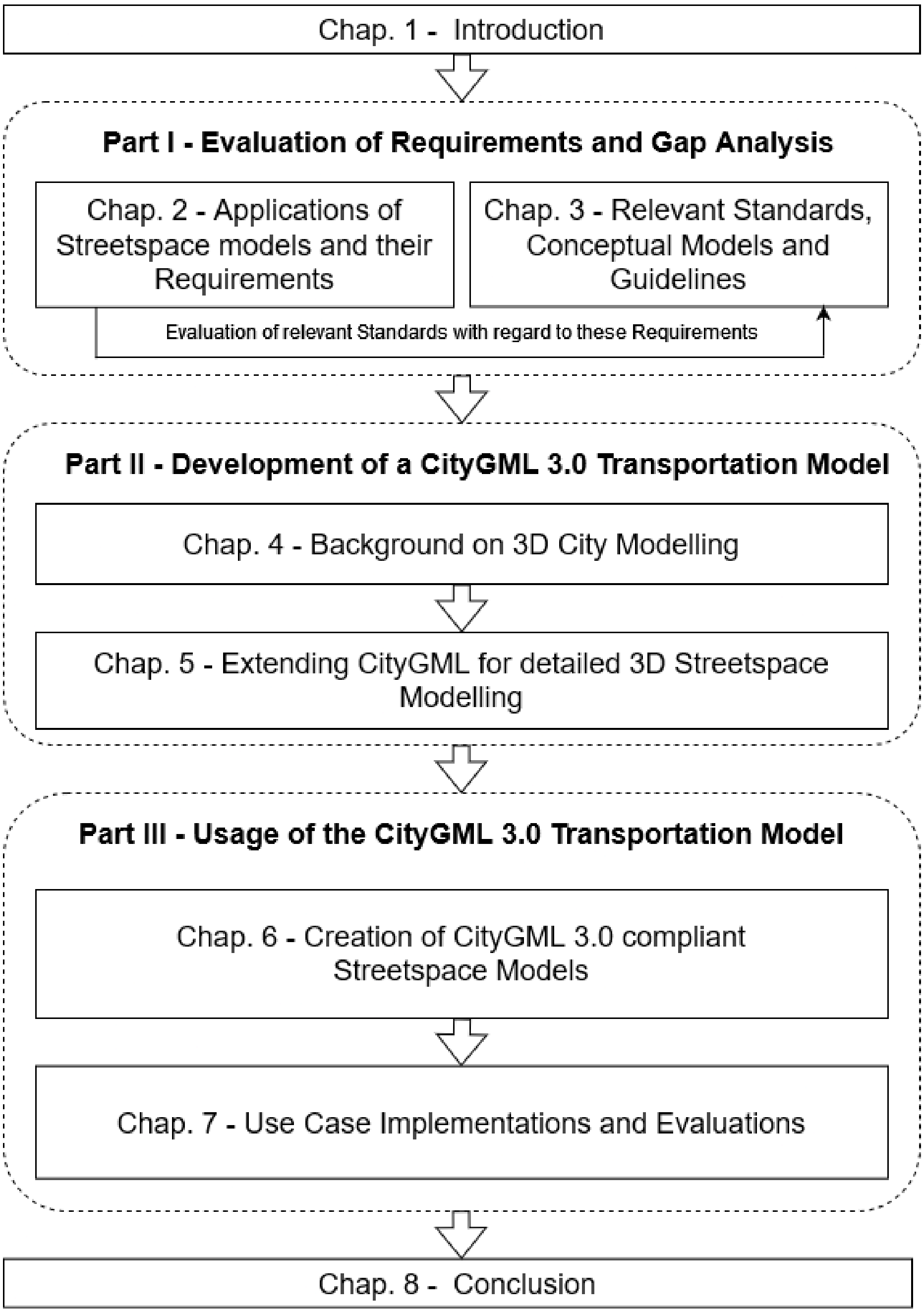


Figure 1.2: Structure of this thesis divided into three main parts and 8 chapters.

After an introduction in chapter 1, the thesis is segmented into three main parts. In the first part, use cases for semantic 3D streetspace models and their respective data requirements are defined and evaluated in chapter 2. Chapter 3 then presents and discusses relevant standards, data formats and guidelines in the field of semantic road modelling and evaluates the capabilities of these specifications with regard to the determined requirements. This gap analysis provides the foundation for the development of revised and extended concepts for modelling roads and the streetspace in the context of semantic 3D city and landscape models. In the second part, chapter 4 provides background information in the context of 3D city modelling. Concepts for extending the international OGC standard CityGML for modelling transportation infrastructure are then developed and explained in chapter 5. This results in the conceptual data model of the Transportation Module of CityGML 3.0, which was issued by the Open Geospatial Consortium (OGC) in 2021 based on the findings presented in this thesis and is a central result of this doctorate. In the third part of this thesis, these concepts are then applied in different contexts. Data compliant to the CityGML 3.0 data model is generated for several cities and from different data sources in chapter 6. These models are then used for implementing a number of use cases, demonstrating the extended capabilities of the newly available CityGML 3.0 concepts in chapter 7. Finally, chapter 8 concludes with key findings and an outlook to the research presented in this thesis.

1.5 Projects

In the course of this dissertation work, concepts and implementations have been developed and applied within the following projects:

1. **Development of the international OGC standard CityGML version 3.0:**
   In order to increase the usability of CityGML for other user groups and fields of application, the OGC City Geography Markup Language Standards Working Group (CityGML SWG) and the Special Interest Group 3D (SIG 3D) of the German Spatial Data Infrastructure Initiative (GDI-DE) have been working on the further development of CityGML since 2014. This development has resulted in the new version CityGML 3.0, which was published in September 2021 and issued by the Open Geospatial Consortium (OGC) (Kolbe et al., 2021). A corresponding GML Encoding specification was published in 2023 (Kutzner et al., 2023). The extended and revised data model for the Transportation module, developed as part of this dissertation, was directly adopted in the latest version 3.0 of the standard.

2. **Digital Twin Munich and Connected Urban Twins (CUT)**
   The digital twin Munich is developed within the framework of the project 'Digital Twin Munich' funded by the Federal Ministry for Digital and Transport (BMDV) and the project 'Connected Urban Twins (CUT)' funded by the Federal Ministry of the Interior (BMI). In the course of this project, a 'Lane Model' representing roads with lane-level accuracy was conceptualized and created by the Geodatenservice Munich. The aim of this Lane Model is a consistent and complete areal as well as linear representation of Munich's roads for different use cases and applications. Results of

this dissertation work contributed to the Lane Model concept, the subsequent conversion of the Lane Model to concepts of CityGML (version 3.0) and the applications of Lane Model data for use cases such as bicycle path quality analysis.

3. **PLIMOS - 'Planning intermodal mobility services based on 3D city models'**
   The aim of the project PLIMOS funded by the Bavarian Ministry of Economic Affairs, Regional Development and Energy (StMWi) is to provide services that can be used to plan, simulate and optimize intermodal public transport for the municipality of Grafing near Munich on the basis of a digital 3D city and road model. One of the aims is to operate a (partially) autonomous e-shuttle bus. In the course of this project, a proposal for a CityGML OpenDRIVE Application Domain Extension (ADE) was developed to increase the interoperability between the two standards. Additionally, concepts for web-based visualizations of traffic simulation results were developed and implemented.

4. **SaveNow - 'Functional and traffic safety for automated and connected mobility - benefits for society and ecological impact'**
   The SAVeNoW project funded by the Federal Ministry for Digital and Transport (BMDV) of Germany explores the development and deployment of a digital twin based on the example of the city of Ingolstadt and its surroundings. The project was led by the AUDI AG and done in collaboration with 13 project partners from industry and academia including the TUM Chair of Geoinformatics. In this context, a virtual model of a (real) digital test field is created for analyses and simulations. The virtual model of roads and the streetspace were created according to concepts of CityGML 3.0 developed in the course of this dissertation work.

Part I

Evaluation of Requirements and Gap Analysis

Chapter 2

Applications of Streetspace Models and their Requirements

Some of the contents in this chapter have been presented in the following peer-reviewed and published papers:

Beil, C. and Kolbe, T. H. (2017). 'CityGML and the streets of New York - A proposal for detailed street space modelling'. In: *Proceedings of the 12th International 3D GeoInfo Conference 2017*. Ed. by Kalantari, M. and Rajabifard, A. Vol. IV-4/W5. ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences. This paper has received the 2nd Best Paper Award. University of Melbourne. ISPRS: Melbourne, Australia, pp. 9–16. URL: https://doi.org/10.5194/isprs-annals-IV-4-W5-9-2017

Beil, C., Ruhdorfer, R., Coduro, T. and Kolbe, T. H. (2020). 'Detailed Streetspace Modelling for Multiple Applications: Discussions on the Proposed CityGML 3.0 Transportation Model'. In: *ISPRS International Journal of Geo-Information* 9(10), p. 603. URL: https://doi.org/10.3390/ijgi9100603

Beil, C. and Kolbe, T. H. (2024). 'Applications for Semantic 3D Streetspace Models and Their Requirements - A Review and Look at the Road Ahead'. In: *ISPRS International Journal of Geo-Information* 13(10), p. 363. URL: https://doi.org/10.3390/ijgi13100363

2.1 Methodology

Specific use cases are often the motivation for cities to develop urban digital twins of roads and the streetspace. However, in order to carry out these use cases, the usage of functionalities of one or multiple software tools is necessary, which have certain requirements towards input data. In order to determine relevant use cases, functionalities and their requirements, the methodology described in this chapter is applied.
There are some publications focusing on applications of semantic 3D city models in general with a focus on models of buildings (Biljecki et al., 2015; Saran et al., 2018; Willenborg et al., 2018). These references were studied with regard to respective research methodologies, included use cases and defined taxonomies and classifications. Based on these findings, use cases that specifically rely on or at least benefit from semantic representations of roads and the streetspace are investigated. A systematic literature review was conducted based on the method described in Carrera-Rivera et al. (2022). The general methodology and workflow structure of this chapter are illustrated in figure 2.1. Research

question 1.1 is answered with results of this literature review. This was achieved by conducting a continuous and extensive literature review, including scientific publications, project reports and online resources on use cases of semantic 3D road and streetspace models as well as relevant standards and data formats.

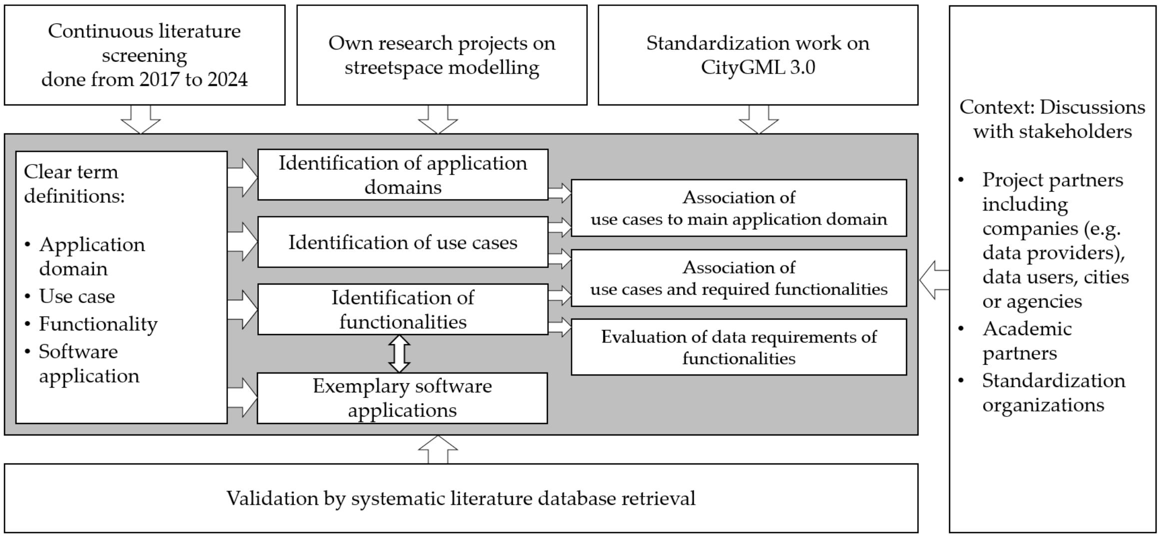


Figure 2.1: Methodological workflow.

The presented literature was collected utilizing databases such as Google Scholar and validated by a systematic literature retrieval using Scopus. For this, the Scopus database was searched for appropriate search strings[2]. A large number of papers resulting from this search focus on the generation processes of road models from different data sources, which is not the focus of this chapter and thus is not included. Papers focusing on use cases and applications of semantic 3D city models, in general (not focusing on roads and the streetspace), are also outside of the scope of this chapter and are only cited with respect to relevant research methodology.

In order to be included in the review, literature must be relevant for semantic 3D streetspace models and respective use cases. The literature review does not solely contain results from this database search but includes additional suitable sources gathered continuously from 2017 to 2024. Experiences from implementing a number of the presented use cases within our own research projects as well as standardization work such as the development of the CityGML 3.0 Transportation module also contributed to the knowledge that is comprised in the evaluations in this chapter. Additionally, discussions with stakeholders and experts in related fields of research, industry and administration have been conducted to identify additional use cases and respective requirements. Stakeholders and experts consulted for these evaluations include:

[2]Scopus search string: TITLE-ABS-KEY ((citygml AND transportation) OR (citygml AND road) OR (citygml AND street*) OR ("city model" AND "use case") OR ("HD-map" AND "use case") OR ("city model" AND application) OR (opendrive AND "use case") OR ("IFCRoad") OR ("traffic simulation" AND "city model") OR ("Geographic Data Files") OR (Opendrive) OR ("urban planning" AND "city model" AND road) OR ("traffic simulation" AND "city model") OR (gis AND "road model*"))

- Members of state mapping agencies include OrdnanceSurvey GB, the Bavarian Agency for Digitization, High-Speed Internet and Surveying (LDBV), and the State Office for Geoinformation and Surveying of Hamburg.
- Several cities and countries such as Helsinki, Grafing near Munich, Munich (Geodata Service, Mobility Department), and Japan (PLATEAU project).
- Academic colleagues such as the 3D geoinformation group of TU Delft, the University of Vigo, the German Aerospace Center (DLR), the RWTH Aachen University, HafenCity University Hamburg, and the TUM Chair of Traffic Engineering and Control.
- Members of standardization organizations such as the OGC CityGML standard working group, the Association for Standardization of Automation and Measuring Systems (ASAM), and BuildingSMART.
- Companies including data providers, users, and managers such as CADFEM/ virtualCitySystems GmbH, 3DMappingSolutions GmbH, EFS TechHub GmbH, Audi, and Volkswagen.

Figure 2.2 illustrates components evaluated in this chapter and their relations in the form of a UML diagram.

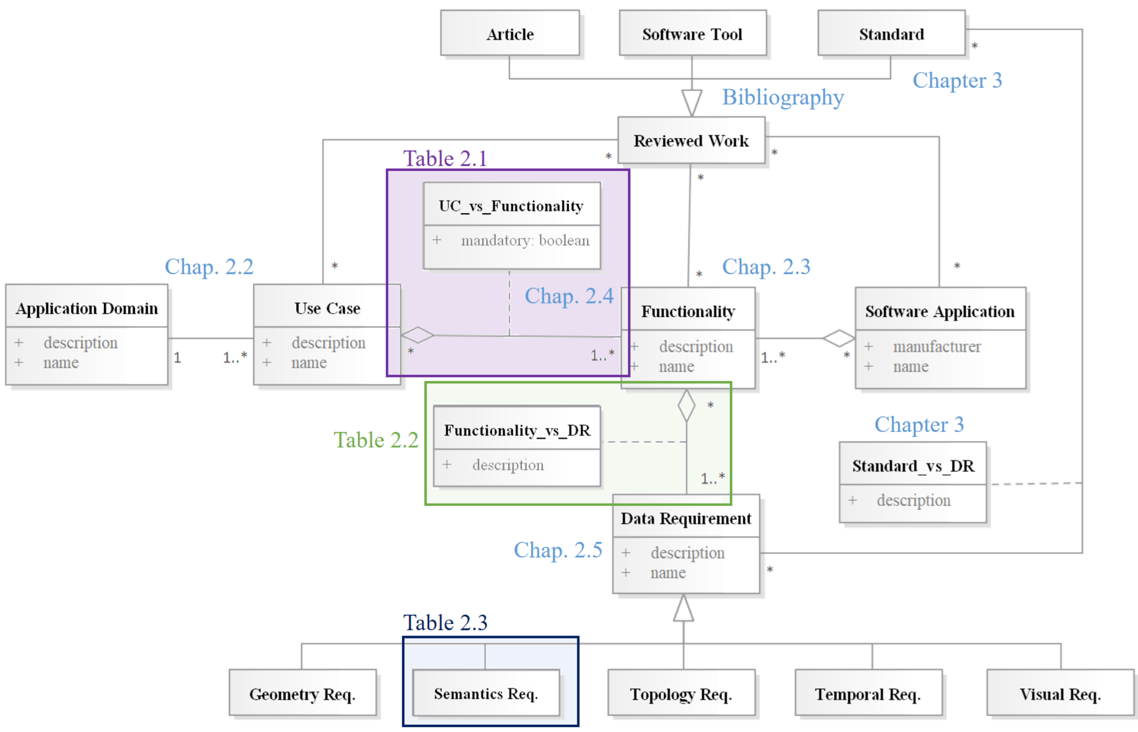


Figure 2.2: UML diagram of the components and their relations evaluated in this part of the thesis.

First, clear and unambiguous definitions for the terms ’application domain’, ’use case’, ’functionality’ and ’software application’ (as used in this thesis) are given. Then, main application domains according to which use cases can be categorized are introduced. A number of use cases are identified and a corresponding literature review is conducted. Concrete requirements for 3D streetspace models cannot be evaluated directly for these individual use cases as (1) several different software applications are typically required and used to fulfill the goal(s) of individual use cases and (2) the specific requirements on the data and its form of representation and properties solely depend on the functionalities of respective software applications. Thus, current and potential use cases for 3D streetspace models (categorized according to main application domain) are linked with functionalities of relevant software applications necessary to achieve the goal(s) of each use case. For each use case, required and optional functionalities are listed. The presented list does not claim to be exhaustive, however, it can provide an overview of the most relevant use cases and respective required functionalities. On this basis, requirement categories towards information provided by 3D streetspace models are defined and evaluated for the presented functionalities. In order to determine the data requirements of individual use cases, the data requirements for corresponding relevant functionalities need to be unioned.

2.1.1 Term Definitions

The term 'streetspace' is used in this thesis to describe not only roads (and objects that can be part of roads such as bike lanes or sidewalks), but also quite literally the space above road surfaces, where traffic actually takes place (Zlatanova et al., 2020). This space may be occupied by city furniture such as traffic signs and lights, roadside vegetation or buildings. Furthermore, the underlying terrain has a direct impact on the shape, slope or inclination of road surfaces. The streetspace may also intersect with railways or extend into buildings (e.g. within a parking garage), through tunnels or over bridges and thus directly interact with other city objects. Other transportation infrastructure such as the detailed modelling of railway networks individually are out of the scope of this thesis.
In the context of Geographic Information Systems (GIS) and 3D city models, Biljecki et al. (2015) define a *use case* as "[..] a meaningful set of spatial operations that accomplish a goal a user wants to achieve with a spatial data set.", while an *application* is defined as "use case [...] employed in the context of a specific domain (e.g., archaeology) to solve an application problem [...]". While the UML specification Object Management Group (OMG) (2017) provides guidelines on how to model use cases and their relationships using Use Case Diagrams, it does not offer a formal definition of the term 'use case'. For the purpose of this thesis, definitions of the terms 'application domain', 'use case', 'functionality' and 'software application' with regard to spatio-semantic 3D representations of the streetspace are refined as follows:

- An *application domain* in the context of 3D streetspace modelling refers to the broader range of scenarios, without specifying detailed tasks or objectives. Application domains can include infrastructure planning and management, transportation-related applications or environmental simulations and analysis.
- A *use case* in the context of 3D streetspace modelling refers to a specific task involving the utilization of a 3D streetspace model to achieve a particular objective. Use cases in 3D streetspace modelling can include tasks such as emergency response planning, traffic flow optimization, bicycle path quality analysis, etc. The goal of a specific use case is reached by utilizing one or several functionalities of software applications.

- A *functionality* in the context of 3D streetspace modelling is a capability or function required for solving or realizing a specific (sub)task. To utilize these functionalities, geometric, semantic, topological, temporal or visual information provided by input data is required.
- A *software application* in the context of 3D streetspace modelling refers to a software program, tool or system that utilizes information contained within 3D streetspace models and implements one or multiple functionalities. Examples for software applications are SUMO, VISSIM, QGIS, Autodesk Revit, VirtualTestDrive (VTD), etc.

The terms 'functionality' and 'software application' need to be separated, since one software application typically covers a range of functionalities but only the latter define the requirements on the input data provided by streetspace models

2.1.2 Categorization of Use Cases

Biljecki et al. (2015) argue, that it is not feasible to categorize use cases according to the relevance of semantics, required level of detail or granularity, spatio-semantic coherence, nature of the output or texture, since this might result in unclear assignments and thus decide to use a categorization according to visualization aspects. However, transferring this categorization approach to use cases specifically focusing on semantic 3D streetspace models might again result in ambiguities. While some use cases clearly require a realistic visualization (e.g. driver training simulator), others might rely on appealing visualization depending on intended users or recipients of simulation results (e.g. solar irradiation of roads and urban heat islands). Batty et al. (2001) categorize use cases of 3D city models according to their main application domain, which is also applied in this thesis. In order to allow a structured discussion, use cases are categorized according to the following four main application domains:

- Infrastructure Planning, Construction and Management
- Automotive, Transportation and Navigation
- Environmental Simulations and Analyses
- Land Administration and Topographic Mapping

The exact assignment of individual use cases to one of these four application domains in some cases may be debatable. This is why use cases are assigned to the category, which corresponds to their *primary* application domain.

2.2 Review and Evaluation of Use Cases for detailed 3D Streetspace Models

In this chapter, a detailed review and evaluation on current and potential use cases for detailed 3D streetspace models is conducted.

2.2.1 Infrastructure Planning, Construction and Management

Detailed models of the streetspace can be used in the context of infrastructure planning, construction and management. The emerging topic of digital urban twins will include not only buildings but also transportation infrastructure. Models of the streetspace can be used for use cases such as facility management, road planning, construction and maintenance, planning street excavations, emergency planning or road degradation analyses (and calculating potential repair costs).

2.2.1.1 Urban planning

A major use case of semantic 3D streetspace models is urban planning. Figure 2.3 shows a digital representation of a road corridor and a planned version of the same area. While in this case, the current scenario features eight car driving lanes, some of these lanes are planned to be substituted with bike lanes and pedestrian areas. Detailed virtual models of real-world entities can serve as a foundation for urban planners or decision-makers to determine long-term goals regarding urban planning (Dembski et al., 2020; Sindram and Kolbe, 2014; Agugiaro et al., 2020). High positional accuracy of these objects with precise (georeferenced) coordinates is necessary to ensure accurate assessments. Ross (2010) states that information related to land management can be integrated into virtual city models. Robles-Ortega et al. (2013) present a method for creating areal street surfaces and managing this information using geographic information systems in order to provide information for urban planning applications. Aboushal (2021) presents a procedural process to generate designs of buildings and infrastructure for unplanned urban areas using CityGML. Depretre and Jacquinod (2021) describe the value of information on sealed surfaces, surfaces allocated for different types of mobility and city furniture such as lighting for applications supporting urban planning decisions. This information can also be used to derive indicators for evaluating alternative scenarios (Elfouly et al., 2015). For most of these use cases, cadastral accuracy is necessary to plan different scenarios and evaluate existing land uses. It is important to be able to distinguish between individual lanes. The distinction between road surfaces used for cars and sidewalks used by pedestrians, for example, should be possible. Urban planning applications rely on up-to-date spatio-semantic information. It should also be possible to create different planning scenarios for urban planners to make the best decision. This can be achieved using versioning concepts (Chaturvedi et al., 2017a).

2.2.1.2 Public participation (in urban planning)

Public participation before and during the planning process is closely linked to urban planning. Realistic 3D visualizations (as depicted in figure 2.3) can be helpful to minimize potential resistance of citizens against planned constructions and provide the foundation for public participation in the

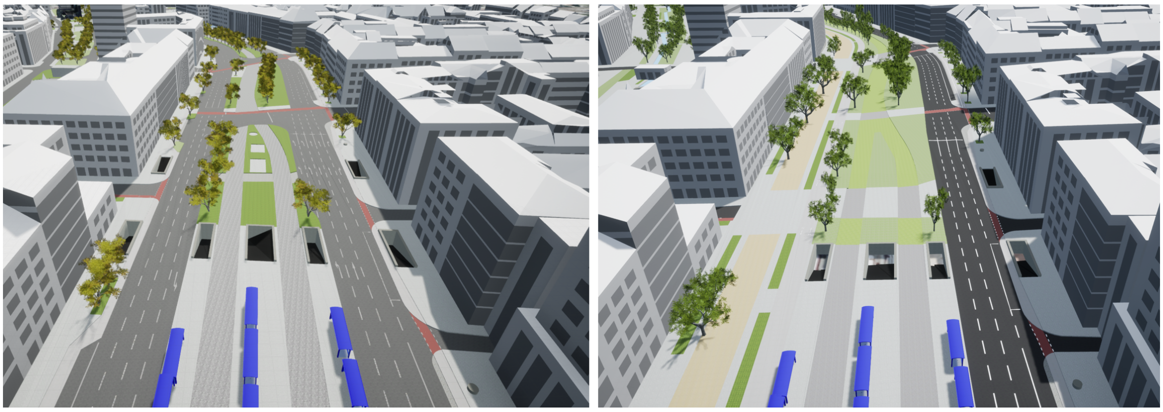


Figure 2.3: Current (left) and planned (right) scenario of an urban street section. This illustration shows an example of a current city planning and development project in the Munich city center. The visualization was created in the course of the project "Digital Twin of Munich" and used for public participation events.

planning phase. Digital models of roads and the streetspace can also be used as an interactive platform for gathering feedback from the public with commenting functionalities. Engel and Döllner (2012) present methods for creating immersive visualizations from 3D city models intended for different stakeholders such as citizens or decision-makers. These models can also be helpful in gaining interest from new audiences. In this context, the term 'serious gaming' describes games developed or used not only for entertainment but to create insight in a certain topic or for educational purposes (Susi et al., 2007). Freese et al. (2020) discuss challenges in using serious games for scientific research in transportation including a game for public transport. Ariffin et al. (2010) present a game developed to transfer knowledge on road safety to schoolchildren. Laksono and Aditya (2019) describe the usage of real-world data for creating serious gaming environments including models of roads. Game engines such as Unity3D or the UnrealEngine provide options for importing data such as 3D models of buildings or road infrastructure. Geodata of buildings and roads can also be used to create Minecraft worlds. These worlds can be helpful for interesting younger age groups in urban planning topics and offer possibilities for participation. Schrotter and Hürzeler (2020) present a Minecraft world representing parts of Zurich in Switzerland created from geo-data and used for public participation. The city of Vantaa in Finland also provides a Minecraft representation of the city area as open data[3]. Other Minecraft world examples for cities such as Berlin or Helsinki are also available.

2.2.1.3 Street excavations

Combined with information on buried utility infrastructure, detailed surface-based streetspace models can be used to assess areas that would be affected by street excavations (Becker et al., 2013). This requires areal and up-to-date representations of road surfaces with an accuracy of at least a decimeter. Topological relations between utility network elements are important (Kutzner et al., 2018; Vishnu and Saran, 2018; Vishnu and Sameer, 2021), corresponding road surfaces, however, do not require

[3] https://tinyurl.com/493eukdt

this information. It can be beneficial to visualize street space models to compare their position with respect to utility networks. This can also be useful for creating location or site plans.

2.2.1.4 Disaster prevention, preparedness and recovery

Disaster prevention, preparedness and recovery use cases largely require similar source information. (3D) geoinformation is a valuable resource for risk assessment and disaster management in general and can also be employed to transportation related use cases in particular. Toma-Danila (2013) evaluates the vulnerability of transportation networks for natural disasters such as floods, earthquakes or landslides using GIS tools. Numerous countries define response times for emergency services in the form of guidelines or even laws. In Germany, for example, the maximum response time for firefighters is legally defined with 8.5 minutes and needs to be ensured for any potential site. 3D city models and especially accurate representations of roads can provide essential information for planning and analyzing such requirements for different aspects of disaster management. For planning rescue operations the information quality is important. This applies to spatial resolution, geometric accuracy, topological consistency, and spatial dimensions of the data (Kolbe et al., 2008; Lee and Zlatanova, 2008). Rupprecht et al. (2011) describe methods for performing simulations of pedestrian flows on navigable surfaces to identify bottlenecks. Visconti et al. (2021) present a disaster scenario simulation using a semantic streetspace model of New York City, including knowledge on roads, squares and walkable tracks. This topic is closely related to disaster response use cases described in section 2.2.2.15.

2.2.1.5 Road construction and design

While Building Information Modeling (BIM) and its corresponding standard Industry Foundation Classes (IFC) have mainly been used for representing buildings, the newest version 4.3 of the specification includes concepts developed in projects such as IFC Bridge, IFC Road, IFC Rail and IFC Ports & Waterway (Jaud et al., 2020; Vignali et al., 2021). IFC projects are often planned within a local coordinate system. Jaud et al. (2022) describe the challenges of georeferencing large infrastructure such as roads within IFC, where the Earth's curvature significantly affects the geometry of an object. So far, infrastructure projects are mostly modelled using IFC alignment, describing a linear course of a road with parametric information on street widths. Biancardo et al. (2020) demonstrate how to create 3D road models according to IFC concepts using procedural modelling techniques. Lamas et al. (2022) and Justo et al. (2021) describe methods for deriving road trajectories from point cloud data and convert results to IFC compliant Alignments. Large construction projects require descriptions at different planning stages. Barazzetti et al. (2020) give an example for an integrated BIM-GIS approach for generating models of roads from point clouds and GIS data according to IFC. Several cities provide detailed guidelines for the design of urban streets, including specifications on bicycle paths, lane widths or traffic island heights (e.g. the New York City Street Design Manual (New York City Department of Transportation, 2020)).

2.2.1.6 Road maintenance / pavement condition assessment

Detailed street space models can be used to store information on pavement conditions. In combination with accurate representations of roads or public places, potential repair costs as well as maintenance plans can be evaluated. This requires accurate 3D models of road infrastructure (Buuveibaatar et al., 2022). Zhao et al. (2018) highlight the benefit of spatial models for assessing road degradation parameters. Boersma (2019) discusses requirements of road maintenance applications such as de-icing in the context of semantic road models. Information on road markings can be used to estimate painting costs. Floros et al. (2019) argue, that concepts in previous versions of IFC mostly concentrate on the construction phase of buildings, while representations of roads and road maintenance are limited and present an extension to IFC to overcome these limitations.

2.2.1.7 Traffic light / sign visibility analysis

Biljecki et al. (2015) state that 3D city models can be used for visibility analysis to determine the line of sight between two points. This method can also be used to find optimal locations for traffic lights or signs. Hirt et al. (2022) present a method for analyzing the visibility of traffic signs and traffic lights from the position of vehicles using digital 3D representations of roads, city furniture and vegetation, as illustrated in figure 2.4. This is achieved using a ray-tracing approach based on an occupancy grid generated from a voxelized semantic 3D streetspace model.

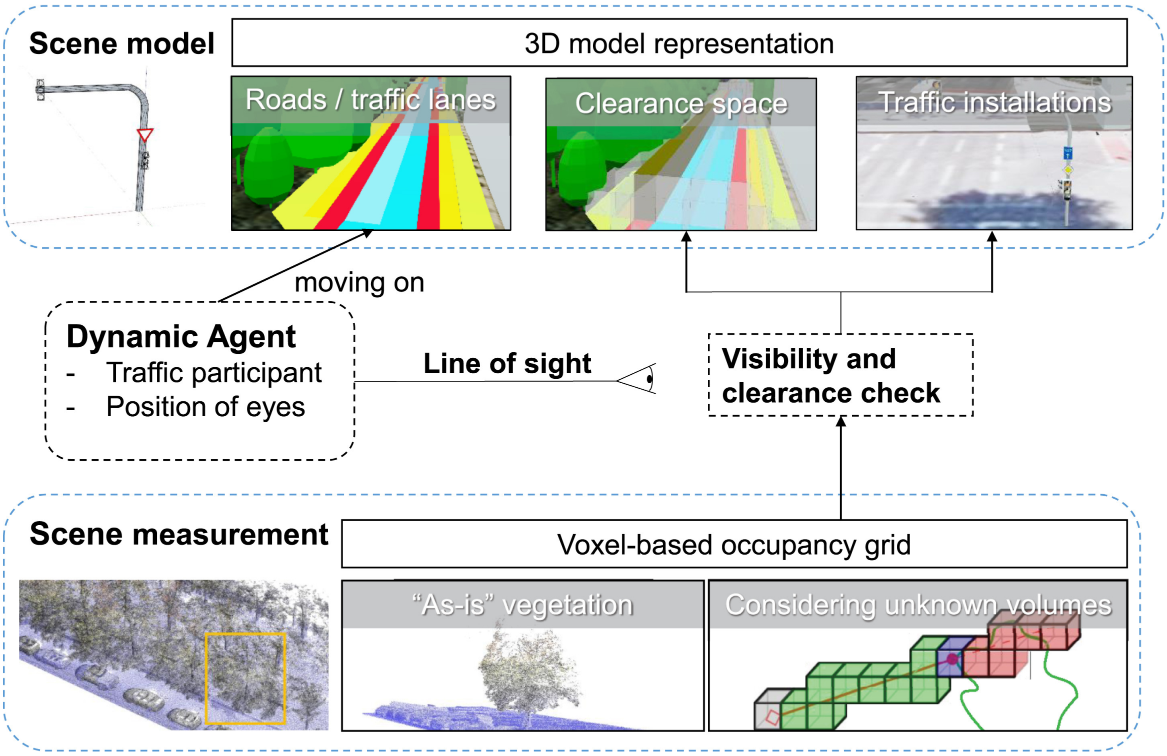


Figure 2.4: Visibility and line-of-sight analysis of traffic installations including obstacles such as vegetation (Hirt et al., 2022).

A high absolute positional accuracy, as well as a high relative geometric accuracy of streets or sidewalks, are necessary for this task. Some methods use point clouds (Huang et al., 2017) or voxels (Aleksandrov et al., 2019) as input data for visibility and occlusion analyses. In both cases, a semantic detection or classification of city furniture or vegetation is a necessary first step before the actual visibility analysis can be performed.

2.2.1.8 Street lighting planning / optimization

Information on roads, sidewalks and plazas, in combination with current or potential locations of city furniture objects such as lanterns, allow simulations of street lighting scenarios. Scorpio et al. (2020) describe the development of lighting designs for roads, green areas and buildings using VR environments within game engines. In this publication, different lighting classes are defined based on information on road classification (e.g. motorway or urban road), intensity of traffic or speed limits. Additionally, conflict areas such as intersections or shopping streets need to be considered for creating optimal lighting designs. Vegetation, city furniture objects and obstacles such as parked vehicles influence the perception of street lighting. Redweik (2016) shows implementations of street light energy simulators based on semantic 3D city models.

2.2.1.9 Parking space planning

In addition to roads, large sealed surfaces such as public plazas or parking lots also contribute to spaces used by pedestrians and vehicles and can be part of semantic 3D streetspace models. Bock and Sester (2016) describe methods for creating real-time parking availability maps in order to reduce searching times of traffic members and thus air pollution. This requires information on the location of parking lots and on-street parking possibilities, a road network to calculate driving distances and sensor data indicating available parking spaces. Similarly, Martens et al. (2010) describe required GIS data for conducting parking analyses, which includes the road networks and segments, information on destinations as well as locations of on- and off-street parking spaces.

2.2.1.10 Road / city furniture asset management

As mentioned before, the streetspace includes not only roads but also traffic signs, traffic lights, or poles. A digital inventory of city furniture can be useful for managing and maintaining such objects. This especially requires persistent and unique object identifiers. Varela-Gonzalez et al. (2014) present a CityGML extension for traffic signs to improve road infrastructure management. Niestroj et al. (2018) show how information on roads can be used for asset management using various standards. Sabato et al. (2023) describe using BIM models and GIS data for road safety evaluations and asset management. Moradi and Assaf (2023) present a method for pavement maintenance using 3D city models. Luiten et al. (2019) describe methods for asset management of roads using linked data. Crampen and Blankenbach (2023) and Crampen et al. (2024b) propose a level of as-is detail (LOAD) concept for representing road infrastructure for planning and maintenance.

2.2.2 Automotive, Transportation and Navigation Applications

Several use cases related to the automotive industry benefit from detailed semantic 3D streetspace models. These include traffic planning, navigational purposes, virtually testing automated driving systems, or (emergency) driver training.

2.2.2.1 Traffic planning (just mobility without considering environmental aspects)

Microscopic traffic simulations are often used in traffic planning to model the movement of individual traffic members (agents) and are mostly done using linear simulation networks (Chao et al., 2020). Boersma (2019) and Tamminga (2019) discuss requirements towards 3D models of roads with respect to traffic simulations. Wilkie et al. (2011) demonstrate how GIS data can be transformed to be usable by traffic simulations and emphasize the importance of geometric and topological consistency. Fellendorf (2013) presents requirements towards road designs for traffic simulations by incorporating information provided by digital terrain models. Grigoropoulos et al. (2019) use car trajectories and geodata to conduct traffic simulations and derive 3D road models from simulation networks. Ruhdorfer et al. (2018) show how accurate information on the streetspace can be used to derive information needed for traffic simulations. Keler et al. (2023) present methods for data integration and conversion processes to create traffic simulations from different data sources. While most micro-traffic simulation tools require (graph-based) road networks, this information can also be derived from areal representations. High positional and geometrical accuracy of the used data is important to achieve reliable results. Semantic information on lane types (e.g. driving, pedestrian, etc.) as well as driving directions and detailed topological information (e.g. turning rules) are required. Most micro-traffic simulation tools offer the possibility to specify different types of traffic including bicycles. Keler et al. (2018) show how urban environment models are useful for creating bicycle simulators. Ullmann et al. (2020) present how such simulators can be coupled with virtual reality applications. This requires geometric and semantic information on bicycle paths with lane-level accuracy and accurate representations of other streetspace features such as traffic lights or signs. Weißmann et al. (2023) also describe benefits of using virtual reality models of the streetspace for traffic scenario planning.

2.2.2.2 Traffic planning (considering environmental aspects)

While traffic planning use cases mostly focus on traffic itself, additional environmental simulations such as evaluations of traffic with regard to emissions are possible using traffic simulation tools (Abou-Senna et al., 2013). This can be combined with other environmental evaluations such as noise or particulate matter dispersion analysis.

2.2.2.3 Public participation (for traffic planning)

The results of micro-traffic simulations (e.g. conducted with the open-source tool SUMO) can be visualized within a semantic 3D city model. In combination with models of vegetation, city furniture, buildings and detailed roads, current as well as planned scenarios can be represented. Information on these objects must be available at a consistent level of accuracy. Ruhdorfer et al. (2018) present methods for visualizing traffic simulation results in GoogleEarth using KML. While traffic visualizations are also possible using game engines (e.g. UnrealEngine or Unity), interactive engagement with these visualizations (e.g. by the public) is limited. Beil et al. (2022) show how dynamic processes such as traffic movement and changing traffic lights can be made accessible using a web-based 4D Cesium visualization using the Cesium Language (CZML).

2.2.2.4 Traffic flow optimization

With growing numbers of citizens living in cities, problems such as traffic congestion and inefficient transportation movement are a growing challenge. Using traffic optimization techniques, the efficiency and effectiveness of traffic flow within transportation networks can be improved. This can involve aspects such as traffic signal coordination based on (current) traffic volume or route guidance systems for traffic members, which require real-time data. Concepts such as Dynamizers for linking semantic 3D city models with sensor data can be implemented for road and streetspace objects (Chaturvedi and Kolbe, 2016; Chaturvedi et al., 2019). Integrating sensor and time-dynamic data with semantic 3D streetspace models can be useful for monitoring urban environments. Sensors such as induction loops, bicycle counting stations, or dynamically changing traffic light signals can be linked with corresponding objects such as individual driving lanes to create (near) real-time visualizations and evaluations (Gitahi and Kolbe, 2024). This integration allows for monitoring of traffic flows, congestion or number of cars and bicycles passing through a given lane. The data collected can also be used to evaluate the performance of infrastructure and provide feedback to decision-makers for further improvements.

2.2.2.5 Virtually testing automated driving functions

While microscopic traffic simulations model the movement of individual agents, sub-microscopic driving simulations additionally consider vehicle behaviors and driving manoeuvres and impose a number of requirements towards 3D models of roads and the environment (Campos et al., 2015). Barz et al. (2020) describe the generation of virtual environments from different data sources for driving simulations. Richter and Scholz (2019) present guidelines for gathering geodata to allow conversion processes to the OpenDRIVE format. Richter et al. (2020) present an extensive overview on challenges and requirements of testing automated driving as part of future mobility concepts. Furda and Vlacic (2010), Schwab and Kolbe (2019), Wagener et al. (2022) and Pechinger (2023) describe requirements for virtually testing automated driving functions using digital models of the streetspace. These models need to maintain a high level of accuracy with respect to geometric, semantic and topological aspects in order to be usable for such simulations. For testing automated driving functions, it is also necessary to simulate sensors virtually. In order to analyze the information provided by these virtual sensors, an accurate representation of the environment (including information on surface materials and reflective behaviors) needs to be available. While georeferenced models are required to test real-world scenarios, (fictional) 3D test environments within a local system are sufficient for general simulations. Kutsch et al. (2022) present a test field designed for developing connected and automated driving functions. A highly accurate semantically rich 3D representation of roads and the environment are the basis for this project. Strosahl et al. (2022) use information provided by a 3D streetspace model as ground truth to validate estimated vehicle trajectories. In addition to highly accurate geometric data, this use case puts high demands on the quality of topological information. In order to have smooth and realistic simulation results, objects such as connected lanes do not only need to provide information about predecessors and successors but must ensure G2-continuity.

2.2.2.6 Driving dynamics evaluations

Driving dynamics simulations are used for vehicle development and mostly depend on precise geometric detail to describe rough or uneven road surfaces accurately. Especially in professional motorsports the development and testing of driving dynamics is increasingly based on simulation models (Butz et al., 2004). In contrast to autonomous driving, driving dynamics simulations do not rely on up-to-date scenarios. Since these simulations are mostly conducted to test different behaviours of vehicles depending on different surfaces, it is not essential to use real world data. OpenCRG is a common data format for describing road surfaces using a grid-based representation (Barsi et al., 2018). This often requires sub-centimeter information on the road's surface including holes or road damages (Lovas et al., 2022).

2.2.2.7 Operational automated driving

Digital and highly accurate models of roads and the streetspace are also important in the operational stage of self-driving cars. While some systems purely rely on sensor data gathered while driving, some systems require so-called "HD-maps" as ground truth and a-priori knowledge (Seif and Hu, 2016). The required geometric, semantic, and topological details also depend on the desired level of automated driving. Requirements of autonomous driving vehicles with respect to representations of their environment are presented and discussed in publications such as Schwab and Kolbe (2019), Richter et al. (2020) and Chiang et al. (2023). While these maps need to provide highly accurate information, requirements towards geometric and topological capabilities are lower than for virtual models used to develop and test automated driving functions. Althoff et al. (2017) and Althoff et al. (2018) describe the creation and usage of road information in the Lanelet format for motion planning of automated road vehicles. Poggenhans and Janosovits (2020) analyze requirements of routing applications in the context of automated driving focusing on representations of roads using the data format Lanelet2. Modelling the streetspace quite literally as 'the space traffic members use', allows a seamless navigation between indoor and outdoor spaces (Yan et al., 2021). While usually static road networks are used for navigational purposes, Li et al. (2022) propose the integration of dynamic and time-dependent topological relations such as traffic control measures.

2.2.2.8 Driving / bicycle safety analysis

3D information can also be useful for pedestrian and cycling navigation applications and even provide information to find the safest route (Santhanavanich et al., 2020). Bassani et al. (2015) analyze the available sight distance and potential obstructions (such as vegetation or city furniture) from a driver's perspective based on a digital surface model and GIS data. Determining the visibility of cyclists is crucial for assessing their safety and identifying potentially hazardous areas. This can involve assessing which parts of a city are visible to cyclists, such as at intersections, or evaluating how visible cyclists are to other road users like car drivers. To achieve this, the position of cyclists and driving lanes can be combined with information on traffic directions to calculate lines of sight. Figure 2.5 illustrates the potential of semantic 3D streetspace models including detailed information on city furniture, buildings and vegetation as well as traffic spaces for line-of sight-analyses. Positions on driving lanes at a height of 1.6 meters above the ground are connected with a position on a bicycle path (also at a height of 1.6 meters). Then lines of sight are intersected with 3D city objects and colored depending on obstructions (red) or free field of view (green). Information on traffic directions can also be used to limit the relevant field of view of bicyclists and other traffic members.

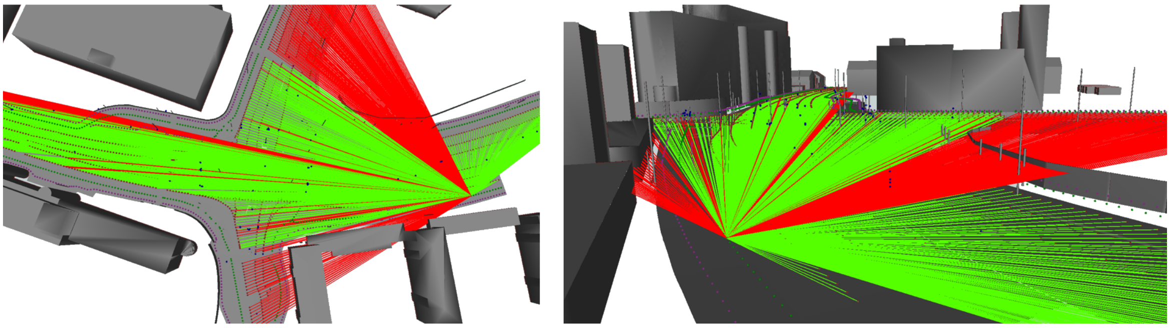


Figure 2.5: Visibility analysis calculating 3D lines of sight between a position on a bicycle path and positions above driving lanes within a 3D model including obstacles (own visualization).

2.2.2.9 Bicycle path quality analyses

Geometric properties such as bicycle lane width or slope in traffic direction directly impact the service quality of bicycle paths since it affects the rate of disturbances on cyclists (Wierbos et al., 2019). The German Research Association for Roads and Traffic provides guidelines for calculating the Bicycle Level of Service (BLOS) from geometric and semantic parameters in combination with information on traffic volumes (bicycles per hour) (FGSV, 2015). This requires very detailed geometric information with a centimeter accuracy as well as semantic information on bicycle paths. Additionally, information on traffic directions is required. Visualizing analysis results within an interactive web client has the potential for increased public awareness of planned improvements of bicycle infrastructure (Beil et al., 2023).

2.2.2.10 Pedestrian movement analysis

Traffic simulations of cars or bikes usually require a linear (graph-based) network. Pedestrians however can move more freely and thus need to be simulated differently. While it is possible to simulate the movement of pedestrians with tools such as SUMO (by specifying linear walking paths), tools such as the pedestrian simulator momenTUM require areal input data on surfaces used by pedestrians (e.g. sidewalks or plazas) (Kielar et al., 2016). Additionally, areal obstacles such as driving lanes, buildings or vegetation can be specified. Schwab et al. (2020) show how areal information on roads, sidewalks, or pedestrian crossings derived from semantic streetspace models can be used for creating a momenTUM scenery description. Valls and Clua (2023) describe a method for extracting a pedestrian network for walkability analysis from polygonal sidewalk representations. Slingsby and Raper (2008) highlight the potential of topologically connected navigable spaces between buildings to provide information for pedestrian simulations and describe the necessity of considering geometrical aspects such as staircases linking different height levels. Information on ramps, raised traffic islands or lowered curbs need to be considered in accessibility simulations for people with limited mobility. Wheeler et al. (2020) propose an extension to CityGML in order to enhance way-finding applications with accessibility information. In a related use case, Kasemsuppakorn and Karimi (2008) discuss data requirements for wheelchair navigation applications.

2.2.2.11 Lane-free traffic planning

In the context of connected and automated driving (CAD), lane-free traffic describes a concept of cars moving freely within a road and without restricting individual lanes. A major claim of lane-free traffic is that it will increase vehicle capacity without increasing road widths. Since research in this field is currently at an early stage, there are few publications describing simulations in order to test this flexible driving strategy (Sekeran et al., 2022). Requirements for these simulations include information on widths of driveable roads as well as accurate representations of road boundaries - especially in urban intersection areas. Additional information on the location of sensors or cameras are also relevant.

2.2.2.12 Route optimization for snow / leaf / garbage trucks

Municipal tasks such as snow, leaf or garbage removal can be supported by planning routes based on semantic 3D road models. Park et al. (2019) present a method for optimizing routes of snow removal vehicles using geometric information on slopes, road lengths and surfaces widths as well as topologically connected networks including emergency roads in order to calculate optimal routes.

2.2.2.13 (Emergency) Driver training

Randt et al. (2007) discuss how realistic 3D models can enhance realism in driving simulations and for virtual driver training (e.g. for police or bus driver training). These driving simulators do not rely on accurate representations of the real world (unless a specific, existing route should be trained). Thus, absolute positional accuracy is of minor importance. In contrast to many use cases of 3D streetspace models, a (photo-)realistic visualization of the environment is essential (Piga et al., 2020). Additionally, information relevant to traffic simulations (e.g. traffic rules and topological relations) is important. This can be achieved by integrating highly realistic virtual 3D models with traffic simulations using game engines (Nakasone et al., 2011). Boffi et al. (2022) and Shi et al. (2022) present the influence of virtual road environments in different LODs to evaluate the perceived safety of drivers within a simulation. Driver training simulators can also be created for rail vehicles such as trams. In this context, a consistent and integrated representation of multiple transportation types (e.g. intersecting roads and railways) is needed (Gnatz, 2018).

2.2.2.14 Navigation and routing

A common use case of road information is navigation and routing. In most cases, graph-based representations with carriageway accuracy are sufficient. A. Chen et al. (2010) describe high-precision road maps for lane-level navigation. Surface-based representations, along with models of the environment (e.g. buildings), are useful to increase the clarity of visual interfaces of navigation systems and help with orientation (Biljecki et al., 2015). Olbrich et al. (2024) demonstrate the usability of semantic 3D road models for navigational use cases by mapping semantic and topological information provided by a 3D CityGML model onto a graph-database. Nedkov (2012) presents advantages of 3D maps for navigational purposes in comparison to classic 2D representations. Raubal and Winter (2002) describe a method to detect and include local landmarks for improved way-finding instructions. Harrie et al. (2022) describe methods for using information on roads and their environment for optimal (and automated) label placement for way-finding maps. Boersma (2019) conducts a requirement analysis of navigational use cases towards three-dimensional representations of roads. Prandi et al. (2013) describe a CityGML Application Domain Extension (ADE) for routing purposes.

2.2.2.15 Disaster response

For disaster response use cases, navigational applications with additional capabilities are required. Roads typically not accessible to cars, but wide enough to be used in case of an emergency (e.g. by police or ambulance cars) can be identified with geometrically detailed and up-to-date streetspace models. This requires accurate topological information on adjacent road surfaces. Lee and Zlatanova (2008) as well as Bandrova et al. (2012) describe benefits of 3D geo-information and corresponding 3D maps for disaster response use cases to provide accurate geometric and topological information in order to quickly identify the location of an emergency. Kwan and Lee (2005) present an emergency response system linking transportation networks with 3D GIS data of multi-story buildings.

2.2.2.16 Heavy-load transport planning

In contrast to regular cars, heavy-load trucks may not be able to traverse every road available. Additional information such as maximum vehicle height and weight, slopes or turning angles as well as information on clearance spaces and potential obstacles such as vegetation or city furniture are required for heavy-load transport planning. This information can be provided by detailed 3D streetspace and bridge models. Clearance spaces can easily be generated from road surface data (or sidewalk areas) by extruding these areas by a certain amount (e.g. 4.5m for driving lanes, 2.5m for sidewalks). This requires detailed information (coordinates) on absolute positional as well as relative geometric positions of individual surfaces. In order to be able to generate clearance spaces for different transportation modes, it is important to be able to distinguish between traffic surfaces used by cars and surfaces intended to be used by other modes of transportation such as pedestrians. Wysocki et al. (2022) describe the detection of underpasses within buildings from MLS point clouds. Resulting geometries cut out from original building objects directly correspond to respective clearance spaces. As depicted in figure 2.6, it can be beneficial to create visualizations of clearance spaces in order to detect possible conflicts between street space and other city objects such as traffic lights, signs or vegetation more easily. However, simulations such as heavy load transports can also be conducted without a visual representation of the results. Godavarthy et al. (2016) describe a simulation-based swept path analysis to evaluate road layouts in order to allow oversized vehicles to traverse through roundabouts. While such analysis is so far mostly done in 2D, the increasing availability of three-dimensional road and streetspace models allow more realistic analysis to be conducted using 3D models.

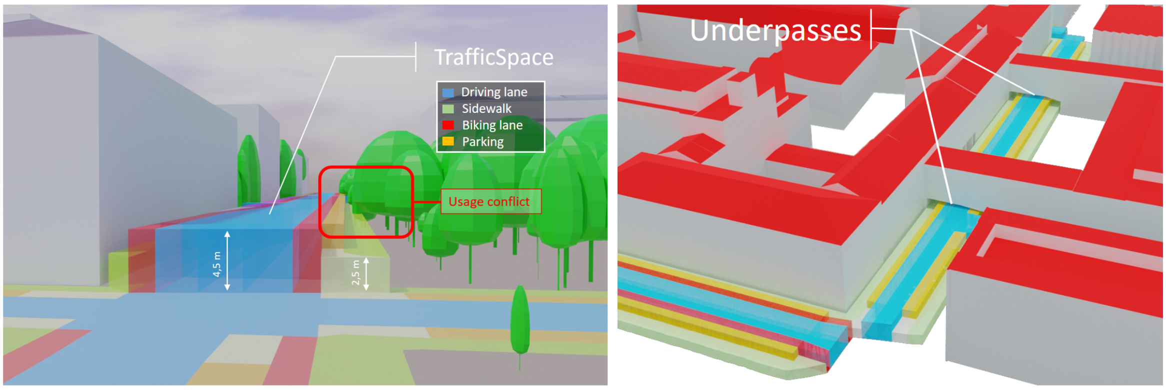


Figure 2.6: Volumetric representation of traffic spaces underneath building underpasses for clearance space simulation (own visualizations).

2.2.2.17 Urban air mobility (UAM) evaluation

With steadily growing numbers of people living in urban areas, transportation and mobility is a major future challenge for cities. In this context, new concepts such as Urban Air Mobility (UAM) (e.g., transportation drones or flight-taxis) have recently become more relevant. While there are developments for creating safe and efficient air mobility concepts, there are currently no standardized methods for modelling and representing 3D air spaces for UAM applications (Bauranov and Rakas, 2021). However, concepts for representing 3D (traffic) space can be suitable to close this gap. Additionally, information on potential starting and landing zones can be derived from 3D representations of urban streetspaces and their environment to connect traditional mobility concepts with UAM.

2.2.3 Environmental Simulation and Analyses

While there are many environmental simulations and analyses that are supported by semantic 3D city models, most use cases still mainly focus on models of buildings or the terrain. However, there are several examples for these kind of simulations that could be done using detailed models of the streetspace. These can include use cases such as environmental planning, air quality analysis or urban heat island analysis.

2.2.3.1 Environmental planning

Several functionalities can be employed to support environmental planning and decision making. Detailed road models including elevation information can serve as the basis for highly detailed water run-off and flood simulations (Schulte and Coors, 2008). Accurate absolute positional information, as well as accurate relative geometric information on streets, can be derived from streetspace models. Information on thematically different surfaces can be interesting to evaluate in order to determine which parts of a road would be affected by flooding scenarios. Shen et al. (2020) present a CityGML ADE to represent urban flooding events and Amirebrahimi et al. (2015) show flood damage assessment for models of buildings, which could also be transferred to areal street space models. Street space models can also be used to visualize flooding scenarios as well as potential damages. Lu et al. (2017) present a method for mapping 3D noise propagation originating from different types of traffic using semantic city models. This requires information on the direction, orientation and distance of buildings relative to roads. Czerwinski et al. (2013) discuss strategies for environmental noise mapping by applying spatial data infrastructure techniques. This requires information on roads such as road centerlines, road type, road surface materials, road widths, speed limits and additional parameters such as traffic flow and surrounding models of obstacles such as buildings. Czerwinski et al. (2006) highlight the importance of a common and integrated model of buildings, transportation infrastructure, vegetation and city furniture for ensuring accurate noise simulation results. J. Stoter et al. (2008) describe a method for calculating 3D noise maps using 3D models of buildings. Kumar et al. (2017) present a method for creating input data for noise simulations and visualizing results within 3D city models. Konde and Saran (2017) implement a web GIS framework for traffic noise analyses based on a semantic 3D city model. Guarnaccia (2010) discusses the complexity of calculating noise simulations in intersection areas by considering different intersection configurations. Similarly, Quartieri et al. (2009) analyze the noise impact at different categories of intersections.

2.2.3.2 Public participation (for environmental planning)

Results of environmental planning concerning noise, flooding or related analysis can be visualized and communicated using visualizations of 3D streetspace models. Drazkiewicz et al. (2015) present several case studies in Germany of public participation with a focus on environmental planning aspects. Henningsson et al. (2015) discuss a public participation process in a Swedish highway road-planning project considering environmental impacts such as noise or pollution. Aspects already discussed in section 2.2.1.2 on public participation in urban planning generally also apply for public participation process focused on environmental aspects.

2.2.3.3 Air quality analysis

Ghassoun et al. (2015) illustrate how city models can benefit air quality analysis. Parameters like the number of intersecting streets, their widths and the angles between street corridors can be derived from accurate streetspace models (Brand and Löwner, 2014). While 2D information can be sufficient for some analysis in this field, 3D data is useful for more accurate fine dust distribution simulations (Ghassoun and Löwner, 2017; Willenborg et al., 2018). In combination with other components of a city model such as buildings and vegetation, precise simulations can be performed. W. Zhu et al. (2016) present work on integrating 3D city models with air pollution sensors and a corresponding Cesium visualization. Padsala et al. (2024) show a method for integrating 3D city models with Computational Fluid Dynamics (CFD) simulations to evaluate and visualize air pollution. While georeferenced objects are necessary to achieve reliable results, the exact geometric shape of individual streets, plazas etc. can be more coarse since these simulations are mostly conducted on a larger scale. Results of CFD (simulating the movement of particulate matter) can be intersected with traffic spaces in order to analyze dust pollution of spaces used by pedestrians.

2.2.3.4 Rockfall analysis

Rua et al. (2023) present a method to calculate road slopes from point cloud data and subsequently estimate areas of roads that would be affected by potential rockfalls. Similarly, geometric information from 3D streetspace models can be used to calculate the trajectory of a rockfall. Using the digital elevation model (DEM) data combined with 3D models, the software can predict the path of a rock that detaches from a source area and rolls down the slope. The trajectory can be analyzed to determine the potential impact zone, which can be useful for designing protective measures. Since this does not require lane-level accuracy, a more general layout of road surfaces is sufficient. Lamas et al. (2022) present a method for determining mountainous roads from point cloud data, which can be useful in this context.

2.2.3.5 Urban heat island analysis

Urban and local heat islands are a well-known phenomenon and have a direct effect on temperatures within cities (Bornstein, 1968). Using LoD 2 buildings in combination with vegetation and areal road objects, global, diffuse and direct irradiation values can be estimated (Willenborg et al., 2018). It can be beneficial to be able to distinguish irradiation effects for different thematic areas. Information on surface materials can be included in estimating resulting heating effects. Topological information (e.g. which street space objects lie next to each other) is not of great importance in the context of local heat island simulations. Accurate and interactive visualizations of solar potential and heat island simulations can be necessary for a quick and intuitive understanding of the results (Chaturvedi et al., 2017b). Semantic information on road surface material and respective reflection properties are beneficial to urban heat islands simulations (Pena Acosta et al., 2020). Some publications suggest using road surfaces for photovoltaic power production (Liu et al., 2019). Estimations of potential energy productions can be calculated using virtual 3D road and city models. Vegetation directly influences solar irradiation values of road surfaces and thus urban temperatures. Different vegetation types can have varying cooling effects on urban heat islands (Pauleit et al., 2020; Rahman et al., 2022). The effect of replacing sealed surfaces with vegetation or planting trees in certain locations can be simulated using semantic 3D streetspace models. The installation of PV modules on buildings influence the visual appearance of cities and thus may be rejected by the public. Florio et al. (2021) conduct analyses on the visual impact of PV modules based on viewpoints derived from pedestrian areas and sidewalks. Related to solar irradiation analyses are shadow simulations. Using a digital city model of New York, (Miranda et al., 2019) analyze the impact of shadows cast by buildings on spaces used by pedestrians (e.g. within Central Park). Simulation results can be transferred to corresponding street space objects.

2.2.3.6 Sun glare analysis

Gonzalez-Collazo et al. (2022) present a method for simulating sun glare incidents in road environments using MLS and ALS data and vehicle trajectory data. 3D streetspace models including individual lanes and obstacles such as buildings or vegetation can be used for similar analysis.

2.2.4 Land Administration and Topographic Mapping

Models of the streetspace can also be used by state mapping agencies and other authorities for use cases related to administration and topographic mapping.

2.2.4.1 Official 3D map creation

Several national and regional mapping agencies have started to build up three-dimensional representations of topographic information in the form of 3D digital landscape models (Oude Elberink et al., 2013). While topographic 2D data, as well as digital terrain models in 2.5D, are available nationwide in many countries, consistent and integrated 3D landscape models are still part of ongoing research and developments. Heipke (2016) presents some of the challenges in the context of generating 3D landscape models from heterogeneous data sources. Most of these models still focus on representations of the terrain and LoD2 building models. Recently, infrastructure objects such as bridges and dams, as well as vegetation, have (in some cases) also been included (Soon and Khoo, 2017; Wong and Ellul, 2018; Uggla et al., 2023). Fiutak et al. (2018a) and Fiutak et al. (2018b) describe results of a project for generating a 3D Digital Landscape Model (3D-DLM) for an area near Lake Constance at the border of Bavaria and Baden-Wuerttemberg. The model was generated using the software *3dfier* (Ledoux et al., 2021) and includes areal representations of roads. Roads were generated using linear information on streets and buffering these lines either according to a street width attribute or (since this information is not always available) by specific standard values according to respective street types. Holland et al. (2020) describe efforts of the national mapping agency of Great Britain Ordnance Survey (OS) to provide data useful for automated vehicle testing. In Switzerland, swisstopo provides and extensive topographic 3D landscape model including linear representations of roads. Japan's digital twin project "PLATEAU" also features representations of transportation and bridge infrastructure (Seto et al., 2023).

2.2.4.2 Cadastral ownership management

The Land Administration Domain Model (ISO, 2024b) is designed to cover basic information-related components of land administration, including legal/administrative information (land use rights, ownership, taxation, etc.), mapping, and surveying (Lemmen et al., 2015). This also concerns surfaces that are part of roads and other infrastructure. Detailed streetspace models can be beneficial for integrating this information with spatial representations. This is also important for road assets and closely linked to maintenance tasks mentioned before. A 3D cadastre extends a 2D cadastre, which is a traditional land-based cadastral system that is used to record and manage information about land ownership, boundaries, and other spatial properties of real-world objects. Adding the third dimension of geometric representations to cadastral information has been subject to research for some time (J. E. Stoter, 2004; J. E. Stoter et al., 2016). Gristina et al. (2016) describe requirements of a 3D road cadastre and highlight the potential of three-dimensional representations of roads for several applications, with a special focus on legal aspects.

2.2.4.3 Parking space evaluation for building permits

There are laws and regulations for building and maintaining garages, as well as determining the number of parking spaces required for certain developments or buildings which can be evaluated using 3D models (Noardo et al., 2021). In order to efficiently perform the automated checks of these regulations, required information such as number of parking lots, information on entries and exits or ramps can be determined from semantic 3D streetspace (and building) models.

2.3 Functionalities employed to solve the Tasks of the different Use Cases

In order to achieve the goals of the presented use cases, one or multiple functionalities (typically provided by software applications) need to be employed. In this chapter, a number of functionalities in the context of road and streetspace models are identified and defined. The following list provides concise descriptions of the evaluated functionalities. Additionally, exemplary software applications implementing one or many of these functionalities are mentioned. Presented functionalities are then associated with respective use cases in chapter 2.4.

- *Model management and editing* functionalities provide capabilities for creating, modifying or persistently storing 3D (streetspace) models (e.g. 3DCityDB (Z. Yao et al., 2018), QGIS (QGIS Development Team, 2023), RoadRunner (MathWorks, Inc., 2023), Trian3DBuilder (TrianGraphics, 2024)). Software such as SketchUp or Blender can also be used to create 3D road and streetspace models. BIM modelling software such as Autodesk AutoCAD Civil 3D or Revit increasingly support road model creation (Vignali et al., 2021). Biancardo et al. (2020) present several tools for road design such as Rhinoceros 3D and Grasshopper. Procedural modelling software such as the ESRI CityEngine also support the generation of road infrastructure models (Moradi and Assaf, 2023).
- *Scenario generation / Concurrent version control* functionalities are required for generating and managing different scenarios. This is required by all planning-related use cases, particularly where simple copies can quickly lead to confusion. A system can support concurrent version management, even though the actual data records cannot be exchanged with different versions at the same time or with a complete history. This functionality is often provided by GIS software such as ESRI ArcGIS and is especially relevant in the context of urban digital twins (e.g., to create “what-if” scenarios).

- *Historization* functionalities enable managing different (historic) versions or scenarios of streetspace models (Chaturvedi et al., 2017a). This is a crucial functionality of urban digital twins, since they comprise a cumulative digital representation of the physical real-world object over time, which is also relevant for legal reasons. Software such as the Oracle Workspace Manager available in corresponding relational database management systems, ArcGIS Pro or the version control system Git provide historization functionalities.
- *Facility management* functionalities are designed to optimize the management of physical assets (such as city furniture), properties (such as pavement condition), and infrastructure (such as individual roads). GIS software such as QGIS or ESRI ArcGIS can be used for road facility management (Fukada et al., 2008). Additionally, many dedicated facility management (CAFM) software solutions exist. Enterprise Resource Planning (ERP) software systems like SAP typically comprise FM functions.
- *Macroscopic traffic simulation* is a functionality used to model and analyze traffic flow on a broader scale, focusing on overall traffic patterns rather than individual vehicles (e.g. PTV VISUM (PTV Group, 2021)).
- *Microscopic traffic simulation* functionalities are specialized to model and analyze individual vehicle movements within a traffic network (e.g. SUMO (Behrisch et al., 2011) or PTV VISSIM (Fellendorf and Vortisch, 2010)).
- *Bicycle simulation* functionalities simulate the behavior and movement of bicyclists. This functionality is sometimes available within microscopic traffic simulation software. Bicyclists can be simulated using SUMO, however this is currently an experimental feature of the software tool.
- *Pedestrian simulation* functionalities are designed to model and analyze the movement and behavior of pedestrians. Since pedestrians usually move more freely compared to vehicles, this requires different information such as space layout maps (e.g. momenTUM (Kielar et al., 2016)).
- *Sub-microscopic driving simulation* functionalities go beyond traditional microscopic traffic simulation and can model and analyze individual vehicle movements at a very detailed level. It takes into account factors like individual driver behavior, vehicle interactions, or variations in road and driving conditions (e.g. CARLA (Dosovitskiy et al., 2017), VirtualTestDrive (VTD) (Hexagon, 2023) or IPG CarMaker (IPG Automotive, 2024)).
- *Vehicle dynamics simulation* is a specialized functionality used to model and analyze the dynamic behavior of vehicles and simulates how vehicles respond to various driving conditions. Some software for microscopic driving simulations also include vehicle dynamics simulations (e.g. VirtualTestDrive (VTD) (Hexagon, 2023) or IPG CarMaker (IPG Automotive, 2024)).
- *Autonomous vehicle control* functionalities are a critical component of self-driving vehicles, responsible for managing and executing driving tasks without human intervention. Depending on the operating principle, these functionalities can rely on high-definition (HD) maps of roads and/or on information of the environment collected by sensors in real-time. An open-source software example implementing this functionality is Autoware (Kato et al., 2018), which uses sensing as well as map data for enabling autonomous driving functions.

- *Navigation functionalities* are capabilities that provides turn-by-turn directions and route guidance to users for efficient and safe travel. Often combined with routing software. E.g. GoogleMaps or navigation systems built into cars.
- *Route planning* are designed to determine the most efficient path or route between two or more points on a map or network. Often combined with navigation software.
- *Noise dispersion / propagation simulation* functionalities are used to model and predict the noise generated by road traffic. E.g. SoundPLAN or LimA (Khan et al., 2018).
- *Visibility analysis* functionalities are used to model and analyze the visibility of objects or features (such as obstacles, signs or other traffic members). This is supported by 3D GIS software such as ArcGIS Pro and CAD software like Autodesk Revit or Rhinoceros 3D.
- *Wind field simulation and gas and particulate matter dispersion* functionalities are used to model and analyze the dispersion and concentration of particles, such as fine dust or pollutants. First, a wind field is simulated. Then, based on the results, the transport and accumulation of gases and particulate matter can be simulated. Examples for software applications implementing this functionality are ANSYS (Jeong et al., 2022) or PALM4U (Jose and Perez-Camanyo, 2023).
- *Solar irradiation simulation* functionalities determine the distribution of solar radiation immission in urban areas. This can also be used to evaluate local or urban heat island effects for large sealed surfaces such as roads or plazas. E.g. TUM Solar Tool (Willenborg et al., 2018), PVLib, CitySim Pro (Robinson et al., 2009).
- *Shadow casting analysis* functionalities determine and predict the patterns of shadows cast by objects such as vegetation or buildings. This is also supported by 3D GIS software such as ArcGIS Pro and CAD software like Rhinoceros 3D.
- *Collision detection and swept path analysis* functionalities are used in transportation and traffic engineering to identify and prevent collisions between vehicles, pedestrians and infrastructure elements on roads. It can also be used to plan heavy-load transports. Collision detection functionalities are also relevant for street excavation use cases in order to determine utility networks and other underground structures affected by excavations. E.g. AutoTURN (Godavarthy et al., 2016), Autopath or Vehicle Tracking in AutoCAD Civil 3D.
- *Water run-off and water-flow simulation* functionalities are used to model and predict the movement of water across the landscape (including roads) during rainfall or flooding (e.g. ANSYS (Jeong et al., 2022) or OpenFOAM (G. Chen et al., 2014)).
- *Rockfall simulation* functionalities are used to model and analyze the risk of rocks falling onto roads. This can be used to assess the safety of roads in rocky or mountainous areas (e.g. RockGIS extension (Rua et al., 2023)).
- *Visualization and rendering* functionalities are used to create realistic and visually appealing representations of streetspace objects (e.g. game engines (e.g. UnrealEngine (Huo et al., 2021) or Unity (Buyuksalih et al., 2017)), Blender or Cesium-based web-visualizations (3DCityDB Web-Map-Client) (Z. Yao, 2020)). GIS applications as well as model management and editing software also typically offer visualization capabilities.

2.4 Association of Use Cases with required Functionalities

The use cases identified in chapter 2.2 are now associated with functionalities described in the previous chapter that are required in order to fulfill the aim of respective use cases. Table 2.1 summarizes the result of this association. Required (✓) and optional (o) functionalities are indicated for each use case.

Table 2.1: Required (✓) and optional (o) software functionalities to reach the goal a of certain use case.

Application Domains and their Use Cases	Functionalities																						
	Model management and editing	Scenario generation / Concurrent version control	Historization	Facility management	Macroscopic traffic simulation	Microscopic traffic simulation	Bicycle simulation	Pedestrian simulation	Sub-microscopic driving simulation	Vehicle dynamics simulation	Autonomous vehicle control	Navigation / Guidance	Route planning	Noise simulation	Visibility simulation	Wind field simulation	Gas and particulate matter dispersion simulation	Solar irradiation simulation	Shadow casting simulation	Collision detection	Water run-off and water-flow simulation	Rockfall simulation	Geospatial visualization or rendering
Infrastructure Planning, Construction and Management																							
Urban planning	✓	✓	o	o	o	o	o	o					o	o	o	o	o	o	o	o	o	o	✓
Public participation (in urban planning)	✓	o	o	o	o	o	o	o					o	o	o	o	o	o	o	o	o	o	✓
Street excavation	✓	o		o																✓			✓
Disaster prevention, preparedness and recovery	✓	o		o	o	o	o	o					o		o	o	o			o	o	o	o
Road construction and design	✓	o		o										o	o	o	o			o	o		✓
Road maintenance / Pavement condition assessment	✓	o	o	✓																			o
Traffic sign / light visibility analysis	✓	o				o	o	o							✓								o
Street lighting planning / optimization	✓	o		o											o				o				✓
Parking space planning	✓	✓		o		o							o					o					o
Road / city furniture asset management	✓		✓	✓																			o
Automotive, Transportation and Navigation																							
Traffic planning (just mobility w/o environmental aspects)	✓	✓	o		✓	✓	✓	✓				o	o							o			✓
Traffic planning (considering environmental aspects)	✓	✓	o		✓	✓	✓	✓				o	o	✓	o	✓	✓	o	o	o	o	o	✓
Public participation (for traffic planning)	✓	o	o		✓	✓	✓	✓				o	o	o	o	o	o	o	o	o	o	o	✓
Traffic flow optimization	✓	o			✓	✓	✓	✓					o							o			o
Virtually testing automated driving functions	✓					o			✓				o		o			o	o	o	o		✓
Driving dynamics evaluations	✓								✓	✓													o
Operational automated-driving	✓			o							✓	✓	✓		o					o			o
Driving / bicycle / pedestrian safety analysis	✓	o		o	o	✓	✓	✓	o			o	o		✓					o	o	o	✓
Bicycle path quality analysis	✓	o		o			o								o								✓
Pedestrian movement and flow analysis	✓	o		o		o		✓					o		o			o	o	o			✓
Lane-free traffic planning	✓	✓		o		✓			✓			o	o							o			✓
Route optimization for snow / leaf / garbage trucks	✓	o				✓						o	✓	o									✓
(Emergency) driver training	✓					✓	o	o	✓			✓	✓										✓
Navigation and routing	✓											✓	✓										✓
Disaster response	✓			o								✓	✓										✓
Heavy-load transport planning	✓			o		o						✓	✓							✓			✓
Urban air mobility planning	✓	o				✓						o	✓	o	o	o				✓			✓
Environmental Simulations and Analyses																							
Environmental planning	✓	✓	o											✓	✓	✓	✓	✓	o		✓		✓
Public participation (for environmental planning)	✓	o	o											o	o	o	o	o	o		o		✓
Air quality analysis	✓					o										✓	✓						o
Rockfall protection	✓																					✓	o
Urban heat island analysis	✓							o								✓		✓	o				✓
Sun glare analysis	✓												o		✓			✓	o				✓
Land Administration and Topographic Mapping																							
Official map creation	✓		✓																				✓
Cadastral ownership management	✓		✓																				✓
Parking space evaluation for building permits	✓																						o

While every use case requires some sort of model management and editing functionally, requirements of more specific functionalities depend on the goals of each task. A functionality to visualize results or processes of each use case is at least optional for all use cases and essential for some. In addition, each use case typically requires more specific functionalities provided by software applications. While, for example, urban planning can be done solely using model editing and management functionalities without considering specific traffic related aspects, traffic planning use cases require additional functionalities to perform macroscopic, microscopic, pedestrian or bicycle traffic simulations (depending on the specific focus of the traffic planning scenario). To consider further environmental aspects such as traffic noise or air pollution, additional functionalities are required to perform these tasks.
Several use cases such as disaster response or route planning and optimization mainly require software with navigation and/or routing functionalities. Use cases categorized as environmental simulations and analyses typically require at least one kind of simulation functionality such as visibility analysis, solar irradiation simulation or wind field and particulate matter dispersion simulation.
Use cases employed in the context of land administration and topographic mapping usually mainly require model management (and optionally versioning), editing and visualization functionalities without further traffic or environmental simulation functionalities.

2.5 Data Requirements with regard to different Functionalities

2.5.1 Definition of Data Requirement Categories

In this chapter, data requirement categories are defined. These represent key capabilities a semantic 3D streetspace model should provide in order to serve requirements of respective functionalities.

- *Coordinate space:* Spatial dimension / coordinate space (2D, 2,5D or 3D) of streetspace models required for a certain use case (higher dimensional data may be beneficial but not essential). Some functionalities are implemented using 2D (and could be improved using 3D data), while other functionalities require 2,5D or true 3D models. This can include 3D slopes and profiles, 3D details such as raised curbstones or 3D objects such as bridges or underpasses.
- *Absolute positional accuracy and georeference:* Determining the relevance of absolute real-world coordinates and georeferenced data as opposed to the usage of a Local Coordinate System (LCS). In contrast to CAD or BIM, standards such as CityGML are tailored towards georeferenced 3D representations, which is especially important to represent geographically large extended structures such as roads, where the Earth's curvature significantly effects the geometry of an object. This ensures that 3D models accurately represent physical objects with precise spatial information. Georeferenced models can also easily be combined with other geospatial data (e.g. point clouds) and allow a direct and efficient management of the data in GIS systems and spatial geodatabases.
- *Relative geometric accuracy:* Relative geometric accuracy refers to how accurately the relative positions of streetspace objects need to be determined. Defining specific numerical values for relative

geometric accuracy requirements can vary greatly depending on the context and the project-specific needs. However, some general examples of relative geometric accuracy can be defined as follows:

  - Very high accuracy: Within less than a centimeter (down to millimeters)
  - High accuracy: Better than 3 cm (accuracy of most cadastral data)
  - Moderate accuracy: Between 3 and 20 cm
  - Low accuracy: Within 20 cm to a meter
  - Very Low: Within a few meters

- *Geometry representation:* This refers to geometries representing individual objects necessary for certain software functionalities. Roads and the streetspace can be represented using linear, areal, volumetric or point cloud geometries. While for some applications, a linear or graph-based representation is sufficient, other applications require exact areal (surface-based) information, which can also be used to derive volumetric representations of the traffic space above individual surfaces. Roads can be represented using parametric (e.g. used by OpenDRIVE (ASAM, 2023)) or explicit coordinate-based (e.g. used by CityGML (Kolbe et al., 2021)) geometric representations. Parametric representations of roads usually define all objects relative to a reference line. While this is a common representation for automotive-related applications or BIM/CAD systems, GIS software or geo-databases (usually) cannot directly work with this kind of data.
- *Differentiated object classes:* Individual semantic objects such as buildings, roads or railways need to be specified.
  - Semantic objects above the ground: Objects such as buildings, roads, railways, markings, manholes, city furniture, vegetation or waterbodies and their parts.
  - Semantic underground objects:
    * Utility networks such as underground power, gas or water systems
    * Geotechnical underground models containing information on sub-surface models or road material layers
- *Semantic decomposition:* The necessity to segment large road networks into smaller objects, and conversely the ability to aggregate these objects into larger objects / structures. (e.g. hierarchies such as a driving lane is part of a section, which is part of a road, which is part of a city etc.).
- *Thematic granularity:* Roads can be semantically segmented in different levels of granularity. Figure 2.7 shows a proposal for three levels of thematic granularity.

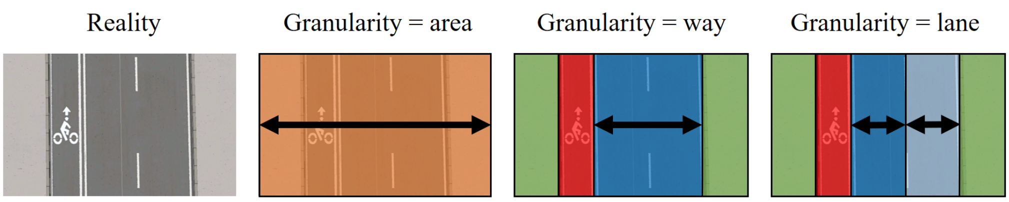


Figure 2.7: Thematic decomposition of roads into three levels of granularity.

Granularity level 'area' represents the entire width of a road (including sidewalks or bicycle lanes), granularity level 'way' represents individual objects per traffic type (e.g. one surface per carriageway) and granularity level 'lane' represents individual lanes. This concept can also apply to linear or volumetric representations of roads.

- *Thematic attributes:* Describes the necessity of semantic attributes, such as class, function or usage assigned to objects in order to provide semantic meaning and further thematic information to individual streetspace objects.
  - class: This attribute further specifies already classified objects. A road object, for example, can be classified as a public or private road.
  - function: Indicating object functions such as driving lane, sidewalk, parking slot, traffic island, bicycle path, crossing, curb, manhole, road damage, traffic light or traffic sign. In CityGML, one or multiple function attributes can be in specified using existing codelist values. This can be used to represent combined sidewalk and bicycle paths, etc.
  - usage: Indicating objects allowed to use certain parts of the streetspace such as car, pedestrian, bicycle, bus, taxi, train, tram
- *Logical relations:* Describes the necessity of semantic relations between streetspace objects (e.g. expressed via relation attributes or linking mechanisms), for example, to express the relation of an intersection belonging to multiple roads, the validity of a traffic signal for a specific lane, parts of a bridge simultaneously representing surfaces of a road or roads that are part of buildings (e.g. within a parking garage).
- *Network topology:* Whether topological relations between linear representations of road networks or streetspace objects such as incidence, adjacency predecessor and successor relations are necessary or not.
- *Areal topology:* Whether topological relations between areal representations of roads or streetspace objects such as adjacency or predecessor and successor relations or information on adjacent surfaces are necessary or not.
- *Topicality:* Describes the necessary up-to-dateness of the model. While topicality of cadastral data is regulated by law and is usually updated within several months, other use cases require up-to-date (e.g. daily updated) information on roads. For some applications, near real-time information on the surrounding streetspace is required.
- *Evolution and historization:* Availability of concepts within the data model to explicitly represent and exchange different versions of a streetspace model. This requires unique and persistent identifiers for each streetspace object. This is relevant for keeping track of the changes in the streetspace model over time and managing different but consistent versions (or stages within the lifecycle) of objects.
- *Moving objects:* Concepts in the data model for considering moving objects such as vehicles, pedestrians of bicyclists.
- *Sensor data:* Concepts in the data model for consideration of (highly) time-dependent information and linking objects with (highly) dynamic and (near) real-time information such as sensor data, dynamic traffic (light) data or time-dependent simulations.
- *Appearance and visualization:* Importance and type of visualization defined as follows:

- by class: individual colors per object class (e.g., gray driving lanes) or generic textures (e.g., asphalt texture)
- computed texture, e.g., textures computed from noise or solar irradiation simulation results
- photo-texture: realistic textures, e.g., extracted from high-resolution images

2.5.2 Evaluating the Data Requirements imposed by the different Functionalities

The functionalities presented in chapter 2.3 are now evaluated for their requirements with respect to the information provided by semantic 3D streetspace models defined in chapter 2.5.1. Each functionality is evaluated in detail for required geometric, semantic, topological, temporal and visual information. Table 2.2 summarizes the results of this evaluation in a compact form, indicating required (✓) and use case dependent (*) information.

Information such as relative geometric accuracy should be regarded as general guideline values, which are determined based on (currently) available data and systems. Requirements towards this information may change in the future. While some functionalities can also be performed in 2D, 3D information can improve simulations results. Microscopic traffic simulations for example can already be done in SUMO using 2D input data on road networks, with the possibility to include 3D information on elevation to consider slopes. Visualizations can be done in 2D or 3D, depending on respective use cases. Most presented functionalities related to environmental simulations and analysis such as visibility analysis or particulate matter analysis require true 3D information on roads and streetspace objects. Absolute georeferenced data is required for most functionalities. While models can be represented in a local coordinate system (which is often the case for local road planning scenarios), georeferenced data on roads allows an easy combination with other objects such as buildings, vegetation, city furniture or geodata such as point clouds. Furthermore, while traffic or pedestrian simulations could be done in a local coordinate system, simulation results often are connected to real-world scenarios, which should be visualized accordingly.

The relative accuracy of required data ranges from sub-centimeter information (required for driving dynamics functionalities) over sub-decimeter accuracy (required for functionalities such as solar irradiation or micro-climate simulation) to a lower accuracy that is sufficient for functionalities such as microscopic or even macroscopic traffic simulations.

Geometric requirements can be further analyzed for geometry type (linear, areal, volumetric, point cloud) and geometric modelling paradigm (explicit coordinate-based representation usually provided by GIS data such as CityGML or parametric representations e.g. provided by OpenDRIVE). Some software tools implementing traffic simulation functionalities such as SUMO are able to use parametric OpenDRIVE as well as explicit OpenStreetMap data as source information. Other tools such as momenTUM implementing pedestrian simulation functionalities require explicit coordinate- and surface-based representations of roads, sidewalks or pedestrian crossings (Kielar et al., 2016). Volumetric or point cloud based representations of road space objects can be required for visibility analysis or collision detection functionalities.

Concerning semantic information, all functionalities are evaluated for requirements of differentiated object classes and the degree of required semantic decomposition of road data. While macroscopic traffic simulations can be performed using generalized information on roads, microscopic traffic simulations typically require lane-level information. For functionalities such as navigation or route planning, information on individual carriageways are often sufficient. A semantic decomposition of large road networks into more manageable objects as well as logical relations are required by most functionalities. Semantic objects above the ground are required by all functionalities. Additionally, underground information on either utility networks or geotechnical information are relevant for some functionalities. Underground data is relevant for collision detection (e.g. in the use case 'street excavation'), but also for road / urban planning and visualization. Information on underground material layers are relevant for model editing functionalities (e.g. in road construction).

Semantics refers to the meaning or interpretation of the elements within a 3D streetspace model. It involves relations including object hierarchies, and concepts that define how different elements interact and what they represent in the real world (e.g., driving lanes part of a specific road). This includes object definitions and classifications. A subset of semantic information is described using thematic attributes. Attributes are specific information or characteristics assigned to elements in a 3D streetspace model. They provide quantitative or qualitative details about an object, such as finer classification, function, surface material or speed limit. A more detailed list of required thematic attributes is given in table 2.3.

While a unique object identifier is recommended for every functionality in order to be able to track changes over time, only modelling, versioning and facility management functionalities explicitly require this information. Unsurprisingly, many attributes related to traffic such as speed limits or traffic rules are required by traffic and transportation related functionalities. Network topology, including information on predecessors and successors, is also mainly required by traffic related functionalities. While (microscopic) traffic simulations only require topologically connected networks, sub-microscopic driving simulations additionally require G2-continuity between adjacent road parts in order to ensure smooth simulation and visualization results. Pedestrian simulation functionalities require areal topology, such as information on adjacent surfaces (e.g. a pedestrian crossing next to a sidewalk). The required topicality of the used data often depends on individual use cases making use of respective functionalities.

In case current real-world scenarios need to be analyzed or simulated, up-to-date representations of roads and the streetspace are required. While some automated vehicle control systems use up-to-date HD-maps, information on their environment is often gathered in real-time. The historization of road and streetspace models is mainly relevant for facility and model management functionalities. Moving objects such as vehicles or pedestrians are relevant to functionalities such as traffic simulations. Additional information gathered by sensors such as traffic volumes or air pollution is also relevant to a number of functionalities. In this case it is important to be able to associate sensor information with corresponding streetspace objects.

Table 2.2: Evaluation of data requirements imposed by functionalities with regard to capabilities of semantic 3D streetspace models. Required (✓) and use case dependent (*) information is marked accordingly.

Data Requirements	Functionalities																						
	Model manag. and editing	Scenario generation / Concurrent version control	Historization	Facility management	Macroscopic traffic simulation	Microscopic traffic simulation	Bicycle simulation	Pedestrian simulation	Sub-mic. driving simulation	Vehicle dynamics simulation	Autonomous vehicle control	Navigation / Guidance	Route planning	Noise simulation	Visibility simulation	Wind field simulation	Gas and partic. matter disp. sim.	Solar irradiation simulation	Shadow casting simulation	Collision detection	Water run-off and water-flow sim.	Rockfall simulation	Visualization or rendering
Road Geometry																							
Coordinate Space	2D/3D	2D/3D	2D/3D	2D/3D	2D/3D	2D/3D	2D/3D	2D/3D	3D	2,5D/3D	3D	2D/3D	2D/3D	3D	3D	3D	3D	3D	3D	2D/3D	2.5D/3D	3D	2D/3D
Absolute georef. or local coord. system	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Relative geometric accuracy	*	*	*	≤ 0.5 m	≤ 5 m	≤ 1 m	≤ 1 m	≤ 1 m	≤ 0.03 m	≤ 0.01 m	≤ 0.5 m	≤ 1 m	≤ 1 m	≤ 2 m	≤ 0.1 m	≤ 2 m	≤ 2 m	≤ 0.2 m	≤ 0.2 m	≤ 0.1 m	≤ 0.5 m	≤ 0.5 m	*
Linear representation	*	*	*	*	✓	✓	✓	*	✓		*	✓	✓	✓	*								✓
Explicit areal representation	*	*	*	✓				✓	✓	✓/ grid	*				✓	✓	✓	✓	✓	✓	✓	✓	✓
Parametric areal representation	*	*	*						✓		*												
Non-redundant surface rep.	*	*	*	✓				✓	✓	✓								✓	✓		✓	✓	✓
Volumetric representation	*	*	*													✓	✓			*			*
Point cloud representation	*	*	*								*				*					*			*
Road Semantics																							
Differentiated object classes	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	*
Semantic decomposition	*	*	*	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	*
Objects above the ground	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	*
Underground objects	*	*	*	*																*			*
Thematic granularity	*	*	*	way/lane	area	lane	lane	way/lane	lane	way	lane	way/lane	way/lane	*	way/lane	area	area/way	area	area/way	*	area	way	*
Thematic attributes (cf. table 2.3)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	*
Logical relations	*	*	*	*	✓	✓	✓	✓	✓		✓	✓	✓	*	*	*	*	*	*	*	*	*	
Road Topology																							
Network topology	*	*	*		✓	✓	✓	*	✓		✓	✓	✓										
Areal topology	*	*	*				*	*	*		*												
Temporal aspects																							
Topicality / Up-to-dateness	*	*		up-to-date	*	*	*	*	*	*	(near) real-time	up-to-date	up-to-date	*	*	*	*	*	*	*	*	*	*
Historization support	*	✓	✓	*																			*
Moving objects	*				✓	✓	✓	✓	✓	✓	✓												*
Sensor data	*	*		*	*	*	*	*	*	*	✓					*	*						*
Visual aspects																							
Type of appearance	*	*	*	by class	by class	by class	by class	by class	photo-texture	by class	*	by class	by class	computed texture	computed texture	computed texture	computed texture	computed texture	computed texture	computed texture	computed texture	computed texture	*

Table 2.3: Required (✓) and optional (o) thematic attributes relevant for specific functionalities.

	Functionalities																						
Required thematic attributes	Model manag. and editing	Scenario generation / Conc. version control	Historization	Facility management software	Macroscopic traffic simulation	Microscopic traffic simulation	Bicycle simulation	Pedestrian simulation	Sub-mic. driving simulation	Vehicle dynamics simulation	Autonomous vehicle control	Navigation / Guidance	Route planning	Noise simulation	Visibility simulation	Wind field simulation	Gas and particulate matter dispersion sim.	Solar irradiation simulation	Shadow casting simulation	Collision detection	Water run-off and water-flow sim.	Rockfall simulation	Visualization or rendering
stable object ID	o	✓	✓	✓	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
object validity time period	o	o	✓	✓																			
class	o	o	o	o	o	o	o	o	o		o	o	o										
function	o	o	o	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	o	o	o	o	o	o	o	o	o
usage	o	o	o	o	✓	✓	✓	✓	✓		✓	✓	✓	✓									
road name	o	o	o	o	o	o	o	o	o			✓	✓										o
surface material	o	o	o	✓		o			o	o	o	o	o	o				o			o	o	o
surface area	o	o	o	✓														o					
pavement condition	o	o	o	o		o	o	o	o	o	o		o	o									o
width	o	o	o			o	o	o				o	o							o			
length	o	o	o				o					✓	✓										
slope	o	o	o		o	o	o	o	✓	o	o	o	o	o							o	o	
speed limit	o	o	o		✓	✓			✓	o	✓	✓	✓	✓									
traffic direction	o	o	o		✓	✓	✓	o	✓		✓	✓	✓										o
traffic volume	o	o	o	o	✓	✓	✓	o	✓					o									
pred. / successor	o	o	o		✓	✓	✓	✓	✓		o	✓	✓										
max. traffic capacity	o	o	o	o	o	o	o							o									o
max. load capacity	o	o	o	o	o	o			o		o	o	o										o
owner	o	o	o	o																			

2.6 Utilizing the presented Tables and Evaluations

The detailed information provided in this chapter (especially within tables 2.1, 2.2 and 2.3) can be used by different groups interested in creating or working with 3D streetspace models. The following list gives an overview on how this information can be useful and instructive to different stakeholders:

- *Data users* such as city planners, transportation agencies or emergency responders can use the provided information to understand the specific requirements of software functionalities when working with road and streetspace data. This is useful when preparing tenders to gather such information and to decide which semantic, geometric, topological, temporal or visual information is required in what detail depending on intended use cases. Furthermore, appropriate standards and data formats can be chosen (cf. chapter 3). Usually, specific use cases are in the center of focus for data users. With the information provided in table 2.1, required functionalities can be identified for specific use cases and linked with data requirements given in tables 2.2 and 2.3.
- *Data collectors and providers* such as government agencies or private companies collecting data on roads and the streetspace can use the presented information to ensure that the data they supply aligns

with the outlined requirements of software functionalities. The information can also be used to identify gaps or areas for improvement in their data collection processes based on the requirements specified in the tables 2.2 and 2.3.

- *Standardization organizations* such as ISO, ASAM or the OGC can use the comprised information to identify potential gaps and missing concepts in existing standards and to further develop or refine standards for road and streetspace models. Information required and summarized in tables 2.2 and 2.3 should be available in a standardized form in order to serve respective functionalities needed for domain-specific use cases. The presented investigations, for example, are the basis for the revised and extended concepts for modelling transportation infrastructure developed in the course of this doctorate and presented within this thesis. Results of this work were incorporated into the newest version of the international OGC standard CityGML 3.0 (Kolbe et al., 2021).
- *Scientists* can benefit from the proposed term definitions, categorizations and evaluations of road and streetspace models, by applying the methodology to other fields of research e.g. in the context of urban digital twins. A similar analysis could be done with other thematic components of semantic 3D city models such as buildings or vegetation. Proposed geometric, semantic or topological capabilities of 3D road models can also serve as a guideline for developing (automated) methods and processes, that are able to produce this kind of data from semantically unstructured data such as point clouds.
- *Software application developers* can use the information to design and develop software functionalities that meet the specific needs and expectations of users and stakeholders working with streetspace data in order to serve specific use cases.

Demands regarding semantic and thematic information, positional accuracy, geometric resolution, topological information and visual capabilities of 3D streetspace models can vary depending on the specific use case (even within the same main application domain) and respective required functionalities. Thus, stakeholders interested in creating and using an urban digital twin of the streetspace must consider capabilities of data formats and standards with respect to these requirements depending on intended (main) use cases. A challenge in this endeavor is to create a digital 3D representation of the streetspace, which is capable of serving as a foundation for many relevant use cases, while managing the complexity of gathering, structuring and updating required data and information sources.

While the presented review contains a comprehensive description of use cases for 3D streetspace models and their requirements, there are also some limitations. As mentioned before, the assignment of use cases to a specific application domain can be ambiguous. We have assigned use cases to their most relevant application domain. More use cases with additional requirements will come up in the future. The presented requirement evaluations such as relative geometric accuracy should be regarded as general guideline values, which are determined based on (currently) available data and systems. Requirements for this information may also change in the future. Furthermore, additional functionalities may be available in the future or existing functionalities may be deprecated. Presented functionalities are a current snapshot; nonetheless, the assignment of use cases and functionalities is not dependent on currently available software.

With the current advancement of artificial intelligence methods, additional functionalities and use cases employing this technology will be available in the future. Automatic scenario generation, e.g., for urban planning to generate a new roundabout layout to replace a previous intersection, is a current research topic and potential future use case for 3D streetspace models. Existing road layouts can be used for training respective AI models. Data models and corresponding instances of (semantically rich) 3D streetspace model datasets can be used for training AI methods in the context of 3D object reconstruction.

The utilization of Large Language Models (LLM) for querying information from semantic 3D streetspace models and providing additional analysis of the query results is another potential future use case of semantic models using AI technologies. The semantic structure of these models allow queries on data stored within GIS or spatial relational databases. LLMs can be utilized to assist users such as city planners or citizens with this interaction, for example, by translating text or audio queries into corresponding SQL statements.

Chapter 3

Relevant Road Modelling Standards, Conceptual Models and Guidelines

Some of the contents in this chapter have been presented in the following peer-reviewed and published papers:

Beil, C. and Kolbe, T. H. (2017). 'CityGML and the streets of New York - A proposal for detailed street space modelling'. In: *Proceedings of the 12th International 3D GeoInfo Conference 2017*. Ed. by Kalantari, M. and Rajabifard, A. Vol. IV-4/W5. ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences. This paper has received the 2nd Best Paper Award. University of Melbourne. ISPRS: Melbourne, Australia, pp. 9–16. URL: https://doi.org/10.5194/isprs-annals-IV-4-W5-9-2017

Beil, C. and Kolbe, T. H. (2020). 'Combined modelling of multiple transportation infrastructure within 3D city models and its implementation in CityGML 3.0'. In: *Proceedings of the 15th International 3D GeoInfo Conference 2020*. Vol. VI-4/W1-2020. University College London. ISPRS: London, UK, pp. 29–36. URL: https://doi.org/10.5194/isprs-annals-VI-4-W1-2020-29-2020

Beil, C., Ruhdorfer, R., Coduro, T. and Kolbe, T. H. (2020). 'Detailed Streetspace Modelling for Multiple Applications: Discussions on the Proposed CityGML 3.0 Transportation Model'. In: *ISPRS International Journal of Geo-Information* 9(10), p. 603. URL: https://doi.org/10.3390/ijgi9100603

In this chapter, standards, conceptual models and guidelines relevant for digitally modelling and representing roads and the streetspace are presented and discussed with regard to their capabilities to serve requirements of functionalities and use cases identified in the previous chapter. Modelling concepts of the latest version (as of August 2024) of these specifications are discussed with respect to geometric, semantic, topological, temporal and visual aspects. Additionally, since standards such as GDF have recently been updated, earlier and thus more frequently used versions of the standards are also included. These standards, conceptual models and guidelines are organized based on their primary application purpose, Some standards might not primarily be used for representing roads but still contain concepts to do so. Specifications are thus presented with respect to most relevant aspects of modelling roads and the streetspace. Table 3.1 presents an overview on these standards with information on respective main application domain, available encoding(s), issuing bodies and latest version. Only standards that provide concepts (e.g. conceptual data models) for semantically structured representations of roads are considered. Other standards and data formats primarily used for visualization purposes such as OBJ, 3D Tiles, etc. are not considered, even though they might be suitable for pure visualization use cases. Similar to the presented use cases, standards, conceptual models and data formats can also be categorized according to their intended main field of application. Standards with a similar application focus generally also tend to have similar modelling and representation concepts, as this typically has an influence on their modelling approach. Thus, the presented standards, conceptual models and data formats are grouped according to their main application domain and presented, explained and discussed in the following sections.

Table 3.1: Overview on main application domains, encodings, issuing bodies and latest versions (as of August 2024) of relevant standards, conceptual models and data formats.

	Main Domain	Encoding(s)	Issued by	Latest version
IFC	Architecture, engineering, construction	STEP / XML / binary	buildingSMART ISO/TC 59/SC 13	4.3.2.0
LandInfra	Land and civil engineering	GML / XML	OGC	1.0
OKSTRA	Road documentation and asset management	GML / XML	PG OKSTRA	2.021
GDF	Navigation	binary / XML	ISO/TC	5.1
OpenDRIVE	Driving simulation	XML	ASAM	1.8
RoadXML	Driving simulation	XML	OKTAL	3.0
Lanelets	Driving simulation	XML	FZI	—
Vissim	Traffic simulation	XML	PTV	—
OSM	Generation of open maps	XML / PBF	OSM community	—
INSPIRE	EU data harmonization and integration	GML / XML	EU TWG	3.2rc1
GeoInfoDok	National mapping and surveying documentation	GML / XML	AdV	7.1
CityGML	City models and their applications	GML / XML / JSON / relational database schema	OGC	3.0

3.1 Urban and Infrastructure Planning, Design and Management

3.1.1 Industry Foundation Classes (IFC)

The Building Information Modeling (BIM) data format Industry Foundation Classes (IFC) is a standardized, digital data model used to represent, exchange, and share information throughout the lifecycle of a building or infrastructure project, from initial design through construction and maintenance. The previously valid ISO standard IFC 4.0.2.1 was released in 2018 (ISO, 2018). The most recent release, which is an official buildingSMART standard and approved by ISO is IFC standard version 4.3.2.0[4], which was released in 2024 (ISO, 2024a).
The standard IFC contains *IfcAlignment* to define a reference system for linear construction structures such as roads or rails. This may consist of a horizontal alignment defined in the x/y plane accompanied with a vertical alignment defined along the horizontal reference line. Additionally, a relative alignment within another alignment and / or at constant / variable offsets can be defined. A 3D alignment computed from horizontal and vertical alignment or derived from geospatial data is also possible (Amann et al., 2015). This is very similar to concepts presented in LandInfra. In fact, the alignment concept has been jointly developed for LandInfra and IFC. Jaud et al. (2019) address issues of IFC concerning georeferencing. While IFC has included support for georeferencing, it is currently not possible to correctly exchange IFC data of a project where no EPSG code is available. While smaller IFC projects are often georeferenced with only an anchor point and corresponding rotation, this is not sufficient for large infrastructure projects (such as roads or tunnels) where the Earth's curvature needs to be taken into account.
IFC 4.3.2.0 includes concepts developed in projects such as *IFC Bridge, IFC Road, IFC Rail* and *IFC Ports & Waterway* that aimed to extend the data model towards different infrastructure (Jaud et al., 2020). The conceptual model of *IfcRoad* includes several road types such as street, highway, bikeway or footpath. *IfcFacilityPart* provides for spatial breakdown of built facilities. In the case of *IfcRoad, IfcRoadPart* as subtype of *IfcFacilityPart* are planned to represent parts of a road as *IfcLongitudinalRoadPart, IfcLateralRoadPart* and *IfcVerticalRoadPart*. A *IfcLongitudinalRoadPart* is either of type *RoadSegment, Junction* or *LevelCrossing*. Each of these types can be further specified (e.g. *Segment, Intersection, Roundabout*, etc.). An *IfcLateralRoadPart* can be one of multiple types such as *Carriageway, TrafficLane, Sidewalk*, etc.
Moon et al. (2019) describe a method for representing two *IfcRoads* which consist of multiple *IfcLongitudinalRoadParts* (Segments and an Intersection) and are connected to corresponding *IfcLateralRoadParts*. The *IfcLongitudinalRoadPart* representing the intersection is connected to both *IfcRoads* using a *IfcRelCrossesSpatialStructure* relation. This concept can also be transferred to roundabouts or roads on bridges. Concepts for modelling (volumetric) spaces within buildings were available in IFC. Version 4.3.2.0 of IFC adapts this concept for modelling spatial zones above transportation infrastructure. Furthermore, individual material layers below the road surface can be represented.

[4]https://standards.buildingsmart.org/IFC/RELEASE/IFC4_3/

3.1.2 Land and Infrastructure Conceptual Model Standard (LandInfra)

The OGC standard ‘Land and Infrastructure Conceptual Model Standard’ (LandInfra) defines concepts for providing and understanding information about land and civil engineering infrastructure (Gruler et al., 2016). These concepts are formally defined using UML diagrams. The standard relies on the ISO 19XXX series of geographic information standards. It covers various subject areas defined by so-called requirement classes. The most relevant in terms of road modelling are *Alignment* and *Road*. An *Alignment* is described as a positioning element that establishes a linear referencing system to locate physical elements. It can be defined in several ways such as horizontal, vertical or 3D alignment. For roads, there is typically an *Alignment* for the centerline. For dual carriageway roads, separate alignments should be realized, however they may also share a reference horizontal alignment at the approximate center of the entire road. Based on a Linear Referencing Method (LRM) locations along the *Alignment* can be defined as linearly referenced locations. *DistanceAlong* and *offsetLateralDistance* values shall be measured in the horizontal plane and ignore any vertical displacement, if *Alignment* is used as a linear element. *OffsetVerticalDistance* values can be considered. The class *Road* contains multiple alternatives for representing a road design such as *RoadElements*, *3D StringLines* (profile views), *2D CrossSections* and *3D Surfaces* and layers. *RoadElements* can include many different types such as pavement, sidewalk or curb defined by an attribute called *RoadElementType*. Multiple road elements can be grouped together as *RoadElementSet*. *RoadElements* can be physically located optionally by a spatial representation or a linearly referenced location. Any particular point in a cross section can be represented by a *3D StringLine*. A triangulated irregular network (TIN) can represent the surface of a road. This is not limited to the top surface of the constructed road but can also be used to model sub-surface information. However, LandInfra has not been widely adopted yet.

3.1.3 Objektkatalog für das Straßen- und Verkehrswesen (OKSTRA)

The ‘Objektkatalog für das Straßen- und Verkehrswesen’ (OKSTRA) released by the Federal Ministry of Transport and Digital Infrastructure of Germany, is a standardized catalogue for the uniform recording, manipulation and provision of street object characteristics (BASt., 2021). The current version of the specification is 2.021. OKSTRA focuses on formal descriptions using data schemas and UML representations of streetspace objects. The model is based on several ISO standards including ISO 19107 (2019) and ISO 19109 (2015). OKSTRA is used by German administrations to collect and store uniform information on municipal streets and traffic infrastructure. First, types of streets that should be included are designated. A linear representation is used to illustrate the described modelling concept. Every street is divided into several sections (Abschnitte) with each section being bounded by two uniquely identified nodes. Every section inherits a stationing system, starting at the first node and ending at the second. A node can be made up of multiple smaller branches (Äste) like ramps or driveways connecting different sections. Concepts are explained with examples in a corresponding ’Anweisung StraßeninformationsBank (ASB) version 2.05’ BASt. (2024) focusing on network-based descriptions of roads consisting of nodes and edges as displayed in figure 3.1. The document proceeds by giving numerous detailed examples, again illustrated via line and node representations, on how to represent various streetspace scenarios. These include intersections with different levels of complexity, roundabouts, bridges, and overpasses. While it is possible to model objects with areal representations, streets are commonly represented with linear structures. The specification also contains a 'Flaechenmodell' (area model) for representing road objects using areal geometries. Representations of lateral profiles and cross-profiles of roads are possible.

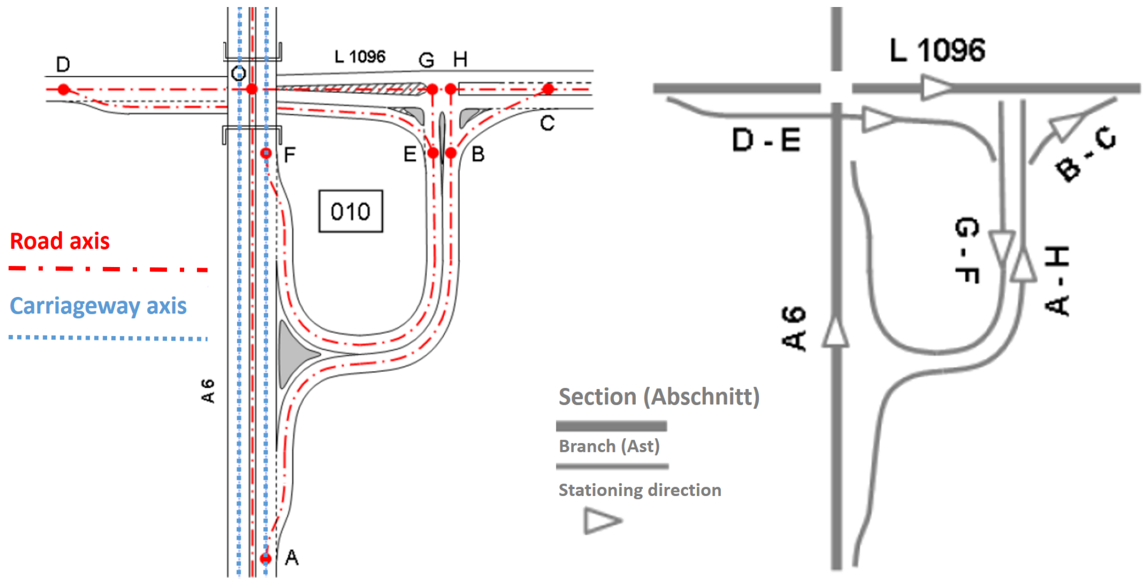


Figure 3.1: Road network representations as presented in BASt. (2024).

3.2 Automotive, Navigation and Transportation

3.2.1 Geographic Data Files (GDF)

Geographic Data Files (GDF) is an ISO standard mainly used in vehicle navigation for the exchange of digital maps between map manufacturers and navigation system integrators. Additionally, GDF provides numerous rules for data capture and representation in regard to many streetspace objects. Version 5.0 of GDF was published in 2011 and contained limited capabilities for areal representations of roads. The current specification GDF 5.1 was published in 2020 by ISO and is divided into two parts. GDF 5.1 part 1 (ISO, 2020a) is an evolution of the conventional GDF 5.0, while GDF 5.1 part 2 (ISO, 2020b) provides concepts and a data model for new requirements. Part 1 of GDF is itself divided into several parts. Real world objects (called *Features*) and their database representation form the core of the general GDF data model. Furthermore, topological and non-topological relations between these features as well as their characteristics are described. Additionally, these features are organized semantically by categorizing them into different thematic feature themes defined in the so-called Feature Catalogue. Possible attributes and relationships of these features are specified in a corresponding Attribute Catalogue and Relationship Catalogue. Features can also be subdivided based on the topology of the underlying graph by which the features are defined. Moreover, all objects can be conceptually divided over three levels called Level-0, Level-1 and Level-2 as displayed in figure 3.2. This concept can be illustrated by explaining the most relevant thematic category with regard to streetspace called *Roads and Ferries*. This contains a so-called *Road Network*, which can be represented in Level-1 and Level-2 respectively. A representation in Level-0 would consist of basic topological building blocks such as nodes, edges or faces. Simple features such as *Road Elements* or *Junctions* make up Level-1 objects and can be aggregated to form more complex features called *Road* or *Intersection* in Level-2. Road networks are usually represented by linear structures.

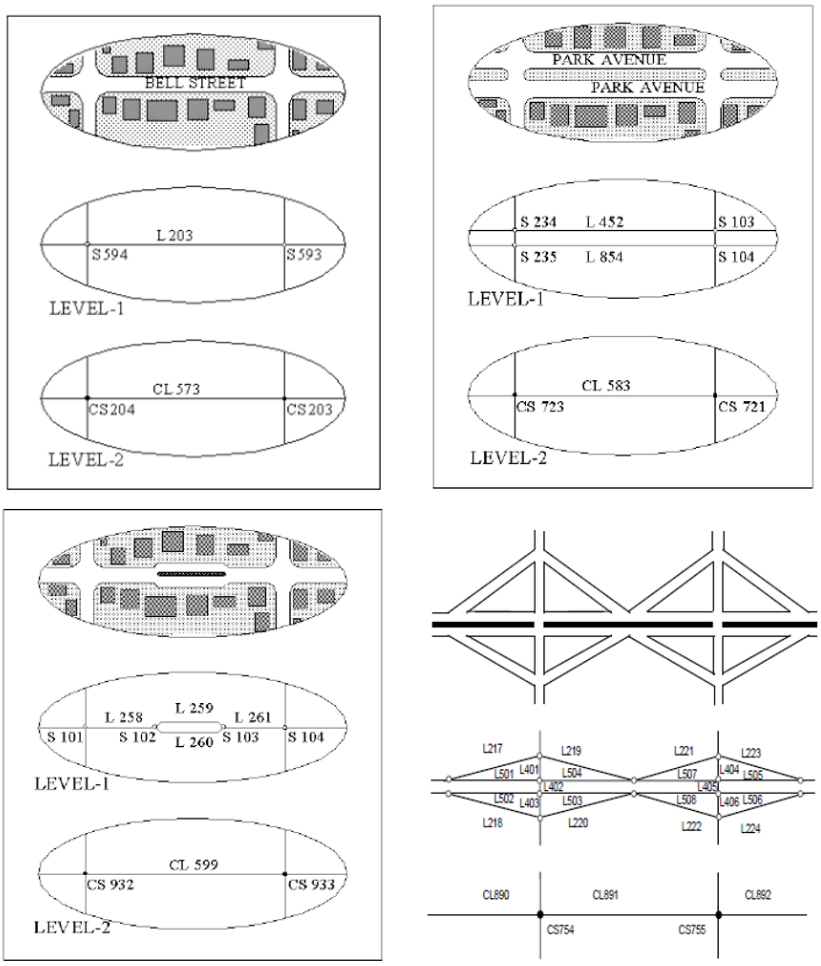


Figure 3.2: GDF modelling examples of roads for different scenarios in multiple levels according to ISO 20524-1 (ISO, 2020a).

Enclosed traffic areas, defined as areas within unstructured traffic movements such as car parks, can be represented as areas. GDF supports a mechanism of linearly referencing points along line features. Furthermore, all geodetic parameters needed for the correct interpretation of X, Y and Z-values shall be described explicitly to make a transformation into any other coordinate system possible. While many basic concepts of GDF are explained using Unified Modeling Language (UML) diagrams, there is also a complete XML schema defined within the standard document. While previous versions of GDF focused on linear (graph-based) representations of roads, GDF version 5.1 part 2 introduces a so-called *Belt* concept for representing areal features with actual width that can be degenerated into linear shapes. This contains concepts for segmenting roads into so-called *RoadBeltElements* and *IntersectionBelts*, which are further split into individual *LaneSections* and *LaneBelts* as illustrated in figure 3.3. This segmentation approach is similar to semantic concepts of OpenDRIVE. However, there are no openly available data examples making use of these concepts yet. Lateral boundaries of *RoadBelts* are defined using lines such as the outline of the road. Additionally, so-called terminal lines are used for virtually defining the boundary between *RoadBelts* and *IntersectionBelts*.

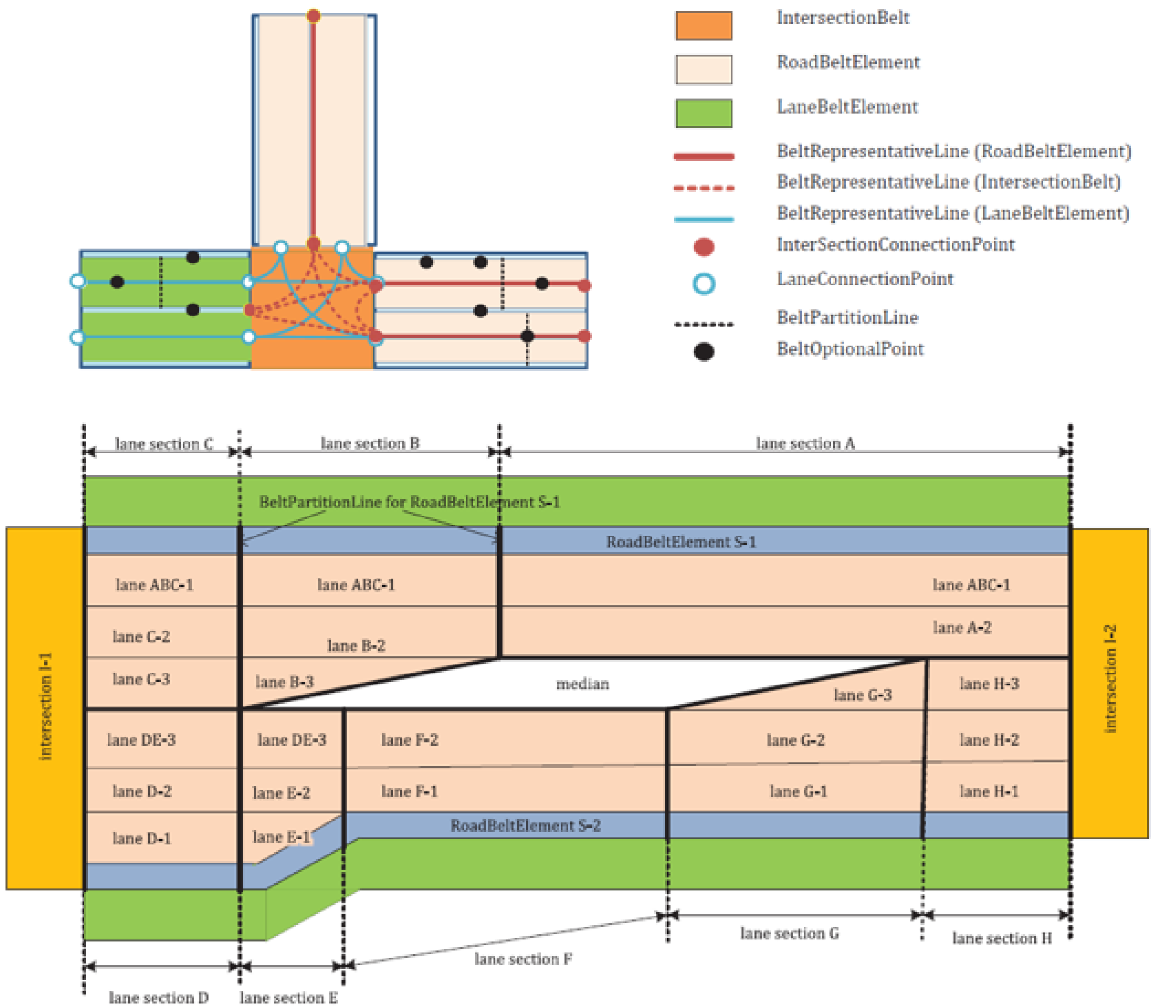


Figure 3.3: Belt concept for representing areal road features introduced in GDF 5.1 (ISO, 2020b)

3.2.2 OpenDRIVE and OpenCRG

OpenDRIVE is an open data format originally developed by VIRES Simulationstechnologie GmbH to describe street networks and is commonly used for driving simulations by automobile manufacturers including BMW, AUDI or Daimler. Management of the standard was transferred to the Association for Standardization of Automation and Measuring Systems (ASAM) in 2018. The current format

specification - version. 1.8 - was published in 2023 (ASAM, 2023).
There are three types of coordinate systems that can be used simultaneously in OpenDRIVE and that are nested into each other as illustrated in figure 3.4. An inertial system according to ISO 8855 (ISO, 2013) defines the position of objects with x- (= right / east), y- (= up / north) and z- (= coming out of drawing plane / up) coordinates. A referenceline-based system defines coordinates with s-values following the tangent of the reference line (measured in meter in the x/y-plane), t-values orthogonal to the s-axis and h-values pointing in the up-direction. A local system can only be positioned relative to the reference line system contains u-coordinates (matching s), v-coordinates (matching t) and z-coordinates (matching h).

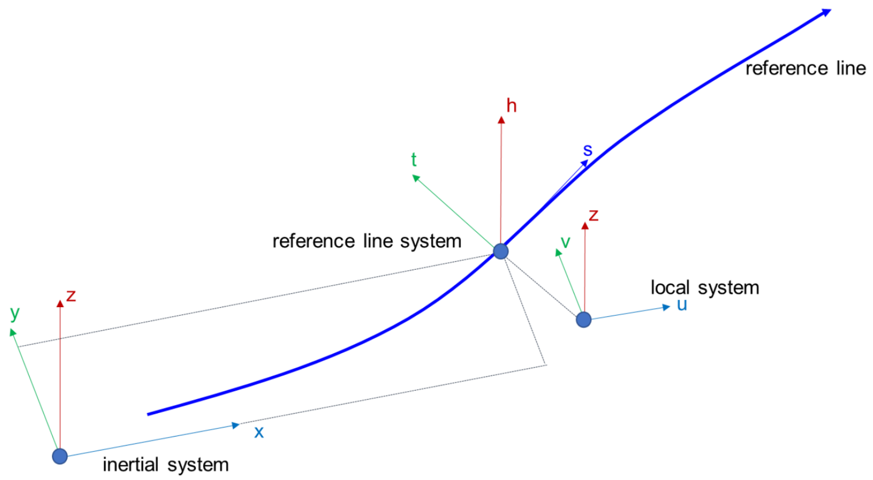


Figure 3.4: Coordinate systems in OpenDRIVE (ASAM, 2023)

OpenDRIVE provides several geometry elements to define reference lines. These are straight lines, splines or clothoids, arcs and parametric cubic polynomials (cubic polynomials have been deprecated in version 1.8). Each of these geometries is described using x- and y-coordinates in an inertial coordinates system, an s-value to determine the start of the geometry along the reference line, information on inertial heading and length of the geometry and additional parameters depending on the used geometry (e.g. curvature of an arc or parameters of a parametric cubic polynomial). All further shapes and properties of roads are then described with respect to a corresponding reference line. The geometry of individual lanes for example is described using a parametric description of lane width or lane border with respect to their reference line. Additionally, lateral and elevation profiles can be represented using parametric descriptions. This parametric description is used for all geometries except for 3D objects that have an influence on a road and are to complex to be described by parameters. These objects can be represented using their explicit outline or bounding box.
The main element in OpenDRIVE are so called *Roads*, each described with an individual reference line. *Roads* can either be standard roads (illustrated in blue in figure 3.5) or connecting roads within a *Junction* (illustrated in red in figure 3.5). Multiple Junctions in close proximity may be part of a junction group. *Roads* within *Junctions* (and their corresponding lanes) can overlap and be represented

with respect to multiple reference lines simultaneously. *Junctions* contain information on connections of *Roads*. All *Roads* in OpenDRIVE require a minimum definition of a center lane (the reference line itself, with zero width and ID = 0) and an additional *Lane* with a certain width. All *Lanes* are numbered with descending IDs to the right of the reference line (negative t-direction) and ascending ids to the left of the reference line (positive t-direction). Furthermore, *Lanes* may be split into multiple *Lane Sections*. Each *Lane Sections* needs to contain a fixed number of *Lanes* as also illustrated in the right image in figure 3.5. Each *Lane* can contain a lane type attribute, further describing the purpose of each lane (e.g. driving, sidewalk or biking). Additional attributes such as material or speed limit are available.

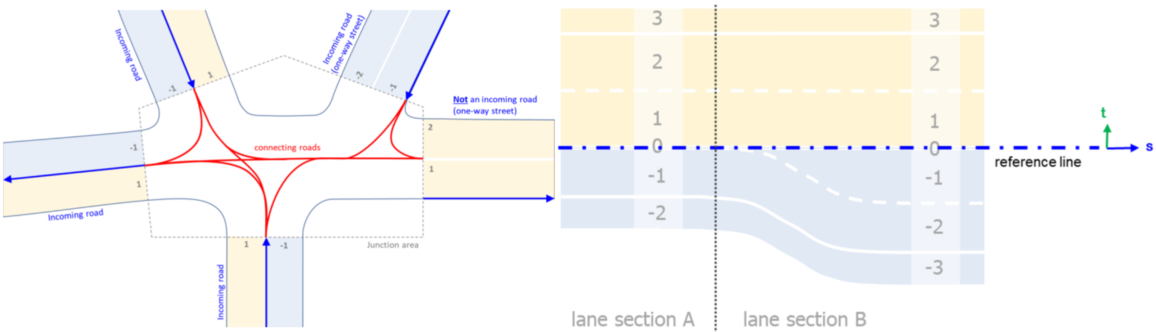


Figure 3.5: Semantic concepts in OpenDRIVE: Left: Standard reference lines (blue) and reference lines within a Junction (red); Right: Lanes and LaneSections (ASAM, 2023)

Additionally, traffic signs, traffic lights or road markings for the control and regulation of road traffic are represent using so called signals, which are defined with respect to reference lines. Road markings can be represented in association with individual lanes (e.g. at lane borders) or as Objects (e.g. crosswalks, stop lines or parking spaces). Road(segments) that are part of tunnels and bridges are also modelled as *Objects* in OpenDRIVE, indicated by a starting s-value and length information that is valid for the entire cross section of a *Road*. Rail-based transportation systems can be modelled with so called *Railroads*. However, this should only be used for *Railroads* interacting with *Roads* and thus provides limited capabilities in that regard.
OpenDRIVE Roads contain information on preceding and succeeding *Roads* using so-called road links. *Roads* outside of a *Junction* need to be connected to each other in order to use this road linkage method. Additionally, individual lanes can be linked with information on predecessors and successors. *Junctions* enable the connection of more than two *Roads* and contain information on incoming *Roads*. *Roads* may also have connections to *Signals, Objects* and *Railroads*. *Signals* and *Objects* are also represented in relation to a specific *Road*. The validity of *Signals* and *Objects* is given for all *Lanes* of a *Road* by default but can be specified by an attribute. OpenDRIVE does not contain an XML specification for detailed surface descriptions. In this context, the standard refers to a related standard called OpenCRG (ASAM, 2020a) for extended road surface descriptions. OpenCRG is an open file format specification closely linked to OpenDRIVE aiming at providing a standardized description of detailed road surfaces. A Curved Regular Grid (CRG) is used for representing and visualizing road elevation data near a reference line as illustrated in figure 3.6.

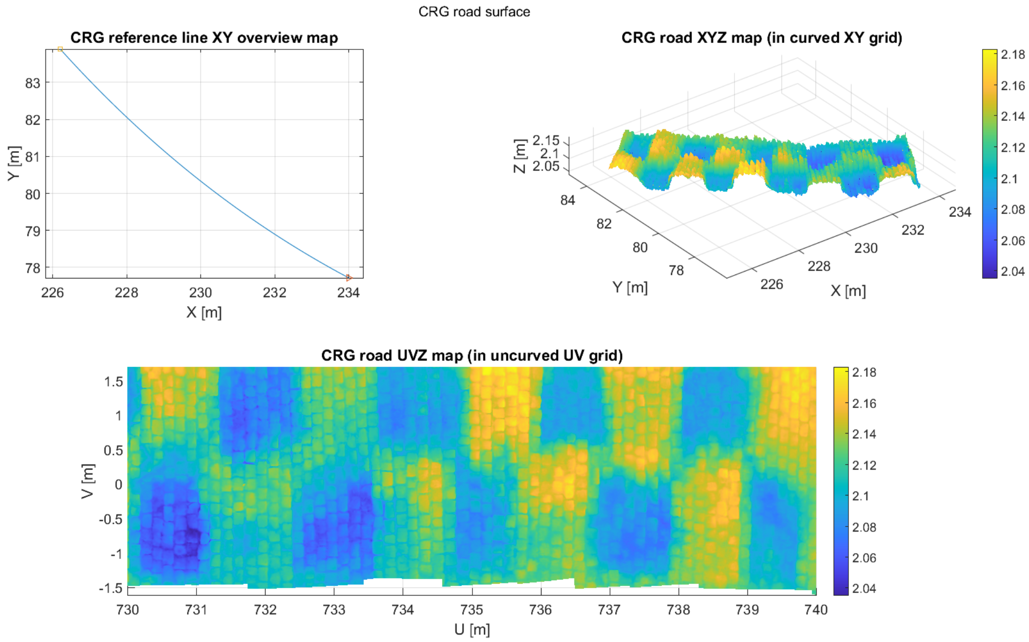


Figure 3.6: Grid-based road surface description according to (ASAM, 2020a).

In order to streamline the process of surveying routes and transforming cadastre data into simulation formats, the Road2Simulation Guidelines have been developed by the German Aerospace Center (DLR) (Richter and Scholz, 2019). These guidelines aim to establish a standardized approach to surveying road and surface data, with a focus on the OpenDRIVE road description format and the OpenCRG surface description format. The latest version 1.2.1 was published in 2019.

There have been some efforts for adapting modelling concepts of OpenDRIVE in order to be more compatible with real-world geospatial data (ASAM, 2020b). This includes the development of a so-called *Area Concept* which incorporates the modelling of transportation infrastructure using polygonal geometries, avoiding complex referenceline-based constructs. The concept introduces multiple mandatory and optional layers. This includes a so-called traffic area layer representing polygonal surface descriptions for each transportation type supported by a ground layer for TIN-based information on the underlying terrain. Markings and restrictions as well as traffic signs or signals are proposed to be represented with respective layers. Optional path, routing and lane layers are also possible.

3.2.3 RoadXML

Similar to OpenDRIVE, RoadXML is a format originally developed for driving simulators. The traffic space is organized into several layers of data including traffic data, surface data, topologic data, sound data and user data. The current version 3.0.0 of RoadXML was published as an open file format in 2020 (RoadXML, 2020). A network is subdivided into smaller regions, so-called sub-networks. Road linkages are modelled on lane basis. The road geometry is described horizontally by a *XYCurve* and vertically by a *SZCurve*, approximated by line, circular and clothoid shaped elements. Lateral geometry is to be defined through profiles including lanes and its borders. Point-like objects can be positioned using a linear referencing approach. For visualization purposes textures and 3D models can be integrated. In contrast to OpenDRIVE the group of active users of RoadXML is fairly limited. As of August 2024 the official website of the data format is not accessible.

3.2.4 Lanelets and Lanelet2

Lanelets are a lightweight concept for representing roads using information on lane boundaries, traffic signs and other objects relevant for autonomous driving (Bender et al., 2014). As illustrated in the left part of figure 3.7, a lanelet is used to describe a lane segment with polylines representing its left and right boundary (thus also specifying the driving direction). Adjacent lanelets can be combined into a graph representation for routing applications (right part of figure 3.7). Regulatory elements such as traffic lights, traffic rules or traffic lights can also be linked with corresponding lanelets. Lanelets are representable using the OpenStreetMap (OSM) formalism, which defines an XML-based file format. Althoff et al. (2018) present an automatic conversation method from OpenDRIVE data to lanelets. Lanelet2 is an open source map framework for representing and working with lanelets in the context of autonomous driving (Poggenhans et al., 2018). Lanelet2 primitives include points, line strings, polygons, lanelets, areas and regulatory elements[5]. Lanelet2 provides 'tags' for lanelets such as driving direction, road user, speed limit or road surface material. Routing graphs can be derived from lanelets and routing graphs from different participants (e.g. vehicles and pedestrians) can be connected to identify conflicting lanelets.

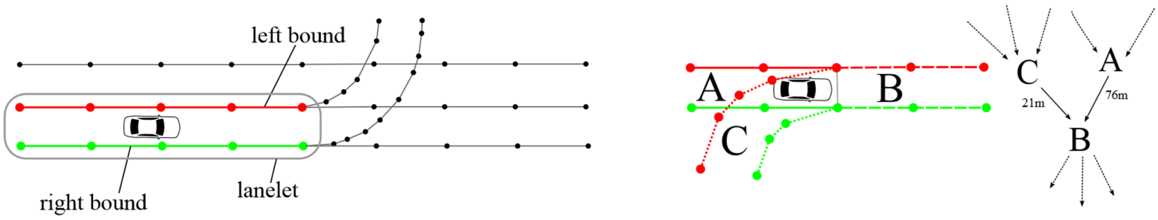


Figure 3.7: Basic concept of lanelets describing lane boundaries (left) and a graph derived from adjacent lanelets (right) (Bender et al., 2014).

3.2.5 Vissim Model

Vissim is a software tool to perform microscopic, behaviour-based multi-purpose traffic simulations to analyse and optimize traffic flows (Fellendorf and Vortisch, 2010). Vissim is a widely used multimodal traffic simulation software and can be applied for planning of different traffic scenarios or with regard to traffic light control. Potential traffic members include cars, busses, trucks, bikes, pedestrians or trams. In contrast to other standards and data formats, UML descriptions are not available. Ruhdorfer et al. (2018) describe the Vissim traffic model in detail. The road network is modelled by a Link-Connector concept. A Link corresponds to a network edge containing all characteristics of a road segment. Every link contains attributes and geometry, described with its start- and endpoint as well as

[5] https://github.com/fzi-forschungszentrum-informatik/Lanelet2

possible intermediate points. The coordinates of these points are stored with metric x, y and z values based on a coordinate system with sphere-mercator projection. In combination with knowledge on lane number and width, areal models can be derived. Connectors describe the node topology enabling a lane-per-lane linkage by tying two links pairwise, which is essential for microscopic analyses. Linear objects approximating the road trajectory and parameters on lane width and number of lanes describe the road geometry parametrically. Additional parameters define visualization, function and traffic logics such as access restrictions or priority rules. Further network objects such as traffic signals, stop lines or parking lots allow a comprehensive mapping of the traffic space and simulation relevant settings. Attributes such as speed restrictions or priority rules enable realistic traffic simulation scenarios. Vissim allows the simulation of multimodal traffic by combining different traffic members such as cars and pedestrians. Additionally, 3D graphic models such as SketchUp or Autodesk data can be integrated in order to achieve detailed visualizations of the simulation results. In addition to streetspace objects, models of vehicles can be integrated into the simulation.

3.3 Digital Landscape Modelling and Mapping

3.3.1 OpenStreetMap (OSM)

OpenStreetMap is a community project that provides user-generated maps available for web viewing and downloads (Haklay and Weber, 2008). Map features defined on the project homepage are identified by so-called keys. These include *highway=** used for any kind of road, street or path. An assigned attribute value further indicates the importance of each highway within the road network. Potential highway attributes include *primary, secondary* or *tertiary* roads as well as motorway and other road types. Additional attributes such as cycleway, pedestrian or many others further define specific characteristics of a highway object. Information on speed limits, width, etc. can give detailed information. However, this information often is not available. Streets are represented as linear structures, often enriched with information on number of lanes, speed limits, street names or width. There are proposals for areal modelling of streets. OSM data is often used for map making and sometimes for navigation applications. While an OpenStreetMap Linear Referencing (OSMLR) concept was developed for providing linear referencing to OSM road data, this concept is not used by default. OpenStreetMap data is user generated open data, thus accuracy and availability can vary heavily depending on the location (Helbich et al., 2012).
While OSM so far only supports linear representations of roads, there are some projects[6,7] discussing possibilities to create or derive areal representations from OSM data (Strassenburg Kleciak, 2016).

3.3.2 INSPIRE

The 'Infrastructure for Spatial Information in the European Community' (INSPIRE) is a European initiative aiming for interoperability of spatial data and services from different sources across the European Community. Regarding transportation, the INSPIRE Data Specification on Transportation

[6] https://github.com/SupaplexOSM/strassenraumkarte-neukoelln
[7] https://github.com/jakecoppinger/osm2streets-vector-tileserver/

Networks is a technical guideline that intends to establish a framework for an integrated transport network and related features that are seamless across international borders (INSPIRE Thematic Working Group Transport Networks, 2014). The INSPIRE Generic Conceptual Model (GCM) relies on the ISO 19100 series of geographic information standards. This includes a network connection mechanism to establish cross border connectivity and intermodal connections, object referencing to avoid redundant representations and a linear referencing system. Spatial object types are defined within a feature catalogue and attributes are enumerated in code lists. Modelling concepts are described with UML diagrams. The data specification covers all major transport network types including road, rail, water, air transport and cableways. Elements in the network are handled as nodes, links, aggregated links, areas and points and can have temporal validity. Three types of geometry are included: (topographic) area objects, centerline objects and point objects. Centerlines and areas offer alternative representations of identical real-world objects, while points are (apart from network nodes) only included for marker posts. Where both exist, centerline and area representations need to be consistent at any level of detail. Connected linear elements (Transport Links) with optional nodes (Transport Nodes) at the end of lines build the geometric basis of transport networks. Nodes are only represented if an intersection between Links exists in the real world. Transportation Link sequences can be further combined to form Transportation Link Sets with no geometry of their own. It is recommended that transportation network information is positionally, logically and semantically consistent with spatial objects from other themes and across state borders. Topology is not handled explicitly within the data specification. However, it is stated, that the data provided must be suitable for the reconstruction of the topological relationships. INSPIRE also addresses linking mechanisms for multi- and intermodal connections of transportation networks such as road and railway.

3.3.3 AFIS-ALKIS-ATKIS (AAA) / GeoInfoDok

ALKIS-ATKIS-AFIS is the conceptual application schema for spatial geoinformation in Germany described in the 'Documentation for Modelling Geoinformation of Official Surveying and Mapping' (GeoInfoDok) (AdV, 2022). Version 7.1 of the specification document GeoInfoDok is valid since 23.12.2023. The specification has a modular structure and is divided into several parts including an AFIS-ALKIS-ATKIS application schema as central data model, external data models with reference to the AAA application schema, e.g. on land cover and land use and modules with a descriptive character (metamodels). A so called *Normbasierte Austauschschnittstelle* (NAS / standards-based exchange interface) defined using XML-schemata and GML is used to exchange the data. A significant extension of version 7.1 of GeoInfoDok compared to previous versions are the application schemas for land use (LN - Landnutzung) and land cover (LB - Landbedeckung). These are separate application schemas outside the AAA application schema. Roads are modelled with different types of representation. A linear representation of road centerlines (and in some cases also carriageway centerlines) are available with a positional accuracy of approx. 1-5 meters. Additionally, areal based representations of land covers (called *Tatsächliche Nutzung*), describes areas used for traffic and transportation. However, this data typically does not contain information on individual carriageways or lanes. The mentioned administrative data is available in 2D, regularly updated and quality assured.

3.3.4 City Geography Markup Language (CityGML) version 2.0

The international OGC standard City Geography Markup Language (CityGML) is an open data model and data format to represent, store and exchange semantic 3D city and landscape models. It defines classes and relations for many different thematic city objects with respect to their spatial, semantic, and visual properties (Kolbe, 2009). Version 2.0 of CityGML was published in 2012 and defines a conceptual data model as well as a corresponding data format (Gröger et al., 2012). It is an application schema of the Geography Markup Language version 3.1.1 (GML3), which is an extensible international standard for the exchange of spatial data published by the Open Geospatial Consortium (OGC) and the ISO TC211. The specification defines classes and relations for relevant topographic objects in city and landscape models with reference to their geometric, topological and semantic properties as well as their appearance. Concepts of CityGML 2.0 are presented in the standard document using Unified Modeling Language (UML) diagrams. For better readability, classes belonging to an UML package that are discussed in a certain section are colored yellow, classes belonging to a different CityGML UML package are colored blue and classes defined in GML3 are colored green. A detailed evaluation of deficits of the CityGML 2.0 Transportation Module with respect to the requirements determined in chapter 2.5.1 is given in chapter 5.1.

CityGML 2.0 Modules
The CityGML standard employs a modularization approach with a core module that comprises basic concepts and components of the model as well as thematic extension modules representing specific aspects such as buildings, vegetation, transportation and other thematic parts illustrated in figure 3.8.

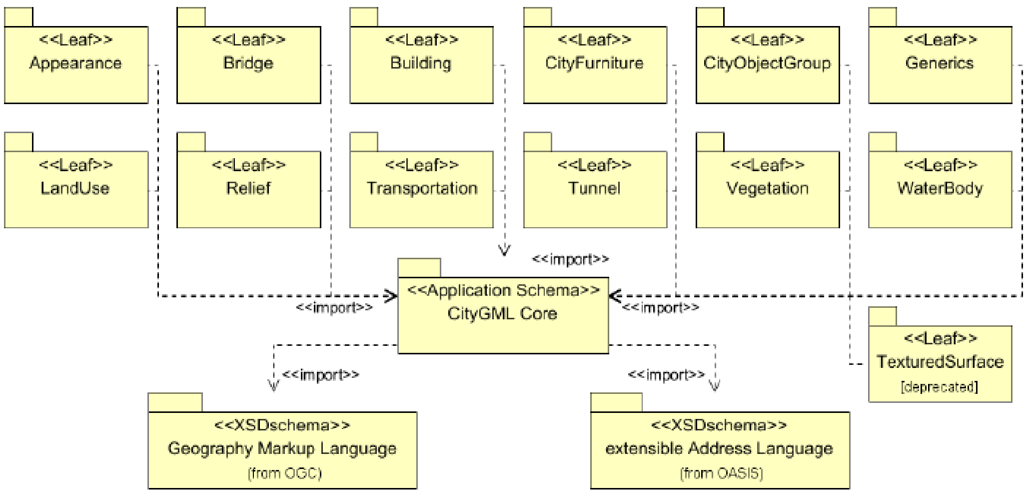


Figure 3.8: Overview of CityGML 2.0 modules (from Gröger et al. (2012)).

Since the Core module comprises fundamental concepts and components of the CityGML conceptual model, it must be implemented by any CityGML complaint data structure. Based on this core module, thirteen extension modules are defined in CityGML 2.0 each comprising logically related sub-parts of a semantic city model. For completeness, the class *TexturedSurface* is also illustrated.

However, this approach of appearance modelling of previous versions of CityGML has been deprecated. When implementing the CityGML data model, any combination of thematic extension modules in conjunction with the required Core module is allowed depending on desired use case or application. This is called a CityGML profile. The Core module and the Transportation module, which are the most importation modules for this thesis, are described and explained in more detail in the following sections.

CityGML 2.0 geometric and topological concepts
CityGML 2.0 uses a subset of the GML3 geometry package, which is based on the ISO 19107 ’Spatial Schema’ standard (ISO 19107, 2019) and expresses 3D geometry through Boundary Representation (B-Rep). The GML3 geometry model comprises primitives that can be assembled into complexes, composite geometries or aggregates. Each geometry can have its own coordinate reference system and each dimension corresponds to a specific geometrical primitive such as zero-dimensional points, one-dimensional curves (restricted to a straight line (*LineString*) in CityGML 2.0), two-dimensional surfaces (represented by planar polygons in CityGML 2.0) bounded by curves and three-dimensional solids bounded by surfaces. These geometrical primitives can be combined to aggregates (e.g. *MultiCurve, MultiSurface or MultiSolid*), complexes (e.g. *GeometryComplex*) or composites (e.g.*CompositeCurve, CompositeSurface* or CompositeSolid). Unlike aggregates, a complex has a clear topological structure. Its parts must not overlap, must be separate and can touch only at their boundaries or shared parts of their boundaries. A composite is a unique complex that exclusively includes elements of the same dimension and its components need to be separate, yet they should be topologically connected along their boundaries. Surfaces can be represented with an *OrientableSurface*, which have an explicit orientation (e.g. front, back or tow sides) defined using the normal vector of a surface in relation to the order of surface coordinates. This es especially relevant when assigning textures to surfaces or in order to distinguish between indoor and outdoor surfaces. *TriangulatedSurfaces* with a subclass TIN are used to represent surfaces using a composition of explicit triangles.
Additionally, the concept of implicit geometries is defined in the CityGML Core module and may be used for representing city objects in different thematic modules much as Vegetation of CityFurniture. An implicit geometry is a geometric object represented by a prototypical shape stored only once. This prototypical geometry (e.g. a 3D model of a traffic sign) can be reused or referenced multiple times across a 3D city model dataset whenever the corresponding feature appears. Each occurrence is linked to the prototypical shape geometry through a reference in a local cartesian coordinate system. This link involves a transformation matrix applied to every 3D coordinate of a prototype and it includes an anchor point designating the object’s base point in the world coordinate reference system. Implicit geometries offer the advantage to describe complex shapes in a more concise and adaptable manner and thus provide space efficiency.
Almost all geometries in CityGML use three-dimensional coordinates, where individual points as well as those defining the boundaries of surfaces and solids are represented by three coordinate values each (x, y, z). Coordinates are typically provided within a coordinate reference system (CRS). Unlike CAD or BIM, CityGML ensures absolute georeferencing. This feature makes CityGML particularly well-suited for representing geographically large extended structures such as roads, where the Earth’s

curvature cannot be neglected. According to ISO 19111, numerous 3D CRS can be used. This includes global as well as national reference systems, which can utilize geocentric, geodetic or projected coordinate systems.

In CityGML it is possible to explicitly model topology. For example, the shared use of a geometry by several objects or other geometries can be implemented. The spatial object is only explicitly represented by one geometry object and merely referenced by all other objects or more complex geometries to which it also belongs. This approach avoids redundant geometries while maintaining topological relationships. Differences are made here between three cases. First, two objects are spatially represented by the same geometry. Second, geometry may be shared between a feature and another geometry. And third, two geometries can refer to the same geometry. To implement such topological relationships, the GML encoding of CityGML uses the so-called XLink concept. Each geometric object that is part of several geometric aggregates or thematic objects receives a unique ID. This can then be referenced by GML geometries using the *href* attribute. The XLink topology has the advantage of being simple and flexible, but also has the disadvantage that navigation between topologically linked objects can only be carried out in one direction.

CityGML 2.0 spatio-semantic coherence

A fundamental concept of CityGML is spatio-semantic coherence of city objects. In addition to the geometry model, CityGML provides a semantic model which consists of class definitions. Semantic classes are derived from a basic class called 'Feature', which is defined for the representation of spatial objects and their aggregates according to ISO 19109 and GML3 (Stadler and Kolbe, 2007). Additionally, spatial and non-spatial attributes can be available for each object. A number of attributes is standardized in the specification by giving codelists containing coded attribute values for attributes such as class, function or usage in order to improve interoperability. This results in corresponding spatial and semantic hierarchies as illustrated for the example of buildings in figure 3.9.

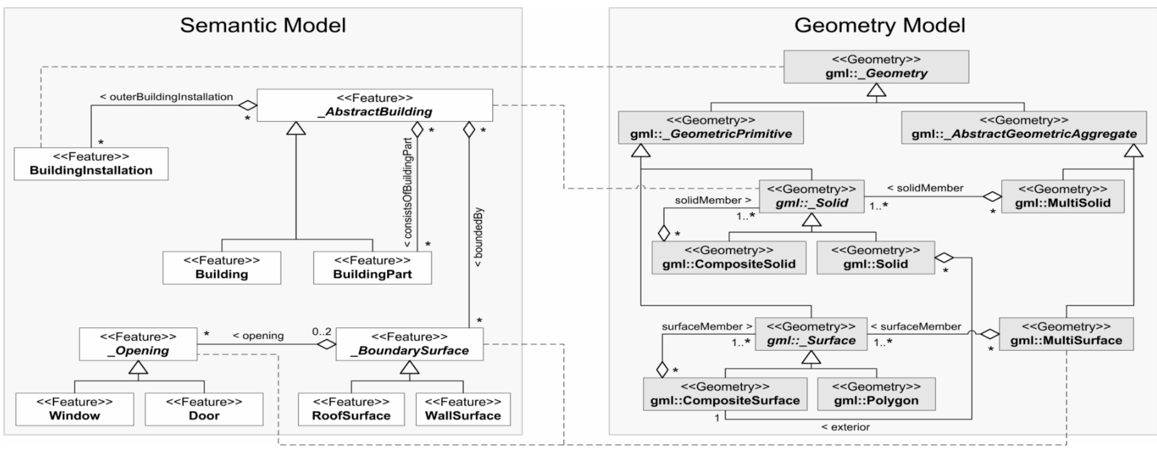


Figure 3.9: Spatio-semantic coherence of CityGML illustrated with CityGML's semantic and geometry model of a Building as presented in Stadler and Kolbe (2007).

Coherence in this geospatial context is defined by Stadler and Kolbe (2007) as "consistent relationships of spatial and semantic entities". In the given example, an *_AbstractBuilding* object is represented using a solid geometry. The *_AbstractBuilding* is semantically decomposed into individual *_BoundarySurfaces* (e.g. *RoofSurfaces* or *WallSurfaces*), which are related to the building object. In turn, *RoofSurfaces* or *WallSurfaces* are geometrically represented by corresponding *MultiSurface* geometries.

CityGML 2.0 Level of Detail (LOD) concept

All city objects can be represented in five consecutive LoDs as defined in the standard and displayed in figure 3.10. The lowest level of detail, Level of Detail (LOD) 0, essentially consists of a 2.5-dimensional digital terrain model on which an aerial photograph or a map can be superimposed and buildings can be modelled using their footprint. In the next highest LOD 1, buildings are represented by simple block objects. Starting from LOD 2, generalized roof structures can be represented. LOD 3 is characterized by architectural models with detailed roofs and walls including dormers, doors or windows. Finally, LOD 4 allows modelling the interior of buildings. Concepts to further refine these definitions are presented and discussed in Löwner et al. (2016) and Biljecki (2017). Since this LOD concept was originally mainly developed in the context of Building models, some of these definitions are difficult to apply to other thematic modules (especially the Transportation module as discussed in section 5.1).

LOD0 LOD1 LOD2 LOD3 LOD4

Figure 3.10: Five Levels of Detail (LOD) in CityGML 2.0 as specified in Gröger et al. (2012).

3.3.4.1 The CityGML 2.0 Core Module

The CityGML 2.0 Core module (shown as a UML diagram in figure 3.11) comprises the basic concepts and the fundamental components of the CityGML data model. It provides abstract basic classes from which further thematic modules can be derived. The base class within the CityGML data model is the abstract class *_CityObject*, which is a subclass of the GML class *_Feature* and thus inherits the metadata property (e.g. to express information on data quality or local CRS). A *_CityObject* contains attributes for defining creation and termination dates as well as an option for specifying external references. In addition, information about the exact location of an object relative to the terrain or water surface can be provided. Additional components such as address information or defining implicit geometries is also embedded into the Core module.

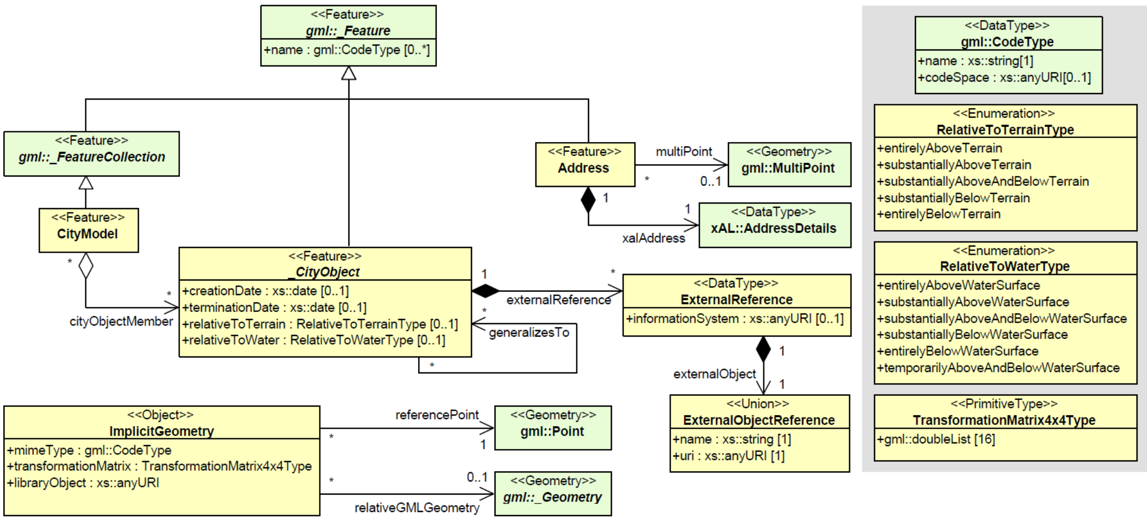


Figure 3.11: UML diagram of the CityGML2.0 Core Module (Gröger et al., 2012).

3.3.4.2 The CityGML 2.0 Transportation Module

The most relevant thematic module in the context of representing streetspace is the Transportation module. The UML diagram of the CityGML 2.0 Transportation module is shown in figure 3.12. It consists of the main class *TransportationComplex* and can be thematically specialized into 4 subclasses called *Road, Track, Square* and *Railway*. The class *Road* contains all objects that can be assigned to a road, including driving areas, adjacent sidewalks, curbs or lane markings. The class *Track* primarily describes narrower paths mainly used by pedestrians such as footpaths in parks. Railroad tracks are represented by the class *Railway*, while the class *Square* is used to describe public plazas or large sealed areas. Each *TransportationComplex* can contain *class, function* or *usage* attributes defined using codelists enumerating possible attribute values.

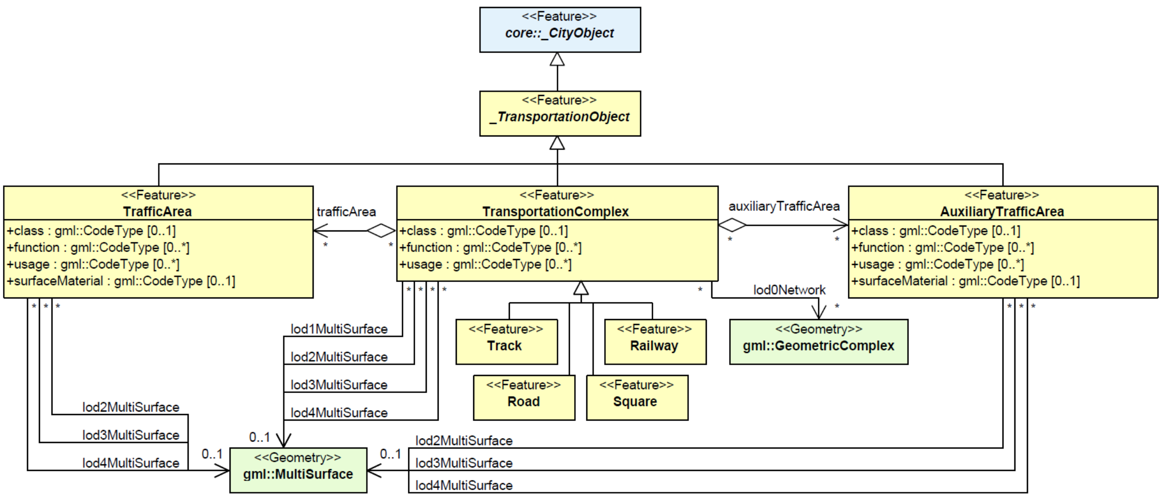


Figure 3.12: UML diagram of the CityGML2.0 Transportation Module (Gröger et al., 2012).

Transportation top-level features are represented as linear networks in LOD 0 using *GeometricComplex* geometries. Starting from LOD 1 transportation objects are spatially represented by *MultiSurfaces* geometries describing their entire width using 3D surfaces. LOD 2-4 representations allow a further semantic decomposition of *TransportationComplex* objects into *TrafficAreas* intended for traffic usage (e.g. driving lanes or bicycle lanes) and objects not intended to be used by traffic members such as vehicles or pedestrians called *AuxiliaryTrafficAreas* (e.g. medians, curbstones or grass areas). In addition to *class, function* and *usage* attributes, a *surfaceMaterial* attribute can be specified. The CityGML 2.0 specification contains the illustration displayed in figure 3.13. However, no further explanations on detailed concepts for modelling transportation infrastructure are given. Deficits and unclear specifications of the CityGML 2.0 Transportation module are discussed in section 5.1.

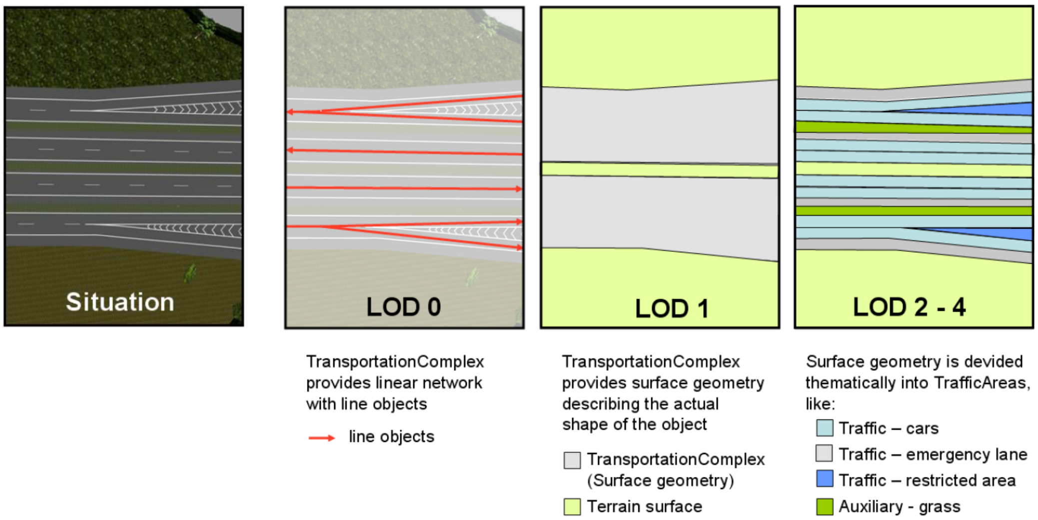


Figure 3.13: Concepts of the CityGML2.0 Transportation Module (Gröger et al., 2012).

CityGML 2.0 extension mechanisms

CityGML 2.0 provides two main approaches for modelling information not originally specified within the specification as well as the possibility to define additional attribute codelists.

- **Generic objects and attributes:** While CityGML provides some standardized attributes such as function, usage or surface material, it is possible to create and use generic attributes. Depending on intended use case this can include attribute such as pavement rating, maximum speed, number of lanes, etc. Similarly, objects not covered by thematic modules provided in the standard, can be included by defining generic objects. Concepts for specifying generic objects and attributes are defined within a thematic extension module called *Generics*. This s a quick and easy method for defining additional objects and attributes without requiring extensions to the CityGML data model.

- **Application Domain Extensions (ADEs):** CityGML also provides a built-in extension mechanism called Application Domain Extensions (ADEs). This is a formal method for specifying extensions to the CityGML conceptual model. In contrast to generic objects and attributes, ADEs must be defined in an extra conceptual schema (using UML diagrams) with its own namespace. Biljecki et al. (2018) present a number of existing CityGML ADEs such as the UtilityNetwork ADE Kutzner et al. (2018). Tamminga et al. (2013) present a proposal for an ADE to CityGML 2.0 for traffic and transportation use cases, however this ADE is not widely used.

- **Defining additional codelists:** As mentioned before, the CityGML 2.0 specification contains codelists defining attribute values for standardized attributes such as class, function, usage, surfaceMaterial, etc. Allowed values for these codelists can be extended by required information.

CityGML 2.0 Appearances
In addition to semantic, geometric and topological information, CityGML features can have Appearances, which are defined in a corresponding module. The CityGML Appearance module offers the representation of surface data by presenting observable properties for surface geometry objects through textures and materials. These appearances can extend beyond visual data (e.g. photo-realistic textures) and include diverse themes such as solar irradiation, noise pollution or other themes. Each Level of Detail (LOD) can possess a distinct appearance tailored to a specific theme. For road surfaces this may be corresponding colors, synthetic textures (e.g. asphalt) or aerial images (e.g. a high resolution digital orthophoto of actual road surfaces).

3.4 Other Standards and Data Formats

While the most important standards, conceptual models and data formats have been explained in more detail in the previous sub-chapters, there are some other specifications related to the topic of road and streetspace modelling, which are mentioned in this section. Due to their limited spatial validity or application specific use, they are not evaluated in more detail. The presented list of standards and data formats does not claim to be exhaustive but aims to include most specifications relevant for this thesis.

- **CommonRoad:** Composable benchmarks for motion planning on roads (CommonRoad) is a project focused on providing a standardized framework for evaluating and benchmarking motion planning algorithms for autonomous vehicles (Althoff et al., 2017). Lanelets are used for road network representations and combined with information on static and dynamic obstacles, potential goal regions of vehicles (planning problem) and other relevant information[8].
- **OpenSCENARIO:** The current version 1.2.0 of OpenSCENARIO is issued by the Association for Standardization of Automation and Measuring Systems (ASAM) and mainly used in the context of automated driving for the description and exchange of dynamic driving scenarios.
- **OpenMATERIAL:** OpenMATERIAL is a proposed standard by the Association for Standardization of Automation and Measuring Systems (ASAM) focusing on a standardized description of material properties in the context of automotive and mobility simulations (e.g. to describe surface properties relevant for sensor simulations).

[8]https://commonroad.in.tum.de/

- **Navigation Data Standard (NDS):** NDS is a standard for automotive navigation databases maintained by the Navigation Data Standard (NDS) e.V. group. Members of this group include several car manufacturers, data providers and manufacturers of navigation systems. NDS uses the database format SQLite and contains several layers and building blocks (Behrens et al., 2015).
- **Bundesinformationssystem Straße (BISStra)**: BISStra is a central system in Germany that provides comprehensive information on the federal highway and road network. It is operated by the Federal Ministry of Digital and Transport (BMDV) and is used for the administration and planning of federal highways and federal roads. This includes information on road surface conditions.
- **Graphenintegrations-Plattform Österreichs (GIP Austria)**: GIP is an initiative for the standardization and integration of geographic data in Austria and contains information on road and transportation networks in the form of nodes and edge representations with additional semantic information such as number of lanes (Kollarits, 2011).
- **swissTLM3D:** The topographic landscape model of Switzerland *swissTLM3D*[9] contains information on roads in 3D. The data is provided as ESRI File Geodatabases and provides linear representations of roads including attributive information on road type, width or name. Some traffic related areas such as parking lots are provided with areal geometries.

3.5 Evaluation of relevant Standards and Data Models for the determined Requirements

After presenting and discussing relevant standards, conceptual models and data formats in the previous sub-chapter, these specifications need to be evaluated with respect to their capabilities of providing information required by use cases and functionalities presented in chapter 2. This is done for the previously defined geometric, semantic, topological, temporal and visual requirement categories. As explained the previous chapter, functionalities require certain information in order to be used in the context of several use cases. This information is typically provided by data stored according to these commonly used standards and data formats. The evaluation of CityGML version 2.0 furthermore provides the foundation for identifying its limitations when it comes to representing roads and the streetspace in the context of semantic 3D city models, which is evaluated in more detail in chapter 5.1. There are some related publications, focusing on selected examples of the listed standards and data formats. Gilbert et al. (2020), for example, examine and compare LandInfra, IFC and CityGML, focusing on disparities in concepts, semantics, used coordinate reference systems or employed geometries and address challenges associated with these differences. Weise et al. (2018) present a combined usage of OKSTRA and IFC in a BIM related context of modelling road infrastructure. Krausz et al. (2022) compare standards related to driving simulations and navigation including OpenDRIVE and GDF. Concepts for representing and validating information on roads according to OpenDRIVE are given in Schwab and Kolbe (2022). Kumar et al. (2019) provide an explanation of the LandInfra standard and discuss its relation to CityGML and IFC. Results of these studies are considered in the evaluations presented in this chapter. Results of this evaluation are summarized in

[9] https://www.swisstopo.admin.ch/en/landscape-model-swisstlm3d

table 3.2. The additional table 3.3 further investigates capabilities of these standards and data formats for modelling multiple transportation infrastructure as well as multiple transportation modalities within a combined representation.

With the exception of OSM data, which provides 2D information and INSPIRE specifications, which require 2,5 dimensional data, all other standards and data formats allow (true) three-dimensional representations of roads and the streetspace. While roads can be represented with straight line geometries in each case, standards focusing on road construction (e.g. IFC or LandInfra) or traffic and transportation related use cases (e.g. OpenDRIVE) additionally allow more complex linear geometric representations such as clothoids or splines. Standards and corresponding conceptual models for modelling roads such as OpenDRIVE or Geographic Data Files (GDF) focus on a linear or parametric geometric representation of transportation networks and are mostly designed to support navigational or traffic simulation related applications but are not so much tailored for other fields of application such as asset management or environmental simulations and analyses. However, many functionalities and use cases require (or at least would benefit) from detailed models of the streetspace in multiple (but consistent) semantic and geometrically non-redundant representations using linear, areal, volumetric or point cloud geometries. While standards such as Industry Foundation Classes (IFC) in the Building Information Modeling (BIM) domain started to include concepts for modelling transportation infrastructure, these models are mostly indented to be used in a spatially limited area and not on a city- or nation-wide scale and are often not georeferenced (Jaud et al., 2019).

Semantic attributes such as information on surface material or function types are available for all evaluated standards and data formats. Most specifications do not support all three levels of semantic granularity. For example, while lane level representations are available in OpenDRIVE, aggregated representations of the entire width of a road, without individual lanes is not supported. Further limitations of OpenDRIVE are discussed in chapter 6.1.1. A more generalized representation may be sufficient for some functionalities needed to implement a certain use case and thus reduce the amount of required data complexity. Since not only roads but also other components of a city, such as tunnels, bridges, street furniture or vegetation are relevant, it is evaluated if certain standards and data formats explicitly support modelling these kinds of objects.

Regarding road topology, a linear referencing system is used by many standards and data formats, with CityGML as one notable exception. Predecessor and successor relations, required especially for routing and navigational functionalities, are mainly supported by standards and data formats used in the automotive, transportation and navigational domain such as GDF, OpenDRIVE or Lanelets.

With regard to visual capabilities, limitations of most standards and data formats concerning (photo) realistic visualizations become apparent. While some standards and data formats offer colored surfaces, Vissim allows the integration of textured 3D models. CityGML further contains a dedicated Appearance module specifying surface data such as colors, textures or material properties.

Table 3.2: Comparison of relevant standards, conceptual models and data formats for geometric, semantic, topological, temporal and visual capabilities. Adapted and extended from Beil et al. (2020).

	IFC 4.3.2.0	LandInfra 1.0	OKSTRA 2.021	GDF 5.0	GDF 5.1	OpenDRIVE 1.8	RoadXML 3.0	Lanelets	Vissim	GeoInfoDok 7.1	INSPIRE	OSM	CityGML 2.0
Road Geometry													
Dimension / Coord. space	3D	3D	3D	3D	3D	3D	3D	3D	3D	3D	2,5D	2D	3D
Straight lines / Linestrings	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Splines	✓	✓	✓	-	-	✓	✓	-	-	1)	-	-	-
Clothoids	✓	✓	✓	-	✓	✓	✓	-	-	-	-	-	-
Explicit areal rep.	✓	✓	2)	3)	✓	-	-	4)	✓	5)	✓	-	✓
Parametric areal rep.	✓	✓	✓	6)	6)	✓	✓	-	✓	-	✓	-	-
Lane borders only	-	-	-	-	-	-	-	✓	-	-	-	-	-
Volumetric traffic space	✓	-	-	-	-	-	-	-	-	-	-	-	-
Point clouds	-	-	7)	-	-	-	-	-	-	8)	-	-	-
Material layers	✓	✓	✓	-	-	-	-	-	-	-	-	-	-
Non-overlapping areal geom.	✓	✓	✓	-	✓	-	-	-	-	✓	✓	-	✓
Road Semantics													
Surface material	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Function / Type	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Granularity area	9)	10)	✓	11)	11)	-	-	-	-	✓	12)	-	✓
Granularity way	✓	✓	✓	✓	✓	-	-	-	✓	13)	✓	✓	14)
Granularity lane	✓	✓	✓	-	✓	✓	✓	✓	✓	15)	-	-	✓
Section / Intersection segm.	✓	16)	17)	✓	✓	✓	✓	-	✓	-	18)	-	-
Driving direction	-	-	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	-
Bridge model	✓	✓	✓	19)	19)	20)	-	-	-	✓	-	✓	✓
Tunnel model	✓	✓	✓	19)	19)	21)	-	-	-	✓	-	✓	✓
Road marking	✓	✓	✓	✓	✓	✓	✓	✓	✓	-	-	22)	✓
Street furniture	✓	-	✓	✓	✓	✓	✓	23)	24)	-	-	25)	✓
Vegetation objects	✓	✓	✓	✓	✓	✓	-	26)	27)	✓	✓	✓	✓
Road Topology													
Linear referencing	✓	✓	✓	✓	✓	✓	✓	-	✓	-	✓	-	-
Lane linkage: pred. / succ.	-	-	-	✓	✓	✓	✓	✓	✓	-	-	-	-
Temporal aspects													
Versioning concept	✓	28)	✓	-	-	-	-	-	-	✓	✓	-	-
Linking dynamic (sensor) data	29)	-	-	-	-	-	-	-	-	-	29)	-	29)
Appearance													
Colored surfaces	✓	-	-	30)	30)	-	-	-	-	-	31)	-	✓
Textured surfaces	32)	-	-	-	-	-	-	-	-	-	-	-	✓

Legend: fully supported: ✓, not supported: - , numbered cells are explained in more detail on the following page

Annotations to table 3.2

1. Geometry type GM_CubicSpline is available.
2. S_Flaechenmodell, Verkehrsflaeche, GM_MultiSurface are available objects / geometry types. However, linear representations are commonly used to describe road networks.
3. Only 'Enclosed TrafficAreas' with undirected traffic can be modelled with areal representations.
4. Lanelets represent the borders of lanes. 'Areas' can be used to represent undirected traffic.
5. Areal geometric representations for 'Tatsächliche Nutzung: Verkehrsfläche' are available representing entire transportation areas (no distinction between individual carriageways or lanes).
6. Linear Referencing Features are available for the parametric description of position of objects.
7. Feature type 'Punktwolke' available. The actual point cloud data must be specified in the form of an external dataset that refers to an external file in the LAS format.
8. Representation of objects with point clouds using the feature type 'AU_Punkthaufenobjekt'.
9. Not explicitly specified, however 'RoadElements' can be grouped together to 'RoadElementSets' to represent the entire width of roads.
10. Not explicitly specified, however it is possible to represent the entire width of roads.
11. Roads can be segmented in RoadElements in Level 1, which can be seen as one Road in Level 2.
12. 'RoadAreas' can be used to model entire roads or carriageways.
13. 'AX_Fahrbahnachse' (as compared to 'AX_Strassenachse').
14. Granularities are not explicitly specified, however LOD 0 can be interpreted as granularity=area, LOD 1 as granularity=way and LOD 2-4 as granularity = lane.
15. 'AX_Fahrwegachse' is available (as compared to 'AX_Fahrbahnachse' and 'AX_Strassenachse').
16. Roads consist of RoadElements that can be grouped together to RoadElementSets.
17. Roads can be segmented into sections (Abschnitte / Äste) and Nodes.
18. RoadLinks and RoadNodes can be distinguished.
19. Bridges and tunnels can be represented in a generic way as 'Structures'.
20. It can be indicated if roads are on a bridge. Actual 3D bridge models are not standardized.
21. It can be indicated if roads are within a tunnel. Actual 3D tunnel models are not standardized.
22. Key: 'road_marking' for highways is available.
23. Regulatory elements such as traffic lights can be included.
24. Static 3D models (e.g. COLLADA) can be included but have no influence on the simulation.
25. Street furniture objects such as 'traffic_signals' can be represented with point geometries. 'Traffic_signs' can be modelled with point geometries or as part of a way.
26. Areas of 'subtype' vegetation can be specified.
27. Static 3D models (e.g. COLLADA) can be included but have no influence on the simulation.
28. A number indicating the version of a dataset can be given (datasetVersion) in the header.
29. Limited capabilities of IFC v4, INSPIRE and CityGML v2.0 for covering time-dependent properties are discussed in Chaturvedi (2021).
30. Colour parameters are available (e.g. divider colour).
31. Styles supported by INSPIRE view services are described (e.g. geometry colors).
32. 'IfcSurfaceTexture' is available to provide 2-dimensional image-based texture maps.

Table 3.3 summarizes which transportation types (and combinations of multiple transportation modes) can be represented using a specific standard or data format. While some standards only allow functional representations, others provide possibilities for combined functional and topographical representations. Graph-based functional integration can be achieved in different degrees of complexity. Basic functional integration of multiple transportation types (allowing simple routing applications) is provided by most standards (*). Standards intended for transportation related purposes such as GDF or OpenDRIVE additionally provide a predecessor / successor concept and include detailed specifications on aspects such as speed limits, turning restrictions or traffic control, while also integrating traffic signs and traffic lights (**). Additionally, multimodal topological connections are necessary for route planning or navigational purposes, where switching between different transportation types is considered.
Cells contain a checkmark if transportation types are available either as classes or with attributes further describing a more general class. For example: Tramways are not modelled as a specific class in CityGML 2.0 but can be represented using a *Railway* object with a function attribute value 'Tram'. Subways can be represented using a combination of CityGML *Railway* and *Tunnel* modules. A dash indicates that there is no explicit concept in the standard to represent these transportation types.
Numbered cells are explained in more detail below. For example: CityGML 2.0 does provide function attributes for *TransportationComplexes* called 'Ferry' or 'Waterway', however an explicit class for 'Waterways' is not available. Additionally, table 3.3 indicates if relations between multiple transportation types such as level crossings of road and rail objects, pedestrian crossings or tramways using part of road surfaces can be represented with the respective standard. Objects typically used for multimodal connections of different transportation types such as railway stations, bus stands or subway entrances are also listed.
In summary, most standards presented are able to represent multiple transportation types. Different transportation types are often taken into account by using multiple attribute values indicating an intended function of specific parts of a transportation network. INSPIRE also uses specific classes to model transportation relations such as pedestrian or level crossings. Modelling multimodal connections for representing switches between transportation modes is available for a limited number of standards. While most standards use a linear representation for modelling transportation infrastructure, multimodal topological connections between these networks are not always possible.

Table 3.3: Support of various transportation modes and their combinations in relevant standards, conceptual models and data formats. Adapted and extended from (Beil and Kolbe, 2020).

	IFC 4.3.2.0	**LandInfra 1.0**	**OKSTRA 2.021**	**GDF5.0**	**GDF 5.1**	**OpenDRIVE 1.8**	**RoadXML 3.0**	**Lanelets**	**Vissim**	**GeoInfoDok 7.1**	**INSPIRE**	**OSM**	**CityGML 2.0**
Modelling information													
Non-redun. topogr. integration	✓	-	✓	-	✓	-	-	-	-	✓	✓	-	✓
Multimodal topol. connections	✓	-	-	✓	✓	✓	-	1)	✓	-	✓	-	-
Degree of func. integration	*	*	*	**	**	**	**	**	**	*	*	*	*
Transportation modes													
Road	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Railway	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Sidewalk / Footpath	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Cycle path / Bikeway	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Tramway	✓	-	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Busway	✓	-	✓	✓	✓	✓	✓	✓	✓	-	✓	✓	✓
Waterway / Shipping routes	✓	-	✓	✓	✓	-	-	-	-	✓	✓	✓	2)
Aeroway (e.g. Airports)	✓	-	✓	✓	✓	-	-	-	-	✓	✓	✓	✓
Air spaces	-	-	-	-	-	-	-	-	-	-	-	-	-
Cableway / Lift	-	-	-	-	✓	-	-	-	-	✓	✓	✓	3)
Subway	✓	-	-	4)	4)	-	-	-	✓	5)	-	6)	✓
Transportation relations													
Level crossing	✓	-	✓	✓	✓	-	-	-	-	-	✓	7)	✓
Pedestrian crossing	✓	-	✓	✓	✓	✓	-	✓	✓	-	✓	8)	✓
Shared road / tramway	✓	-	-	9)	9)	10)	-	-	-	-	-	-	11)
Multimodal connections													
Railway station / platform	12)	-	13)	✓	✓	✓	-	-	✓	✓	✓	✓	✓
Bus station	14)	-	✓	✓	✓	✓	-	-	✓	✓	✓	✓	✓
Tram station	15)	-	✓	✓	✓	✓	-	-	✓	-	-	✓	✓
Bike parking	-	-	✓	-	16)	✓	17)	-	-	-	-	✓	✓
Taxi stand	-	-	✓	✓	✓	-	17)	-	-	-	-	✓	✓
Subway entrance	-	-	-	-	18)	-	-	-	-	-	-	✓	✓

Legend: fully supported: ✓, not supported: - , numbered cells are explained in more detail on the following page, *: Basic functional integration of transportation types (allowing simple routing use cases), **: Detailed specifications on aspects such as an explicit predecessor / successor concept, speed limits, turning restrictions or traffic control, while also integrating traffic signs and traffic lights

Annotations to table 3.3

1. Routing graphs can be derived from lanelets and routing graphs from different participants (e.g. vehicles and pedestrians) can be connected to identify conflicting lanelets. However, one routing graph is only valid for one single participant.
2. Not explicitly modelled. However, *TrafficArea* usage attribute values *boat, ferry, ship* are defined in a codelist.
3. Not explicitly modelled. However, *TransportationComplex* attributes function and usage *Ski-lift* are defined in a codelist.
4. *Railway Type Name: Underground/Metro* available.
5. Bahnverkehrsanlage: U-Bahn / AX_Bahnkategorie_Bahnstrecke: U-Bahn available, however not modelled in 3D.
6. *Tag:railway=subway* available, however not modelled in 3D.
7. *Tag:railway=level_crossing* available for point geometries (nodes) but no areal representation of shared surfaces.
8. *Key:crossing* available for pedestrian crossings.
9. *JunctionType: fixedGuidewayVehicleCrossing* available, however unclear how to model shared surfaces of trams and roads outside of junctions.
10. Railroads can be modelled in addition to roads, however a non-redundant representation of tramways within a road is not possible.
11. Multiple function and usage attributes can be assigned to one *TrafficArea* indicating that some surfaces are used by cars and trams at the same time.
12. Railway stations can be modelled as buildings.
13. Object type *Haltestelle* (bus stop) available.
14. Bus stations can be modelled as buildings.
15. Tram stations can be modelled as buildings.
16. Parking areas can be represented as *EnclosedTrafficAreas*, however the type of parking area is not specified.
17. Parking type of *ParkingSpot* elements can be defined.
18. Object *Entrance to or Exit of Service* available.

Part II

Development of a revised and extended CityGML 3.0 Transportation Model

Chapter 4

Background on 3D City Modelling

4.1 3D City and Landscape Models

4.1.1 Classification of 3D models

In general, it is possible to distinguish 3D modelling approaches of the (urban) environment into Virtual Reality (VR) models primarily focusing on 3D visualizations and Urban Information Models (UIM), which represent real-world objects including thematic and semantic information (Kolbe and Donaubauer, 2021). Well-known examples of VR models include 3D representations available in GoogleEarth and similar applications. These models are usually constructed using textured 3D meshes, which provide visually appealing and geometrically detailed representations of landscapes, however contain limited (if any) semantically structured information. While these models are easily understandable by humans, automated computer-aided evaluations and analyses with these models are only possible to a very limited extent. In contrast, UIM provide rich thematic and semantically structured data as well as spatial information, which is useful for urban simulations and analysis. Kolbe and Donaubauer (2021) give an overview on different kinds of 3D (+ time) modelling approaches in various domains including computer graphics and gaming, planning and construction, urban simulation and geomatics as displayed in figure 4.1.

Each of these domains has its own specific requirements, use cases, and challenges, leading to different approaches to creating 3D city models (Kaden, 2014). In computer graphics (CG) and gaming, the focus is primarily on the graphical representation of objects, while semantic information is mostly neglected. Methods developed in this field aim to achieve effective and detailed 3D visualization of urban landscapes. Typically, these 3D views are VR models that depict the geometry and visual appearance of objects using so-called scene graphs. In the context of computer games, efficiency and real-time rendering are often priorities. Game developers may use techniques such as level of detail (LOD) modelling to optimize performance, especially when dealing with large and complex urban environments. Simplified models might be used at a distance and more detailed ones as the player gets closer. Software such as the UnrealEngine or Unity are powerful and widely-used game development engines that enable developers to create interactive and immersive 3D experiences. Additionally, the simulation of physical interactions and behaviors of objects within a game environment (object physics) can be incorporated using physics engines.

Urban simulation models frequently rely on dividing urban space into individual elements, which can be either regularly or irregularly structured. Given that all features within such representations share a

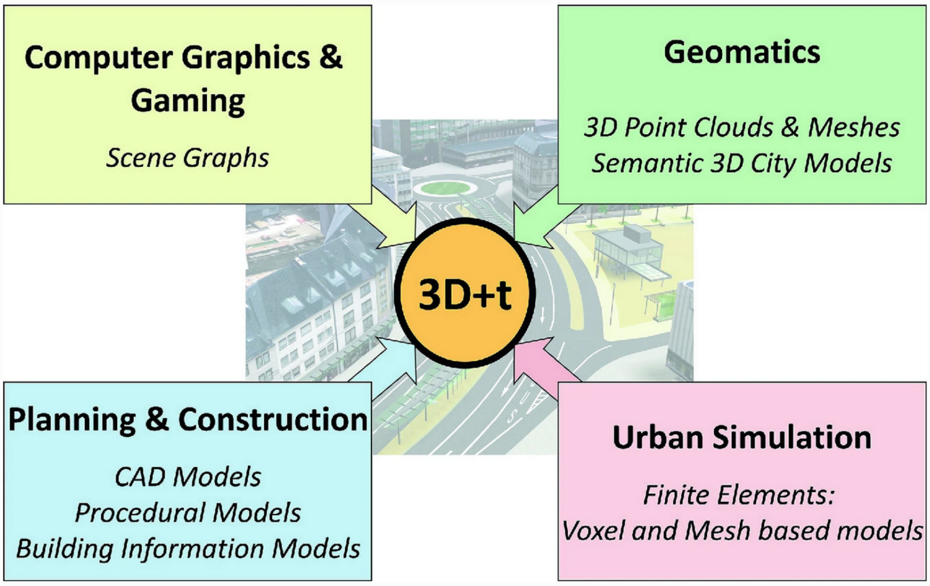


Figure 4.1: Different domains and their approaches to the definition, generation and usage of urban 3D/4D models as presented in Kolbe and Donaubauer (2021).

common modelling paradigm (such as voxels or mesh based models), simulation tools can handle them uniformly.

The focus of the Architecture and Engineering (AEC) domain is the modelling of human-created objects to support the planning and processes within a construction project. Two related concepts in this field are Computer-Aided Architectural Design (CAAD) and Building Information Modeling (BIM). While CAAD primarily focuses on using computer technology to assist architects and designers in the creation and analysis of architectural designs, BIM is a broader and more comprehensive approach that extends beyond the geometric representation of buildings and also contains rich information about the various components and their relationships. The Industry Foundation Classes (IFC) is an open data format for the exchange of Building Information Modeling (BIM) data. These models are often represented using local coordinate systems. The focus of these models so far very much laid on the representation of buildings and only recently began to include objects such as road or railway infrastructure. In this field the concept of Constructive Solid Geometry (CSG) is commonly used for constructing geometries. CSG represents objects through combinations of simple geometric primitives using Boolean operations such as union, intersection or difference. This is related to procedural modelling, where models of objects are constructed using a series of rules applied to a (simple) source geometry (Parish and Müller, 2001).

In the context of geomatics, 3D city and landscape models are representations of real-world objects with an emphasis on semantic and topological information in combination with (georeferenced) 3D geometries (Kolbe and Donaubauer, 2021). These objects are often derived from data gathering methods such as surveying (e.g. tachymetric recordings or laser scanning) or photogrammetry. Geometries are usually used to represent observable objects with Boundary Representation (B-rep) by describing feature boundaries using vertices, edges, and faces. The most commonly used standard in the field of semantic 3D city modelling is the international OGC standard CityGML, which is presented in more detail in section 4.3. In addition to the previously mentioned differences between the IFC and CityGML data formats, they are usually also applied on different scales. IFC models mostly focus on spatially limited projects such as individual buildings or infrastructure, while semantic 3D city models can provide information on entire cities or even countries.

Another aspect by which 3D representations can be differentiated is the degree of syntactic and semantic interoperability provided by respective data exchange formats. Figure 4.2 illustrates different kinds of common 3D representations and respective data formats. Since these representation types contain different advantages and disadvantages, many cities and regions create and maintain all (or at least many) of these models simultaneously. While three-dimensional point cloud data can be generated automatically for large areas and thus enable frequent data updates, semantic capabilities of point cloud formats are mostly limited to assigning points to a certain category (classification). Similarly, 3D meshes can be easily generated from point clouds but again usually do not contain structured semantic meaning. Thus, data formats such as LAS (commonly used for storing 3D point cloud data) or OBJ (commonly used to represent 3D meshes) for the most part merely provide syntactic interoperability. This means that the exchange of any data is possible without defining and guaranteeing its structure and interpretation. The same is true for data formats often used in GIS systems such as Shapefile, which increasingly also include 3D information. In contrast, exchange formats such as the CityGML XML encoding commonly used for semantic 3D city modelling are derived from conceptual data models and thus ensure syntactic as well as semantic interoperability.

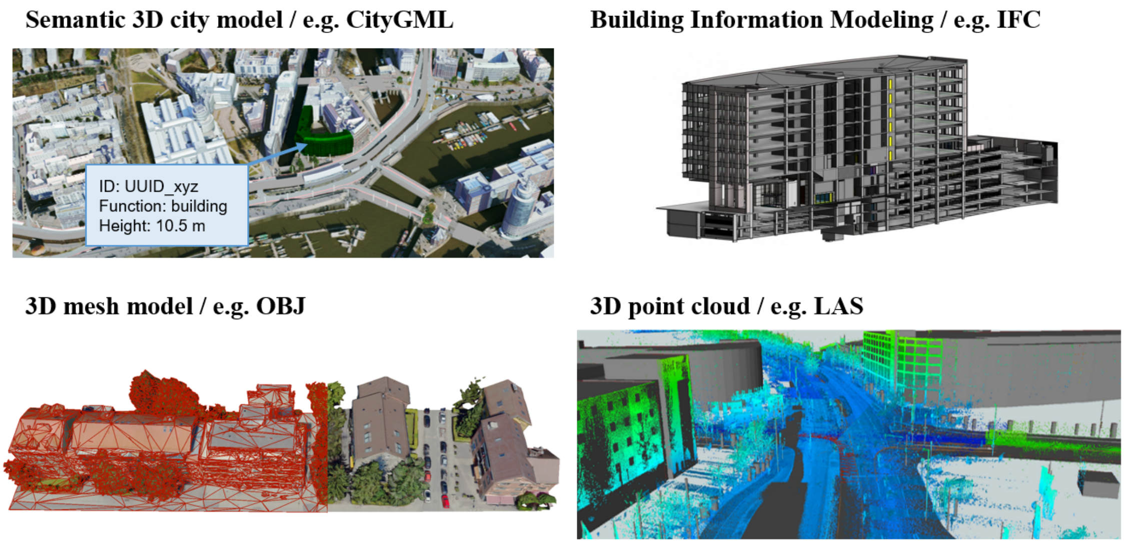


Figure 4.2: Different kinds of 3D representations of urban environments and commonly used data formats.

4.1.2 Semantic 3D City Models

Semantic 3D city and landscape models are commonly used for analyses and simulations on large (urban) areas by digitally representing objects of the urban environment. In addition to geometric accuracy and visual aspects, topological and semantic capabilities including hierarchical object structures, relations and attributive information are key advantages of these models in comparison to mere visualization models or (even classified) 3D point clouds. As mentioned before, the most commonly used standard for facilitating these properties of semantic 3D city models is the international OGC standard CityGML, which is presented and discussed in detail in section 4.3. Representations of cities according to this data format are available for a growing number of cities and countries including Germany, Japan, the Netherlands, Finland and many more[10]. While point clouds can be gathered relatively efficiently using airborne or terrestrial laser scanning (ALS/TLS) methods and thus often are the foundation from which semantic city models are reconstructed (Y. Xu and Stilla, 2021), they lack semantic capabilities required by many use cases. Digital terrain models (DTMs) representing solely the terrain and digital surface models (DSMs) additionally representing natural (e.g. vegetation) and man-made (e.g. buildings) features are two types of digital models of the environment (Kolbe and Donaubauer, 2021). However, the automatic segmentation and aggregation of semantically meaningful 3D objects from these data sources remains challenging. Biljecki (2017) lists a number of acquisition methods such as surveying, laser scanning or remote sensing for generating 3D city models from different data sources. Kolbe et al. (2009) give an overview on processing chains and workflows for generating semantic 3D city models.

Semantic 3D city models are used for a wide range of use cases in different application domains (Biljecki et al., 2015). Typically, most of these use cases require or at least benefit from the rich semantic information contained within these models. Kolbe and Donaubauer (2021) explain the descriptive modelling paradigm of semantic 3D city models, which is used to mostly represent existing physical real-world objects of the urban environment. Depending on the intended use cases, digital representations of different thematic parts of the environment may be required. Until recently, the focus of semantic 3D city models was very much of representations of buildings and their parts such as (generalized) roof or wall surfaces. Other constructions such as tunnels or bridges are also more often represented. Natural objects such as vegetation can be part of semantic 3D city models either as more abstract representations (e.g. an entire forest represented with a simple volumetric geometry) or down to individual trees and plants. Rivers, lakes or similar water bodies are also frequently included in semantic 3D city and landscape representations. While road and other transportation infrastructure makes up a large part of urban environments, detailed semantic representations of the streetspace including road and city furniture were not available on a larger scale until recently. However, as mentioned before, the increasing availability of source data (e.g. from mobile mapping campaigns) as well as emerging use cases and applications led to an increased relevance of semantic 3D streetspace models in recent years.

4.1.3 Semantic 3D Streetspace Models

While until recently models of buildings and the terrain have been the focus of most semantic 3D city models and corresponding use cases, there is an increasing number of examples for semantic models representing roads and the streetspace as part of semantic 3D city models. With the emergence of new fields of application such as digital urban twins or autonomous driving, detailed models

[10] https://github.com/OloOcki/awesome-citygml

of the streetspace as part of semantic city models recently have gained in significance. The term *semantic 3D streetspace model* implies several aspects, which are defined in this chapter. First, as presented in the previous section, semantic capabilities are required for a number of use cases and include a hierarchical decomposition of complex objects (such as entire road networks) into sub-parts (e.g. individual lanes) as well as corresponding attributive information (e.g. street names or speed limits). This distinguishes semantic streetspace models from purely visual representations of roads. Second, objects are represented using true 3D representations. The streetspace is interpreted not only as describing roads (and objects that are part of roads such as individual lanes or sidewalks) but quite literally as the space above a road surface were the actual traffic takes place including components such as traffic lights, traffic signs or vegetation, etc. as displayed in figure 4.3.

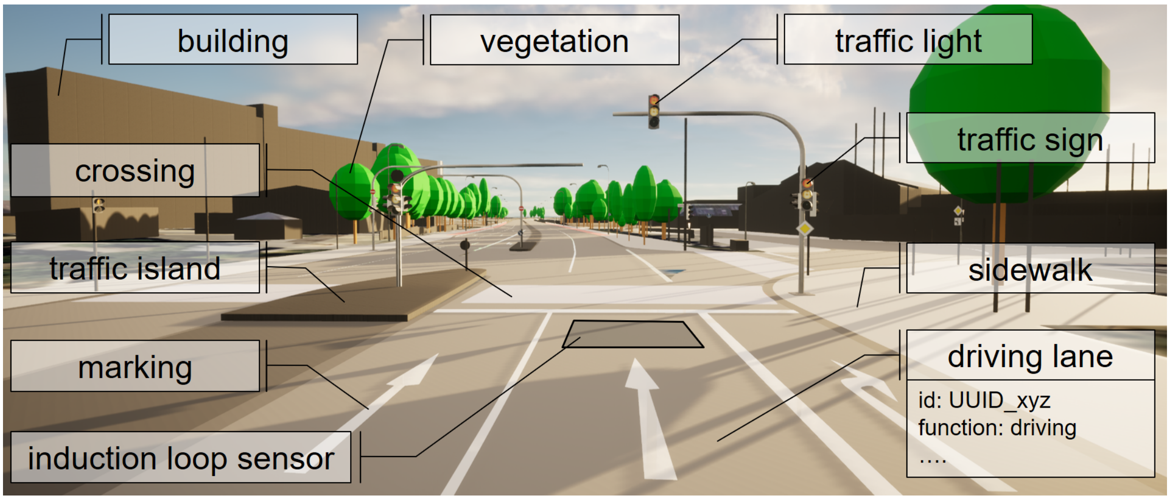


Figure 4.3: Components of semantic 3D streetspace models.

Concepts and modelling approaches presented earlier in a more general way, can also be applied and transferred to models and representations of roads and the streetspace. As illustrated in figure 4.4, there are different fundamental geometric modelling principles with varying semantic capabilities commonly used for representing transportation infrastructure such as roads. As previously explained, VR models mainly created for visual purposes usually have very limited (if any) semantic capabilities. The models can be automatically generated by creating meshes from 3D point clouds, thus creating geometrically detailed and visually appealing models. A procedural modelling approach for creating VR models is often used for models of buildings but can also be applied for road model creation. In this case, a basic road geometry such as its centerline is used for generating realistically looking road models by applying a rule-based generation of additional lanes. Semantic capabilities of these models however, are usually still very limited. This method also has its limitations when it comes to modelling geometric details such as irregular changing road widths (e.g. at a bus stop).
UIMs of roads can be categorized into three most common geometrical representation types, which are illustrated in figure 4.5. Centerline-based representations focus on the central axis of a road, carriageway or lane using linear geometries. This kind of representation is commonly used for navigation, routing or traffic simulation related use cases. Parametric representations define roads

using mathematical equations or parameters. Often parameters relative to a reference line specify the outline of roads by providing information on number of lanes, lane width or complex parametric descriptions on the actual areal shape of lanes and roads. For the application of these models for use cases such as quantity take-off measurements, urban simulations or realistic visualizations however, this kind of geometrical description of roads requires an interpretation and conversion into explicit coordinate-based geometries. This surface-based representation is commonly used in GIS environments to describe the actual areal shape of objects such as roads using the aforementioned boundary representation. Each type of representation has its own advantages, intended main use cases and level of data gathering complexity.

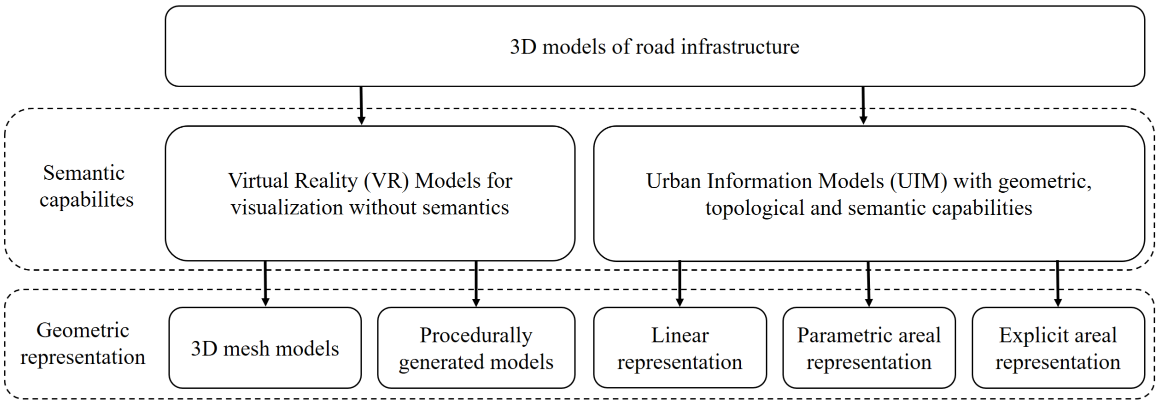


Figure 4.4: Classification of road and streetspace models according to semantic capabilities and geometric representation.

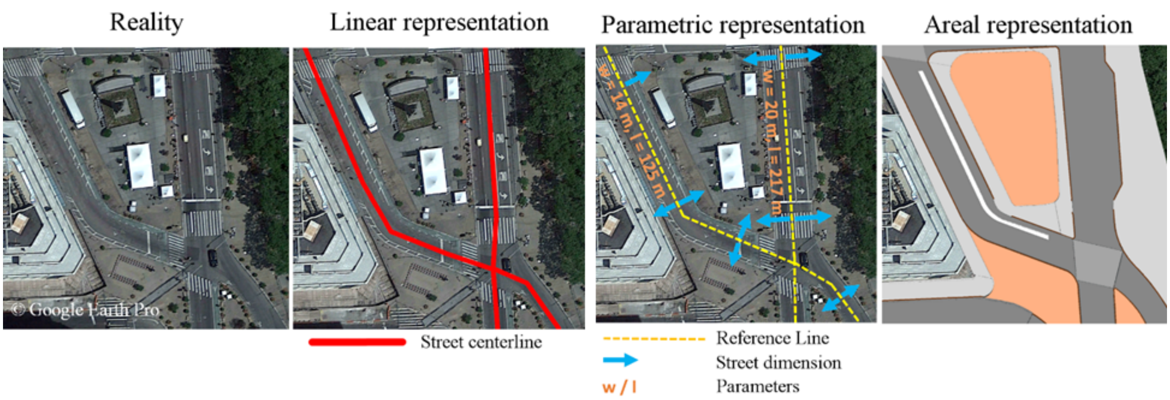


Figure 4.5: Comparison of different geometric modelling principles for the representation of roads (Beil and Kolbe, 2017).

The increasing relevance of the streetspace in the context of semantic 3D city models is also reflected by several recent publications in this field of research. Tamminga et al. (2013) present a proposal for a CityGML Application Domain Extension (ADE) in order to address transportation related shortcomings of the CityGML 2.0 Transportation module. Labetski et al. (2018) make additional suggestions such as explicitly modelling intersections and waterways. Boersma (2019) examines various use cases of digital road models, such as traffic modelling, maintenance and navigation, by analyzing their specific data requirements. Tamminga (2019) analyze modelling requirements focusing on traffic and transportation models. Soon and Khoo (2017) present a 3D city model of Singapore, which includes the representation of roads. Papers published in the context of this dissertation work such as Beil and Kolbe (2017) and Beil and Kolbe (2018) discuss weaknesses of the CityGML 2.0 Transportation module and propose revised and extended concepts for modelling the streetspace. Beil and Kolbe (2020) present methods for combined modelling of multiple transportation infrastructure within an integrated, consistent and standardized city model. Beil et al. (2020) discuss capabilities of a proposed CityGML 3.0 Transportation module with respect to specific requirement categories.

4.2 Relevant Standards for Information Representation

4.2.1 The Unified Modeling Language (UML)

The Unified Modeling Language (UML) is a standardized graphical language in the field of software engineering for the analysis, design and implementation of software based systems developed by the Object Management Group (OMG) (2017). It provides notation concepts for visual modelling and was adopted by ISO/IEC in 2005. The current version of the ISO 19501 standard (UML 2.4.1) was released in 2012 ISO (2012b). UML includes semantic concepts, notation and guidelines for static structures and dynamic behaviors as well as environmental and organizational parts (Booch et al., 2005). In the context of geospatial information, UML is often used for defining data models with static UML class diagrams by depicting classes, their attributes, methods, and the relationships among them. Figure 4.6 shows UML modelling concepts used in standards such as CityGML and thus relevant in the context of this thesis. Classes represent a blueprint for objects and are illustrated with rectangular boxes that contain a corresponding class name in the top part of a box as well as optional attributes below. Directed associations between classes are represented with thin lines with arrows at one end, which indicate that navigation from one object to another occurs in the arrow's direction. These associations can be further qualified using roles to describe the role that the object(s) of one class play for another class. Associations can be one-to-one, one-to-many or many-to-many and they may have cardinalities (actual number within a dataset) or multiplicities (allowed number) indicating the number of instances involved in the relationship. Aggregations express a 'part-of' association where one object (whole) consists of other objects (parts) and are represented using a white filled diamond symbol on the 'whole' side of the association. Related to this concept are strict aggregations called compositions, where the composite (whole) class owns the component (part) class. This means that the existence of the part is dependent on the existence of the whole, which is represented using a filled diamond symbol. Another important concept are generalizations (inheritances), which represent an 'is-a' relationship between classes, where one class is a specialized version of another. This is expressed using an arrow pointing from the derived (subclass) class to the base (superclass) class.

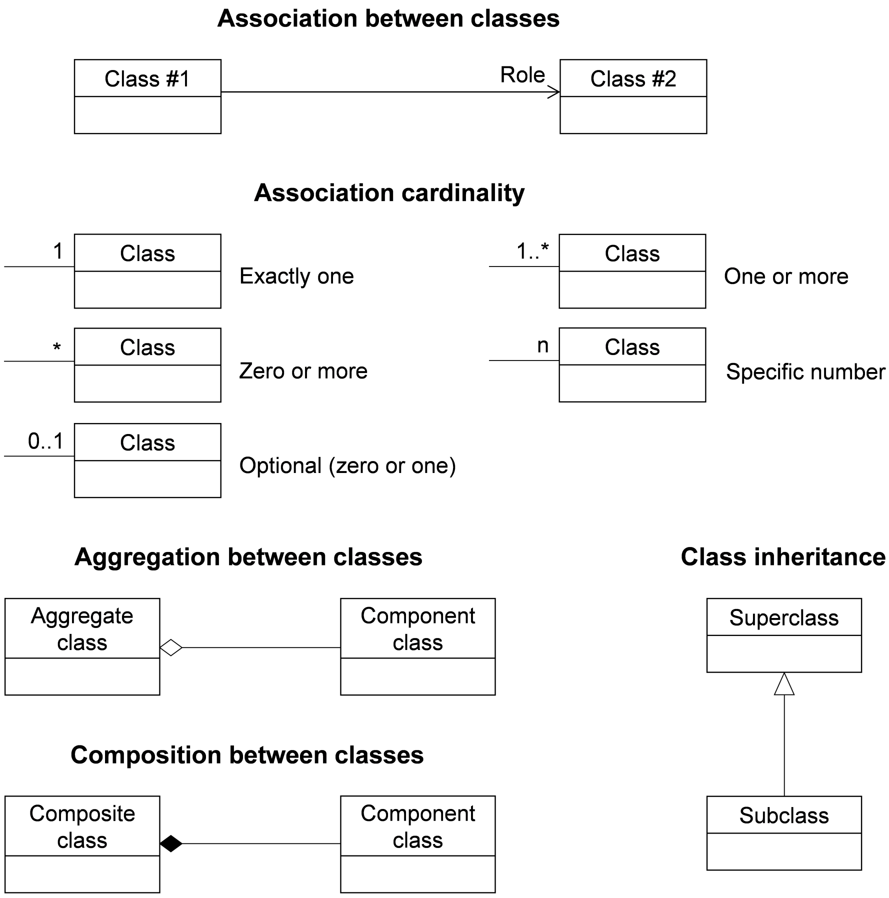


Figure 4.6: UML notations used in CityGML 3.0 and relevant for this thesis as presented in Kolbe et al. (2021).

4.2.2 The Extensible Markup Language (XML)

The Extensible Markup Language (XML) is a meta-language developed by the World Wide Web Consortium (W3C) that specifies rules for encoding documents and can be used to define data formats (W3C, 2008). XML serves as a markup language, enabling the definition of application-specific formats to store and exchange hierarchically structured information through text files. XML files are structured using a set of rules that define how the data should be organized and represented. The basic structure of an XML file consists of elements, attributes and text content. Elements are the building blocks of XML and are defined using tags enclosed by angle brackets. Each element can have attributes, which provide additional information about each element and contains text between opening and closing tags. A simple basic example of the human and machine readable structure of XML documents is give in listing 4.1 using well-defined markup-tags. The example XML document has a hierarchical structure with an XML declaration at the beginning followed by a root element <universityData>, which contains a <university> element with attributes and further nested elements providing details about the university, such as its location, founding year, and total number of students. Comments within the XML document are indicated as shown in the example.

```xml
<?xml version="1.0" encoding="UTF-8"?>
<universityData>
   <!--This is a comment.-->
   <university name="Technical University of Munich" acronym="TUM">
      <location>
         <city>Munich</city>
         <country>Germany</country>
      </location>
      <founded_year>1868</founded_year>
      <total_students>52,000</total_students>
   </university>
</universityData>
```

Listing 4.1: Basic example of the XML document structure.

An XML document is considered well-formed if it adheres to the basic syntax rules of XML. Valid XML, on the other hand, are well-formed and additionally adhere to rules specified in a Document Type Definition (DTD) or an XML Schema Definition (XSD), which can be expressed using UML class diagrams.

4.2.3 The ISO 19100 Standards Series

In this sub-chapter some of the most important standards from the ISO 19000 series on geographic information are introduced and briefly explained. Abstract concepts defined in this ISO series are implemented in standards such as GML3 and thus relevant for this thesis. For the sake of clarity, only a selection of ISO norms from this series most relevant for this thesis is introduced (namely ISO 19103, ISO 19107, ISO 19109 and ISO 19111).

- **ISO 19103:2015, Geographic information - Conceptual schema language** provides rules and guidelines for the use of a conceptual schema language within the context of geographic information (ISO 19103, 2015). The standard defines a language for specifying conceptual schemas that represent the common framework for understanding and describing geographic information.

- **ISO 19107:2019, Geographic information - Spatial schema** defines concepts for describing and manipulating geometric and topological properties of geographic features (ISO 19107, 2019). This contains a Geometry packages defining properties for geometry objects including geometric primitives, aggregates, complexes and composites in several dimensions (0-3). Geometric primitives are simple, continuous objects such as *Points, LineStrings* or *Polygons*. These geometric primitives can be assembled disjointedly to form geometric complexes. Composites are a special type of complexes, which requires a homogeneous composition of primitives and composites of the same dimension. Aggregates represent a collection of individual geometry elements that do not need to be connected and can overlap. An overview on basic geometry classes defined in ISO 19107 (2019) are illustrated in figure 4.7. All geometry classes inherit an optional association to a coordinate reference system. An additional topology package defines properties of topology objects such as nodes and edges. Also topological relations can be derived with spatial operators.

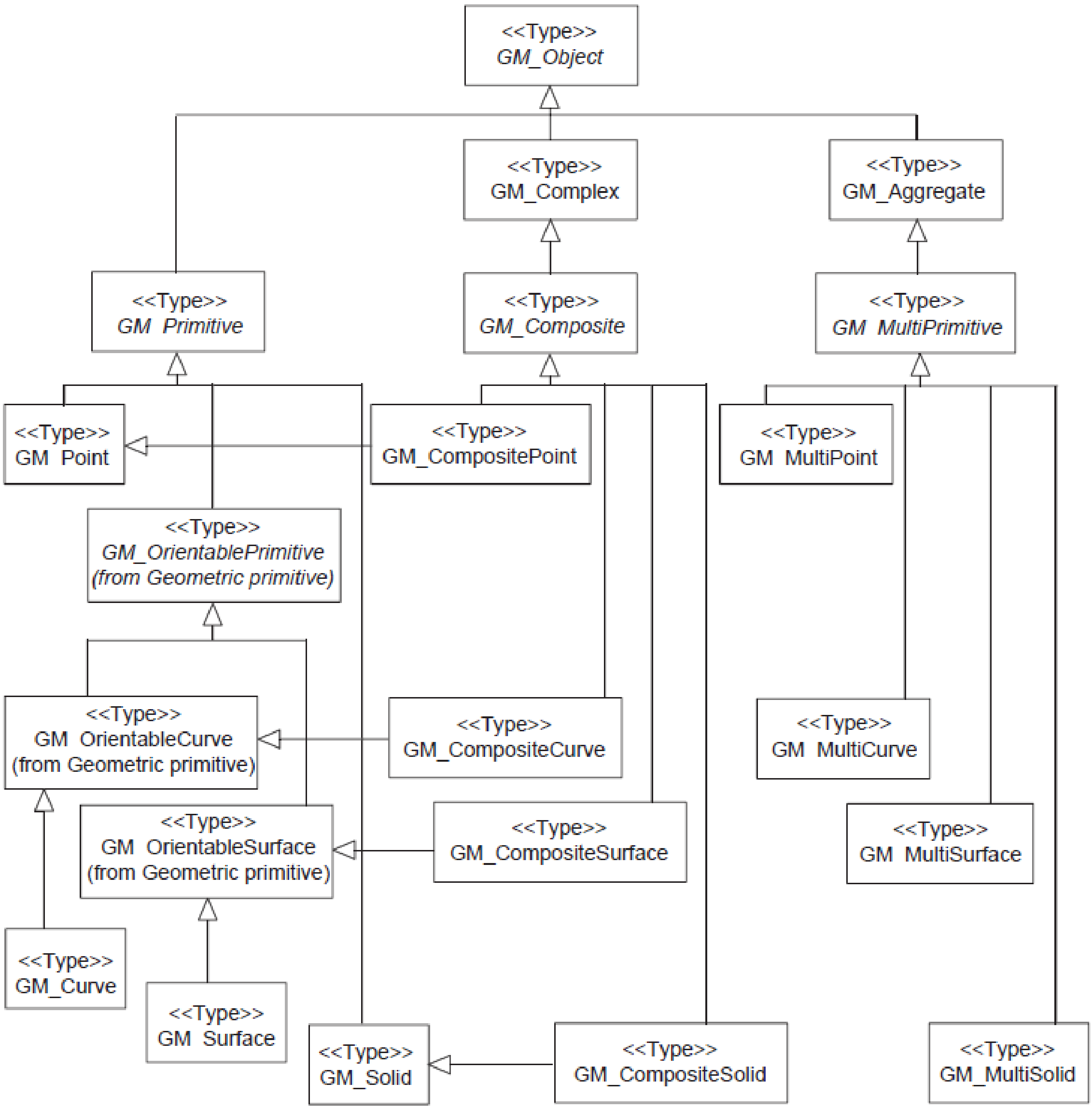


Figure 4.7: Geometry basic classes with specialization relations according to ISO 19107 (2019)

- **ISO 19109:2015 Geographic information - Rules for application schema** provides guidelines rules for creating and documenting application schemas, which include definitions for feature types, attributes, relations (such as associations, generalizations, etc.), and other components of the feature model (ISO 19109, 2015). The goal is to ensure interoperability and consistency in the representation of geographic information across different systems and applications. It includes general rules such as that applications schemas should be noted in a formal language (e.g. UML) and main rules for the definition of features, attributes or relations. The General Feature Model (GFM) is a conceptual model used to express concepts to define features and their relations. *Features* are defined as an abstract representation of real-world phenomena. These features can have spatial attributes, which are restricted to geometrical and topological objects defined in ISO 19107.

- **ISO 19111:2019 Geographic information - Referencing by coordinates** provides a framework for describing and defining spatial references in a consistent and standardized way (ISO 19111, 2019). The document establishes the conceptual framework for describing referencing by coordinates, outlining the minimum data needed to define coordinate reference systems. It supports the definition of various types of spatial coordinate reference systems, including geodetic systems on national, regional or local scales.

4.2.4 The Geography Markup Language (GML)

The Geography Markup Language (GML) is a commonly used format for the transfer of geographic information. It is an XML-based language designed for modelling, transferring and storing geospatial data developed by Open Geospatial Consortium (OGC) and International Organization for Standardization (ISO) and is defined by ISO 19136 (2020). GML provides a structured and standardized framework, allowing for the representation of complex geographic data in a machine-readable format. Additionally, GML incorporates encoding rules that map UML application schemas to GML application schemas, ensuring consistency and compatibility in the representation of geospatial data. Key concepts are extracted from the ISO 19100 standards series. Version 3.2.1 of GML incorporates concepts from a number of ISO norms. Main components of GML are *Features* representing real-world objects such as buildings or roads. *Features* can be combined to *FeatureCollections* and can have spatial as well as non-spatial properties. Spatial properties are represented with geometry and topology objects. The spatial geometry components of GML provide a partial implementation of the ISO 19107 spatial schema.

4.3 The City Geography Markup Language (CityGML)

4.3.1 Historical Background on CityGML

Figure 4.8 gives an overview on the most important milestones in the historical development of the CityGML standard. CityGML has been initiated in 2002 by the Special Interest Group 3D (SIG 3D) a national and international independent working group including several dozen companies, cities, and research groups from Germany, Great Britain, Switzerland, and Austria (Kolbe, 2009). The development of CityGML is currently (as of 2024) handled by the 3D Information Domain Working Group (3DIMD WG) and the CityGML Standard Working Group (CityGML SWG). After a first implementation of a subset of CityGML in 2005, an OGC discussion paper (CityGML version 0.0.3) was published in 2006. After CityGML version 0.0.4 was presented as an OGC Best Practice Paper in 2007, CityGML version 1.0.0 was established as an OGC standard in 2008. This version of the standard already included a basic Transportation module with concepts for modelling road and other transportation infrastructure. These concepts were then adopted by CityGML version 2.0.0, which was issued as an OGC standard in 2012 (Gröger et al., 2012). The newest version 3.0 of the international OGC standard was published in Kolbe et al. (2021). This includes a substantially revised and extended Transportation module for modelling road and other transportation infrastructure, which is a direct result of research conducted in the course of this dissertation work, which is presented in this thesis. For the sake of completeness, the CityGML 3.0 Transportation module is briefly summarized in section 4.3.2.2. However, since the newly developed data model is a central result of this thesis, concepts and modelling strategies are presented and explained in greater detail in chapter 5.

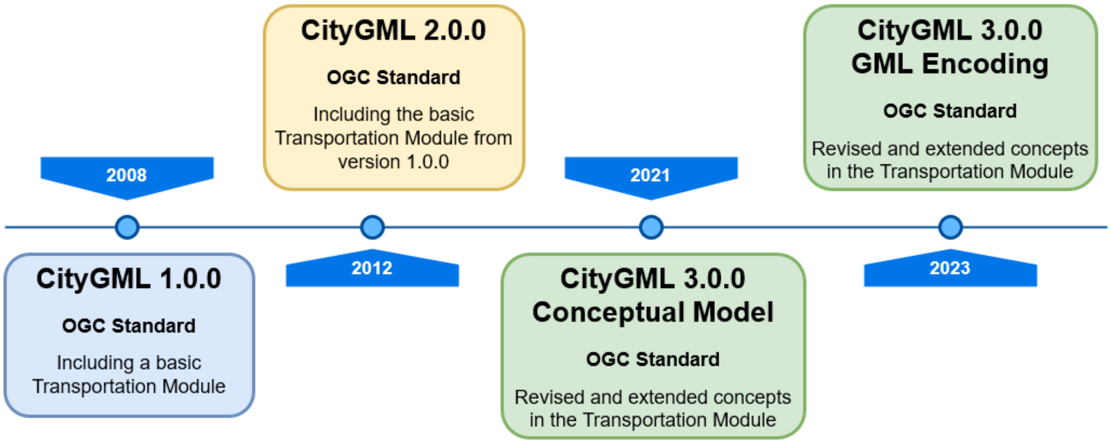


Figure 4.8: Historical development of the CityGML standard

The most relevant versions of CityGML for this thesis are version 2.0.0 and version 3.0.0. While several basic concepts and modelling approaches are identical for both versions, some concepts have been adapted and further developed in the newest version of the standard. Thus, general characteristics of version 3.0 of CityGML are explained in detail in the following sections.

4.3.2 Characteristics of CityGML Version 3.0

While aspects such as spatio-semantic coherence, geometric-topological concepts and many other aspects of CityGML are similar or identical for CityGML versions 2.0 and 3.0, there are also some adaptions and further developments in the newest version of the standard such as new and extended modules, a newly introduced space concept, newly allowed geometries or a revised LOD concept. Thus, these aspects are highlighted in the following section. The development of the conceptual data model of CityGML version 3.0 was initiated in 2014. The standard is specified in two main parts. Part 1 of the standard was issued by the OGC in 2021 and contains the conceptual data model (Kolbe et al., 2021). Part 2 of the standard is a corresponding GML encoding of these concepts published in 2023 (Kutzner et al., 2023). The data model can also be mapped to other encodings such as JavaScript Object Notation (JSON) (Ledoux et al., 2019; Ledoux and Dukai, 2023), Web Ontology Language (OWL) or relational database schemas (Z. Yao, 2020).

CityGML 3.0 Modules

As indicated in figure 4.9, the latest version of CityGML contains several revised and extended as well as new modules for modelling semantic 3D city objects (Kutzner et al., 2020). The Core module of CityGML 3.0 (colored in orange) still defines base concepts inherited by all other modules. Modules defining overarching concepts are highlighted in yellow. Concepts defined in these modules are applicable to all thematic modules are highlighted in blue. A red box highlights the Transportation module especially relevant for this thesis. In addition to modules existing in version 2.0 of CityGML, in CityGML 3.0 new Construction, Dynamizer, Versioning and PointCloud modules are introduced. As was the case previously, any combination of extension modules or the usage of only a subset of modules in combination with the Core module is possible.

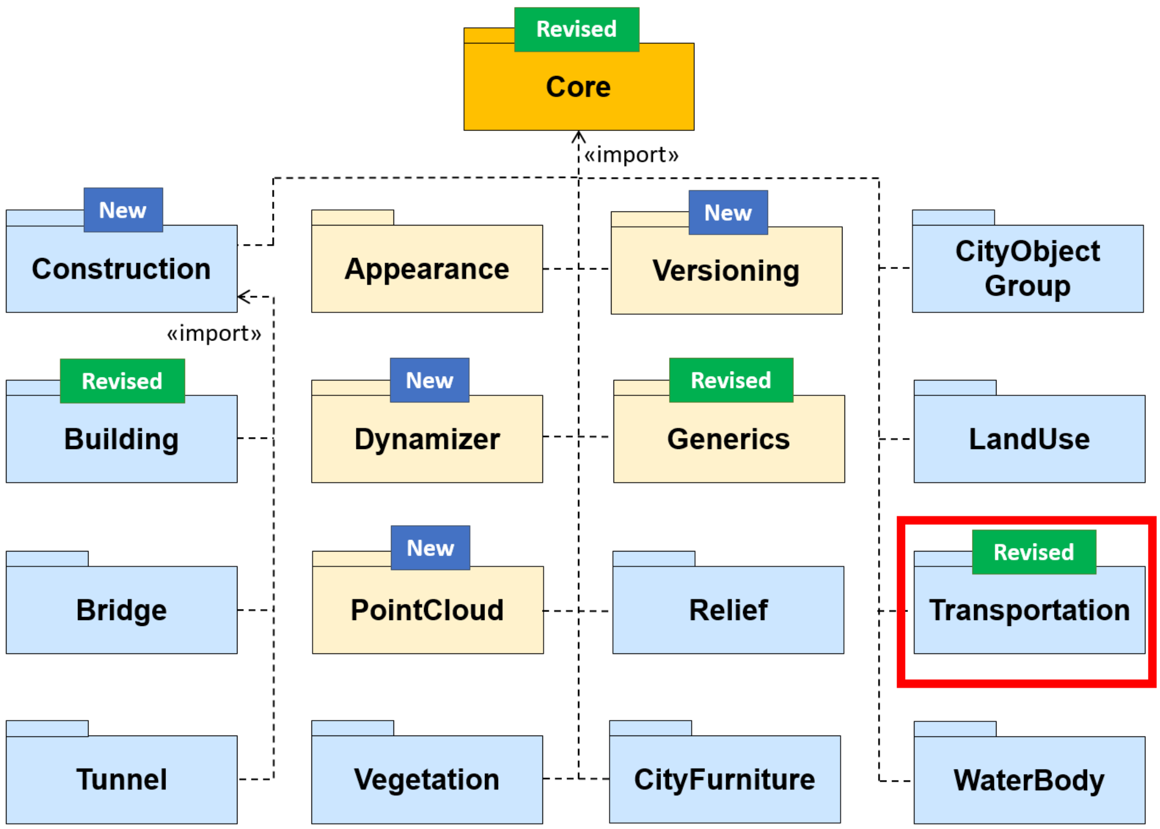


Figure 4.9: Overview of CityGML 3.0 modules and comparison to modules available in CityGML 2.0. Orange: Core module defining base concepts inherited by all other modules. Yellow: Modules defining concepts applicable to all thematic modules. Blue: Thematic modules. Red box: Transportation module especially relevant for this thesis.

4.3.2.1 The CityGML 3.0 Core Module

The UML diagram of the CityGML 3.0 Core module is displayed in figure 4.10. This contains concepts such as geometry definitions for *Spaces* and *Space Boundaries* in different levels of detail. Since all geometric representations are defined in the *Core* module, thematic extension modules inherit these concepts. Concepts such as *CityObjectRelations* or external references are also specified in the *Core* module.

CityGML 3.0 Space Concept

In order to increase interoperability with standards such as IndoorGML, CityGML 3.0 introduces a space concept for mapping all city objects onto the semantic concept of *Spaces* and *Space Boundaries* represented in the UML model of the Core module (Kutzner et al., 2020). While *Spaces* represent objects with volumetric extent in the real world (e.g. rooms or traffic spaces), *Space Boundaries* are used to model objects with an areal extent in the real world (e.g. wall or road surfaces) delimiting and connecting respective *Spaces*. *Spaces* are subdivided into *physical spaces* representing spaces fully or partially bounded by physical objects (e.g. buildings) and *logical spaces* representing spaces not necessarily bounded by physical objects (e.g. city districts). *Physical Spaces* are further categorized into *Occupied Spaces* representing spaces blocked by physical volumetric objects (e.g. buildings or city furniture) and *Unoccupied Spaces* representing volumetric objects not occupying physical space (e.g. traffic spaces). These concepts of representing spaces is entirely based on the semantic aspects of city objects and does not consider their geometric representation. To reflect this concept for road and other transportation infrastructure, transportation objects are defined as a sub-classes of *AbstractTransportationSpaces*. Additionally, *AuxiliaryTrafficSpaces* and *TrafficSpaces* bounded towards the ground by respective *AuxiliaryTrafficAreas* and *TrafficAreas* are introduced. The application of these concepts for transportation infrastructure is further explained and discussed in chapter 5.

CityGML 3.0 Geometry, Topology and Level of Detail (LOD) Concept

While CityGML 2.0 only allowed a subset of the GML3 geometry package, CityGML 3.0 uses all geometry classes defined in ISO 19107 (2019). For the use of *MultiCurve* geometries, this means, that now also clothoids or splines can be used to represent transportation networks (CityGML 2.0 only allowed straight lines). The revised LoD concept of CityGML 3.0 only refers to the geometric but not the thematic resolution of objects. *Spaces* and its subclasses such as *TrafficSpace* can now be portrayed spatially as individual *Points* in LOD 0, *MultiSurfaces* in LOD 0/2/3, *Solids* in LOD 1/2/3 and *MultiCurves* in LOD 2/3. Boundaries of spaces and their subclasses, such as *TrafficArea* on the other hand, can now be represented as *MultiSurfaces* in LOD 0/2/3 and as *MultiCurves* in LOD 2/3. The previously existing LOD 4 used for modelling indoor representations was omitted. It is now possible to integrate the interior of objects within every available LOD. In the context of modelling transportation infrastructure however, the modelling of interior objects plays a minor role.

The conceptual model of CityGML 3.0 does not employ the topology classes from ISO 19107, however topological relations can (optionally) be expressed with shared geometries of multiple objects. In the GML encoding of the standard the known XLink concept can be employed. In order to express relations between geometrically identical but semantically different city objects, *CityObjectRelations* are introduced in the CityGML 3.0 Core module. E.g. road surfaces on a bridge could be modelled as *TrafficAreas* (as part of a *Road* object) and *RoofSurfaces* (as part of a *Bridge* object) at the same time.

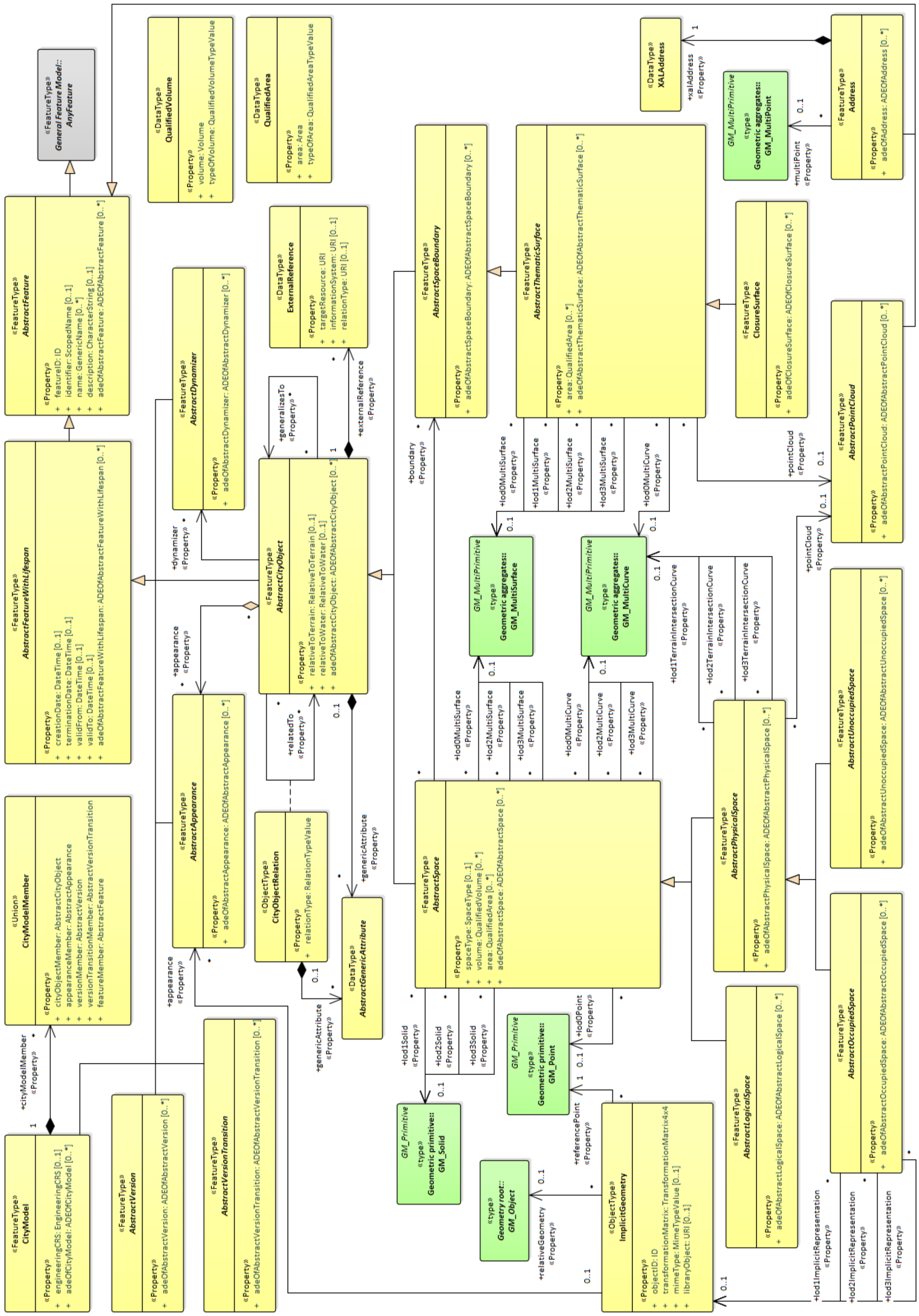


Figure 4.10: UML diagram of the CityGML 3.0 Core Module (Kolbe et al., 2021).

4.3.2.2 The CityGML 3.0 Transportation Module

For the sake of completeness, the CityGML 3.0 Transportation module is briefly mentioned and summarized in this sub-chapter. However, since the new data model was developed in the course of this dissertation work and is a central result of this thesis, concepts and modelling strategies are presented, explained and discussed in much more detail in chapter 5. The revised and extended data model of the Transportation module is illustrated in the UML diagram in figure 5.44. The basic structure of this model consists of *AbstractTransportationSpace* as main class divided into 5 subclasses *Track, Road, Railway, Square* and newly introduced *Waterway*. With the exception of *Square*, all sub-classes can be segmented into new classes called *Section* or *Intersection*. The linking of object parts to different semantic objects avoids redundant representations of intersections that are part of multiple transportation objects in CityGML instance documents. Furthermore, linear representations of streetspace are no longer limited to LoD 0. By specifying which axis of a transportation object should be used, linear representations in different levels of granularity become possible. *Squares* are defined as large sealed surfaces such as plazas or parking lots. *Clearance space* models representing free space above traffic surfaces are proposed. Additionally, *Holes* in a streets surface as well as *Markings* are introduced as individual classes.

4.3.2.3 Other CityGML 3.0 Modules and Concepts relevant for this Thesis

Since the streetspace is defined not only as surface-based representation of transportation infrastructure but can also be interpreted as the actual space that is used by traffic members, this traffic space can interact with other objects defined in the CityGML 3.0 specification. Additionally, further concepts such as point cloud representations or modelling appearances are relevant for road and streetspace models and thus are also briefly introduced in this sub-chapter.

CityGML 3.0 Construction, Building, Bridge and Tunnel Modules
A newly introduced *Construction* module defines common concepts for modules such as *Building*, *Bridge* or *Tunnel* focusing on as-built representations of constructions. Individual surfaces such as *GroundSurfaces*, *WallSurfaces* or *RoofSurfaces* are defined in this module and can be used to specify individual parts of the mentioned objects. The modules *Building*, *Bridge* or *Tunnel* are structured similarly, by defining *AbstractBuilding*, *AbstractBridge* or *AbstractTunnel* classes each specialized as an entire object or its parts. Additionally, classes such as rooms, furniture or installations are defined within each module.

CityGML 3.0 CityFurniture Module
The *CityFurniture* module provides concepts for modelling objects such as traffic signs, traffic lights, street lights, benches or other pieces of equipment available in the outdoor environment of a city and is a subclass of *_AbstractOccupiedSpace*. The fairly simple UML diagram for the *CityFurniture* is displayed on the left side of figure 4.11.

CityGML 3.0 CityObjectGroup Module

The *CityObjectGroup* module allows the aggregation of individual city objects based on logical criteria that can be defined depending on specific use cases or applications. Each city object within a *CityObjectGroup* can be specified with a role name as displayed in the UML diagram on the right part of figure 4.11.

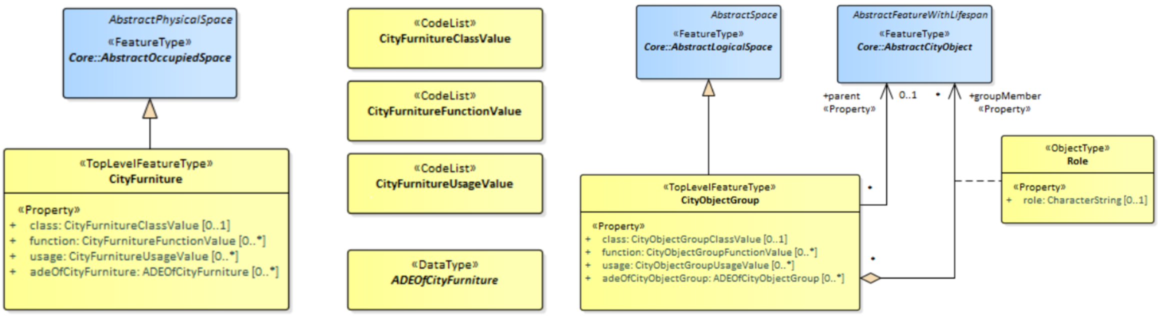


Figure 4.11: UML diagrams of the CityGML 3.0 CityFurniture and CityObjectGroup modules (Kolbe et al., 2021).

CityGML 3.0 PointCloud Module

The *PointCloud* module allows the representation of city objects by 3D point clouds. Figure 4.12 shows the UML diagram of the *PointCloud* module (left) and its relation to the space concept (right). All city objects that represent physical spaces or thematic surfaces can now be represented as point clouds, this also applies to the Transportation objects such as *Road* (subclass of *AbstractPhysicalSpace*), *TrafficArea* or *AuxiliaryTrafficArea* (subclasses of *AbstractThematicSurface*). The point clouds can either be represented inline with the city objects using *MultiPoint* geometries or in external point cloud files that are then referenced by the city objects they represent (which is applied and explained in more detail in section 5.4.5).

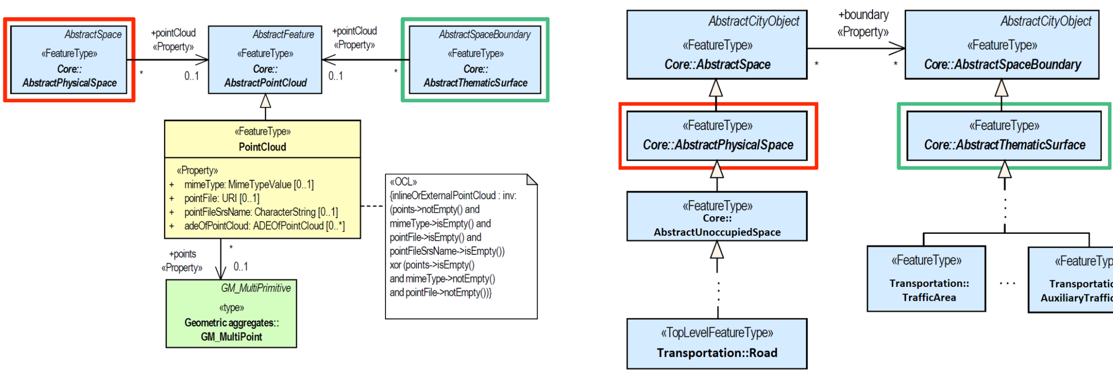


Figure 4.12: UML representation of the Point Cloud module in CityGML 3.0 as presented in Kolbe et al. (2021) and its relation to the space concept (adapted from Beil et al. (2021)).

CityGML 3.0 Vegetation Module

There are two possibilities for modelling vegetation, either as *SolitaryVegetationObjects*, such as individual trees or vegetation areas (*PlantCover*) representing more abstract models such as an entire forest. Similar to *CityFurniture* objects, *SolitaryVegetationObjects* are also often represented using implicit geometries. *Vegetation* models can be abstract representations derived from height, trunk diameter and crown diameter information or more realistic 3D models. *PlantCovers* can be equal to *AuxiliaryTrafficAreas* (e.g. green areas or medians within a *Road*). This relation can be expressed using *CityObjectRelations*. This approach can be helpful for accurately calculating (non-)sealed surfaces within a city. *CityObjectRelations* can also be used to indicate the location of vegetation with respect to a certain *Section*, *Intersection* or other transportation objects. Pantazatou et al. (2024) give a recommendation on how to model vegetation in semantic 3D city models using CityGML 3.0. Petrova-Antonova et al. (2024) propose a CityGML 3.0 Vegetation ADE.

CityGML 3.0 Appearance Module

As explained before, the CityGML standards provide a specific module for the representation of visual and observable properties of surface geometry objects in the form of textures and material. Concepts of this module described in the context of CityGML 2.0 in the sub-chapter 3.3.4.2 remain valid for CityGML version 3.0.

CityGML 3.0 Dynamizer Module

The *Dynamizer* module introduces concepts that allow the representation of time-varying data for city object properties and the integration of sensor data with 3D city models. Chaturvedi (2021) presents concepts for integration dynamic information (such as sensors) with semantic 3D city models in detail. In the context of street space modelling, this can be used for linking driving lanes with dynamic information on induction loops or for representing traffic light signals. This is further demonstrated in chapter 5.6.2.

CityGML 3.0 Versioning Module

Chaturvedi (2021) introduces a version concept for semantic 3D city models, which is incorporated in CityGML 3.0. In order to be able to represent multiple versions of 3D city models, the *Versioning* module provides information of the lifespan of city objects and can be used to model historic conditions as well as multiple planning stages of road and other infrastructure objects.

CityGML 3.0 extension mechanisms

The extension mechanisms of generic objects and attributes, Applications Domain Extensions (ADEs) or extended codelists remain available in CityGML 3.0 (as already presented in sub-chapter 3.3.4). However, CityGML 3.0 provides a method for augmenting predefined CityGML feature types with additional properties from the ADE domain (Kolbe et al., 2021). If a certain feature type is augmented with new ADE properties, the ADE can be 'hooked' by creating sub-classes of predefined *ADEOfFeatureType* data types.

Chapter 5

Extending CityGML for detailed 3D Streetspace Modelling

Some of the contents in this chapter have been presented in the following peer-reviewed and published papers:

Beil, C. and Kolbe, T. H. (2017). 'CityGML and the streets of New York - A proposal for detailed street space modelling'. In: *Proceedings of the 12th International 3D GeoInfo Conference 2017*. Ed. by Kalantari, M. and Rajabifard, A. Vol. IV-4/W5. ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences. This paper has received the 2nd Best Paper Award. University of Melbourne. ISPRS: Melbourne, Australia, pp. 9–16. URL: https://doi.org/10.5194/isprs-annals-IV-4-W5-9-2017

Beil, C. and Kolbe, T. H. (2020). 'Combined modelling of multiple transportation infrastructure within 3D city models and its implementation in CityGML 3.0'. In: *Proceedings of the 15th International 3D GeoInfo Conference 2020*. Vol. VI-4/W1-2020. University College London. ISPRS: London, UK, pp. 29–36. URL: https://doi.org/10.5194/isprs-annals-VI-4-W1-2020-29-2020

Beil, C., Ruhdorfer, R., Coduro, T. and Kolbe, T. H. (2020). 'Detailed Streetspace Modelling for Multiple Applications: Discussions on the Proposed CityGML 3.0 Transportation Model'. In: *ISPRS International Journal of Geo-Information* 9(10), p. 603. URL: https://doi.org/10.3390/ijgi9100603

Beil, C., Kutzner, T., Schwab, B., Willenborg, B., Gawronski, A. and Kolbe, T. H. (2021). 'Integration of 3D Point Clouds with semantic 3D City Models - Providing semantic information beyond classification'. In: *Proceedings of the 16th International 3D GeoInfo Conference 2021*. Vol. VIII-4/W2. ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences. New York University. ISPRS: New York City, USA, pp. 105–112. URL: https://www.isprs-ann-photogramm-remote-sens-spatial-inf-sci.net/VIII-4-W2-2021/105/2021/

Some contents in this chapter are based on modelling recommendations, which have been published in the following modelling guideline:

Beil, C., Kutzner, T., Schwab, B. and Kolbe, T. H. (2023). *Road2CityGML3*. Version 1.0. Zenodo. URL: https://doi.org/10.5281/zenodo.7919560

5.1 Deficits of the CityGML 2.0 Transportation Module

The international OGC standard CityGML version 2.0 was published in 2012. While the standard contains a basic framework for modelling transportation infrastructure (as presented in chapter 3.3.4), the main focus remained on modelling buildings and the terrain. Beil and Kolbe (2017) and Labetski et al. (2018) discuss some of the deficits and limitations of the CityGML 2.0 Transportation module. Missing and unclear concepts are further determined in this chapter with respect to (1) requirements of use cases and respective functionalities required to reach the goal of each use case (cf. chapter 2), (2) capabilities of relevant standards, conceptual models and data formats (cf. chapter 3) as well as (3) ambiguous and unclear definitions in the CityGML 2.0 Transportation module. These deficits are categorized for semantic, geometric, topological and temporal aspects. Levels of Detail are referred to in this section as specified in the CityGML 2.0 standard.

Missing and unclear semantic concepts

1. In contrast to several other standards (e.g. OpenDRIVE 1.8, GDF 5.1 or IFC 4.3), CityGML 2.0 does not provide a concept for segmenting road networks into sections and intersections. On the one hand this allows several interpretations on how large road networks should be divided into smaller and more manageable objects, on the other hand this also hinders interoperability with data created according to standards that do provide such a concept.
2. The segmentation of a CityGML 2.0 *TransportationComplex* into multiple *Road, Track, Square* or *Railway* objects is possible but not specified any further. Until now it is possible to represent the entire street space of a city by just one *Road* object.
3. Since the LOD concept in CityGML 3.0 only refers to geometric but not semantic detail, a new concept for expressing different levels of semantic granularity needs to be introduced. This is necessary since (1) different levels of semantic granularity are relevant for different use cases and (2) it may only be possible to derive a certain level of semantic information from coarser data sources such as satellite imagery.
4. Representations of spaces above transportation surfaces, where the traffic actually takes place (such as traffic or clearance spaces) are not specified. Identifying unoccupied spaces is relevant for a number of use cases related to navigation. Introducing the modelling of spaces would allow a seamless navigation between indoor and outdoor spaces.
5. Intersections can belong to multiple roads. It is not clear how to model this circumstance while avoiding a redundant representation. However, a non-redundant representation is required for example for accurate quantity take-off measurements.
6. *Roads* modelled in LOD 1 are to be represented by *gml:MultiSurface* geometries. It is not clear which objects of street space should be included in this representation. For example, it is unclear whether curbs or sidewalks adjacent to roadways should also be included in the modelling. Exact recommendations for segmenting *Roads* into smaller objects are missing.
7. As of LOD 2, it is possible to divide the road space into *TrafficAreas* and *AuxiliaryTrafficAreas*. How exactly footpaths, public squares or road areas are to be modelled is not defined in detail.
8. The definition of *TrafficAreas* and *AuxiliaryTrafficAreas* is only possible starting from LOD 2. This is intended to prevent an overly detailed representation of the road space in LOD 1, e.g. by

displaying individual lanes. At the same time, however, this prevents a rough division of different areas, which is often already useful in lower LODs.

9. The main difference between LOD 3 and LOD 4 models is the possibility to represent interior structures of buildings such as individual rooms. For many other thematic models, including the *Transportation* module, this can lead to absurd results.
10. Combined representations of different transportation infrastructure (e.g. level crossing of road and railway networks) are not specified. It should be supported to represent areas and structures such as roads, railways, bikeways or sidewalks used by different traffic members (simultaneously or alternately). Several functionalities and use cases require consistent and integrated representations of combined transportation infrastructure. Connections between various transportation types can be relevant for (multimodal) navigational purposes to indicate if traffic members can switch between different transportation systems.
11. There are no definitions for representing roads within buildings (e.g. within a parking garage).
12. Subsurface structures such as material layers are not considered.
13. Objects such as manholes, drains or roadway damages are not defined.
14. Markings are not explicitly represented.
15. Water transportation networks for ships, vessels, etc. (waterways) are not considered (cf. Labetski et al. (2018)).
16. It is unclear if *TrafficAreas* representing parking lots should be part of the subclass *Road* or *Square*.
17. The illustration used in the CityGML 2.0 standard to illustrate *Squares* can be misinterpreted. The displayed intersection should be part of the subclass *Road* and not *Square*. *Square* should be defined as plazas mainly used by pedestrians or large areas with sealed surfaces like parking lots.
18. The illustration displayed in figure 3.13 uses lines with arrows to indicate the direction of travel. However, this is not discussed further in the explanatory text or the data model. Information on traffic directions, however, are especially required by routing, navigation and traffic simulation related functionalities and use cases.
19. While use case specific information can be included using generic attributes, more standardized attributes such as 'traffic direction' could increase interoperability of data created by different stakeholders.

Missing and unclear geometric concepts

1. The geometric-topological model of the CityGML2.0 standard defines all geometric primitives that are permitted for the representation of city objects. One-dimensional objects (lines) are to be represented as *MultiCurve*. It is also specified that only straight lines (GML3 class *LineString*) may be used. In reality, however, more complicated geometries such as circle segments or clothoids) are often used, especially in road construction. In a CityGML 2.0 compliant representation, these must be approximated by curvature-free line strings. This is also problematic for functionalities and use cases where linear representations of roads and lanes with G2-continuity is required (e.g. sub-microscopic driving simulations).
2. Linear representations of *Roads* are only available in LOD 0. While it is stated that the centerline of a *TransportationComplex* should be represented, it is unclear which axis (road centerline axis,

carriageway axis or lane axis) should be used. Linear representations in various levels of geometric and semantic detail are required by different functionalities and use cases and thus should be possible to model in a standardized way.
3. In the illustration shown in figure 3.13, *Roads* are represented by their central axes. This makes sense, as road data is often available in this way. Nevertheless, in some cases it may be necessary to be able to represent roads by individual lane axes. Whether this is possible and how it could be implemented in detail remains unclear.
4. There are no specifications on how to realize non-redundant geometric representations of combined transportation infrastructure (e.g. level crossings) or shared spaces (e.g. intersection areas belonging to multiple roads). The importance of a non-redundant and consistent representation within semantic 3D city models is discussed in Gröger and Plümer (2011).
5. Multiple consistent geometric representations with linear graph-networks, areal surface models or volumetric spaces of the same scenario should be possible depending on the intended use case.
6. Areal representations of *Roads* in LOD 0 are not available.
7. Volumetric representations of transportation spaces are not available.
8. Roads cannot be represented or associated with point cloud geometries directly.

Missing and unclear topological concepts

1. Topological concepts for modelling predecessor / successor relations are not available. This information is essential for several functionalities and use cases such as routing or traffic simulations.
2. Topological concepts such as XLinks are available (e.g. for the GML encoding of CityGML). However, concepts for applying this modelling strategy to transportation objects are not specified.
3. Relations between city furniture objects (e.g. signs or traffic lights) to road objects (e.g. their validity for individual lanes) cannot be expressed.
4. There is no linear referencing concept available in CityGML. This is problematic, when spatially limited changes such as changing road surface materials or changing speed limits need to be represented. Without a linear referencing system, these changes can only be represented by splitting road surfaces into many smaller parts.

Missing temporal concepts

1. Different versions or planning stages of road and transportation infrastructure cannot be represented.
2. There are no concepts for linking transportation objects with dynamic (time-dependent) data such as (near) real-time sensor information.
3. Information on moving objects such as vehicles can not directly be stored in CityGML 2.0.

In order to overcome (most of) the presented limitations of CityGML 2.0, significant extensions and revisions to its Transportation module and the corresponding data model need to be done. In the following chapter, these developments are presented and discussed. These concepts are again categorized for semantic, geometric, topological and temporal aspects.

5.2 General Semantic Concepts

5.2.1 Introducing Spaces and Space Boundaries for Transportation Objects

CityGML 3.0 introduces the concept of modelling all city objects with *Spaces* and *Space Boundaries*. *Spaces* are defined as real world entities of volumetric extend and are subdivided into logical and physical space, bounded by areal *Space Boundaries* delimiting and connecting individual spaces. While logical spaces share thematic or semantic properties such as city districts with artificial administrative boundaries, physical spaces are bounded by physical objects such as buildings or roads. A detailed explanation of the space concept is given in Kutzner et al. (2020). This also affects the way Transportation objects are represented. Transportation objects are bounded by their surfaces against the ground and are therefore defined as physical spaces. Since the space above *Roads, Tracks, Waterways, Railways* or *Squares* are (mostly) free of matter in order to be used by cars, pedestrians, trains or ships, *AbstractTransportationSpace* is a subclass of *AbstractUnoccupiedSpace*. This free space can at the same time be occupied by other objects such as traffic lights or signs represented by the CityGML class *CityFurniture*. The class *AbstractTransportationSpace* is subdivided into *AuxiliaryTrafficSpaces* and *TrafficSpaces*, which in turn are bound by *AuxiliaryTrafficAreas* and *TrafficAreas*.

5.2.2 Introducing three Levels of Granularity

As explained in section 4.3.2, the newest version 3.0 of CityGML contains a revised LoD concept (Löwner et al., 2016). Feature classes in thematic modules are not directly associated with geometry classes anymore. Thus, in order to still be able to express different levels of thematic decomposition within the Transportation module a new attribute called *granularity* is introduced. Different levels of granularity are required, since some functionalities and respective use cases do not require lane-level accuracy data. Additionally, semantically highly detailed data may not always be available. Common data such as land cover information or road centerlines derived from satellite imagery often only represent entire roads without further segmentation into individual carriageways or lanes. Thus, a concept for semantically decomposing transportation objects into three levels of granularity is introduced.

First, areal representations of streetspace using different levels of granularity are explained. As displayed in figure 5.1, an areal representation with *granularity = area* should cover the entire width of the street, including sidewalks or curbstones. A more detailed segmentation into *TrafficSpaces* and *AuxiliaryTrafficSpaces* representing individual traffic ways should be realized with granularity = way. *Granularity = lane* additionally allows the representation of individual driving lanes. This is very similar to how building models are represented thematically more detailed in CityGML 2.0 with increasing LoD. Note that *Markings* or *Holes* in street surfaces can extend over more than one transportation object and therefore should be modelled as a separate class, independent of the level of granularity and spatially represented by *MultiSurface* geometries. In addition to areal models, figure 5.2 further specifies which street axes should be used for linear representations in each level of granularity. Linear structures are represented as *MultiCurve* geometries. Nodes can be derived from this linear network if needed for connectivity or shortest path graph algorithms. The advantage of this representation (in contrast to *GeometricComplex* geometries used in CityGML 2.0) is, that intersecting lines representing different transportation types do not need to have nodes. In this way, different transportation types are not connected if it is not possible to switch between them at a certain point (e.g. *Road* and *Railway* networks intersecting at a level-crossing).

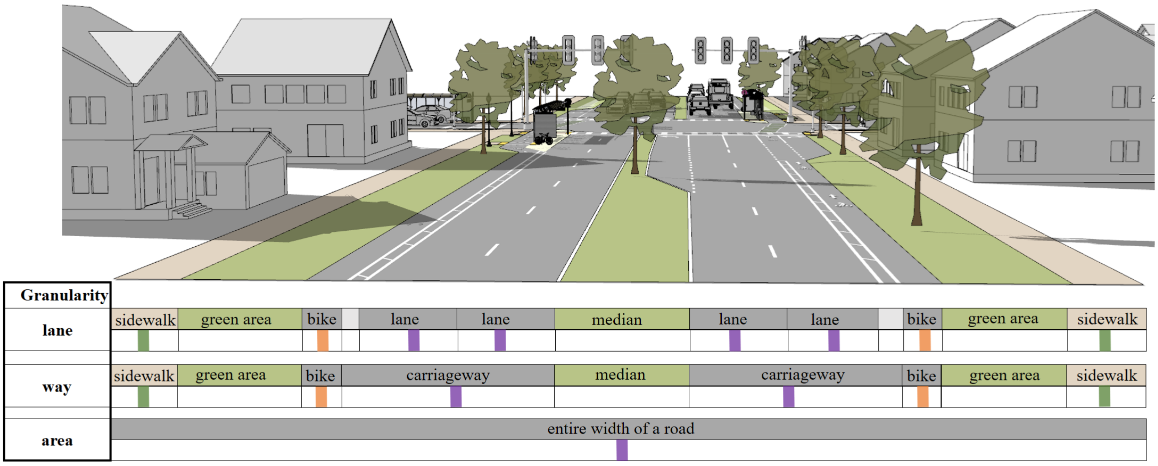


Figure 5.1: Three levels of granularity (linear and areal representation).

As long as roadways are not topologically separated, streets are represented by a single centerline in granularity = area. In addition to the driveway centerline, linear representations for footpaths and bicycle paths become possible with granularity = way, thus enabling a more detailed thematic decomposition of streetspace. While individual driveways (sometimes referred to as carriageways) are represented with individual linear / areal / volumetric *TrafficSpace* objects in granularity=way, granularity = lane representations finally contain one linear / areal / volumetric *TrafficSpace* object for each individual driving lane. This is consistent with proposals made by Boersma (2019) and Tamminga (2019) based on Beil and Kolbe (2017) for linear representations of roads and junctions in different levels of detail. Figure 5.2 shows a direct comparison of linear network representations in different levels of granularity.

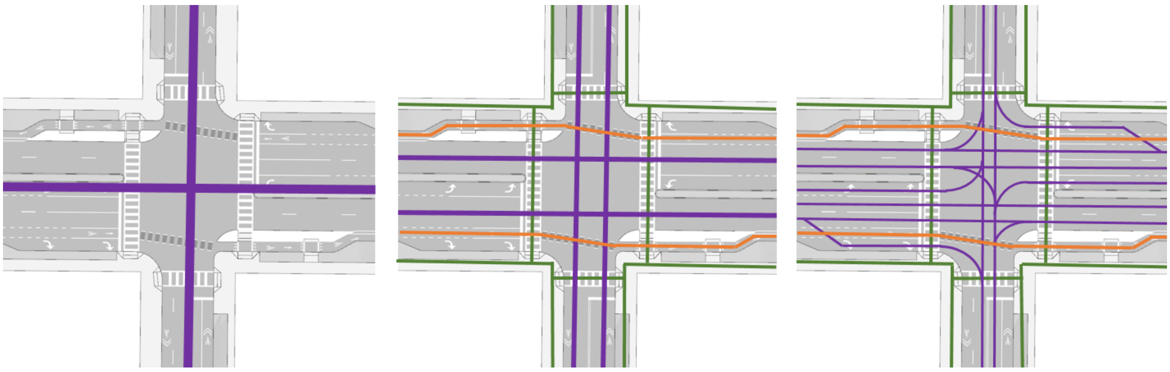


Figure 5.2: Three levels of granularity (linear representation).

While linear representations in granularity = area are modelled with one axis per driveway and section, linear representations in *granularity = lane* contain separate lines for each individual driving lane, following every possible way a car could take. While it is also possible to have linear representations of *AuxiliaryTrafficAreas*, this kind of representation is most useful for *TrafficSpaces* in the context of navigational, routing or traffic simulation related use cases to model possible paths traffic members can take.

5.2.3 Avoiding redundant Representations using XLinks and CityObjectRelations

The concepts of XLinks and CityObjectRelations for expressing relations between city objects are mentioned in chapters 3.3.4 and 4.3.2. Geometrically identical surfaces can be part of semantically different objects. E.g. *Road* surfaces on a *Bridge* could be modelled as *TrafficAreas* (as part of a *Road*) and *RoofSurfaces* (as part of a *Bridge*) at the same time. Transportation networks and *Roads* can also reach into *Buildings* (e.g. within a parking garage). In this case, *TrafficAreas* are also *Floor-* or *RoofSurfaces*. Within transportation networks themselves, some parts such as *Intersection* areas may belong to multiple *Roads* at the same time. This can lead to semantically and/or geometrically redundant representations within semantic city models. Stadler and Kolbe (2007) describe the importance of spatio-semantic coherence and non-redundant representations. This can be important for use cases that require surface area calculations. If, for example, some surfaces are modelled multiple times (e.g. overlapping geometries within an intersection area), quantity take-off measurements will not be accurate. There are different possible methods and concepts for avoiding these problems and ensuring geometrically and semantically non-redundant representations.

1. Directly shared geometry (not feasible): XLinks could be established between geometry definitions directly. In large files however, this would result in linked geometries that may be stored very far apart. Additionally, this is not feasible for objects that could belong to different top-level-features.
2. Shared features: Using XLinks to features with identical semantics has the disadvantage that in large files, linked objects may be stored very far apart. However, semantically and geometrically identical objects do not need to be represented multiple times.
3. Explicit linking of related features using CityObjectRelations: The downside of using *CityObjectRelations* is that the geometry of objects / surfaces needs to be represented redundantly. However, the geometry of each object is stored directly with the object. Information on identical (geometrically equal) surfaces is available and thus can be considered when rendering or analyzing the data.

With these advantages and disadvantages of both concepts in mind, the following recommendation for their application and implementation is given:

1. Using *CityObjectRelations* makes sense mainly for linking semantically different but geometrically identical surfaces / objects (e.g. *TrafficAreas* of a *Road* that simultaneously represent *RoofSurfaces* of a *Bridge* or *Building*).

2. Using XLinks makes sense, when linking a semantically unambiguous feature to multiple top-level objects (e.g. an *Intersection* that is part of multiple *Roads* or an *Intersection* that is part of a *Road* and a *Railway*).

The application of these definitions and recommendations for ensuring a non-redundant representation of transportation infrastructure as part of a semantic 3D city model is demonstrated in detail in the following chapters.

5.2.4 Required and recommended Attributes

A unique object identifier (*gml:id*) for each city object is required in order to be able to distinguish and reference individual objects. Additionally, information on creation/termination date or times of validity can be stored with every city object. *(Auxiliary)TrafficSpaces* require a *granularity* attribute with values 'way' or 'lane'. *Road* objects should contain an individual *gml:name* attribute indicating the road's street name. *Sections* and *Intersections* should contain information to which *Road(s)* they belong. This can be achieved by corresponding *gml:name* attribute(s). *TrafficSpaces* should contain information which *Section* or *Intersection* they belong to. This is implicitly given due to the hierarchical file structure of a GML encoded CityGML document. *(Auxiliary)TrafficAreas* should contain *function* and *usage* attributes. The *function* attribute describes surface types such as driving lanes, footpaths while the *usage* attribute indicates which traffic members are permitted to use it (e.g. cars or pedestrians). Multiple *usage* and *function* attributes can be modelled per feature, e.g. to express that a *TrafficArea* can simultaneously be used by pedestrians and cyclists. Additionally, *(Auxiliary)TrafficAreas* can contain a surface material attribute. A *class* attribute can be used to further specify already classified objects. An *occupancy* attribute, available for all *AbstractTransportationSpace* objects, can give information on number of occupants, their interval and type. Information on traffic directions are provided by a respective attribute of *TrafficSpaces*, giving the direction of traffic with respect to the underlying geometry.
Codelists for defining attributes available for classes in the CityGML 2.0 Transportation module were defined by the Special Interest Group 3D (SIG3D) and included in the CityGML 2.0 specification. This includes codelists for *(Auxiliary)TrafficAreas* and *TransportationComplex* objects (e.g. *Roads* or *Railways*), which can be transferred and applied to respective CityGML 3.0 classes. Since *(Auxiliary)TrafficSpaces* represent to space above *AuxiliaryTrafficAreas*, identical *class, function* and *usage* attributes can be defined.
The tables provided in appendix A contain recommendations for attribute values that should be explicitly modelled by providing respective attributes. This includes suggestions for function, usage, surface material, section and intersection classes as well as marking types and further attribute definitions. CityGML aims to be an application independent standard, thus only few attributes are standardized. More specific attributes such as speed limit, material properties or pavement ratings can be stored using generic attributes or by developing a corresponding ADE.

5.3 Semantic Concepts for Modelling Transportation Infrastructure

One of the main classes of the revised Transportation module is the class *AbstractTransportationSpace*, which has replaced the CityGML 2.0 class *TransportationComplex* in order to reflect the newly introduced space concept. Transportation objects such as *Roads, Tracks, Waterways* or *Railways* are defined as specific sub-classes of the abstract class *AbstractTransportationSpace*. The focus in this chapter is on modelling concepts for *Roads*, which can be transferred to other transportation modes such as *Railways*. Definitions of classes and features given within the following sub-chapters were specified as a result of this dissertation work and already adopted by and published in the CityGML 3.0 specification (Kolbe et al., 2021). The given definitions are thus denoted with quotation marks.

5.3.1 Modelling Roads

A *Road* is defined as "a transportation space used by vehicles, bicycles and / or pedestrians" (Kolbe et al., 2021). Figure 5.3 shows three *Road* objects highlighted in purple, yellow and green. Note that these *Roads* have shared *Intersections*. *Roads* can contain multiple *function* and *usage* as well as one *class* attribute. Proposals for defining codelist values for these attributes are given in appendix A. Individual *Road* objects should be distinguished by individual names stored as a *gml:name* attribute and consist of individual *Sections* and *Intersections*. A *Road* object should cover the entire width of corresponding transportation infrastructure including sidewalks, bicycle lanes, etc., adjacent to carriageways. In case multiple (disconnected) roads within one city model have the same name, individual *Road* objects per road should be created.

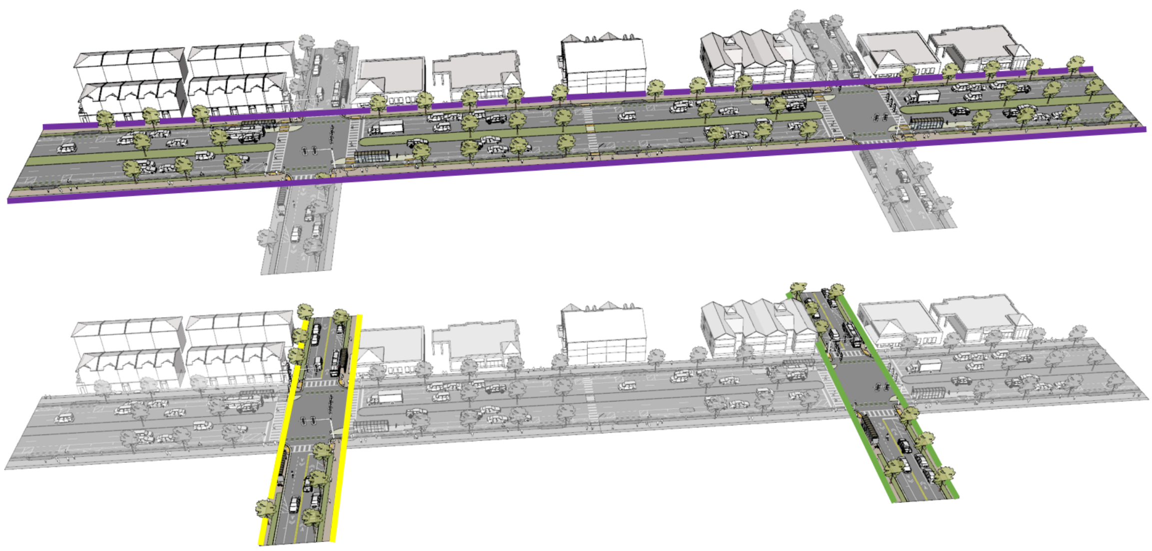


Figure 5.3: Three Road objects highlighted in purple, yellow and green with shared intersection areas (Beil et al., 2023).

Multiple *Roads* can share the same *Intersection*. Long uninterrupted *Roads* (e.g. freeways or motorways) can be segmented into multiple *Sections* directly connected to each other (without intermediate *Intersections*). In case information on individual *Roads* is not available, it is also possible to only model *Sections* and *Intersections* without assigning them to individual *Road* objects.

5.3.2 Segmenting Roads into Sections and Intersections

Roads (or *Tracks, Railways, Waterways*) should be decomposed into individual *Sections* and *Intersections*, which should cover the entire width of a *Road* and thus directly correspond to the representation of transportation objects in granularity ‘area’. *Sections* and *Intersections* can but do not have to alternate. In this way, large transportation networks can be segmented in to smaller hierarchically structured objects.

5.3.2.1 Sections

A *Section* is defined as "a transportation space that is a segment of a *Road, Railway, Track* or *Waterway*)" (Kolbe et al., 2021). *Section* objects should indicate its type (e.g. road corridor, dead end, etc.) by a corresponding *class* attribute. Figure 5.4 shows a typical example of a *Section* within an urban transportation network. Listing 5.1 shows an exemplary XML encoded CityGML 3.0 file including a *Road* object consisting of one *Section*. The hierarchical structure of a *Road* object further segmented into a *Section*, which again is decomposed into smaller parts, can been seen in this representation. Each object contains a *gml:id* attribute. While the geometry of the *Section* could also be stored with the object directly, in this case, geometry definitions are contained within the definition of individual *TrafficAreas* part of this *Section*.

Figure 5.4: Typical example of a Section (surrounded with orange lines) between two intersections (Beil et al., 2023).

```xml
<!--XML namespaces have been omitted from this listing.-->
<core:cityObjectMember>
  <tran:Road gml:id="UUID_Road_1">
    <gml:name>Road_1</gml:name>
    <tran:section>
      <tran:Section gml:id="UUID_Section_F">
        <tran:trafficSpace>
          <tran:TrafficSpace
             gml:id="UUID_TS_id_4c95049e-1b96-4a39-b678">
            <core:boundary>
              <tran:TrafficArea
                 gml:id="UUID_TA_0bd21839-0ced-4660-8c21a">
                <core:lod2MultiSurface>
                  <gml:MultiSurface srsName="EPSG:32755"
                     srsDimension="3">
                    <!--Geometry definition of the TrafficArea.-->
                  </gml:MultiSurface>
                </core:lod2MultiSurface>
                <tran:function>2</tran:function>
                <tran:surfaceMaterial>3</tran:surfaceMaterial>
                <!--Additional attributes such as area in sqm, etc.-->
              </tran:TrafficArea>
            </core:boundary>
            <tran:granularity>way</tran:granularity>
            <!--Optional geometry definition of the TrafficSpace.-->
          </tran:TrafficSpace>
        </tran:trafficSpace>
        <!--Additional (Auxiliary)TrafficSpaces with corresponding
           (Auxiliary)TrafficAreas.-->
      </tran:Section>
    </tran:section>
  </tran:Road>
</core:cityObjectMember>
```

Listing 5.1: CityGML XML encoding example of an individual Section with one carriageway in granularity ‘way’.

5.3.2.2 Intersections

An *Intersection* is defined is "a transportation space that is a shared segment of multiple *Road, Railway, Track* or *Waterway*) objects (e.g. a crossing of two roads or a level crossing of a road and a railway)" (Kolbe et al., 2021). In some cases, it can also be useful to introduce *Intersections* in order to model parts of a transportation network, where traffic members can take multiple paths. Figure 5.5 shows a typical example of two *Intersections* highlighted in blue.

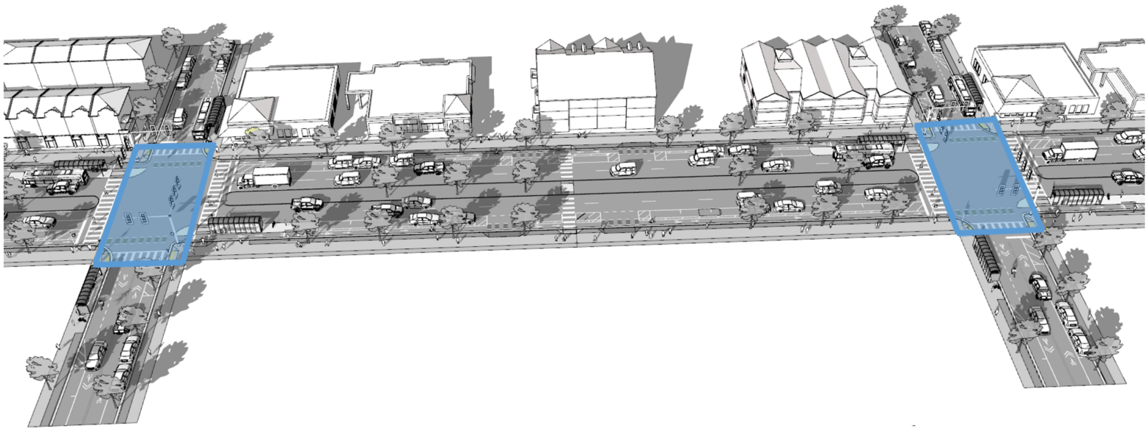


Figure 5.5: Two Intersections highlighted in blue (Beil et al., 2023).

A concept to divide street networks into *Sections* and *Intersections* is illustrated in figure 5.6. *Sections* (A, C, E, F, G, H, I) represent segments that can clearly be assigned to one individual Road. *Sections* are connected by *Intersections* (B and D) which can belong to multiple *Roads* at the same time. Types of *Sections* as well as *Intersections* are defined by respective class attributes. Similar to the proposal made by Labetski et al. (2018), *Intersections* should be modelled as individual objects categorized by different types. In the given example in figure 5.6, *Road 1* (yellow) consists of *Sections* F and G and *Intersection* B, while *Road 2* (purple) is composed of *Sections* A, C and E and *Intersections* B and D. This means *Road 1* and *Road 2* share *Intersection* B. The same is true for *Intersection* D, which is shared by *Road 2* and *Road 3* (green). In order to avoid a redundant representation of this shared object, XLinks are used in the CityGML instance document to reference the shared *Intersection*.

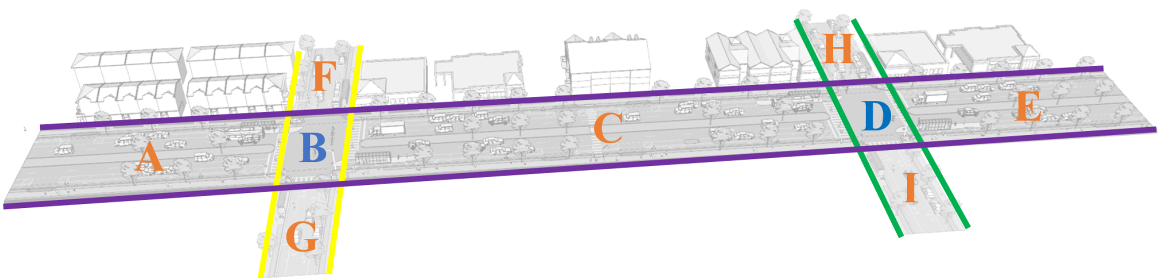


Figure 5.6: Street network segmented into Sections (A, C, E, F, G, H, I) and Intersections (B and D).

This is visualized in figure 5.7, using an instance diagram illustration to represent associations between *Road* objects and individual *Sections* and *Intersections*. Listing 5.2 shows an exemplary XML encoded CityGML 3.0 file including two *Road* objects consisting of multiple *Sections* and a shared *Intersection*. This *Intersection* is shared with another *Road*, which references the shared object using an XLink reference.

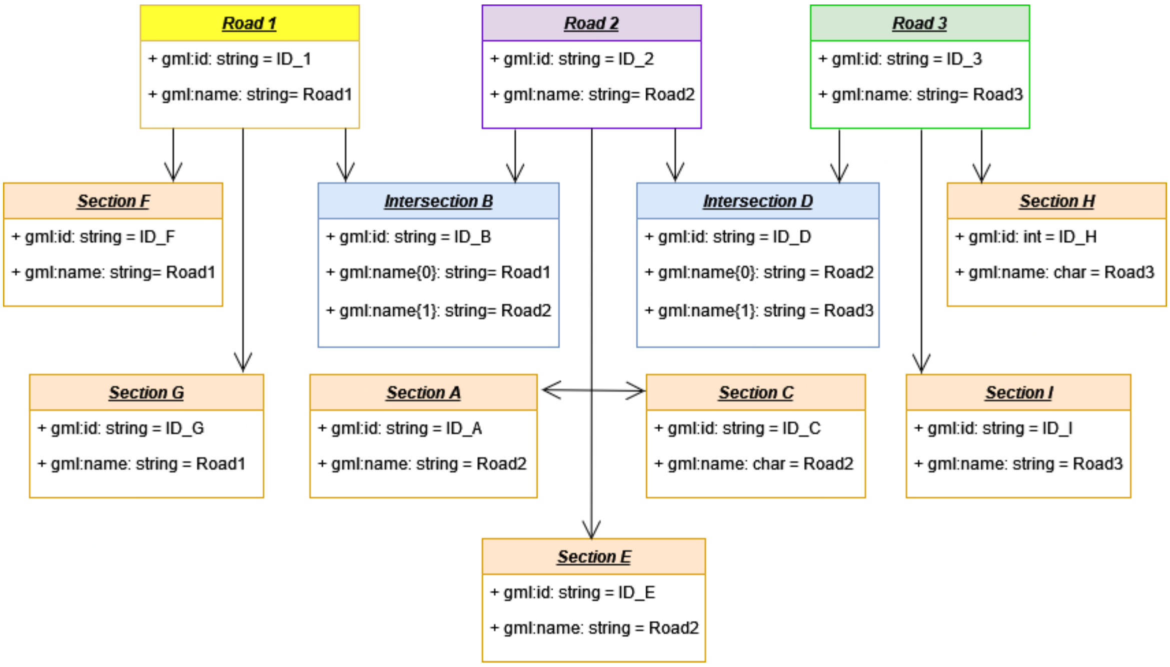


Figure 5.7: Instance diagram of the proposed object linking concept (e.g. Road 1 and Road 2 linked to the same Intersection object (Intersection B).

Depending on intended use cases, different definitions of the extent of individual *Intersections* are possible. It is recommended to model *Intersections* with the minimal extent of surfaces shared by multiple *Roads*. However, it is not prohibited to expand *Intersection* objects into adjacent section areas. In the example below, *Intersections* are reduced to the smallest area used by different *Roads*. In some cases, it might be useful to expand *Intersections* as shown in the right part of figure 5.8. This however makes it difficult to calculate the actual street surface area for each individual *Road*. Both interpretations of an *Intersection* are possible and can be modelled depending on specific use case requirements.

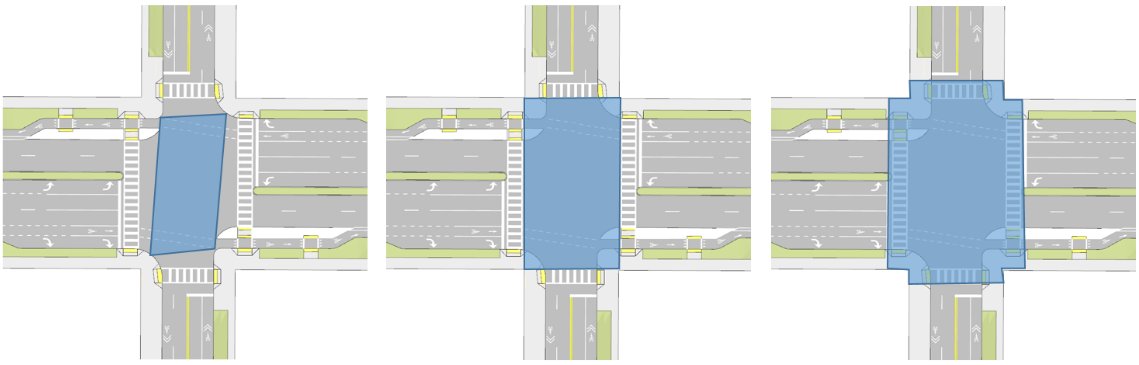


Figure 5.8: Different possible definitions for the spatial extent of an Intersection.

Figure 5.9 illustrates a large roundabout, which is segmented into multiple *Sections* (orange) and *Intersections* (blue). *Intersections* within the roundabout are connected to further *Sections* of the adjacent road network. In the case of a small roundabout, it is also possible to model an entire roundabout with a single *Intersection* object. The presented concepts of modelling a *Road* as *Abstract-TransportationSpaces* consisting of *Sections* and *Intersections* are formalized and illustrated in the UML diagram shown in figure 5.10.

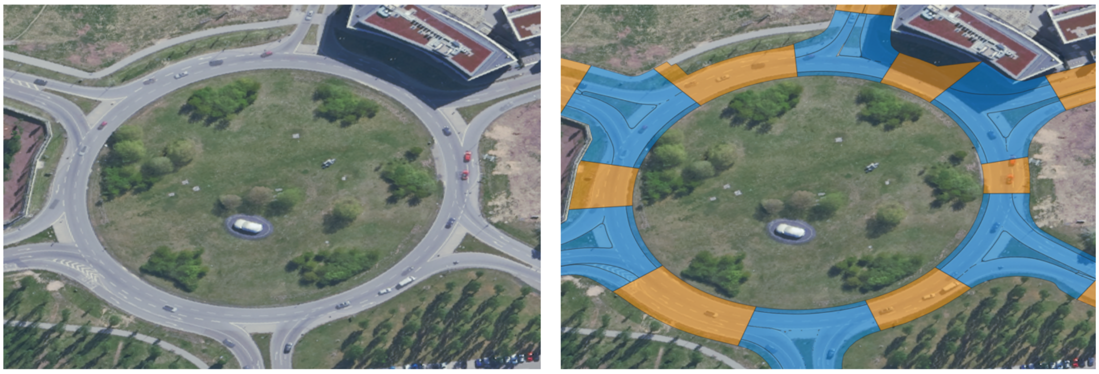


Figure 5.9: A large roundabout segmented into Sections (orange) and Intersections (blue).

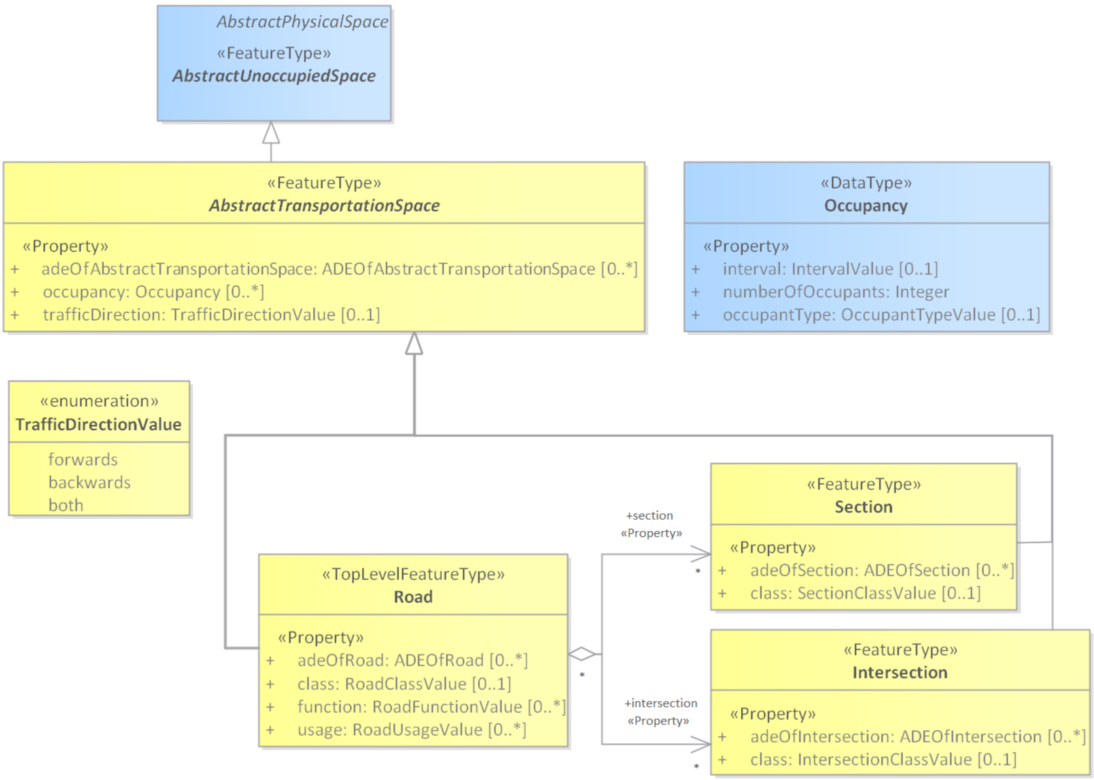


Figure 5.10: UML diagram of the class Road modelled as AbstractTransportationSpace consisting of Sections and Intersections.

```xml
<!--XML namespaces have been omitted from this listing.-->
<core:cityObjectMember>
  <tran:Road gml:id="UUID_Road_1">
    <gml:name>Road1</gml:name>
    <tran:section>
      <tran:Section gml:id="UUID_Section_F">
        <!--Additional (Auxiliary)TrafficSpaces with corresponding
            (Auxiliary)TrafficAreas.-->
      </tran:Section>
    </tran:section>
    <tran:section>
      <tran:Section gml:id="UUID_Section_G">
        <!--Additional(Auxiliary)TrafficSpaces with corresponding
            (Auxiliary)TrafficAreas.-->
      </tran:Section>
    </tran:section>
    <tran:intersection xlink:href="#UUID_Intersection_B"/>
  </tran:Road>
</core:cityObjectMember>
<core:cityObjectMember>
  <tran:Road gml:id="UUID_Road_2">
    <gml:name>Road2</gml:name>
    <tran:section>
      <tran:Section gml:id="UUID_Section_A">
        <!--Additional (Auxiliary)TrafficSpaces with corresponding
            (Auxiliary)TrafficAreas.-->
      </tran:Section>
    </tran:section>
    <tran:section>
      <tran:Section gml:id="UUID_Section_C">
        <!--Additional (Auxiliary)TrafficSpaces with corresponding
            (Auxiliary)TrafficAreas.-->
      </tran:Section>
    </tran:section>
    <tran:intersection>
      <tran:Intersection gml:id="UUID_Intersection_B">
      <gml:name>Road1</gml:name>
      <gml:name>Road2</gml:name>
        <!--Additional (Auxiliary)TrafficSpaces with corresponding
            (Auxiliary)TrafficAreas.-->
      </tran:Intersection>
    </tran:intersection>
    <!--Additional Sections and Intersections.-->
  </tran:Road>
</core:cityObjectMember>
```

Listing 5.2: CityGML XML encoding example of an Intersection with four adjacent Sections.

5.3.3 Introducing Transportation Spaces

As described in chapter 5.2.1, a concept for modelling spaces and space boundaries is introduced to CityGML 3.0 (Kutzner et al., 2020). Thus, new classes are introduced in order to adequately reflect this modelling strategy.

5.3.3.1 Modelling TrafficSpaces and AuxiliaryTrafficSpaces

Transportation objects are not just represented by their surface but also consider the space above used for transportation. In this context, *TrafficSpaces* are defined as "spaces in which traffic takes place" (Kolbe et al., 2021). Traffic in this context refers to the movement of entities including cars, trains, vehicles, pedestrians, ships and other modes of transportation. Correspondingly, *AuxiliaryTraffic-Spaces* are defined as spaces within the transportation space not intended for traffic purposes such as spaces above green areas. Volumetric or linear representations are recommended for modelling individual *(Auxiliary)TrafficSpaces*. Corresponding centerline representations of *TrafficSpaces* in different levels of granularity are particularly important for routing, navigation and traffic simulation related use cases. Point cloud geometries are also possible (see chapter 5.4.5). The geometric representation of a space, however, can be also be omitted in case no information is available or required. *(Auxiliary)TrafficSpaces* do not have to be represented geometrically but should be bounded towards the ground by corresponding *(Auxiliary)TrafficAreas*. The example displayed in figure 5.11 shows a *Section* semantically and geometrically decomposed into spaces representing sidewalks (green) and driving areas (purple) each represented by individual *TrafficSpaces*. For the sake of clarity, other *TrafficSpaces* e.g. for bicycle paths or *AuxiliaryTrafficSpaces* are not shown in the illustration.

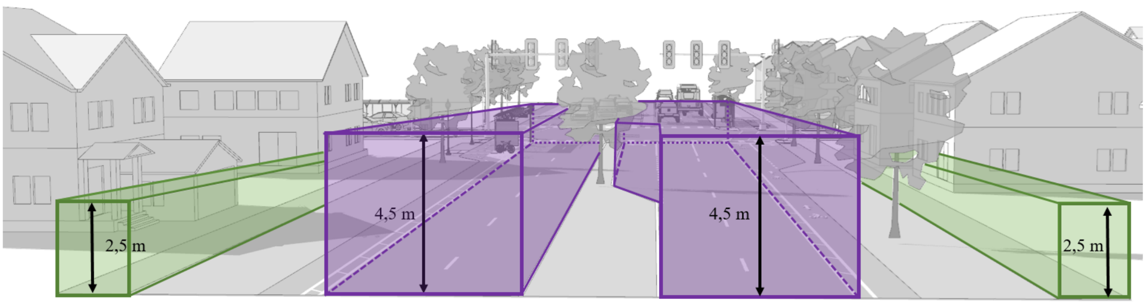


Figure 5.11: Volumetric representations of TrafficSpaces in granularity 'way' with different heights according to respective functions (purple: carriageways, green: sidewalks).

5.3.3.2 Modelling ClearanceSpaces

The newly introduced class *ClearanceSpace* makes it possible to represent space that has to be kept clear in order to ensure safe traffic and is defined as "the actual free space above a *TrafficArea* within which a mobile object can move without contacting an obstruction" (Kolbe et al., 2021). German roads for example, typically require a clearance space of 2.5 meter for sidewalks and 4.5 meter for automobile traffic. In reality, the actual clearance space may be higher or lower depending on potential obstacles such as city furniture, vegetation or underpasses. These *ClearanceSpaces* can be generated by vertically extruding *TrafficAreas* by a certain amount. In combination with other city objects such as city furniture or vegetation potential conflicts can easily be detected. In some cases, *TrafficSpace* and *ClearanceSpace* may be identical. *ClearanceSpaces* can also be represented with point clouds. This can be transferred similarly to other transportation objects such as *ClearanceSpaces* of *Railways, Tracks, Waterways* or *Squares*.

5.3.4 Surface-based Representations of TrafficAreas and AuxiliaryTrafficAreas

TrafficAreas represent the ground surface of each *TrafficSpace* and are defined as "the surfaces upon which traffic actually takes place" (Kolbe et al., 2021), such as car driving lanes, pedestrian sidewalks or bicycle lanes. An *AuxiliaryTrafficArea* is defined as "the ground surface of an *AuxiliaryTraffic-Space*" (Kolbe et al., 2021). *AuxiliaryTrafficAreas* are describing additional features of roads not intended for direct traffic usage such as raised medians or green areas. This is coherent to the semantic decomposition of transportation objects as defined in the CityGML 2.0 standard and thus ensures compatibility between both versions. One *(Auxiliary)TrafficSpace* can be bounded by multiple *(Auxiliary)TrafficAreas*. Figure 5.12 shows an example of a *Section* modelled in granularity 'lane' with individual *TrafficAreas* (depicted in blue) and *AuxiliaryTrafficAreas* (depicted in purple).

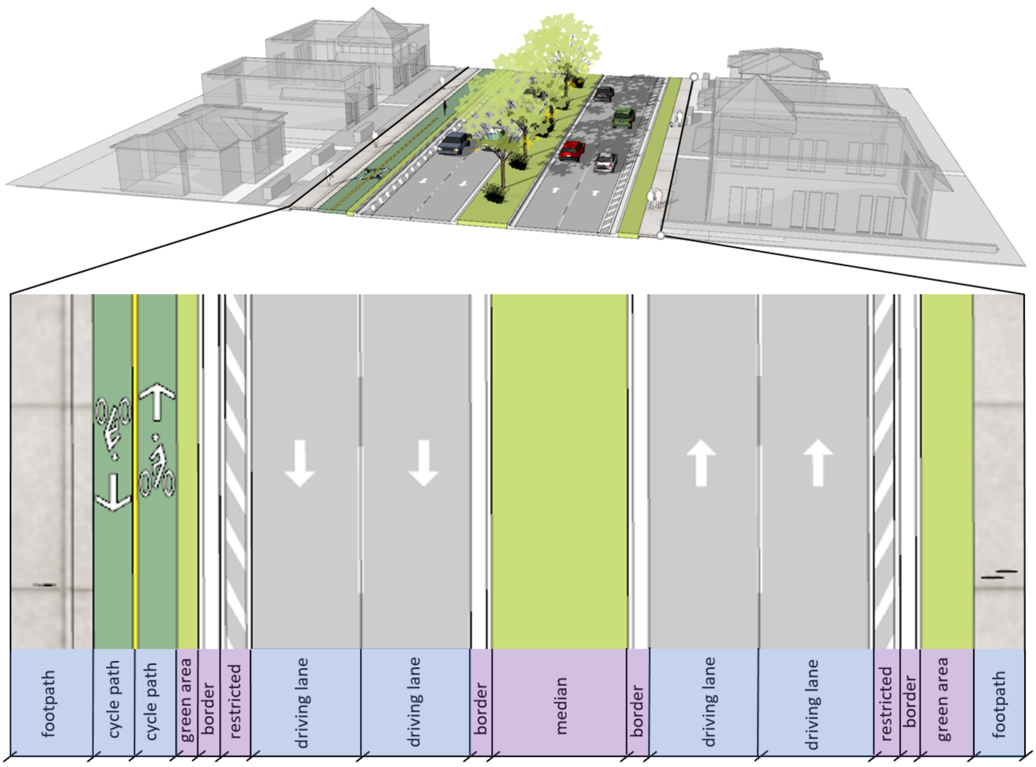


Figure 5.12: Section decomposed into individual TrafficAreas (blue) and AuxiliaryTrafficAreas (purple) (adapted from (Beil et al., 2023)).

The median and green areas in this example are modelled as *AuxiliaryTrafficAreas* with an attribute surface material 'grass'. In addition, these areas can be modelled as *Vegetation* objects (*PlantCover*) linked to corresponding *AuxiliaryTrafficAreas* using a *CityObjectRelation* with the value 'equal'. This approach can be helpful for accurately calculating (non-)sealed surfaces within a city. While curbs normally are intended to separate driving lanes from pedestrian walking areas (and thus are considered as *AuxiliaryTrafficAreas* in CityGML 2.0) one could argue, that curbs can be used by pedestrians and thus should be modelled as *TrafficAreas*. Depending on intended use case, either categorization of curbs is possible.
The presented concept of modelling *AbstractTransportationSpaces* consisting of *TrafficSpaces* and *AuxiliaryTrafficSpaces* is illustrated in the UML diagram shown in figure 5.13. *TrafficAreas* and *AuxiliaryTrafficAreas* are modelled as boundary surfaces or respective spaces. The predecessor / successor concept is indicated with the *TrafficSpace* class. This concept is explained in more detail in sub-chapter 5.5.2. Additionally, a class *ClearanceSpace* is introduced as part of a *TrafficSpace*.

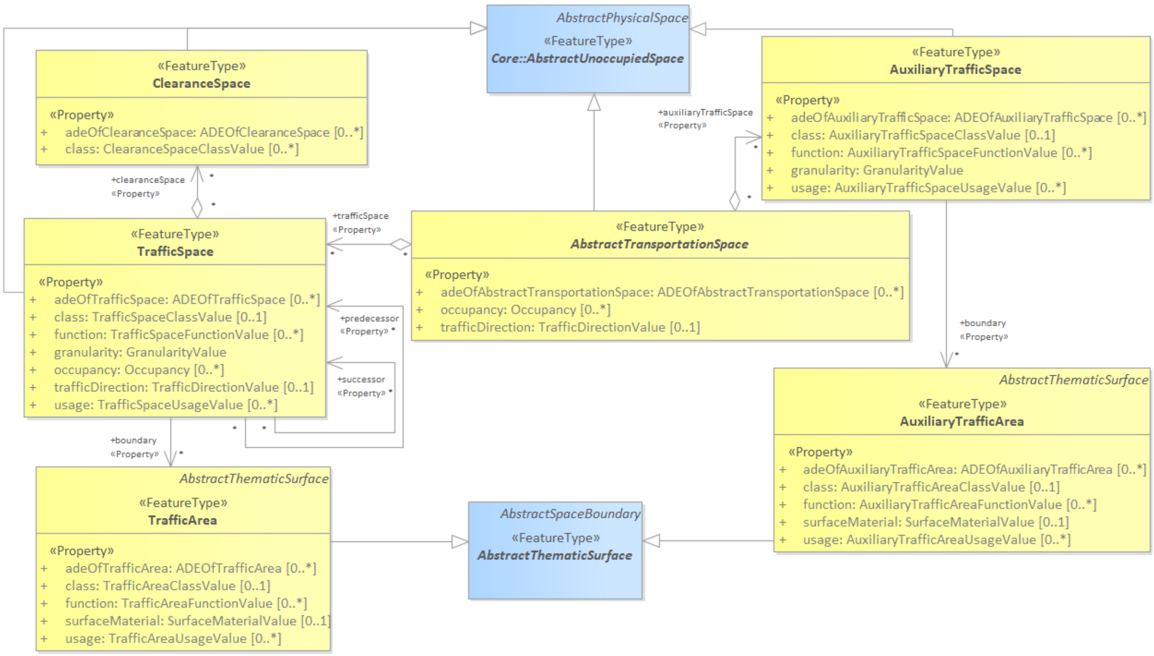


Figure 5.13: UML diagram of the class AbstractTransportationSpace consisting of AuxiliaryTrafficSpace and TrafficSpace classes bounded by AuxiliaryTrafficArea and TrafficArea classes. Additionally, a ClearanceSpace can be part of a TrafficSpace.

5.3.5 Introducing Features for detailed Surface Modelling such as Markings and Holes

Markings as well as *HoleSurfaces* are derived from the abstract class *AbstractThematicSurface* introduced in CityGML 3.0. The classes *Hole* and *Marking* are both part of the class *AbstractTransportationSpace* (Kolbe et al., 2021). Both classes provide concepts for modelling detailed surface structures, which can be modelled independently from underlying road surface objects and are explained in more detail in the following sub-chapters.

5.3.5.1 Modelling Markings

Markings are defined as "a visible pattern on a transportation area relevant to the structuring or restriction of traffic" (Kolbe et al., 2021) and are modelled by an individual class representing additional surfaces independent of the level of granularity. Examples include road markings as well as markings associated with other types of transportation such as railway or waterway traffic. *Markings* can span over multiple *(Auxiliary)TrafficSpaces* and thus lie in the same plane as road objects (see figure 5.14). It is possible to link *Markings* to a corresponding *TrafficArea* via a *CityObjectRelation* (e.g. to indicate the validity of a marking for a certain lane). Colored surfaces (e.g. a red or green bicycle path) should not be modelled as *Marking* objects but rather as corresponding *TrafficAreas* with a suitable color or texture. Depending on available information generalized representations of *Markings* as linear abstractions or point geometries are allowed. The exact shape of *Markings* such as individual arrows can be derived from images or from point clouds making use of different intensity values.

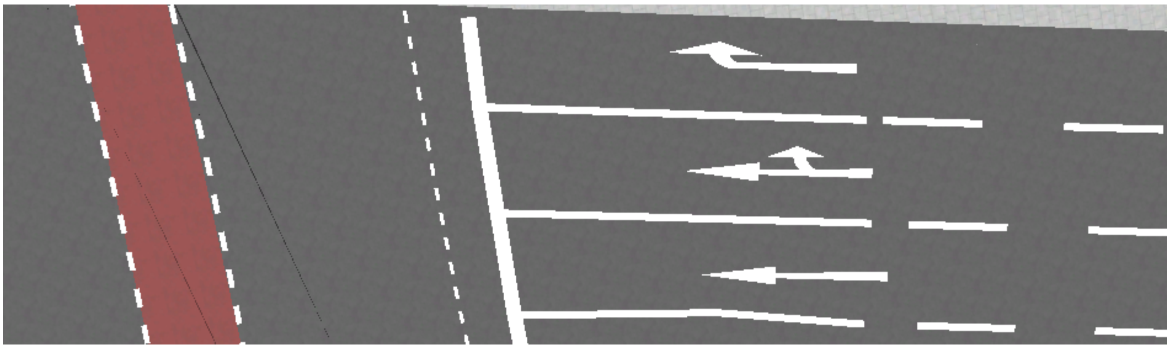


Figure 5.14: Different types of Markings including stop lines, dashed lines or arrows (Beil et al., 2023)

As displayed in figure 5.15, *Markings* should be rendered on top of road surfaces in order to avoid potential z-fighting with other objects or the terrain, which can cause flickering or unwanted visual effects within visualizations.

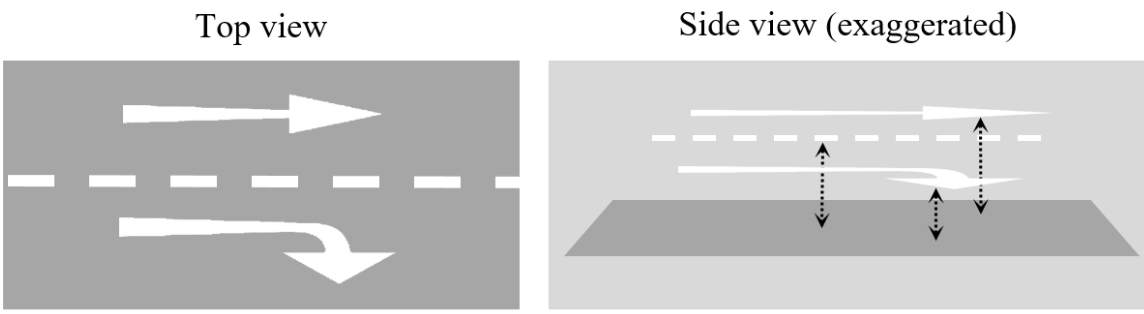


Figure 5.15: Markings rendered slightly above the ground in order to avoid z-fighting.

5.3.5.2 Modelling Holes in a Road's Surface

Holes are defined as "openings in the surface of a *Road, Track* or *Square* such as road damages, manholes or drains" (Kolbe et al., 2021), that can span over multiple transportation objects. In contrast to *Markings*, *HoleSurfaces* representing the ground surface of a hole should be modelled as cut out *ClosureSurfaces* in a *TrafficArea* represented by *MultiSurface* geometries. Locations of manholes are often only gathered with respect to coordinates of their center point, thus point geometries are also possible to represent *Holes*. Polygonal representations can be derived using information on measured (or assumed) radius. *Class* attribute values to further classify *Holes* (e.g. manhole or roadway damage) are proposed in appendix A. A UML diagram illustrating the presented concepts of *Markings* and *Holes* as well as *HoleSurfaces* is illustrated in figure 5.16.

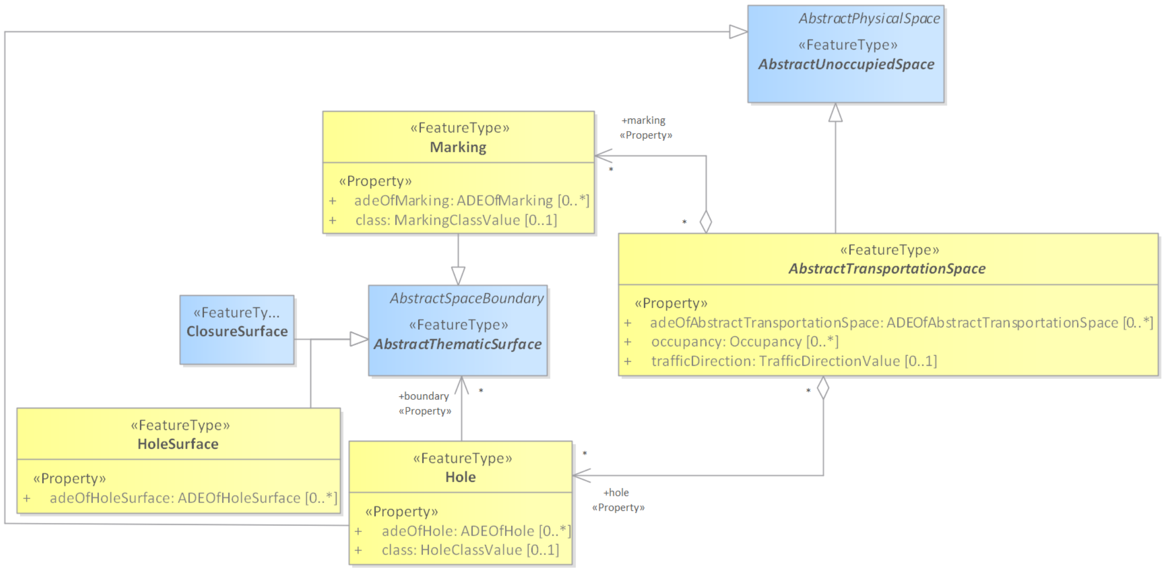


Figure 5.16: UML diagram of the classes Marking and Hole modelled as AbstractTransportationSpaces. Holes are bound with HoleSurfaces.

5.3.6 Modelling Tracks

Tracks are defined as "small paths mainly used by pedestrians, that are independent from roads such as footpaths within a park" (Kolbe et al., 2021). The concept of modelling *Tracks* already existed in CityGML 2.0 and remains in the revised data model of CityGML 3.0 utilizing respective newly introduced concepts. Similar to *Roads*, *Tracks* can be segmented into *Sections* and *Intersections* with corresponding *(Auxiliary)TrafficSpaces* bounded by *(Auxiliary)TrafficAreas* and contain multiple *function* and *usage* as well as a *class* attributes.

5.3.7 Modelling Railways

The concept of modelling *Railways* to represent train and other rail-bound infrastructure already existed in CityGML 2.0. Similar to *Roads*, *Railway* can be segmented into *Sections* and *Intersections*.

The concepts of *(Auxiliary)TrafficSpaces*, *(Auxiliary)TrafficAreas*, *ClearanceSpaces*, *Holes* or *Markings* also apply to railway infrastructure. *Railway* switches, for example can be represented using *Intersection* objects. The level of granularity concept described in section 5.2.2 can also be transferred to *Railways* with representing entire rail beds or individual rail tracks. Concepts for a combined modelling of railway and road infrastructure are given in chapter 5.8.2.1. However, defining more specific concepts for modelling railway infrastructure independently using concepts of CityGML 3.0 is out of the scope of this thesis.

5.3.8 Modelling Waterways

The requirement for representing waterways as additional mode of transportation was discussed by Labetski et al. (2018). While representations of a *WaterBody* were available in CityGML 2.0 already, CityGML 3.0 introduces *Waterways* in order to be able to represent waterways used for traffic. *Waterways* usually are the part of a *Waterbody* that is intended for usage by ships, vessels or other maritime transportation types. Cities such as Amsterdam or Venice rely on canals as an additional means of transportation in addition to road and railway networks. These water-based transportation networks can be modelled using the same semantic, geometric and topological concepts described for road and railway infrastructure, including *Sections, Intersections* or *TrafficSpaces* with linear, areal or volumetric representations. Similar to road networks, waterway networks can be modelled using linear geometries. Areal representations of *TrafficAreas* corresponding to *WaterSurfaces* are also possible. Figure 5.17 shows an instance diagram of *WaterSurfaces* part of a *WaterBody*, which are linked to *TrafficAreas* part of a *Waterway* using CityObjectRelations with the value 'equal'. This indicates, that the respective surface is part of both top-level features simultaneously. The presented *Section* and *Intersection* concept also applies to *Waterways*.

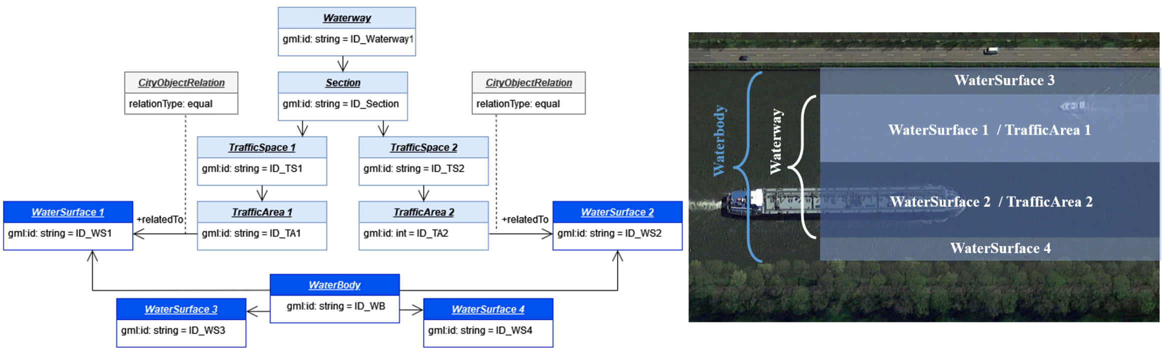


Figure 5.17: Instance diagram of a WaterSurfaces of a WaterBody, which are simultaneously modelled as TrafficAreas belonging to a Waterway. CityObjectRelations are utilized to express the relations between these surfaces. An example illustrating this scenario is given on the right.

A UML diagram illustrating the concept of modelling *Tracks, Railways* and newly introduced *Waterways* consisting of *Sections* and *Intersections* is illustrated in figure 5.18.

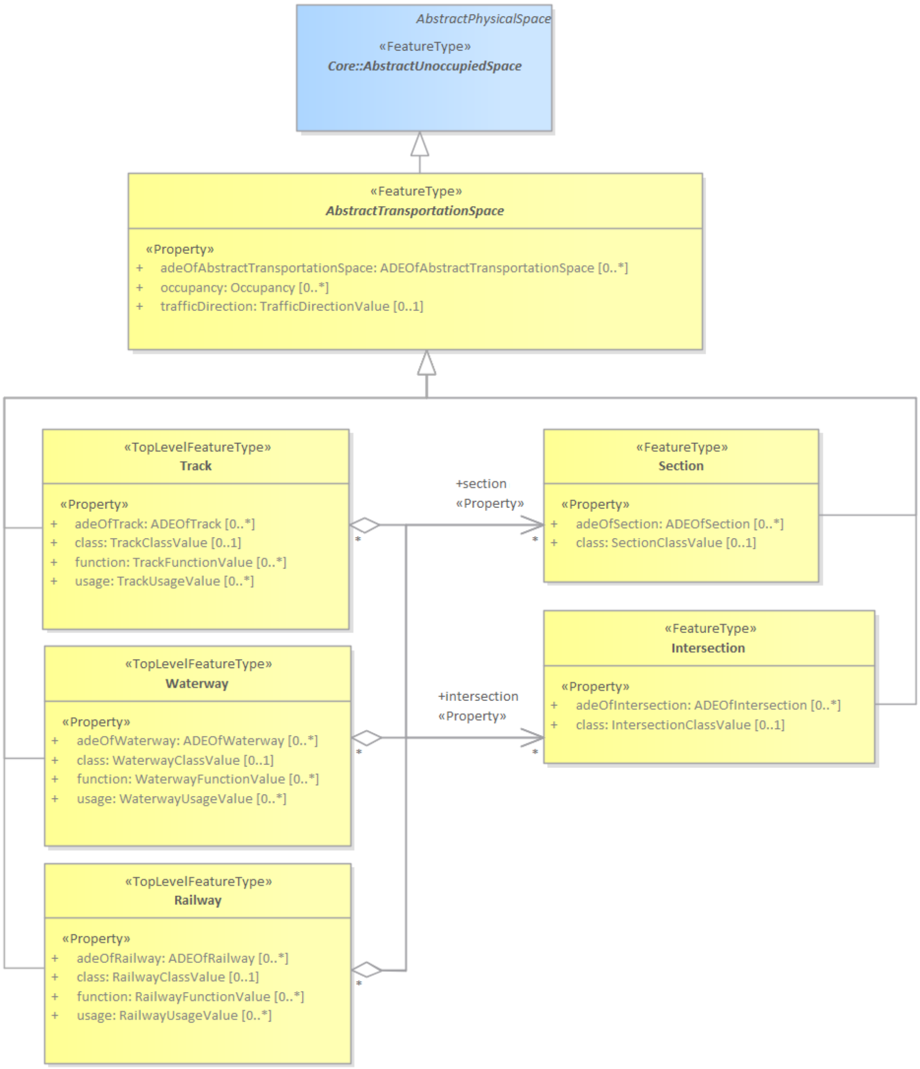


Figure 5.18: UML diagram of the classes Track, Waterway and Railway modelled as AbstractTransportationSpace which can be segmented into Sections and Intersections.

5.3.9 Modelling large sealed Surfaces as Squares

A *Square* is defined as "a transportation space for unrestricted movement of vehicles, bicycles and/or pedestrians. This includes plazas as well as large sealed surfaces such as parking lots or gas stations" (Kolbe et al., 2021). *Squares* are not segmented into *Sections* and *Intersections* but can be segmented into individual *(Auxiliary)TrafficSpaces* bounded by respective *(Auxiliary)TrafficAreas*. Individual parking slots within a bigger parking lot, for example, can be modelled as individual *TrafficAreas*. *TrafficSpaces* within *Squares* can be connected to *TrafficSpaces* part of the regular road network using the predecessor and successor concept explained in chapter 5.5.2. The newly introduced attribute *occupancy* can be used to indicate if parking slots are occupied with parking cars. Similar to transportation networks, areal as well as linear representations of *TrafficSpaces* and

TrafficAreas within a *Square* are possible. A corresponding UML diagram of the class *Square* modelled as *AbstractTransportationSpace* is illustrated in figure 5.19.

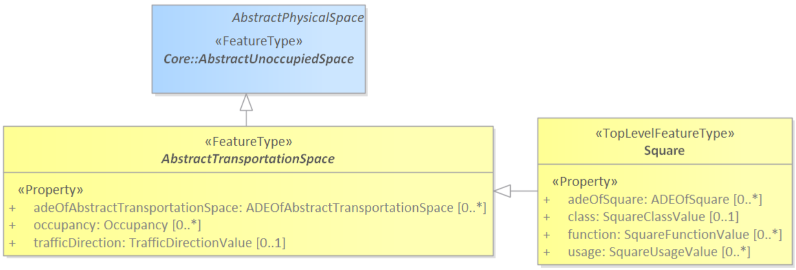


Figure 5.19: UML diagram of the class Square modelled as sub-class of AbstractTransportationSpace.

5.3.10 Modelling Traffic Signs, Traffic Lights and other CityFurniture objects

The CityGML 3.0 *CityFurniture* module is introduced in chapter 4.3.2.3. *CityFurniture* objects can contain *class, function* and *usage* attributes. Values for these attributes were defined in a codelist in the CityGML 2.0 specification, which can be used as a guideline. Many countries use standardized codes to identify different types of traffic signs (e.g. illustrated in figure 5.20 with values to represent different traffic sign types used in Germany).

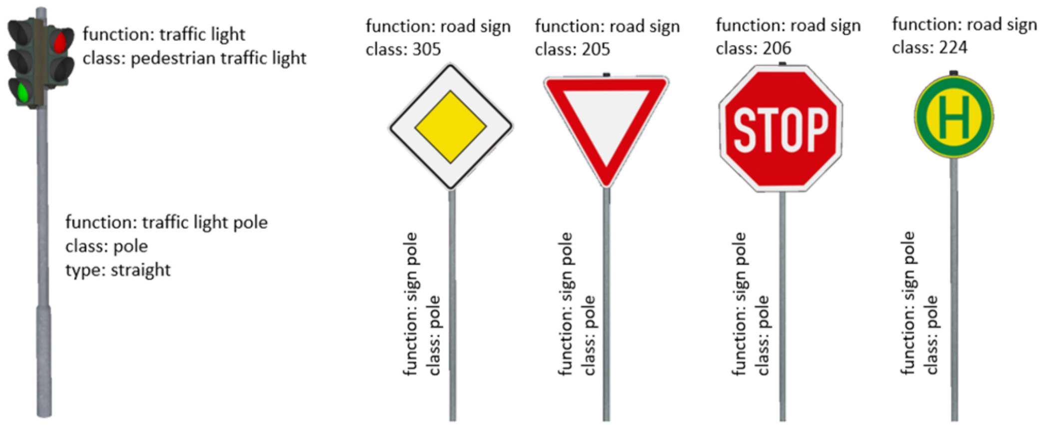


Figure 5.20: Traffic signs and traffic lights with corresponding poles modelled as individual CityFurniture objects (Beil et al., 2023).

It is recommended to use these codes as class attributes with each traffic sign object. Traffic signs can be modelled as one object or separated into individual poles and the actual traffic sign. Multiple logically connected objects (such as all signs and traffic lights connected to one pole) can be part of a *CityObjectGroup*. These objects are typically represented using prototypes that are instantiated several times at various locations (implicit geometries). However, it is also possible to model these objects using a simple point or other more abstract geometric representations. A proposal for modelling city furniture in the context of digital road models in several levels of detail is given in Crampen et al. (2024b). As illustrated in figure 5.21, *CityFurniture* also may include objects such as bike racks, bins, ticket machines or small bus stops (which are not big enough to be considered a building object).

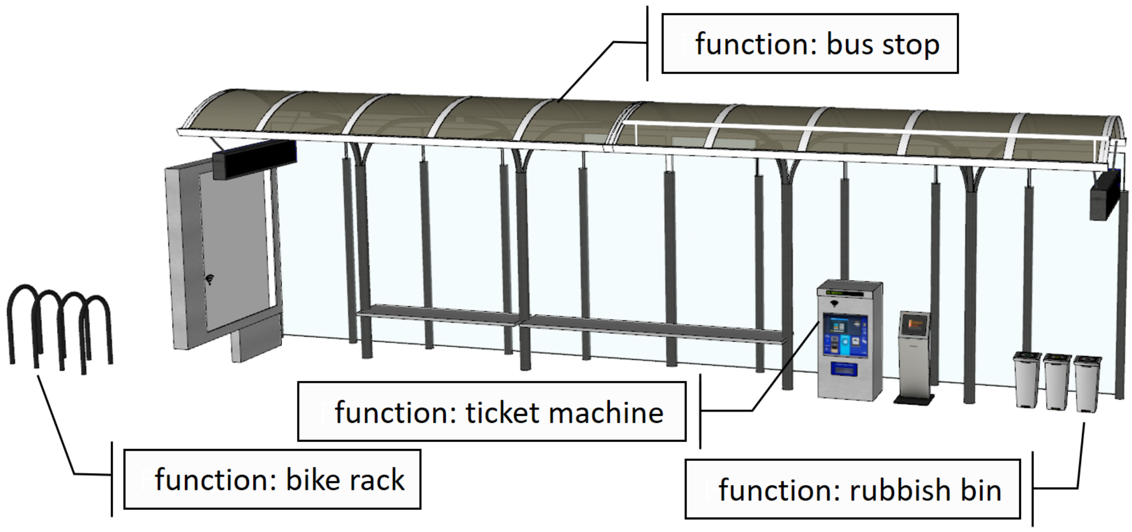


Figure 5.21: CityFurniture objects with different functions such as bus stops or bike racks (Beil et al., 2023).

5.4 Geometric Concepts

The most important geometric concepts of CityGML 3.0 are already explained in section 4.3.2. Spatial properties of all CityGML feature types are represented using the geometry classes defined in ISO 19107 (2019), which are presented in detail in sub-chapter 4.2.3. Spatial representations can have 0-, 1-, 2-, or 3-dimensional extents depending on the respective feature type and Levels of Detail. Geometric types especially relevant for modelling roads include (but are not limited to) *MultiCurves* (which include linestrings, arcs, clothoids, polynomial splines), *MultiSurfaces*, *Solids*, *MultiPoints* and further geometric types specified in ISO 19107 (2019). The following sub-chapters further specify geometric modelling concepts with regard to representations of road infrastructure.

5.4.1 Coordinate Reference Systems

3D coordinates are used to represent almost all CityGML objects. Individual points, as well as those points defining the boundaries of surfaces and solids are defined by three coordinate values (x,y,z) each. These coordinates are typically specified in relation to a Coordinate Reference System (CRS), ensuring a specific connection to a location on Earth using absolutely georeferenced real-world coordinates. This is especially important for large infrastructure objects such as roads or railways in order to take into account the Earth's curvature. This also allows a direct and efficient management of the data in GIS systems and spatial geodatabases. In most CRS, the (x,y) coordinates refer to the horizontal position of a point on the Earth's surface. The z-coordinate typically refers to the vertical height over (or under) the reference surface.

5.4.2 Levels of Detail (LoD)

There are different concepts and definitions of 'LODs' in various domains. Abualdenien and Borrmann (2022) give an overview on this issue presenting concepts of 'Level of Development' commonly used in the BIM domain to describe the completeness of information in different project stages, as well as 'Levels of Detail' as commonly used in the GIS domain for describing (mostly) geometric detail. Crampen and Blankenbach (2023) and Crampen et al. (2024b) further investigate different LOD concepts with respect to models of road infrastructure taking into account geometric (LoGR) as well as semantic (LoSG) aspects and introducing a 'Level of as-is Detail for digital twins' (LOADt) concept including levels of semantic and geometric uncertainty.
The following concepts are in accordance with the newly introduced LOD concept of CityGML version 3.0. As described in sub-chapter 4.3.2.1, CityGML 3.0 differentiates four Levels of Detail (LOD 0-3) defined within the *Core* module. While LOD definitions in CityGML 2.0 also corresponded to the level of semantic decomposition (which is transferred to the level of granularity concept explained in sub-chapter 5.2.2), the definitions of LODs in CityGML 3.0 only correspond to geometric detail. This means, that spaces such as *TrafficSpaces* and space boundaries such as *TrafficAreas* can be represented with different geometric representations. The LOD is not associated with an object's appearance such as textures. Table 5.1 shows all available geometric representations for spaces and space boundaries in each LOD. Highlighted in green are geometric representations that are recommended to be used respectively.

Table 5.1: Available geometry types in different Levels of Detail (LOD) for space and space boundary representations. Most relevant geometry types for transportation objects are highlighted in green.

	LOD 0	LOD 1	LOD 2	LOD 3
Spaces **e.g. TrafficSpaces**	*Point* *MultiCurve* *MultiSurface*	*Solid*	*MultiCurve* *MultiSurface* *Solid*	*MultiCurve* *MultiSurface* *Solid*
Space Boundaries **e.g. TrafficAreas**	*MultiCurve* *MultiSurface*	*MultiSurface*	*MultiCurve* *MultiSurface*	*MultiCurve* *MultiSurface*

Spaces for example should be represented geometrically using *MultiCurves* in LOD 0. Depending on the corresponding Level of Granularity this may correspond to generalized road, carriageway or lane centerlines. *Point* representations, e.g. to represent each *(Auxiliary)TrafficSpace* with its centerpoint or *MultiSurface* representation are also possible. Spaces in LOD 1 should be represented using *Solid* geometries, which represent the volumetric extent of *(Auxiliary)TrafficSpaces* and can be derived from simple extrusions of their footprint (which correspond to respective *(Auxiliary)TrafficAreas)*. Similar to *Buildings*, higher LODs of *(Auxiliary)TrafficSpaces* correspond to more detailed and accurate geometric representations. In LOD 2 and 3, for example, representations of *(Auxiliary)TrafficSpaces* may be adapted to reflect obstacles such as vegetation or city furniture. The geometric *MultiCurve* representations in LOD 2 and 3 also corresponds to a higher degree of geometric accuracy. While the

representation of *(Auxiliary)TrafficSpaces* using *MultiCurve* geometries in LOD 0 might only be accurate within several meters (e.g. OSM centerlines), higher LODs imply a more accurate trajectory down to centimeters. Since *MultiCurve* representations include geometric shapes such as arcs, clothoids, spirals or splines, these geometric primitives are also available to represent *(Auxiliary)TrafficSpaces* in LOD 0, 2 and 3.
For *TrafficAreas* and *AuxiliaryTrafficAreas* the usage of *MultiSurface* geometries to model the actual surface of these objects is recommended. Examples for applying the LOD concept for *TrafficAreas* and *AuxiliaryTrafficAreas* using *MultiSurface* representations are defined in the following section and illustrated in figure 5.22.

LOD 0 - *MultiSurface* representation of *TrafficAreas* and *AuxiliaryTrafficAreas*
In LOD 0 *(Auxiliary)TrafficAreas* can be represented using *MultiSurface* geometries that are potentially adapted to a (generalized) digital elevation model (e.g. with a resolution of 1 meter). This typically does not reflect detailed geometric shapes such as individual sidewalks, curbs or traffic islands in detail.

LOD 1 - *MultiSurface* representation of *TrafficAreas* and *AuxiliaryTrafficAreas*
In addition to the adaption of road surfaces to the terrain, subtle geometric features such as curbs or traffic islands can be modelled. In LOD 1, these structures can be created by extruding respective *(Auxiliary)TrafficAreas* by a certain amount (e.g. 0.15 cm for sidewalks). Since solid geometries are not available for space boundaries, *MultiSurface* geometries are recommended for these objects. These geometric details can be more easily generated, however are often not entirely true to reality since features such as continuously lowered curbs are not represented.

LOD 2 - *MultiSurface* representation of *TrafficAreas* and *AuxiliaryTrafficAreas*
In LOD 2, roads are modelled geometrically including objects such as raised sidewalks or lowered cubs with more exact approximations. Instead of representing these subtleties with fixed vertical extrusions, the actual shape is approximated. In order to accurately model these features, typically detailed data sources such as high-resolution point clouds (e.g. from mobile mapping) are required an used for fitting surfaces representing these objects.

LOD 3 - *MultiSurface* representation of *TrafficAreas* and *AuxiliaryTrafficAreas*
Modelling road objects such as road surfaces, raised sidewalks or lowered curbs with more exact (e.g. sub-centimeter) triangulated mesh surfaces typically derived from laser scanning data is possible in LOD 3. E.g. individual shapes of cobblestone bricks are represented. In this case, typically highly-detailed data such as high-resolution point clouds are directly converted into mesh geometries and triangulated.

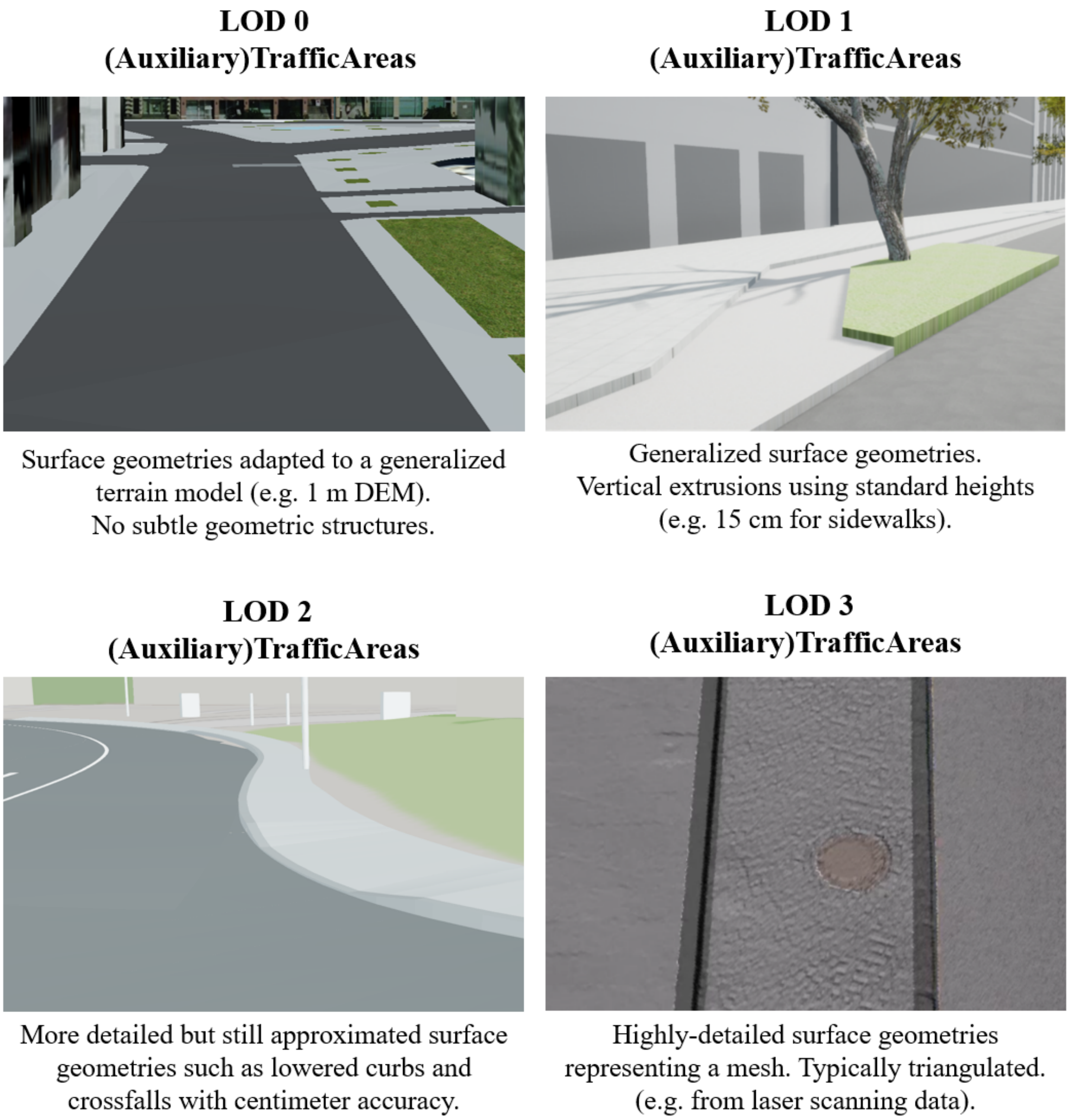


Figure 5.22: *TrafficAreas* and *AuxiliaryTrafficAreas* in different geometric levels of detail using *MultiSurface* representations.

Since the revised LOD concept is no longer associated with semantic segmentation of city features, the three level of granularity (area, way and lane) previously introduced can be combined with the four LODs presented in this sub-chapter. A road surface of an entire *Section* represented by a highly-detailed mesh for example, which is not further semantically segmented into individual carriageways or lanes, corresponds to a geometric representation in LOD 3 with level of granularity 'area'. Conversely, a road semantically segmented into individual lanes, which are only draped over a digital elevation model of 1 meter and thus contain few geometric details, would correspond to a representation in LOD 0 with level of granularity 'lane'. Thus the highest geometric and semantic combination achievable is a highly-detailed mesh representation of roads additionally semantically segmented into individual lanes (LOD 3 + granularity = 'lane'). Figure 5.23 shows a direct comparison of a representation of a road section in LOD 3 in multiple levels of granularity. The detailed geometric information of a mesh derived from laser scanning data is the same in each case. However, the semantic decomposition increases with increasing level of granularity. While in level of granularity 'area' the entire *Section* is represented with one continuous surface representation, this surface is semantically decomposed into an individual carriageway, sidewalks, parking areas and curbs in level of granularity 'way'. In level of granularity 'lane' the carriageway is further segmented into individual driving lanes.

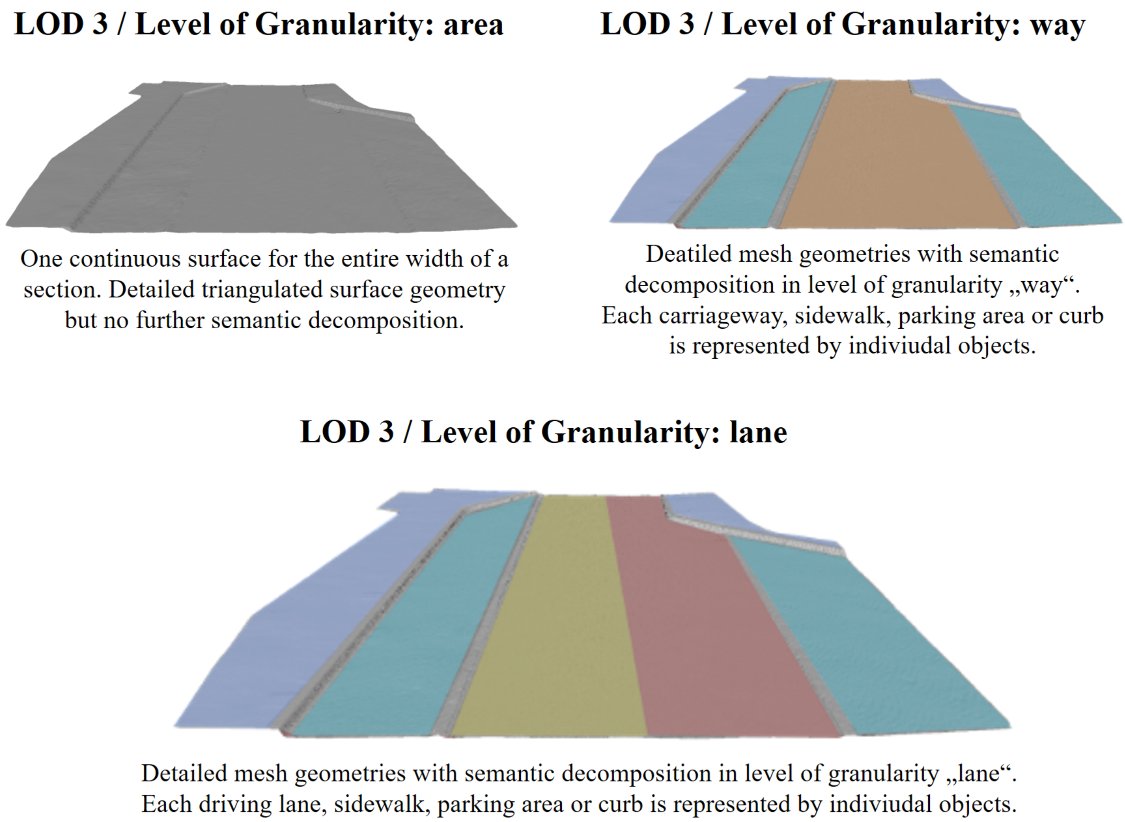


Figure 5.23: Comparison of a road section represented in LOD 3 (detailed triangulated surface geometry, typically generated from laser scanning data) in several semantic levels of granularity. The geometric level of detail is identical in every example. Semantic levels of granularity are increasing with increased semantic decomposition.

Löwner et al. (2016) argue, that due to the flexibility of this LOD concept, *Profiles* making clear recommendations on how to apply these concepts for certain objects should be defined. Table 5.2 shows which geometric (Level of Detail) and semantic (Level of Granularity) concepts of the CityGML 3.0 Transportation module can be used to ensure backwards compatibility with concepts of CityGML 2.0.

Table 5.2: Profile of classes of the CityGML 3.0 Transportation module for backwards compatibility with CityGML 2.0 (similar to profiles for the *Building* module presented by Löwner et al. (2016))

	LoD 0	**LoD 1**	**LoD 2 / LOD 3**
Road	*MultiCurve:* Representation of a Road in granularity 'area', 'way' or 'lane'	*MultiSurface:* Surface representing the shape of roads in granularity 'area' or 'way'.	*MultiSurface:* Aggregation of TrafficAreas and AuxiliaryTrafficAreas in granularity 'lane'.
TrafficArea	Not available.	Not available.	*MultiSurface:* Surface representing the shape of road parts such as driving lanes intended for traffic in granularity 'lane'.
AuxiliaryTrafficArea	Not available.	Not available.	*MultiSurface:* Surface representing the shape of road parts not intended for traffic in granularity 'lane'.

5.4.3 Adaption to 2.5D and 3D using Digital Terrain and Surface Models

While 2.5D or 3D representations are required for a number of use cases, information on road infrastructure is often only provided as planimetric 2D data. For adapting this data to the terrain it is recommended to create a terrain with breaklines of individual *(Auxiliary)TrafficAreas*. On the one hand, simply draping 2D polygons over a digital terrain model will result in non-planar surfaces, which is not sufficient. Re-triangulating surfaces after this process on the other hand will alter the geometry of the original terrain model and thus might provide inaccurate results. Thus, a process for creating an adapted terrain model while staying close to the original surface representations is introduced. Triangles of this new terrain, that are part of individual *(Auxiliary)TrafficAreas*, can then be used to represent the geometry of semantic road surfaces. Robles-Ortega et al. (2013) present an approach for adapting 2D GIS data on roads to the terrain. A similar process is illustrated in figure 5.24. Sub-figure (a) shows a semantic 2D streetspace model including individual and non-overlapping *TrafficAreas* and *AuxiliaryTrafficAreas*. The boundaries of theses objects are derived (b) and draped over a corresponding 2.5D elevation model (c / d). The underlying digital elevation model should have a resolution of at least 1 meter. The draped boundaries of each feature are then incorporated as breaklines into the 2.5D surface model generated from the elevation data and triangulated in order to produce a new digital terrain model including breaklines of road objects (e). In a next step, the adapted surface model is deaggregated into individual triangles with unique IDs. Then internal centerpoints for each triangle are calculated (f) while keeping the ID of corresponding triangles. Each centerpoint is then projected onto a 2D plain and overlayed with the 2D *(Auxiliary)TrafficAreas*. Information on *gml:id* values and other semantic information of each *(Auxiliary)TrafficAreas* are then transferred to the projected centerpoints (g). In a final step, the semantic information now available with each centerpoint are transferred to corresponding 2.5D triangles using the identical unique IDs previously created. After then aggregating all triangles with the same *gml:id* attribute, semantically enriched 2.5D objects which are as close to the original elevation information as possible are the result of this process (h). Depending on the resolution of the original elevation data, road surface models in different LODs can be created using this process. In case the original DEM represents elevation data with e.g. 1 meter resolution, resulting 2.5D models could be considered to represent LOD 0. Highly-detailed mesh models (e.g. generated from mobile mapping) might provide detailed geometric information on road surfaces (down to sub-centimeter level), which can also be used for providing (highly detailed) elevation information, which then should be considered LOD 3.

The process described so far mainly relies on 2.5-dimensional elevation data. In order to produce true 3D models, e.g. representing complex interchanges with roads on multiple levels or below the ground, more detailed 3D information is required. Developing and implementing such (automatic) processes is part of ongoing research.

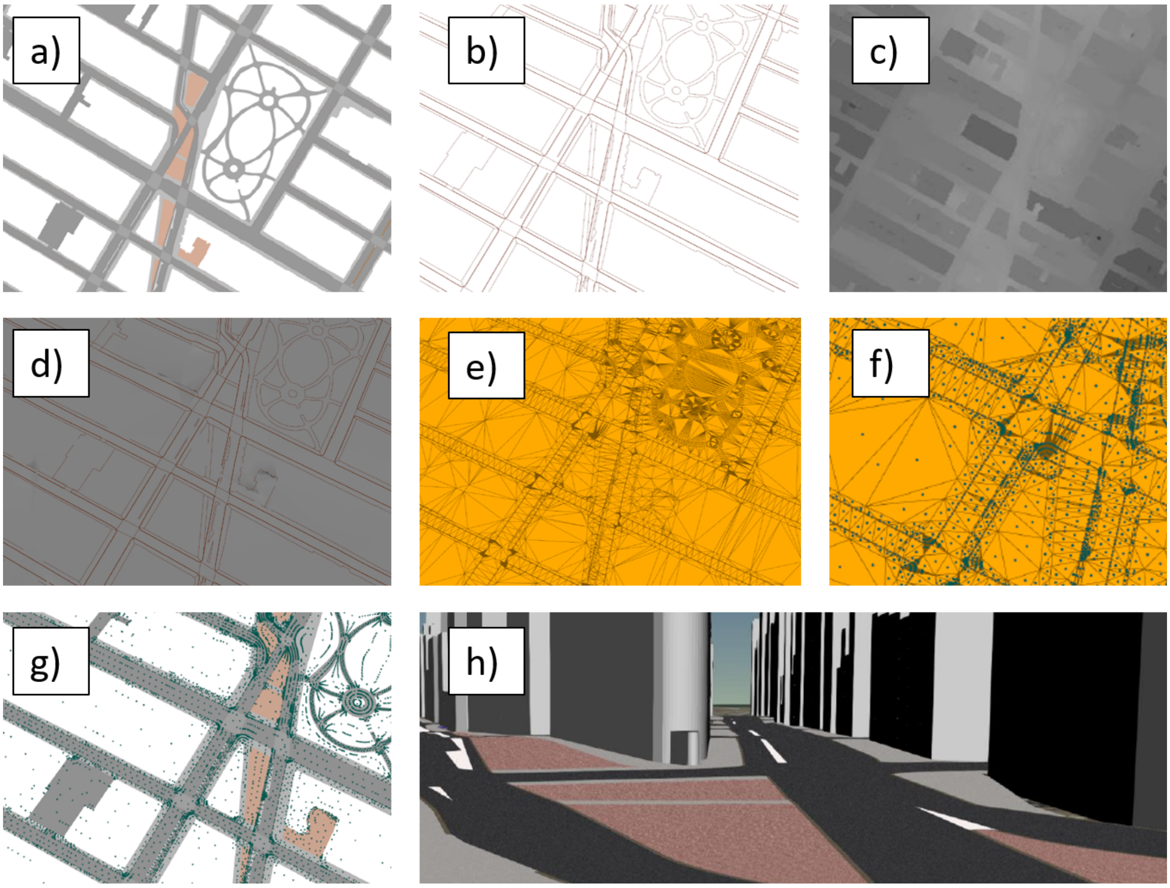


Figure 5.24: Adaption of road surfaces (*TrafficAreas*) to the terrain using breaklines, triangulations and transfer of semantic information (Beil et al., 2023).

5.4.4 Consistency between different geometric Representation Types

Some use cases depend on consistent representations of street networks using multiple geometries (Tamminga, 2019). Boersma (2019) identified missing affiliations between areal and linear representations of the same scenario. Potential matching problems of identical scenarios represented in different ways are displayed in figure 5.25[11]. The left part of the image shows a possible representation of intersecting *Roads* in granularity = area. This scenario could be modelled using three lines representing each street *Section* and meeting in one *Intersection* point. A surface-based model on the other hand could include three *Sections* and one *Intersection* area. In order to generate a consistent model for linear as well as areal models, additional breaking points (represented in yellow within the right image of figure 5.25) should be introduced to split linear representations to match the underlying segmentation into *Sections* and *Intersections*. In this case, three linear representations belong to the same *Intersection* object.

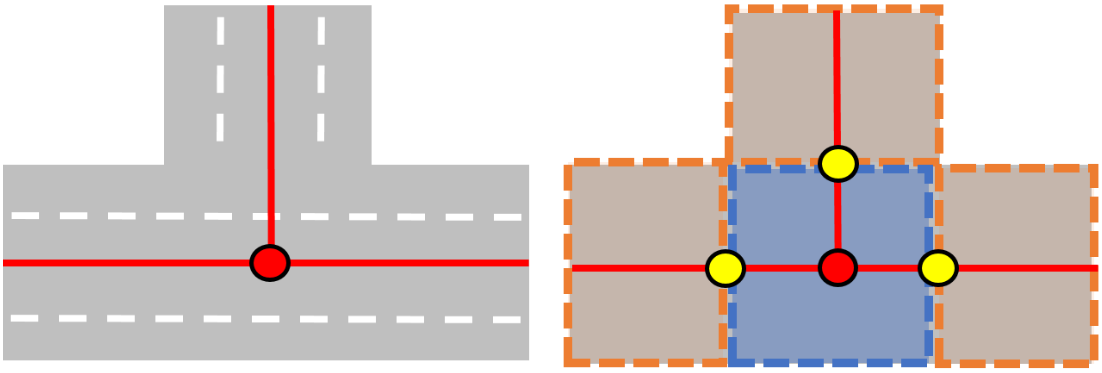


Figure 5.25: Potential inconsistency between linear and areal representation of road sections and an intersection in granularity area and proposed solution.

Figure 5.26 illustrates the same principle with a representation in granularity 'lane', where traffic directions of each lane are indicated with red arrows. Here, individual *TrafficSpaces* are represented with linear geometries, which are split at borders of adjacent *Sections* and *Intersections* and at any point where traffic can switch lanes or take a turn (indicated with yellow dots). Note, that intersections of lines where e.g. cars cannot take a turn, linear representations are not split. The underlying surface-based representation is segmented in such a way, that it is possible to aggregate areal representations for any corresponding linear representation of individual paths a car can take. This means that surfaces are not overlapping and thus geometrically redundant surface-based representations are avoided (which is important e.g. for quantity take-off measurement use cases). This is demonstrated in the right-most part of figure 5.26 for one continuous path of several linear *TrafficSpaces* and a corresponding surface-based representations of several *TrafficAreas*. Since multiple geometric representations per feature are allowed, one *TrafficSpace* can be represented with a linear and a volumetric representation simultaneously.

[11]Note: Yellow dots are meant to indicate points where linear objects should be split in order to achieve consistency with areal representations. *Sections* themselves could also be represented using point geometries, however, in this case the centerpoint of each *Section* should be represented.

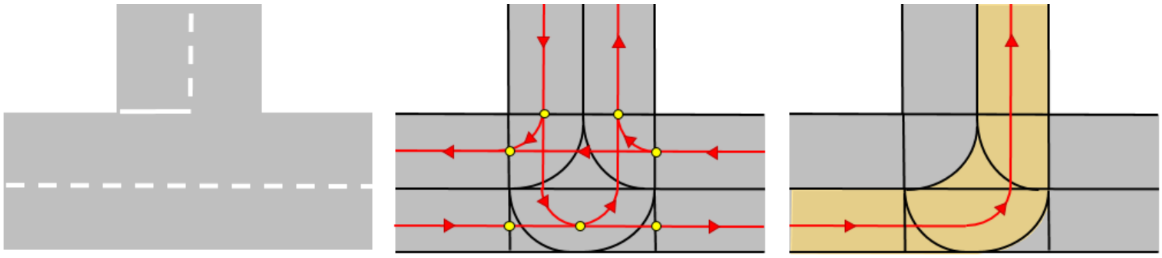


Figure 5.26: Non-redundant surface-based representation of driving lanes and consistent linear representations within an Intersection and adjacent Sections.

Figure 5.27 further demonstrates this principle for all possible traffic paths within this *Intersection*. This however might result in a highly-fragmented representation of many small surfaces. Thus, in case a certain use case does not require a consistent linear and surface-based representation, it is recommended to use a linear representation for modelling lane-level turnings within *Intersections*, while modelling surfaces within *Intersections* aggregated by traffic type (e.g. one continuous surface usable by cars for the entire *Intersection*). In principle, it is also allowed to model each surface-based representation illustrated with yellow surfaces in figure 5.27 individually, which results in overlapping geometries but ensures a clear consistency between linear and surface-based representations. Depending on the requirements of intended use cases, either of the presented modelling strategies is possible.

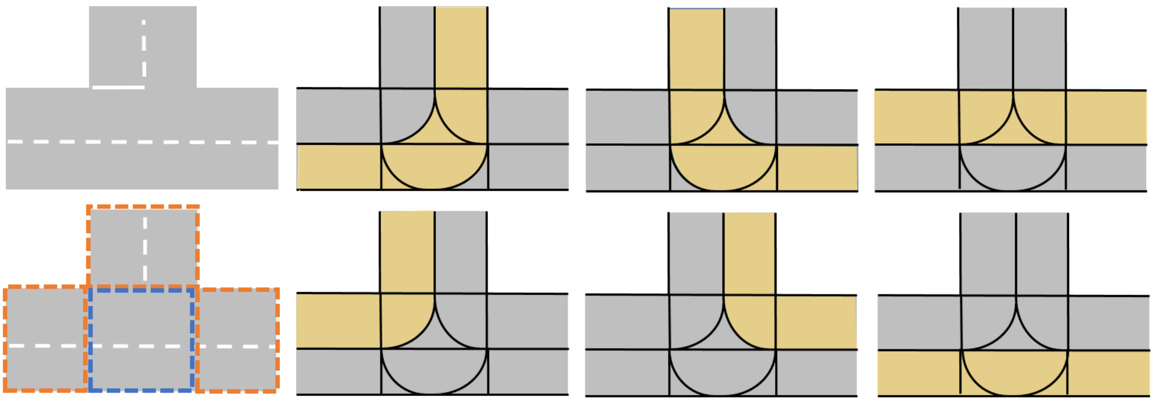


Figure 5.27: Non-redundant surface-based representation of TrafficAreas within an Intersection and adjacent Sections.

5.4.5 Modelling the Streetspace using (semantically enriched) Point Clouds

Point clouds are commonly described as a collection of 3D points, with each point denoted by x-, y-, and z- coordinates and possibly supplemented with extra details such as color (e.g. RGB values), intensity or other characteristics. Commonly used standards for representing point cloud information such as LAS typically provide very limited semantic capabilities such as assigning classification codes to points (ASPRS, 2018). LAS does not provide any concepts for semantic object structures such as hierarchies or aggregation. One of the reasons for the popularity of the LAS format is its simplicity and easy-to-use structure. While in principle, extending LAS point data records with additional user-defined attributes (using extra bytes) is possible, there are no guidelines for making use of this concept in the context of extended semantic capabilities. Furthermore, software tools likely will not be able to interpret these additional attributes. Since attributes can only be assigned to points, the LAS format is not capable of storing information on objects that are not represented with at least one point. As described in section 4.3.2.3, CityGML 3.0 contains a newly introduced *PointCloud* module for the representation of city objects including transportation infrastructure by 3D point clouds. The conceptual design of this module allows for coupling 3D city model objects such as buildings or roads with point clouds in different ways:

1. **Point clouds inline with the CityGML file:**
   The point clouds are represented inline with the city objects using *MultiPoint* geometries. In this way, each city object (e.g. *Roads* and even the individual surfaces such as *TrafficAreas*) can be complemented with its specific point cloud representation directly in the CityGML file. Due to the large file size that results from storing the points directly in the CityGML file, this approach is only recommended for data sets containing a small number of city objects, for example, for providing self-contained data sets for archiving or for homogeneous structuring in databases. This approach is not recommended for larger datasets, instead there are methods for coupling CityGML objects to point cloud data stored in external (e.g. LAS) files.

2. **Reference to one external point cloud file per city object:**
   For each city object, a separate point cloud file is provided (e.g. in the LAS or LAZ format) and each city object in the CityGML file references the corresponding point cloud file. The disadvantage of this approach, however, is that this can result in a huge amount of individual point cloud files, one for each city object represented in the CityGML file.

3. **Reference to one external point cloud file for the entire scene:**
   One point cloud file is provided that contains all points from a specific area. Each point contains information to which city object the point belongs. In LAS files, this can be implemented by using the component *Point Source ID* and setting it to the same value for all points belonging to a specific city object. Each city object in the CityGML file references the point cloud file and all points with the corresponding value in the *Point Source ID* component. Listing 5.3 illustrates this approach with a CityGML *Road* object pointing to points in a corresponding LAS or LAZ file with a *Point Source ID* value of '1'. This means, that all points with this *Point Source ID* value in the linked LAS or LAZ file are associated with the respective *Road* object. This mechanism can be employed with any city object down to individual *TrafficAreas*.

   Since the *Point Source ID* can only store 16 bits, only 65,536 different values are allowed and thus, a maximum of 65,536 city objects can reference the point cloud file. This could be improved by including the component *Classification* that allows for specifying up to 256 different classes. By combining the two components, $256 \times 65,536$ different city objects can reference the point cloud file. The actual semantics of the *Point Source ID* component differs slightly according to the LAS standard, however, it is considered a reasonable option for reuse. Furthermore, it would generally also be possible to store the *gml:id* attribute of the corresponding CityGML object in an extended data field of every point. However, many point cloud tools are not yet able to deal with extended point cloud formats.

```xml
<!--XML namespaces have been omitted from this listing.-->
<core:cityObjectMember>
  <tran:Road gml:id="UUID_road">
    <!--Sections and Intersections with TrafficSpaces and
       TrafficAreas-->
    <core:pointCloud>
      <pcl:PointCloud gml:id="UUID_point_cloud">
        <pcl:pointFile>
          ..\road_pointcloud.las?idattr=point_source_id&amp;id=1
        </pcl:pointFile>
      </pcl:PointCloud>
    </core:pointCloud>
  </tran:Road>
</core:cityObjectMember>
```

Listing 5.3: CityGML XML encoding example of a Road object associated with points in a corresponding LAS file with a *Point Source ID* value of '1'.

Although each approach has its drawbacks, the huge advantage of all three approaches is that the rich semantics of CityGML 3.0 can be coupled with the simple structure of point clouds. By coupling CityGML with point clouds, there is no need to extend point cloud formats to allow for representing more semantic information, the existing semantic concepts from CityGML 3.0 can directly be used to the full extent. The concepts presented in this chapter make use of point cloud data in the LAS format; however, it is possible to apply this method to all point cloud data formats that allow the storage of additional attributes for each point. As described in Meyer and Brunn (2019), point cloud data can be managed by spatial database systems. Thus, using the concepts presented here, CityGML objects and corresponding point cloud data can also be stored and linked within a common database. A remaining challenge is the correct allocation of point cloud data (parts) with corresponding semantic 3D city models.

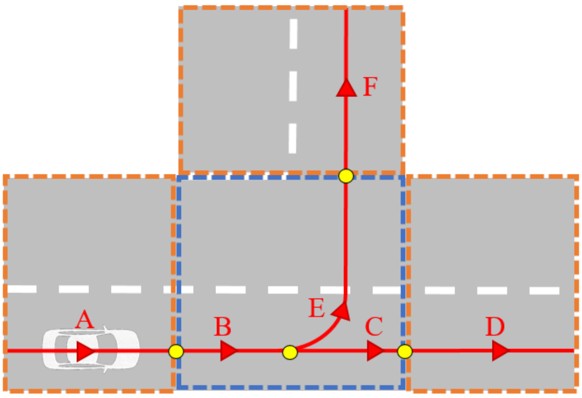
5.5 Topological Concepts

5.5.1 General topological Relations between Streetspace Objects

As described in the CityGML 3.0 specification (Kolbe et al., 2021) and explained before in chapters 3.3.4 and 4.3.2.1, topological relations between city objects can be conveyed through their shared use of geometries. This also applies to objects defined in the revised transportation module. One example given in the standard is a foot path that is part of a transportation object and a vegetation object at the same time by using a surface geometry referenced by both feature types. The explicit representations of transportation objects also allows simple adjacency evaluations such as determining driving lanes next to bicycle paths. The concept of XLinks, which are available for CityGML objects encoded in GML, and its usage for expressing topological relations of *Intersections* belonging to multiple *Roads* has also already been explained in detail. Similarly, the usage of *CityObjectRelations* for linking city and streetspace objects have been introduced and explained previously.

5.5.2 Introducing Predecessor and Successor Relations between TrafficSpaces

An explicit representation of predecessor / successor relations (regarding turning restrictions) can be modelled as shown in figure 5.28. *TrafficSpace* B for example is the successor of *TrafficSpace* A. At the same time the *TrafficSpaces* E and C are successors of *TrafficSpace* B. In this way, all possible routes from or to *TrafficSpace B* are defined. Each *TrafficSpace* also contains a *trafficDirection* attribute indicating the traffic direction relative to the order of coordinates with which the geometry is defined. This can be defined as 'forwards' (along the geometry), 'backwards' (opposite direction of the geometry) or 'both'. The given *function* and *usage* attributes indicate, that this specific *TrafficSpace* is a driving lane which is used by cars. In this example, the *TrafficSpaces* B, C and E are part of the same *Intersection*. The level of granularity in this example is equal to 'lane'. The predecessor / successor concept can also be applied in different levels of granularity and *TrafficSpaces* of different functions and usages. An example for an XML-based encoding of these relations using XLinks is given in listing 5.4.



TrafficSpace	Predecessor	Successor(s)
A		B
B	A	E, C
C	B	D
D	C	
E	B	F
F	E	

Figure 5.28: Exemplary Predecessor/Successor relations between TrafficSpaces.

```
<!--XML namespaces have been omitted from this listing.-->
<!--Road with Sections and Intersections.-->
<tran:trafficSpace>
 <tran:TrafficSpace gml:id="UUID_B">
  <lod2MultiCurve>
```

```
    <gml:MultiCurve>
     <!--Geometry definition-->
    </gml:MultiCurve>
  </lod2MultiCurve>
  <tran:function>1</tran:function>
  <tran:usage>2</tran:usage>
  <tran:granularity>lane</tran:granularity>
  <tran:trafficDirection>forwards</tran:trafficDirection>
  <tran:predecessor xlink:href="#UUID_A"/>
  <tran:successor xlink:href="#UUID_C"/>
  <tran:successor xlink:href="#UUID_E"/>
 </tran:TrafficSpace>
</tran:trafficSpace>
```

Listing 5.4: CityGML XML encoding example of a TrafficSpace with predecessor and successor relations to other TrafficSpaces implemented using XLinks.

This concept is especially relevant for functionalities employed for routing, navigational or traffic simulation related use cases. Since *TrafficSpaces* can reach within *Buildings*, this further allows a seamless integration of indoor and outdoor navigation. Additionally, multi-modal connections between different types of traffic can be established.

5.6 Temporal Concepts

5.6.1 Representing different Versions or Planning Stages

Representing different version of a 3D model e.g. during the planning stage of a road construction project or the historization of past scenarios can be important for a number of use cases (Chaturvedi et al., 2017a). As introduced in chapter 4.3.2.3, CityGML version 3.0 offers a *Versioning* module that defines concepts for representing multiple versions of a city model including road and transportation infrastructure. Detailed explanations on this versioning concept are given in (Chaturvedi, 2021).

5.6.2 Linking (near real-time) Sensor Data with Streetspace Objects

As explained in chapter 4.3.2.3, CityGML 3.0 includes a concept for semantic 3D city objects and their time-dependent properties with dynamic data sources such as sensors using *Dynamizers* (Chaturvedi and Kolbe, 2016; Chaturvedi, 2021). As depicted in figure 5.29, dynamic data provided by sensors such as induction loops, bicycle counting or air pollution sensors can be linked with corresponding *TrafficSpaces* or *TrafficAreas*. Listing 5.5 shows an XML encoding example of a traffic counting sensors linked with a specific *TrafficArea*. In this example, values stored in a generic attribute called ’TrafficCount’ are connected with information provided by a corresponding sensor for a certain time period. This information then can be periodically updated. The sensor itself (in this case an induction loop) can also be represented within the semantic 3D city model, registered with a unique *gml:id* and associated within the *Dynamizer* using the *sensorLocation* information. Gitahi and Kolbe (2024) demonstrate how this concept can be implemented in the context of semantic 3D streetspace models and give examples for visualizing time-depending properties in a web-based visualization.

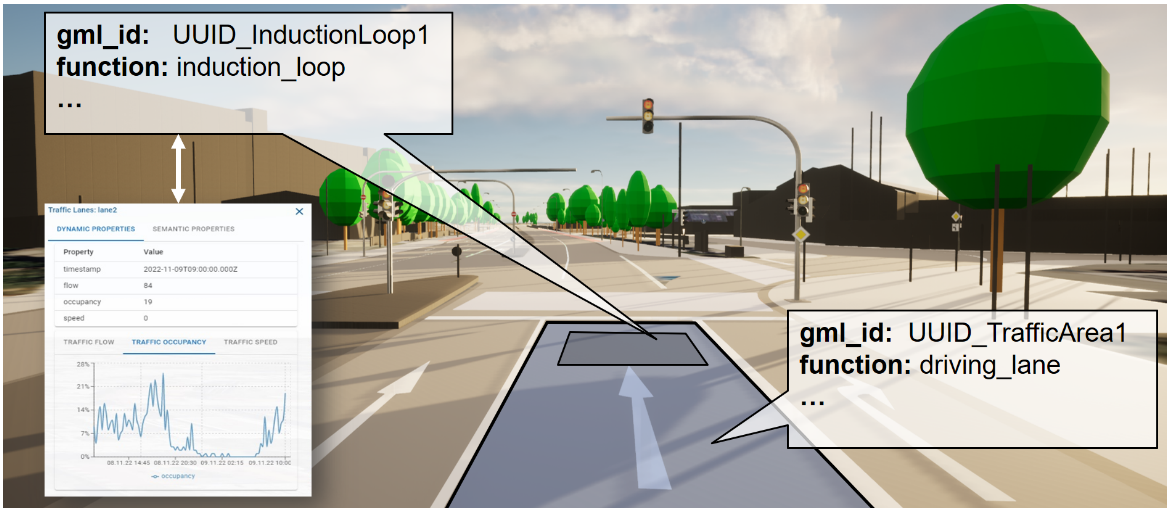


Figure 5.29: Driving lane linked with time-varying traffic occupancy data provided by an induction loop (traffic counting) sensor (Beil et al., 2023).

```
<!--XML namespaces have been omitted from this listing.-->
<!--Roads with Sections and Interections.-->
<tran:trafficSpace>
<tran:TrafficSpace gml:id="UUID_TrafficSpace1">
  <core:boundary>
  <tran:TrafficArea gml:id="UUID_TrafficArea1">
    <!--Time-varying attribute.-->
    <core:genericAttribute>
     <gen:DoubleAttribute>
       <gen:name>TrafficCount</gen:name>
       <gen:value>0</gen:value>
     </gen:DoubleAttribute>
    </core:genericAttribute>
    <!--Dynamizer-->
    <core:dynamizer>
    <dyn:Dynamizer gml:id="UUID_TrafficArea1_Dynamizer">
      <dyn:attributeRef>
        //tran:TrafficArea[@gml:id="UUID_TrafficArea1"]
        /core:genericAttribute/gen:DoubleAttribute
        [gen:name="TrafficCount"]/gen:value
      </dyn:attributeRef>
      <dyn:startTime>2024-06-26T00:00:00.000Z</dyn:startTime>
      <dyn:endTime>2024-06-26T23:59:59.000Z</dyn:endTime>
      <dyn:sensorConnection>
         <dyn:SensorConnection>
```

```
      <!--Information on the sensor connection and location.-->
      <dyn:sensorLocation xlink:href="#UUID_InductionLoop_1"/>
       </dyn:SensorConnection>
     </dyn:sensorConnection>
    </dyn:Dynamizer>
    </core:dynamizer>
    <core:lod2MultiSurface>
       <!--Geometry definition of the TrafficArea.-->
    </core:lod2MultiSurface>
    <tran:function>1</tran:function>
  </tran:TrafficArea>
  </core:boundary>
  <tran:granularity>lane</tran:granularity>
</tran:TrafficSpace>
</tran:trafficSpace>
```

Listing 5.5: CityGML XML encoding example of a TrafficSpace linked with traffic counting sensor data using the Dynamizer concept.

5.7 Visual Appearance and Visualization

As described in sub-chapter 3.3.4.2, CityGML provides an *Appearance* module for the representation of visual properties of city objects using textures or colors. In the context to models of road infrastructure, the *surfaceMaterial* attribute provides suitable information for choosing appropriate colors of synthetic textures (e.g. representing asphalt, concrete or gravel). Additionally, the *function* or *usage* attribute can be useful to identify surfaces such as bicycle infrastructure, crosswalks or bus lanes, which might also be represented using specific colors or textures. Similar to buildings textured with aerial or oblique imagery, true digital orthophotos (in high-resolutions) can directly be used to texture georeferenced road infrastructure objects with a top-down texturing approach in order to achieve a more realistic appearance.

Since CityGML is not a visualization format, it is necessary to derive formats such as 3D Tiles, glTF, COLLADA, KML or i3S from CityGML data for visualization purposes. CityGML data can be converted to formats such as KML or glTF using various open-source solutions such as the 3DCityDB, which additionally provides a tiling-mechanism for the efficient presentation of large-scale 3D city models (Z. Yao, 2020). Furthermore, ETL processes can be used to derive formats such as 3D Tiles from CityGML using the Feature Manipulation Engine (FME). While there are other open-source tools available, that can convert CityGML to 3D Tiles, tools such as py3dtilers[12] do not support transportation data so far (Marnat et al., 2022). A collection of several web-based visualizations of road and streetspace models derived from CityGML representations is available online[13].

[12]https://github.com/VCityTeam/py3dtilers
[13]https://go.tum.de/300369

5.8 Integrated and non-redundant Modelling of multiple Transportation Infrastructure

Transportation networks, especially within large cities, do not only consist of road traffic but also include other transportation types such as bikes, pedestrians, railways, trams or sometimes even waterway traffic on rivers and canals. These different transportation forms do not just coexist next to each other but often directly interact. Level crossings of road and railway infrastructure, pedestrian crosswalks or trams permanently sharing parts of a road surface with cars and other vehicles are very common within urban environments (cf. figure 5.30). Accurately modelling these multimodal transportation relations within 3D city models in a non-redundant and consistent way can be difficult. Nonetheless, it is essential in order to represent realistic real-world scenarios usable for different use cases, especially beyond navigation.

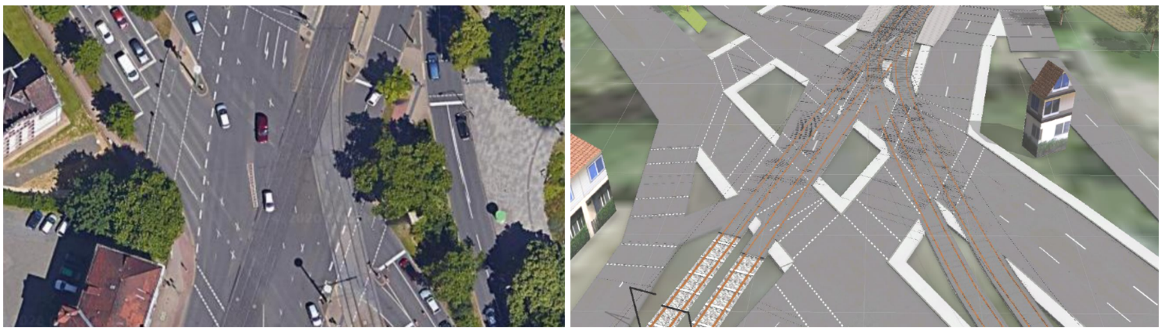


Figure 5.30: Complex intersection of roads and trams. GoogleEarth (left), model generated with the software CityEngine (right) (Gnatz, 2018).

Different geometric representations with linear graph networks, areal surface models or volumetric spaces of the same scenario should be possible depending on the intended use case. This adds another aspect to this topic since different representations of the same multimodal traffic scenario should be consistent with one another. Connections between various transportation types can be relevant for (multimodal) navigational purposes to indicate if traffic members can switch between different transportation systems. In some scenarios different transportation types may intersect, without traffic members being able to change systems. A level crossing for example may share areas used by roads as well as railways, while traffic members obviously cannot switch between the two systems. Thus, this chapter focuses on combined modelling of multiple transportation types, providing concepts for non-redundant geometric and semantic representations.

5.8.1 Modelling multiple Transportation Modes within the same Top-Level-Feature

TrafficAreas or *TrafficSpaces* can be used by multiple transportation types simultaneously or alternatively even if they are part of only one top-level feature. In this case, a *TrafficArea* or *TrafficSpace* is clearly assigned to exactly one *Road, Railway, Track* or *Waterway* object. CityGML offers the possibility to assign multiple *function* and *usage* attributes to the same *TrafficArea* or *TrafficSpace*. Figure 5.31 demonstrates this concept for an intersection with both areal and linear representations. *TrafficAreas* are colored depending on their respective CityGML *function* or *usage* attribute value(s). Each *TrafficArea* is part of a *Section* or *Intersection*. Linear representations of *TrafficSpaces* used by multiple transportation types can be represented with multiple attribute values. Together with predecessor / successor relations this allows (combined) vehicle, bicycle or pedestrian simulations. For linear representations at granularity level 'lane', however, multiple function attributes are most likely not needed, since each transportation type is represented individually. However, in case *TrafficSpace* can be used by multiple transportation types (e.g. a combined pedestrian and bicycle path) this can be also be included in the linear representation. Driving lanes (blue) bicycle lanes (red) and pedestrian sidewalks (green) are modelled with individual linear networks. Parking lanes are not shown here. In order to ensure a consistent representation of linear and areal models, linear segments should also be split at borders of *TrafficSpaces* with areal representation.

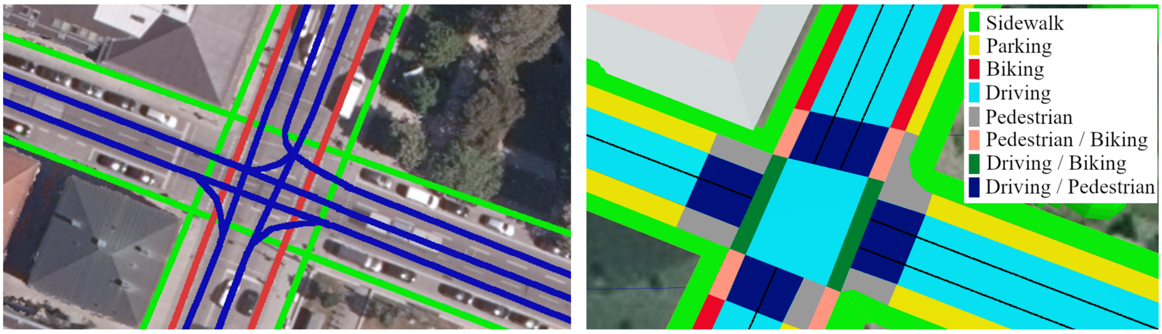


Figure 5.31: Linear and areal representation of *TrafficAreas* and *TrafficSpaces* colored by function attribute(s) (Beil and Kolbe, 2020).

5.8.2 Modelling Level Crossings of Roads and Railways

5.8.2.1 Level crossing of intersecting road and railway infrastructure

Level crossings are part of *Road* as well as *Railway* infrastructure. Thus, *TrafficSpaces* (and respective bounding *TrafficAreas*) that are part of level crossings should be linked to both feature types. Figure 5.32 illustrates a scenario of a level crossing and its areal representation. Figure 5.33 shows a corresponding UML instance diagram of this scenario. While this example explains an intersection of *Road* and *Railway* objects, this concept also applies to intersections of other transportation types such as *Track* or *Waterway*. Beil and Kolbe (2017) describe a linking concept for a non-redundant representation of geometries shared by multiple objects at the same time. The given example shows the intersection of a *Road X* and a *Railway Y* at a level crossing. *Roads* as well as *Railways* can be segmented into multiple *Sections* and *Intersections*, which again are split into individual *TrafficSpaces* and *AuxiliaryTrafficSpaces*. In the given example *Road X* consists of *Section A, Section B* and *Intersection E*, while *Railway Y* consists of *Section C, Section D* and also *Intersection E*. It is indicated that *Intersection E* is shared by *Road X* and *Railway Y* by linking both features to *Intersection E*, thus avoiding redundancies on the geometry level as well as the semantic level. Each *Section* and

Intersection can be segmented into multiple *TrafficSpaces* and *AuxiliaryTrafficSpaces*. In the given example, *Section A* consists of four *TrafficSpaces*, each further specified with CityGML function attributes (two sidewalks and two driving lanes). *TrafficSpaces* within *Intersection E* can have multiple function attributes. *TrafficSpace ‘TS E1’*, for example, would contain function attributes such as ‘sidewalk’ as well as ‘railway track’ since it can be used by both transportation types.

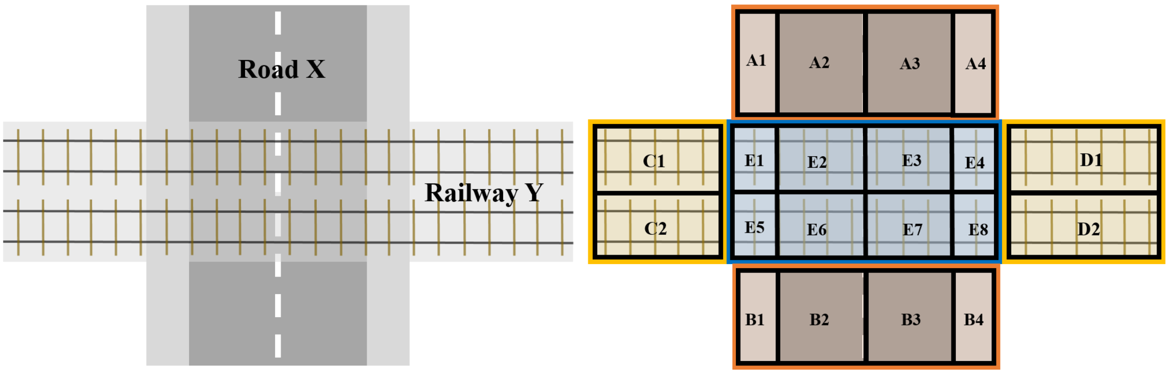


Figure 5.32: Level crossing of road and railway infrastructure (Beil and Kolbe, 2020).

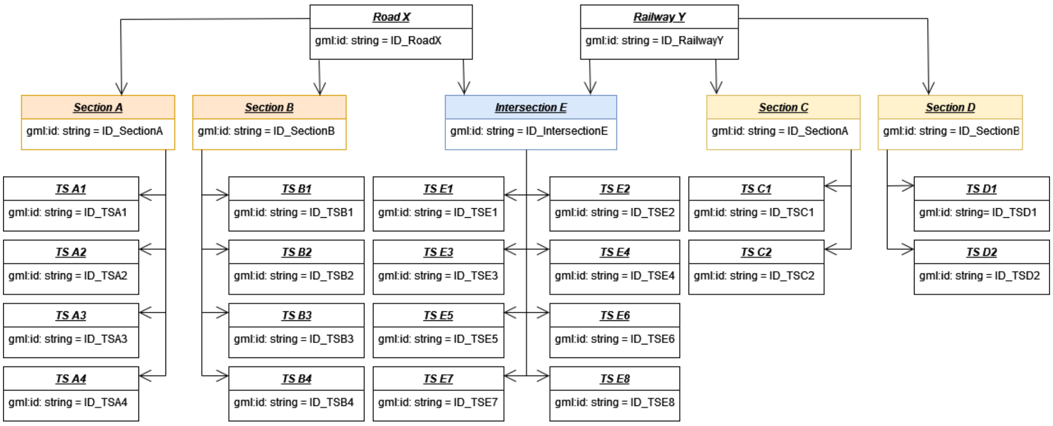


Figure 5.33: Instance diagram of a level crossing (Intersection of *Road* and *Railway* objects). Adapted from (Beil and Kolbe, 2020).

Figure 5.34 shows an areal (left) and a corresponding linear representation (right) of the same level crossing scenario also in level of granularity ‘lane’. As mentioned before, intersecting *MultiCurve* geometries can be continuous without adding nodes. In this case, lines representing driving lanes or sidewalks intersecting lines representing railway tracks are not split, because traffic members are not allowed to switch between the different transportation types. Lines should be split when representing different *TrafficSpaces*, in order to ensure consistency between areal and linear representations. This is indicated with small dashes at the end of each line segment. Note that in contrast to the areal representation, each *TrafficSpace* within *Intersection E* is represented by two linear representations (one for each transportation type).

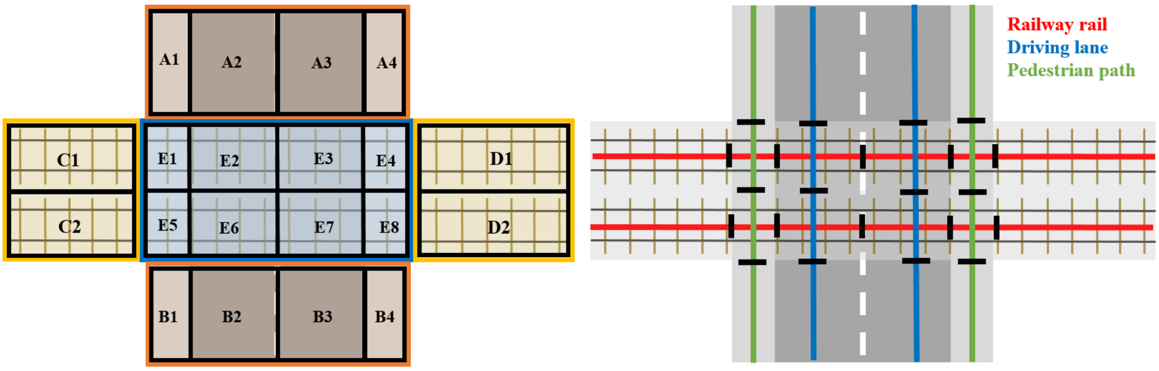


Figure 5.34: Comparison of a level crossing using *TrafficSpaces* with areal and linear geometry representations. Adapted from (Beil and Kolbe, 2020).

5.8.2.2 Areas shared by tramways and driving lanes

Another common scenario, especially within cities, are tramways within road surfaces. In this case, the same physical surface is part of a road and a railway network. This could be modelled in several ways. The first option would be a redundant geometric representation by modelling the same transportation space with overlapping surfaces for *Road* (used by cars) and *Railway* (used by trams). This, however, is a redundant representation of reality. Figure 5.35 illustrates a solution to this problem. The image shows an *Intersection* shared by *Road X* and *Road Y*, while part of *Road X* is simultaneously shared by a Tramway (*Railway Z)*. In this case, a two-level linking concept can be applied.

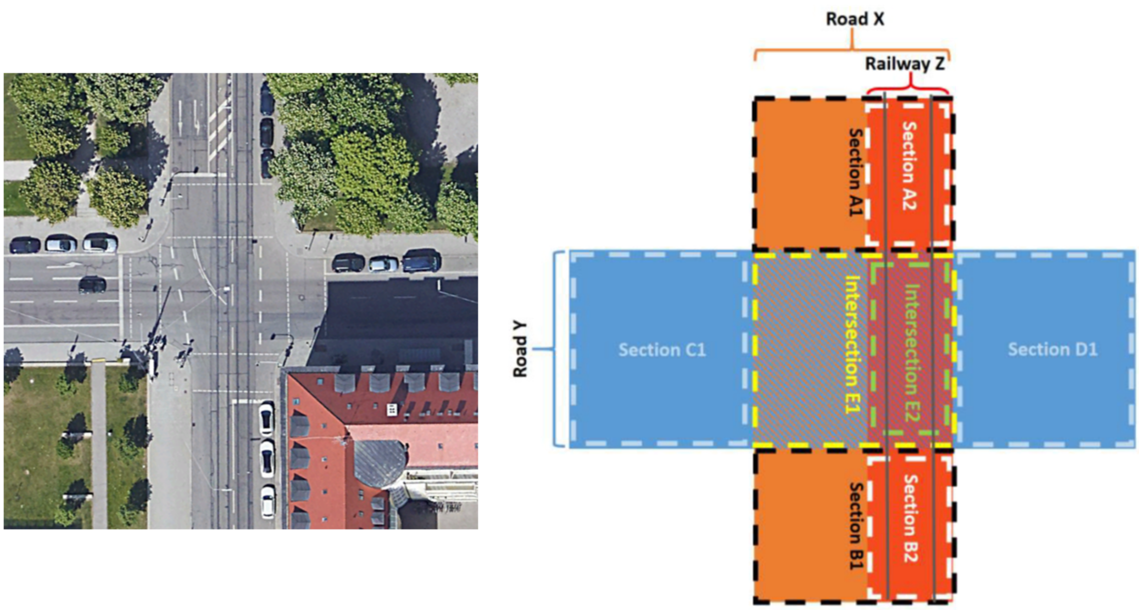


Figure 5.35: Intersection of two Roads, where one Road contains a Tramway modelled as CityGML Railway object (Beil and Kolbe, 2020).

Figure 5.36 shows an instance diagram to illustrate this example. The concept of linking Intersections belonging to multiple Roads is the same as presented earlier. In addition, *TrafficSpaces* can also be part of multiple *Sections* or *Intersections*. In this example, *Road X* consists of *Section A1, Section B1* and *Intersection E1*. *Road Y* consists of *Section C1, Section D1* and also *Intersection E1*. The Tramway sharing surfaces of *Road X* consist of *Section A2, Section B2* and *Intersection E2*. The new part of this concept is that *Sections* and *Intersection* also have links relating them to shared *TrafficSpaces*. This way a redundant representation of *TrafficSpaces* can be avoided. Each *TrafficSpace* can have multiple *function* and *usage* attributes. Linear models in granularity 'lane' can avoid this problem by individual representations for each transportation type. These concepts can also be applied for combinations of other transportation types such as a ford (intersection of *Road* and *Waterway*).

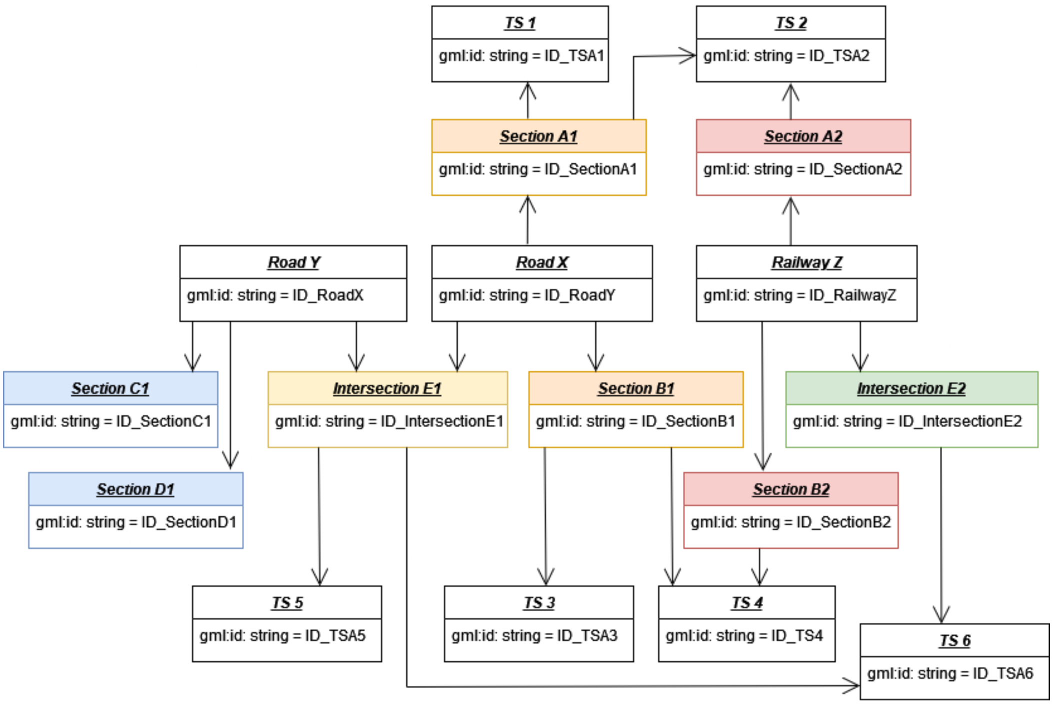


Figure 5.36: Instance diagram of a two-level linking concept for representing tram surfaces shared by road and railway objects. Adapted from (Beil and Kolbe, 2020).

5.8.3 Modelling Roads on Bridges

Roads can also span over bridges and thus share identical surfaces. In the example shown in figure 5.37, a *Road* is crossing a *Bridge*. *Road* surfaces on this *Bridge* are part of a *Section* and further segmented into individual *TrafficSpaces* bounded towards the ground by respective *TrafficAreas*. The same surfaces are simultaneously represented as *RoofSurfaces*, which are part of the *Bridge*. As explained in chapter 5.2.3, this relation should be expressed using *CityObjectRelations* linking geometrically identical but semantically different objects. This object structure is also illustrated in the corresponding instance diagram presented in figure 5.38.

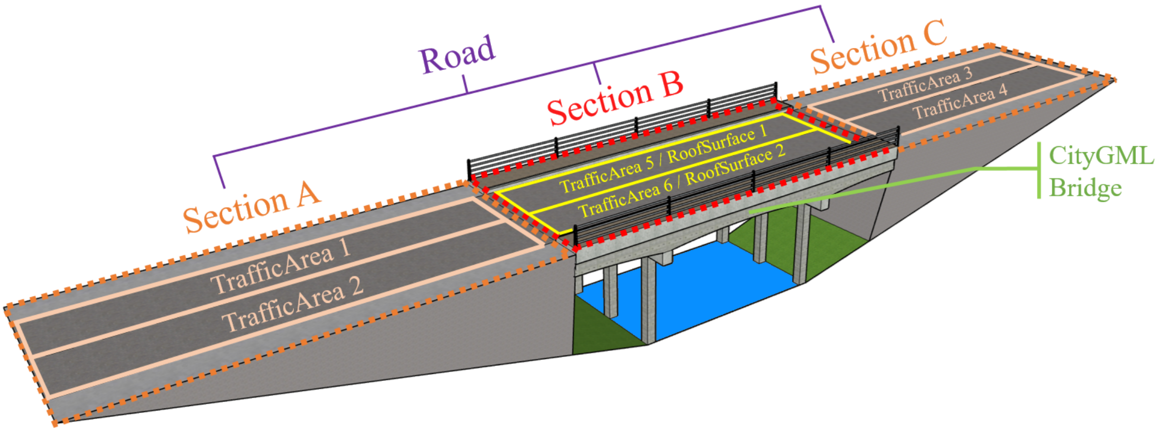


Figure 5.37: Linking *TrafficAreas* that are part of a Road with corresponding *RoofSurfaces* of a Bridge object.

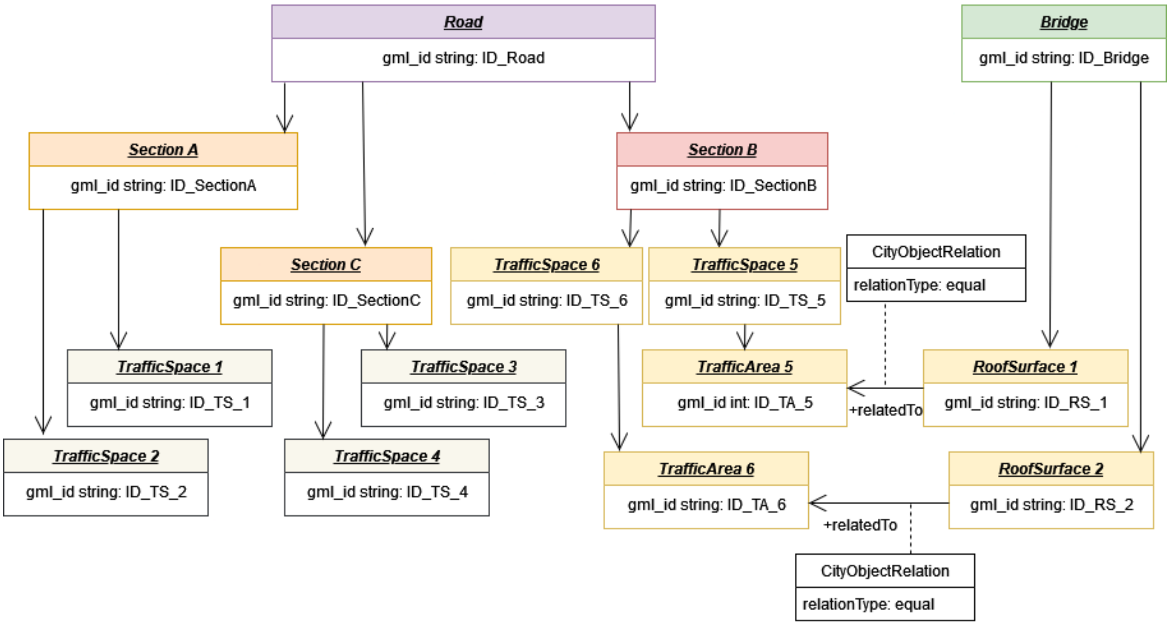


Figure 5.38: Instance diagram of *TrafficAreas* part of a *Road* that are linked to corresponding *Roof-Surfaces* part of a *Bridge* using *CityObjectRelations*. *TrafficSpace* are omitted in this illustration.

Listing 5.6 shows an exemplary XML encoding of a *CityObjectRelation* linking a *TrafficArea* surface to a corresponding *RoofSurface* using the relation type 'equal'. This is realized by pointing to the corresponding *gml:id* attribute of the corresponding object within the *relatedTo* property. In this example, *TrafficArea 5* contains information that it is 'equal' to *RoofSurface 1*.

```
<!--XML namespaces have been omitted from this listing.-->
<!--Road with Sections and Intersections-->
<tran:TrafficArea gml:id="UUID_TrafficArea5">
  <core:relatedTo>
    <core:CityObjectRelation>
      <core:relationType>equal</core:relationType>
        <core:relatedTo xlink:href="UUID_RoofSurface1"/>
      </core:CityObjectRelation>
    </core:relatedTo>
    <core:lod2MultiSurface>
      <!Geometry definition>
    </core:lod2MultiSurface>
</tran:TrafficArea>
```

Listing 5.6: TrafficArea pointing to the gml:id of a corresponding RoofSurface with a CityObjectRelation of value 'equal'.

Figure 5.39 illustrates this concept for a 3D bridge and city model near the 'Frankfurter Ring' in Munich visualized within a Cesium environment. The original bridge model was created using the ESRI CityEngine and the converted to CityGML and corresponding visualization formats using FME.

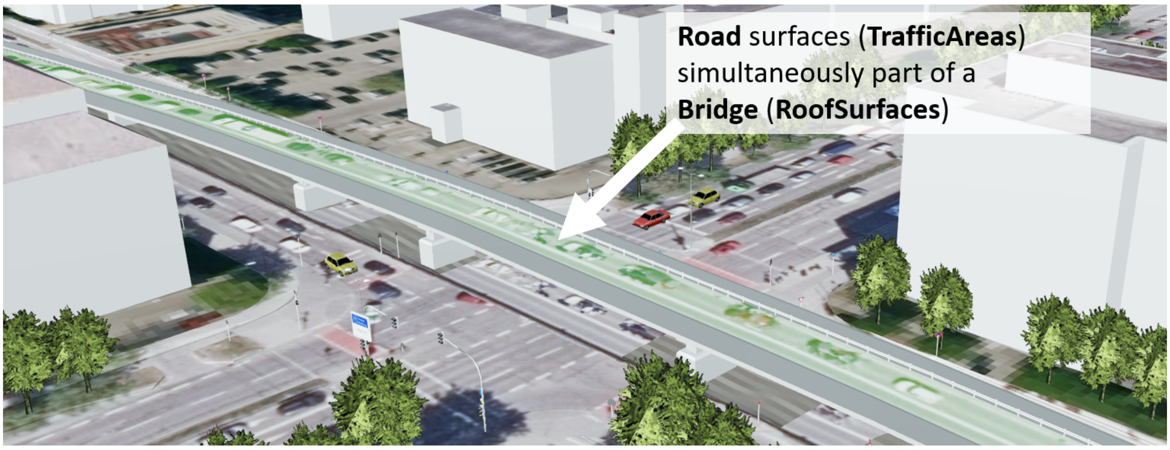


Figure 5.39: *TrafficAreas* part of a *Road* are simultaneously modelled as *RoofSurfaces* part of a *Bridge*.

5.8.4 Modelling Roads within Buildings (Parking Garage)

As displayed in figures 5.40 and 5.41, a parking garage can be modelled as a 'classic' CityGML *Building* consisting of *Ground-, Floor-, Wall-*, and *RoofSurfaces*. Simultaneously, some building surfaces can be part of the *Road* network and modelled as individual *Sections* within the *Building*. These *Sections* may be connected to *Sections* outside of the *Building* in order to allow a seamless transition e.g. for routing or navigational use cases.

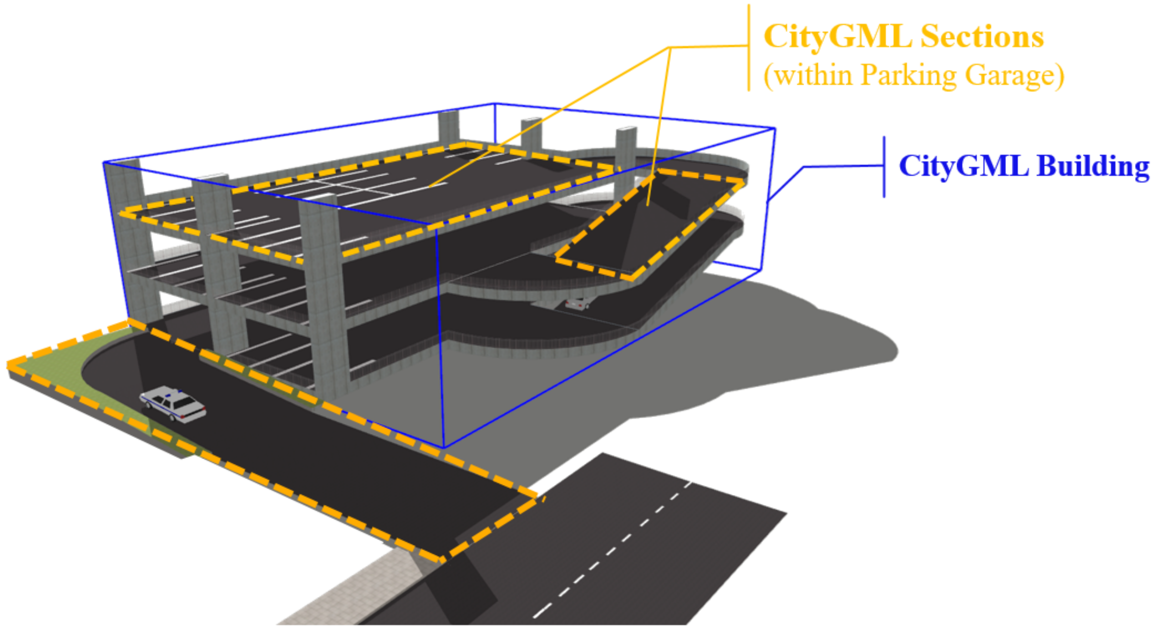


Figure 5.40: Modelling a parking garage with transportation infrastructure within a building.

As described before, *Sections* can be further segmented into individual *TrafficSpaces*, which again are bounded by corresponding *TrafficAreas*. Depending on the chosen level of granularity, *TrafficAreas* within a *Building* can represent entire parking decks (granularity = area), separated parking and driving areas (granularity = way) or driving lanes and individual parking slots (granularity = lane). These *TrafficAreas* are geometrically identical to some building surfaces such as *RoofSurfaces* or *FloorSurfaces*.

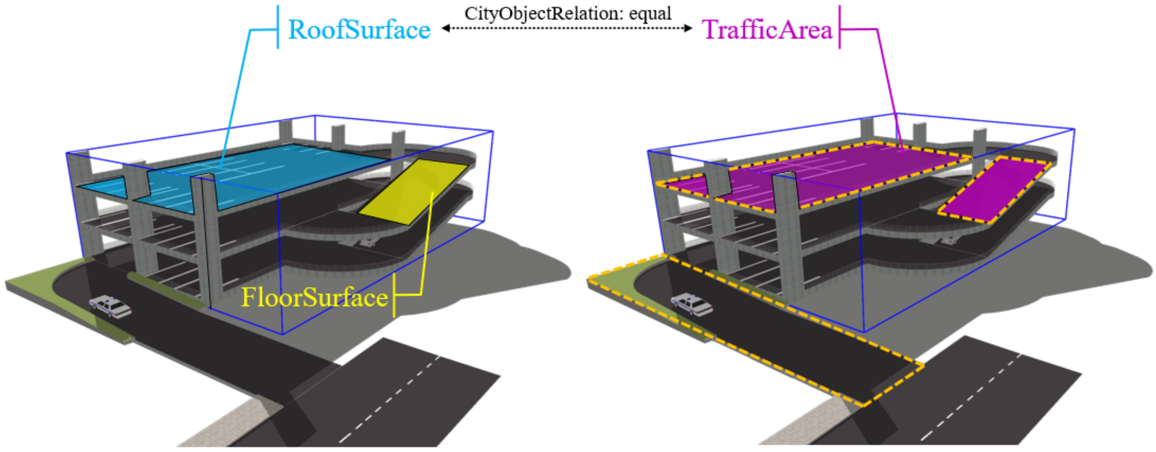


Figure 5.41: Simultaneous representation of RoofSurfaces (light blue) and FloorSurfaces (yellow) or TrafficAreas (purple) within Sections (orange) within a Building that are connected to Sections of the Road network outside of the Building. The two illustrations show the identical garage building.

As illustrated in the instance diagram in figure 5.42, corresponding surfaces that are geometrically identical but semantically different are linked using *CityObjectRelations* with the value *equal* in order to express this relation. This is similar to the previously demonstrated concept for modelling *Road* surfaces on a *Bridge*. In this way, *FloorSurface 1* part of the garage *Building* is linked to *TrafficArea 1* part of a *Road* object, which may be connected to *Roads* outside of the garage.

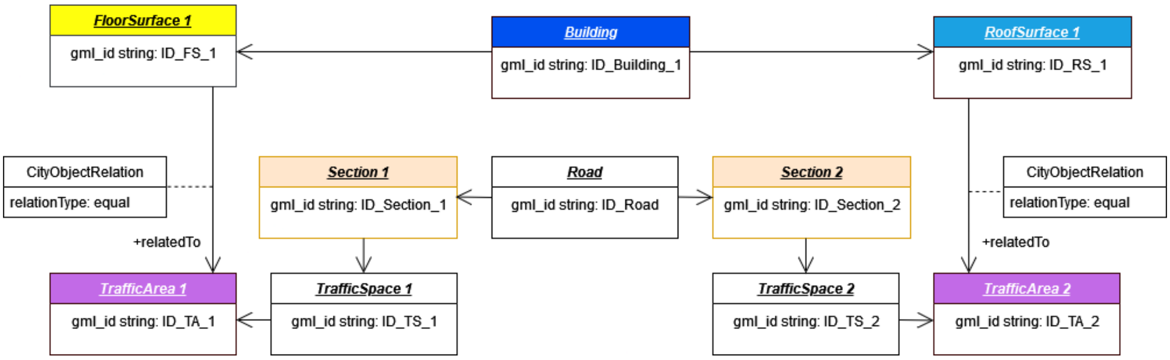


Figure 5.42: Instance diagram of linking building surfaces with corresponding transportation surfaces using CityObjectRelations.

5.8.5 Modelling Roads through Tunnels

Roads can lead through *Tunnels*, which are represented using individual classes defined within the CityGML 3.0 *Tunnel* module. In this case, *FloorSurfaces* part of a *Tunnel* object can be linked to *TrafficAreas* part of a *Road* using the same *CityObjectRelation* concept demonstrated in sub-chapter 5.8.4. Figure 5.43 illustrates a 3D tunnel model created with the ESRI CityEngine, converted to CityGML and visualized in the Cesium virtual globe.

Figure 5.43: Visualization of a Tunnel containing road infrastructure underneath the terrain within Cesium. Left: Adapted terrain, middle: 3D road and tunnel model, right: added relief to close the adapted terrain model.

Since tunnels are typically below the ground (underneath the digital terrain model), initial concepts for visualizing such scenarios are tested. For this, the existing digital terrain model is manipulated in such a way, that new values are calculated in the tunnel area that correspond to the bottom of the tunnel. This information is then converted to the Cesium terrain format 'quantized-mesh' using a docker implementation of the Cesium Terrain Builder (CTB)[14]. Then the 3D CityGML tunnel and road model is converted to 3D Tiles using FME and added to the visualization. Finally, the original information of the digital terrain model is used to create a ’cover surface’ (e.g. as a CityGML *Relief* feature textured with a corresponding true orthophoto) that is added on top of the tunnel model in order to close the previously created gap within the terrain model.

5.8.6 Modelling Level Crossings of Roads and Waterways (Ford)

Since the *Section* / *Intersection* concept also applies to *Waterways* it is also possible model an intersection of *Roads* and *Waterways* (e.g. fords) very similarly to level crossings. A ’ford’ typically is characterized by a natural or man-made place in a river, where the water is shallow enough to be crossed by foot or vehicle. Thus, this area can be used for transportation by water and with vehicles simultaneously. Modelling these parts of transportation networks with *Intersections* part of a *Road* and a *Waterway* allows for a non-redundant representation of such scenarios. However, in most cases, *Roads* might only cross a *Waterbody* that is not deep enough to be used as a *Waterway* at the same time.

5.9 The revised and extended Data Model of the CityGML 3.0 Transportation Module

Based on the concepts presented in this chapter, a revised and extended data model of the CityGML 3.0 Transportation module is created and illustrated in figure 5.44. This comprises the concepts and formal UML descriptions presented in this chapter within one complete data model. Included concepts, classes, attributes and relations were explained in detail in the previous sub-chapters. These concepts were developed in the course of this dissertation work and are adopted within the standard document of CityGML version 3.0 published in 2021 (Kolbe et al., 2021). This data model uses classes and concepts defined in the Core module such as *AbstractUnoccupiedSpace*, from which the central class *AbstractTransportationSpace* is derived. Consequently, specific sub-classes such as *Road, Track, Waterway, Railway, Section, Intersection* or *Square* are sub-classes of abstract transportation spaces. This also allows an easy determination of unoccupied spaces, relevant for navigational purposes. The new class *ClearanceSpace* further provides a concept for modelling navigable spaces. The newly introduced classes *TrafficSpace* and *AuxiliaryTrafficSpace* allow a further segmentation of transportation spaces and are bound towards the ground by the respective classes *TrafficArea* and *AuxiliaryTrafficArea*. The introduction of explicit classes for modelling *Markings* and *Holes* provides further concepts relevant for a number of use cases.

[14]https://github.com/tum-gis/cesium-terrain-builder-docker

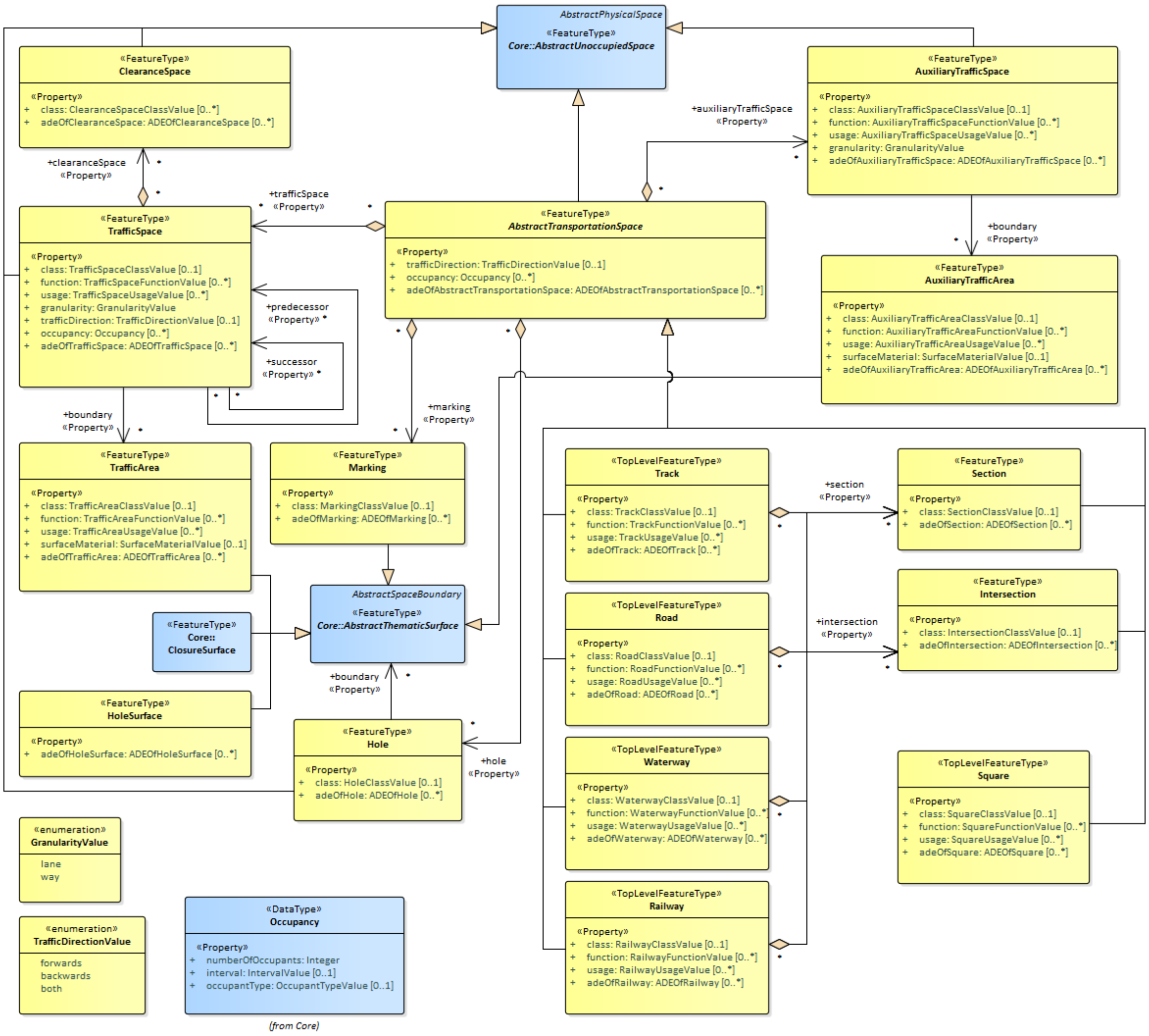


Figure 5.44: UML diagram of the developed Transportation Module, which is included in the CityGML standard version 3.0. Developed in this dissertation work and adopted in Kolbe et al. (2021).

5.10 Evaluation and Discussion of the revised CityGML 3.0 Transportation Module

Semantic, geometric, topological, temporal, visual and multimodal capabilities of relevant standards, conceptual models and guidelines have been summarized in tables 3.2 and 3.3. Data requirement categories of functionalities employed to reach the goal of certain use cases were presented in sub-chapter 2.5.1. The same categories are now evaluated for the revised concepts of the CityGML 3.0 Transportation model and summarized in the following table 5.3. City objects are georeferenced and geometries are specified using 3D real-world coordinates given in a corresponding coordinate reference system, which is especially relevant for large structures such as roads or highways, where the Earth's curvature cannot be neglected. As explained in the previous chapter, several geometric representations including non-redundant linear, areal, volumetric or point cloud geometries are supported in CityGML 3.0. Depending on intended use case and required functionality, each of these representation forms are relevant. Additionally, the presented concepts ensure consistency between different geometric representations (e.g. consistent linear and corresponding areal representation of individual lanes). Since CityGML 3.0 supports all geometry types defined in ISO 19107, linear geometries such as splines or clothoids can be used. Due to the modelling principle of CityGML, parametric geometric representations are not available, since parametric geometries typically cannot easily be consumed and managed by GIS software. Lane border representations can be derived from areal lane representations of individual *TrafficAreas*. Transportation objects are not only represented by their surface but also consider the space above used for transportation. This concept distinguishes the CityGML 3.0 Transportation Model from most of the related standards presented in chapter 4. Following the CityGML principle of focusing on observable parts of objects, sub-surface structures such as material layers or geo-technical aspects of the underground are not considered. The potential development of a corresponding ADE to represent sub-surface road structures is recommended in order to increase the interoperability with standards such as IFC in this context.

Concerning semantic aspects, the introduction of new classes such as *Sections* and *Intersections* segmenting large road networks into manageable parts also increases the interoperability with standards that provide similar concepts such as IFC 4.3 or OpenDRIVE. Additionally, the presented linking mechanisms between *Intersection* objects and multiple top-level-features such as roads allow a non-redundant representation. Three levels of granularity further allow different semantic detail depending on information required for a certain use case or data availability. In addition to the listed standardized semantic information such as surface material and class, function or usage information, any additionally required attributes can be included using the CityGML extension mechanisms of generic attributes. Alternatively, ADEs can be developed to formally describe concepts not provided by the original conceptual model. Since CityGML is not focused on the representations of roads only, further components that can be part of the streetspace also can be modelled according to concepts provided by the standard and thus provide a standardized and consistent 3D city model. This includes 3D representations of bridges, tunnels, buildings, city furniture or vegetation in multiple levels of detail.

The introduction of a predecessor / successor concept for *TrafficSpaces* in combination with attributive information on traffic directions opens up a range of new use cases for CityGML 3.0 compliant road data in the field of routing and navigation. In this way, traffic logic can be included into the 3D road model. This applies to all possible geometric representations of *TrafficSpaces* including linear, areal, volumetric or point cloud representations, which is a unique feature of the CityGML Transportation module. Thus, routing functionalities can also be implemented based on surface-based representations. Since it is possible to represent city objects without any geometry, topological connections could in theory also be expressed without actually modelling the transportation network geometrically. While several standards use a linear referencing system for representing roads, this is not available in CityGML 3.0. Due to this circumstance, information such as changing surface materials in the course of a road or lane can only be modelled by splitting lanes into individual *TrafficAreas* with individual

surfaceMaterial attributes. Extending CityGML 3.0 with a linear referencing concept based on *ISO 19148 - Linear Referencing* (ISO, 2012a) could be realized by developing a corresponding ADE.
Temporal aspects such as relating highly time-dynamic data such as sensor information with streetspace objects or managing different version of past or planned road scenarios are possible by utilizing concepts of the CityGML 3.0 Dynamizer and Versioning modules.
With regard to visual capabilities, the CityGML Appearance module allows colored or texture representations of road objects. Furthermore, realistic 3D models can be included to model street furniture objects such as traffic signs or traffic lights. For creating efficient (and potentially web-based) visualizations, CityGML models can be easily converted into visualization formats such as 3D Tiles or OBJ.
A major advantage of the CityGML Transportation module in comparison to most other standards are capabilities for consistent and non-redundant representations of combined transportation modes such as level crossings or surfaces shared by multiple transportation modes at the same time such as tramway within a road.
In summary, data requirements of all functionalities presented in sub-chapter 2.3 that do not exclusively require parametric representations, linear referencing of streetspace objects or sub-surface information such as material layers, can be served directly with data provided according to concepts presented in this chapter. This covers a large range of current and potential use cases. While CityGML is not intended to replace established standards and data formats in certain domains of road modelling, the revised and extended concepts presented in this thesis provide an increased interoperability and allow models created according to CityGML concepts to be a suitable anchor point for streetspace models and their use cases in the context of urban digital twins.

Table 5.3: Evaluation of geometric, semantic, topological, temporal, visual and multimodal modelling capabilities of the revised CityGML 3.0. Transportation module.

Geometry		Semantics		Transportation modes	
Dimension	3D	Surface Material	✓	Road	✓
Georeferenced geometries	✓	Function / Type	✓	Railway	✓
Straight lines	✓	Usage	✓	Sidewalk / Footpath	✓
Splines	✓	Granularity area	✓	Cycle path / Bikeway	✓
Clothoids	✓	Granularity way	✓	Tramway	✓
Explicit areal rep.	✓	Granularity lane	✓	Busway	✓
Parametric areal rep.	-	Section / Intersection segm.	✓	Waterway routes	✓
Lane border can be derived	✓	Driving direction	✓	Airports	✓
Volumetric rep.	✓	Bridge model	✓	Air spaces	✓
Point clouds	✓	Tunnel model	✓	Cableway / Lift	✓
Sub-surface material layers	-	Road marking	✓	Subway	✓
Geotechnical underground	-	Roadway damage	✓		
Non-overlapping areal geom.	✓	Manholes	✓		
		Street / city furniture	✓		
		Clearance spaces	✓		
		Vegetation objects	✓		
Modelling information		**Temporal aspects**		**Topology**	
Non-redun. topogr. integration	✓	Versioning / Historization	✓	Linear referencing	-
Multimodal topol. connections	✓	Linking sensor data	✓	Predecessor / Successor	✓
Degree of func. integration	1)	Moving objects	2)	Network topology	✓
				Areal topology	✓
Transportation relations		**Multimodal connections**		**Appearance**	
Level crossing	✓	Railway station / platform	✓	Colored surfaces	✓
Pedestrian crossing	✓	Bus station	✓	Textured surfaces	✓
Shared road / tramway	✓	Tram station	✓		
		Bike parking	✓		
		Taxi stand	✓		
		Subway entrance	✓		

Legend: fully available or supported: ✓, not supported: -, numbered cells are explained in more detail below.

Annotations to table 5.3

1. Explicit predecessor / successor concept but no detailed specifications on aspects such as speed limits, turning restrictions or traffic control (could be added with generic attributes or an ADE).
2. Vehicles or pedestrians can be modelled by extending CityGML with generic objects. The CityGML 3.0 Dynamizer concept further allows the representation of time-dependent information such as vehicles moving along a trajectory with changing location and orientation.

Part III

Usage of the revised and extended CityGML 3.0 Transportation Model

Chapter 6

Creating CityGML 3.0 compliant Streetspace Models from different Data Sources

Some of the contents in this chapter have been presented in the following peer-reviewed and published paper:

Beil, C., Ruhdorfer, R., Coduro, T. and Kolbe, T. H. (2020). 'Detailed Streetspace Modelling for Multiple Applications: Discussions on the Proposed CityGML 3.0 Transportation Model'. In: *ISPRS International Journal of Geo-Information* 9(10), p. 603. URL: https://doi.org/10.3390/ijgi9100603

6.1 Generating CityGML 3.0 Streetspace Models from OpenDRIVE Datasets

6.1.1 Motivation

The current OpenDRIVE specification contains some issues, when it comes to modelling real-world scenarios and usability for use cases other than traffic and driving simulations (ASAM, 2020b). As described in sub-chapter 3.2.2, the main modelling concept of OpenDRIVE is based on a reference line representation with parametric definitions of lanes, traffic signs or markings. This modelling concept was originally developed for representing synthetic road network scenarios. However, roads in real-world scenarios are often complex, which makes auxiliary constructions necessary, that lead to even more complexity, ambiguities or data gaps. It is therefore very difficult to update or patch parts of streetspace representations that are available in the OpenDRIVE format. Objects such as road marks or lane surfaces can be defined with respect to multiple referencelines and thus create redundant representations. The strict hierarchy leads to costly and time-consuming update procedures of subordinate elements in one OpenDRIVE file.
OpenDRIVE data is usually file-based, thus scalability and possibilities for data exchange are very limited. Currently there are no openly available database solutions for storing and managing OpenDRIVE data. While the main focus of OpenDRIVE originally was the representation of street networks, emerging use cases such as virtual development and validation of automated driving systems or vehicle sensor simulations also require detailed models of their surroundings (e.g. buildings or vegetation) (Schwab and Kolbe, 2019). While it is possible to include these kinds of models into OpenDRIVE

data, this often leads to increased complexity of datasets and unintended object structures. Nonetheless, there are existing HD-maps according to the OpenDRIVE format available in several cities and regions. While there are software tools that can consume this data format e.g. to perform traffic and driving simulations, the parametric structure of geometry definitions limit its usability for other use cases, which require explicit and non-redundant geometric representations (c.f. chapter 2 and sub-chapter 3.2.2). Thus, a mapping and subsequent conversion of the OpenDRIVE data structure to CityGML compliant concepts opens up a range of additional use cases for existing OpenDRIVE data. The open-source converter r:tron[15] can be used to automatically convert OpenDRIVE data to CityGML (versions 2.0 and 3.0) (Schwab et al., 2020; Schwab and Kolbe, 2022). This converter applies concept mapping strategies presented in the following sub-chapter. Since the terminology of both standards is similar but not identical, the terms "OpenDRIVE" or "CityGML" are used to specify feature descriptions. An "OpenDRIVE *Road*", for example, is semantically different to a "CityGML *Road*" feature.

6.1.2 Mapping of OpenDRIVE Concepts to CityGML 3.0

Figure 6.1 shows a direct comparison of semantic, topological and geometric concepts of CityGML 3.0 and OpenDRIVE 1.8 using the example of a four-way intersection. The image on the left shows how this scenario is represented according to OpenDRIVE. Here, the four standard OpenDRIVE roads (roads 1-4) are represented with individual OpenDRIVE road reference lines, each containing parametric information on OpenDRIVE *LaneSections* and OpenDRIVE *Lanes* as described in chapter 6.1. Additionally, 11 OpenDRIVE *connecting roads* (road 5-16) represented with reference lines within the OpenDRIVE *Junction X*. The same scenario using concepts of CityGML 3.0 is displayed in the illustration on the right. Here, CityGML *Road A* (blue) consists of *Sections A1 and A2* (orange) as well as *Intersection X* (red), while *Road B* (green) consists of *Sections B1 and B2* as well as also *Intersection X*. Note that *Intersection X* only needs to be represented once and can be referenced by multiple *Roads* at the same time using the linking mechanism described in chapter 5.3.2.2. Each *Section* or *Intersection* is further segmented into individual *TrafficSpaces*, which again are bound towards the ground using individual CityGML *TrafficAreas*. This example illustrates the challenge of matching OpenDRIVE concepts and classes to corresponding CityGML representations. It is recommended to map OpenDRIVE *Roads* representing standard OpenDRIVE *Roads* between OpenDRIVE *Junctions* to CityGML *Sections* and to create one CityGML *Intersection* per OpenDRIVE *Junction*.
Geometries of OpenDRIVE *Roads* within OpenDRIVE *Junctions* are converted to CityGML *TrafficSpaces* with corresponding CityGML *TrafficAreas* and assigned to a common CityGML *Intersection*. One CityGML *TrafficSpace* with corresponding *TrafficArea* per OpenDRIVE *Lane* should be created. Since geometries of individual lanes within an OpenDRIVE *Junction* are overlapping, the CityGML *TrafficAreas* initially created from this information also contain overlapping geometries, which need to be converted to non-redundant surface-based representations depending on the desired use case. Since OpenDRIVE uses a parametric description of geometries relative to reference lines, explicit geometries representing individual surfaces need to be derived in the conversion process. Schwab and Kolbe (2022) explain this process of discretizing parametric descriptions into explicit geometry rep-

[15] https://rtron.io/

resentations. Predecessor and successor information of individual lanes can be mapped to respective *TrafficSpaces* and attributes such as *trafficDirection* can be derived. OpenDRIVE attributes such as lane type should be mapped to corresponding CityGML *function* attributes.

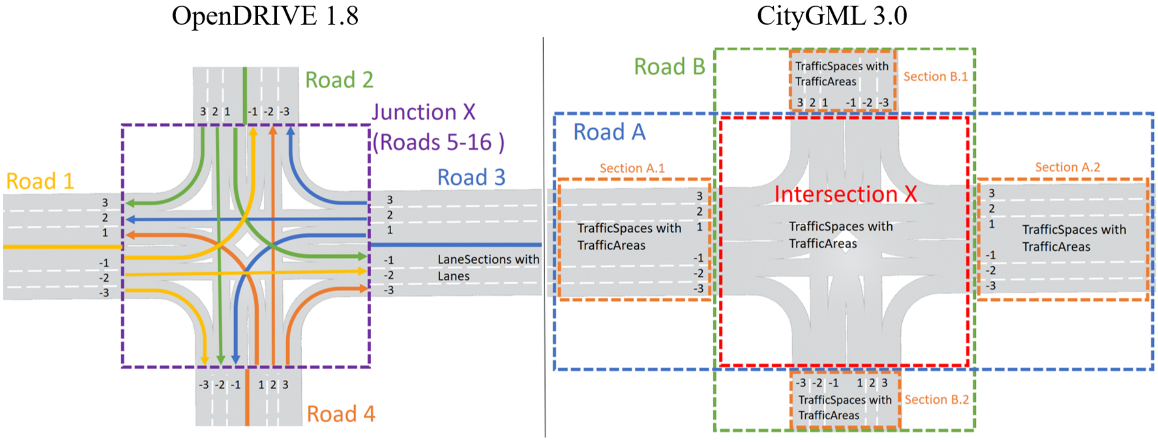


Figure 6.1: Direct comparison of an intersection modelled according to OpenDRIVE 1.8 and CityGML 3.0

6.1.3 Examples for Mapping OpenDRIVE Data to CityGML 3.0

The open-source OpenDRIVE to CityGML converter r:tron[16] introduced by Schwab et al. (2020), allows a fully automatic conversion of OpenDRIVE data to CityGML versions 2.0 and 3.0 following the mapping recommendations presented in the previous sub-chapter and is used for converting existing OpenDRIVE data to CityGML. In the course of the SaveNoW project[17] detailed information on roads were gathered within several mobile mapping campaigns in centimeter accuracy and used as source data for creating OpenDRIVE HD-maps of large parts of the city's road network. The available datasets in total comprise roads of approx. 300 kilometers in length. The resulting data is geo-referenced, contains true 3D representations (including underpasses and roads on multiple levels), subtle geometric structures such as lowered sidewalks and curbs and thus corresponds to information provided in CityGML 3.0 LOD 2 as well as level of granularity 'lane'. Individual lanes include representations of on driving lanes, sidewalks, footpaths, bicycle lanes, medians, curbs, traffic islands, green areas, markings as well as city furniture such as traffic signs and lights (including information in individual types) and vegetation. The transportation network is segmented into *Sections* and *Intersections* according to the previously mentioned mapping rules. The produced CityGML dataset is converted to visualization formats such as glTF/COLLADA using the 3DCityDB and visualized in a Cesium based web-map client. Figure 6.2 shows the resulting visualization for a complex interchange in Ingolstadt including lane level information on roads colored according to surface material and function information. The model is combined with LOD 2 building models and a digital terrain model (1 meter resolution).

[16]https://rtron.io/
[17]https://www.asg.ed.tum.de/en/gis/projects/savenow/

Figure 6.2: CityGML 3.0 compliant interchange in Ingolstadt generated from OpenDRIVE data combined with LOD 2 building models and visualized in a Cesium based web-visualization.

Figure 6.3 shows a CityGML 3.0 compliant *Intersection* including traffic signs and lights, vegetation and markings and textured road surfaces in Ingolstadt generated from OpenDRIVE data combined with LOD 2 building models and visualized in a Cesium based web-visualization.

Figure 6.3: Complex CityGML 3.0 compliant Intersection derived from OpenDRIVE data.

In addition to lane-level surface data on roads, information on the position, orientation and type of traffic signs and lights is available and converted to CityGML CityFurniture objects. Corresponding

3D sign and traffic light models are incorporated into the 3D model automatically by using type attributes. Semantic information such as additional attributes that cannot directly be converted into the CityGML-compliant structure is stored as generic attributes with corresponding features.
Similar to the data of Ingolstadt, a detailed HD-map in the OpenDRIVE format is created from mobile mapping data for the city of Grafing near Munich in the course of the PLIMOS project. The data structure and geometric and semantic detail is identical to the data described before with information provided in CityGML 3.0 LOD 2 as well as level of granularity ’lane’. Further conversion were also done for other cities and regions were OpenDRIVE data is (partially) available such as Hamburg or parts of Munich.

6.1.4 Recommendations for a CityGML OpenDRIVE Application Domain Extension

Schwab et al. (2020) and Schwab and Kolbe (2022) present a method for converting parametric OpenDRIVE data to CityGML models with explicit geometries. However, not all information provided by OpenDRIVE data can be preserved directly. While results of this process are immediately usable for a variety of simulations and analyses that require polygonal representations of the streetspace, there are currently no tools for converting this data back to the original OpenDRIVE format. This is due to the fact, that a discretization method has to be applied in order to derive explicit geometries from parametric descriptions. CityGML does not contain a linear referencing system and also does not support parametric representations of geometries. Thus, this information can not be easily stored in resulting CityGML data. In order to overcome these discrepancies of both standards and to bridge the gap between traffic simulation and 3D city model applications, a recommendation for a CityGML OpenDRIVE Application Domain Extension is proposed. Contents of this proposal were developed within the PLIMOS project and documented within a corresponding technical report (Mueller, 2021). Goals of this ADE include an increased interoperability between CityGML and OpenDRIVE allowing easier bi-directional lossless transformations. Parametric as well as explicit geometric representations should be available within a common data format. A linear referencing system according to ISO:19148 (ISO, 2012a) should be incorporated to CityGML. The ADE allows OpenDRIVE data to be stored and managed open-source (spatial) database systems such as the 3DCityDatabase (3DCityDB) (Z. Yao et al., 2018).

6.2 Upgrading CityGML 2.0 Data to Concepts of the CityGML 3.0 Transportation Module

Some cities and regions already have data on road infrastructure according to concepts specified in the CityGML 2.0 *Transportation* module. Since version 2.0 contained some under-specifications, the structure of these datasets often varies. As illustrated in figure 6.4, there are three most commonly used representations of CityGML 2.0 *Roads* with corresponding *(Auxiliary)TrafficAreas*:

a) Only one *Road* object is used in a dataset for representing all road infrastructure of an entire city or region. All *(Auxiliary)TrafficAreas* in this dataset are child elements of the same *Road* object. In this case, one *Road* object per street and new *Sections* and *Intersections* need to be created.
b) One *Road* object per street is available. In this case, CityGML 2.0 *Road* objects can be mapped to CityGML 3.0 *Roads* directly and new *Sections* and *Intersections* need to be created.
c) One *Road* object is available for each section or intersection in the dataset, ideally indicated with a respective *class* attribute. In this case, CityGML 2.0 *Road* objects can be mapped to *Section* and *Intersection* objects. This means, that new *Road* objects need to be created for each street.

In all three cases, new *(Auxiliary)TrafficSpace* objects need to be created. This can be achieved by creating one *(Auxiliary)TrafficSpace* per CityGML 2.0 *(Auxiliary)TrafficArea* and linking these objects with corresponding *Sections* and *Intersections*. Geometric representations of *(Auxiliary)TrafficSpaces* can be omitted or linear/volumetric representations can be created from *(Auxiliary)TrafficAreas*. CityGML 2.0 *(Auxiliary)TrafficAreas* can be mapped to CityGML 3.0 *(Auxiliary)TrafficAreas* directly. Examples for implementing these mapping strategies are shown in the following sub-chapters.

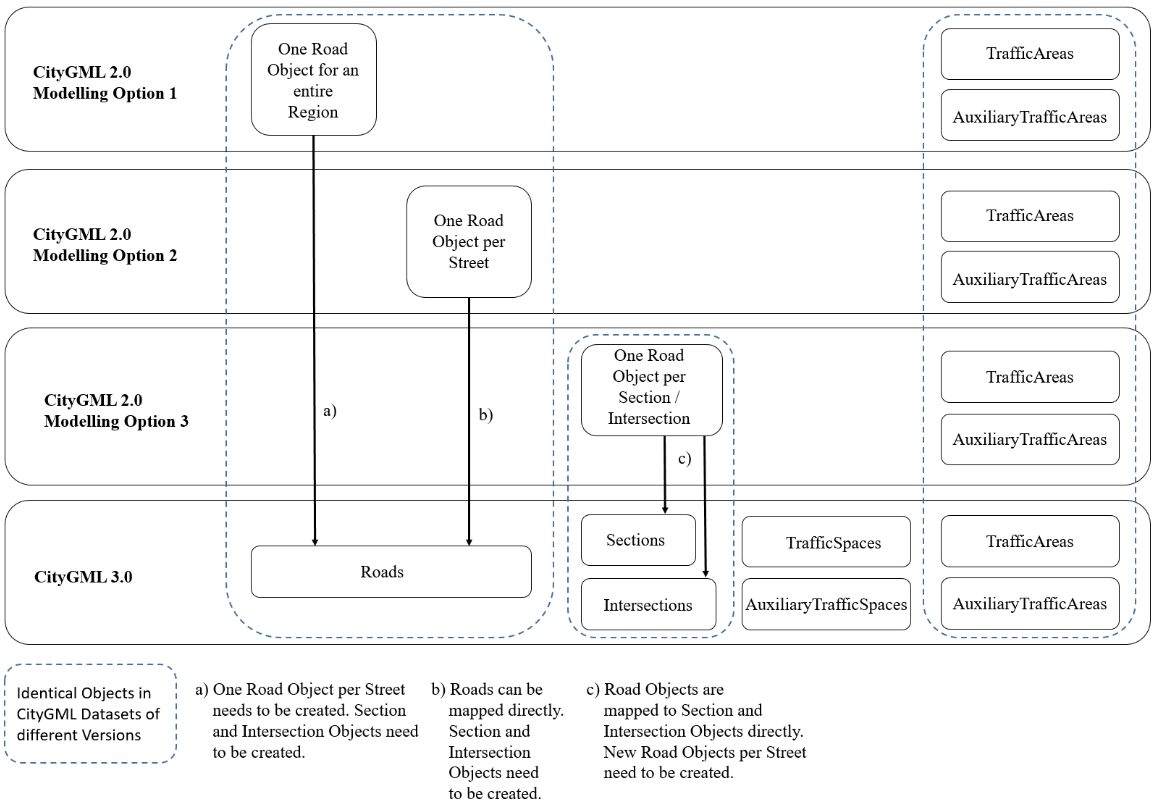


Figure 6.4: Different strategies for mapping CityGML 2.0 objects to CityGML 3.0 depending on common source data structures.

6.2.1 Japanese PLATEAU Project: Mapping CityGML 2.0 Streetspace Data to CityGML 3.0

The PLATEAU project[18], conducted by the Ministry of Land, Infrastructure, Transport, and Tourism (MLIT) in Japan, is dedicated to developing semantic 3D city models for a growing number of Japanese cities. These models are provided as open data, compliant to the CityGML standard version 2.0 and include representations of the terrain, *Waterbodies*, *LandUse*, *Buildings*, *Vegetation*, *CityFurniture*, *Bridges* and *Roads*. The original data is given in a compound CRS using a 2D geographic plus a 1D vertical metric CRS. The data is transformed into a compound projected metric 2D CRS (UTM Zone 54N, JGD2011 datum) plus a 1D vertical metric CRS using the 3DCityDB.
While most of the data is available in CityGML 2.0 LOD 1 and 2, some selected parts are also available in CityGML 2.0 LOD 3. Figure 6.5 shows a 3DCityDB web-map client created from the original CityGML 2.0 compliant LOD 3 data, which was converted to 3D Tiles using the CityGML to 3D Tiles online converter provided by Cesium Ion[19]. This includes a street in the city of Numazu which is converted to a CityGML 3.0 compliant data structure according to the process (c) described in figure 6.4. The available data can be segmented into seven *Sections* and five *Intersections* with lane-level accuracy including *TrafficAreas* for driving lanes, footpaths, parking lanes, etc. as well as *AuxiliaryTrafficAreas* such as green areas. While the original data is already structured and segmented into section and intersection parts (each assigned to one CityGML 2.0 *Road* object), there is no attribute or other information available that indicates if these CityGML 2.0 *Roads* correspond to CityGML 3.0 *Sections* or *Intersections*. Thus, this assignment is done manually. Since all newly created *Section* and *Intersection* objects belong to the same street, only one new *Road* object is created. The data is available in 3D and contains subtle structures such as raised traffic islands or lowered curbs. For each *TrafficArea* and *AuxiliaryTrafficArea* corresponding *TrafficSpace* and *AuxiliaryTrafficSpace* objects are introduced, which are provided in level of granularity equal to 'lane'. Additionally, objects representing vegetation, city furniture, markings and manholes are available, which are mapped to respective CityGML 3.0 compliant classes.

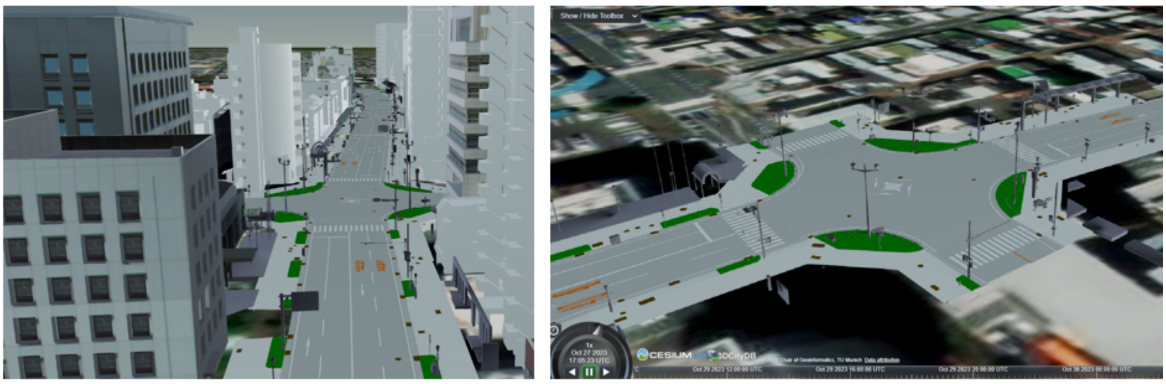


Figure 6.5: LoD 3 streetspace model of a street in Numazu (Japan) containing individual lanes, markings and city furniture visualized in a web-map-client.

[18] https://www.mlit.go.jp/plateau/
[19] https://cesium.com/platform/cesium-ion/

6.2.2 New York City: Converting Open GIS Data to semantic 3D City Models

Beil and Kolbe (2017) describe a process for generating CityGML 2.0 compliant data of roads from Open Data (planimetric, surface-based representations of roads and their parts) provided by the New York Open Data Platform. The produced data contains individual surfaces including roadbeds (granularity 'way'), sidewalks, traffic islands, curbs, markings, plazas or parking lots. The data structure of an 1,5km x 2km excerpt in the center of Manhattan was further specified by introducing *TrafficAreas* and *AuxiliaryTrafficAreas*. In order to express affiliations to top-level features each object was linked to superordinated *Road, Square*, or *Track* objects. Being based on CityGML 2.0, the section / intersection concept introduced in this thesis could not be implemented explicitly then but was already taken into account by creating individual *Road* objects for each *Section* or *Intersection*, indicated with respective *class* attributes. *Intersections* are defined with their minimal area shared by multiple *Roads* in this dataset. This data structure allows for a straight forward conversion and upgrade to CityGML 3.0 compliant concepts by implementing the conversion strategy (c) illustrated in figure 6.4.

Results of this conversion are shown in figure 6.6 with a *Road* object (highlighted in blue), containing multiple *Section* objects (Nr. 1, 5, 9) and *Intersection* objects (Nr. 3 and 7). Additionally, *Square* objects representing public plazas or parking lots are included in the dataset. *(Auxiliary)TrafficSpaces* with corresponding *(Auxiliary)TrafficAreas* representing roadbeds, sidewalks, medians, curbs and other road features part of individual *Sections / Intersections* or *Squares* are created. The dataset in total contains 93 *Squares* and 85 *Roads* consisting of 453 *Sections* and 192 *Intersections* further segmented into 1869 *TrafficSpaces* and 1309 *AuxiliaryTrafficSpaces* bonded by an equal amount of *TrafficAreas* and *AuxiliaryTrafficAreas*.

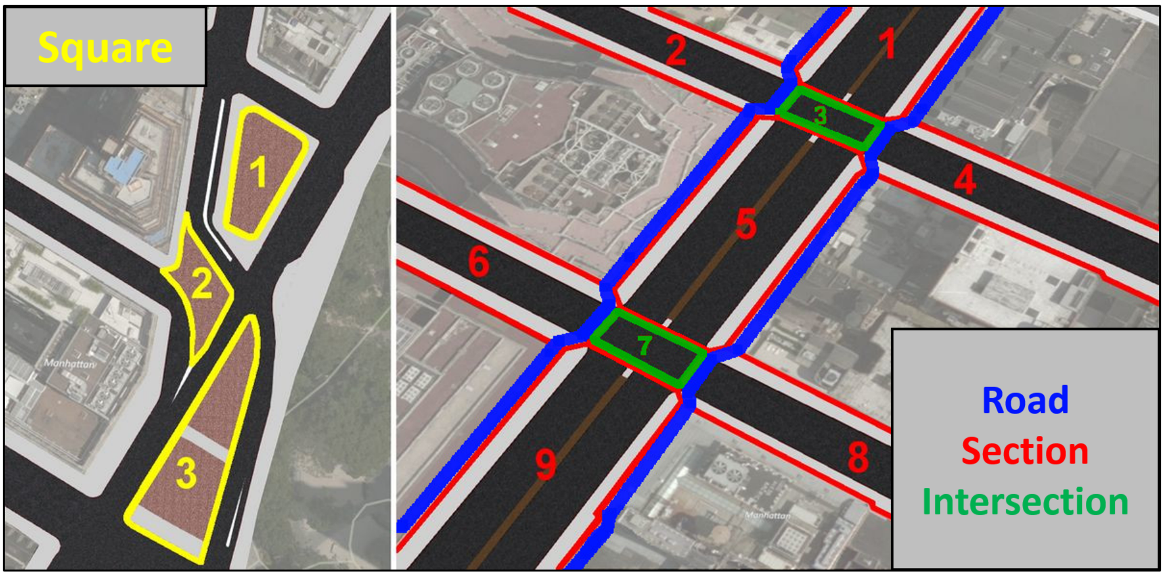


Figure 6.6: Semantic and geometric segmentation of the New York City streetspace dataset including *Roads* containing *Sections* and *Intersections* as well as *Squares* in granularity level 'way'.

6.3 Generating CityGML 3.0 Transportation Models from other Geospatial Data Sources

6.3.1 Munich: Mapping Concepts of the Munich Lane Model to CityGML 3.0

The city of Munich created a city-wide dataset of roads and transportation infrastructure with lane-level accuracy called *Munich Lane Model*. The structure of the data is based on an extended concept described in the *Road2Simulation* guideline (Richter and Scholz, 2019) published by the German Aerospace Center, which is related to the OpenDRIVE standard. The data is available in 2D as shapefile within an ArcGIS environment. Two types of reference lines are included as linear geometries (*ConnectionLines* in the area of *Junctions* and *StandardLines* between *Junctions*) as well as *NetworkLines* for connecting reference lines that are not directly adjacent to each other. *NetworkNodes* are recorded as point geometries at the connection points of the reference lines. Furthermore, *LaneBorders* as line geometries represent the lane boundaries relative to the reference line (an ID attribute indicates with positive / negative values whether the respective *LaneBorder* is located to the right or the left of the reference lines in the direction of travel). *ConnectionLines* and *LaneBorders* have information about their predecessors and successors. *Junction* areas are recorded by their border line and can be part of a *JunctionGroup*. Areas used by pedestrians (*WalkingAreas*) are included separately. In addition, all lane types (e.g. driving lane, cycle path, parking lane, etc.) are recorded with lane-specific areal geometries (*LaneAreas*), with each lane containing information on surface material, speed limits and its level relative to the ground. In future versions of the Lane Model, it is planned to derive the areal (surface-based) *LaneAreas* representations from *LaneBorders* automatically. Figure 6.7 shows an example area of the Lane Model converted to CityGML 3.0.

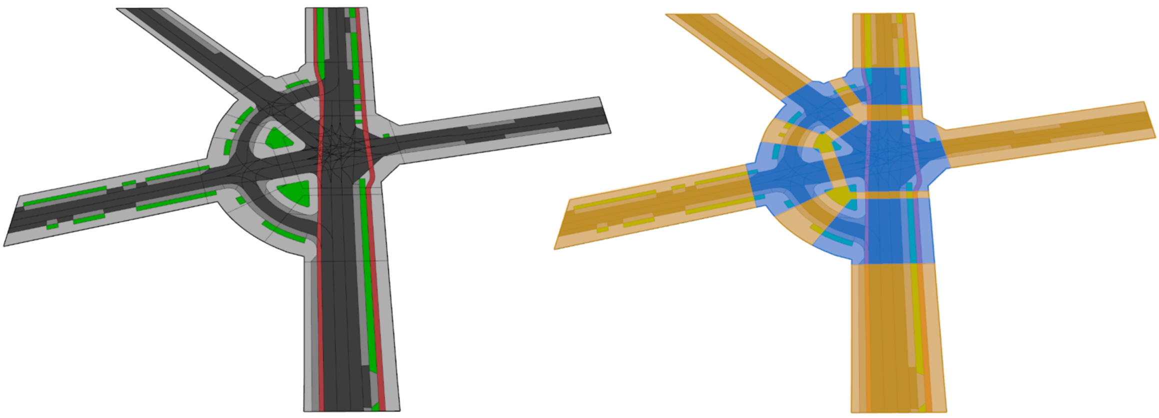


Figure 6.7: Mapping of Lane Areas from the Munich Lane Model to representations in CityGML 3.0 at granularity level 'lane' (left) and assigned to corresponding Sections (orange) and Intersections (blue) (right).

The right part of the illustration shows the segmentation of this area into CityGML *Sections* and *Intersections*, which is derived from the definition of *Junction* areas within the Lane Model. *LaneAreas* as well as *WalkingAreas* and *SpecialAreas* are converted to CityGML *TrafficAreas* and *AuxiliaryTraffi-*

cAreas. Corresponding *TrafficSpace* and *AuxiliaryTrafficSpace* objects are introduced. Geometric or semantic representations within the Lane Model, that cannot be assigned to corresponding CityGML objects directly, are stored as *Generic* objects in order to preserve all original information. This applies for example to *NetworkNodes*, *ConnectionLines* or the *LaneBorder* representations, which is a geometric representation of lanes not used in CityGML. Additionally, all original attributes, that cannot be mapped to CityGML-specific attributes are conveyed as generic attributes.

Mapping tables containing information on mapping Lane Model objects and attributes to corresponding CityGML 3.0 compliant representations are given in appendix B. Information on lane types are mapped to corresponding CityGML *function* and *usage* attributes. Similarly, information on surface material is mapped to the CityGML *surfaceMaterial* attribute using respective codelist values. Since the data structure of the Lane Model is related to OpenDRIVE, similar mapping concepts of Lane Model data to CityGML 3.0 apply.

Since the original geometries of *LaneAreas* overlap within *Intersection* areas, a post-processing to dissolve all areas within *Intersections* is recommended. This allows quantity-take-off measurements directly from the resulting data as well as appealing visualizations. Lane-level accuracy information on individual paths and turns vehicles can take within *Intersections*, should be preserved by deriving corresponding centerline representations from the original overlapping lane areas. The resulting test-datasets are compliant to the developed concepts of the CityGML 3.0 Transportation module.

Since the original data is available in 2D, a subsequent elevation of this model to 3D is required using information from digital elevation models and detailed surface models derived from laser scanning data in combination with the provided level information contained within the Lane Model data.

6.3.2 Melbourne: Converting Open GIS Data to semantic 3D City Models

The city of Melbourne also provides open data on streetspace objects for the city center[20]. The original dataset contains polygonal 2D shapefiles representing different types of surface information, such as carriageways, footpaths, intersections, parking bays, road curbs, or tramways in level of granularity 'way'. The data also contains many attributes, including condition (pavement rating), average width, length or surface material. In combination with datasets such as 'road corridor', 'street furniture', or 'street names', a detailed streetspace model is created using FME. The 'road corridor' dataset represents entire road segments and is therefore suitable to define CityGML *Section* areas. It also contains an attribute on adjacent streets for each segment. This information can be used to determine dead ends to further specify *Section* types. Subtle geometric structures such as sidewalks and traffic areas are produced with vertical extrusions of surfaces with standard values such as 15 cm, thus resulting in a representation of LOD 1 and level of granularity 'way'. Figure 6.8 shows the generated streetspace model with two examples indicating the segmentation of the model into *Sections* and *Intersections* as well as corresponding *TrafficAreas*. The top left image shows a three-way intersection, which is segmented into one *Intersection* with three adjacent *Sections*, each further split into several *TrafficSpace* with corresponding *TrafficAreas*. The bottom left images shows a second example of a larger *Intersection* with five adjacent *Sections*. Figure 6.9 shows further examples of individual *Sections* with one or two carriageways as well as a three-way and a four-way *Intersection*. These

[20]https://data.melbourne.vic.gov.au/explore/dataset/road-segments-with-surface-type/information/

CityGML 3.0 datasets are provided for download as exemplary Open Data[21]. Rui et al. (2024) used the provided data of Melbourne for evaluating road models generated from OpenStreetMap data.

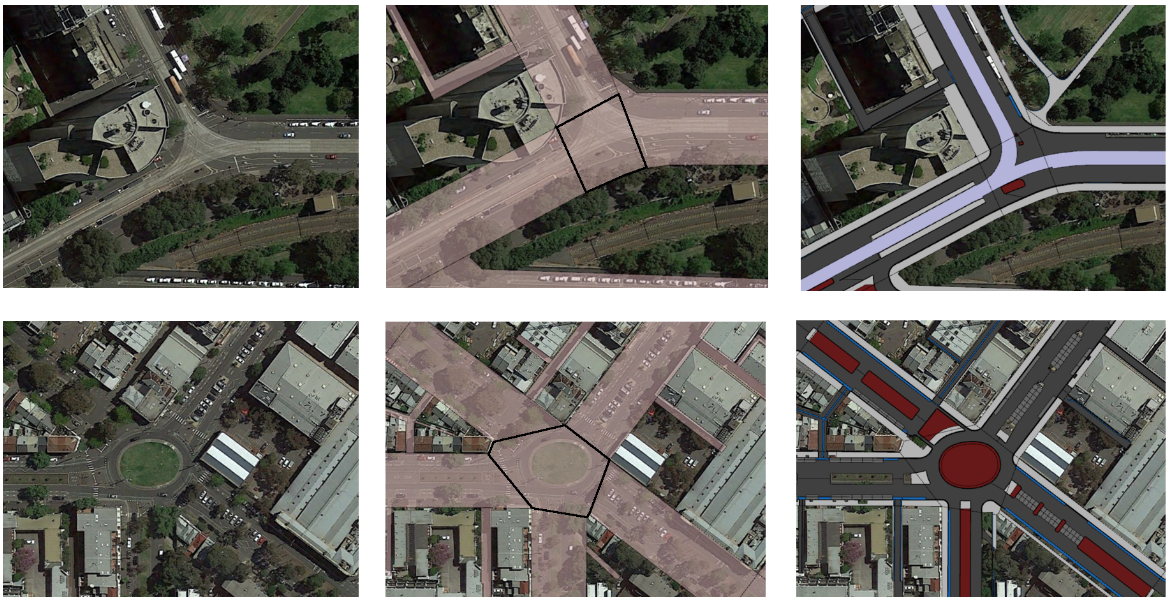


Figure 6.8: CityGML 3.0 level of granularity available for Melbourne datasets and corresponding segmentation into Sections and Intersections.

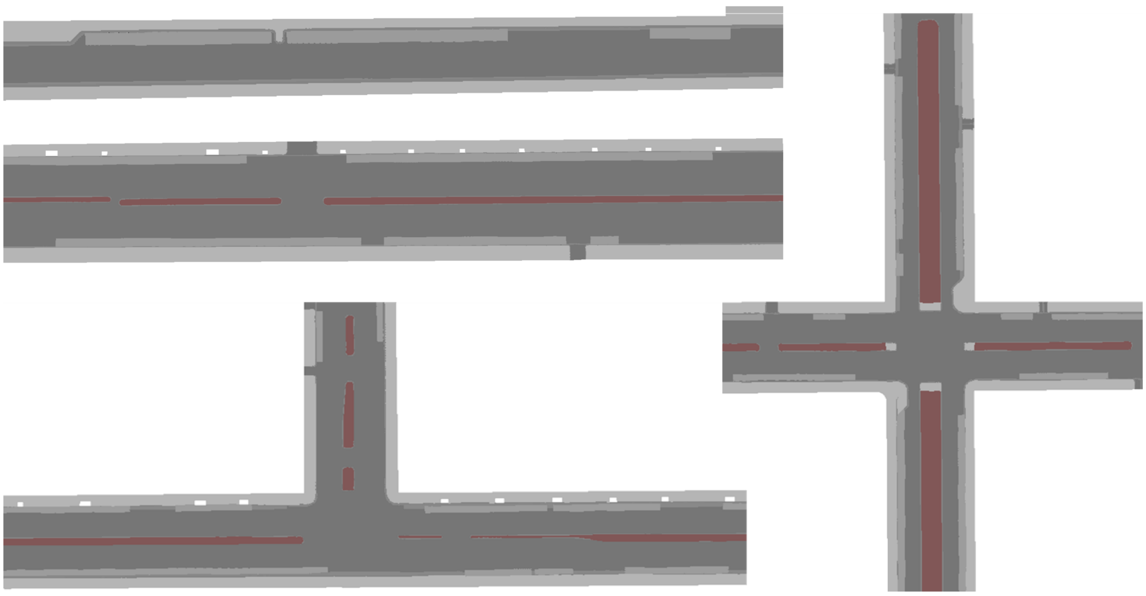


Figure 6.9: CityGML 3.0 compliant dataset examples of Sections and Intersections in Melbourne.

[21] https://github.com/opengeospatial/CityGML-3.0Encodings/tree/master/Moved_to_CITYGML-3.0Encoding_CityGML/Examples

6.4 Generic CityGML 3.0 Transportation Models

In order to implement selected CityGML 3.0 concepts, the 3D modelling software SketchUp is used to create 3D models, which are then converted to CityGML 3.0 compliant data using the Feature Manipulation Engine (FME) in a post-processing. A process for creating CityGML (2.0) LOD 2 *Building* models based on laser scanning data using SketchUp is explained in a modelling guideline[22]. This is done making use of a SketchUp plugin called *CityEditor*[23], which allows to export CityGML 2.0 compliant 3D models from SketchUp. A similar process is used to create synthetic 3D CityGML models of a parking garage building and a bridge, which are then upgraded to CityGML 3.0 and presented in the following chapters. This is achieved by writing GML files with corresponding CityGML 3.0 compliant XML Schema Definitions (XSDs).

6.4.1 Road within a Parking Garage Building

A 3D model of a three-story garage building is created manually using SketchUp and exported to CityGML (2.0) using the mentioned plugin. Individual surfaces such as *WallSurfaces, RoofSurfaces, FloorSurfaces, TrafficAreas and AuxiliaryTrafficAreas* are created and enriched with attributes, which allow an upgrade of the produced data to CityGML 3.0 using FME. Figure 6.10 shows the resulting 3D garage model connected to an adjacent road network.

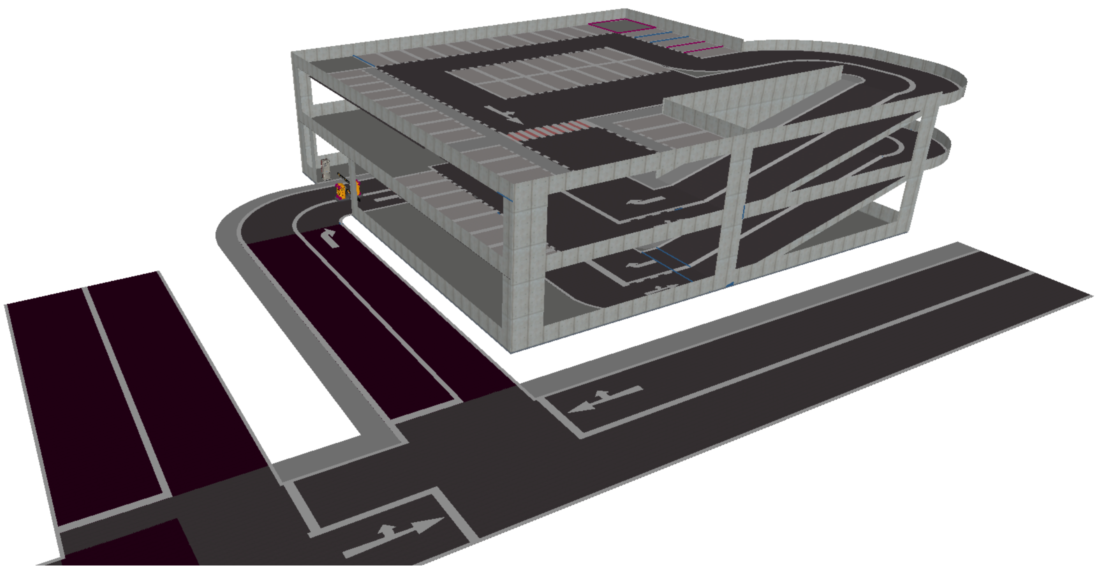


Figure 6.10: CityGML 3.0 compliant 3D garage model connected to a road network outside of the building (Olbrich et al., 2024).

In the course of this process, *CityObjectRelations* between corresponding surfaces are introduced in order to reflect the concept presented in chapter 5.8.4. Additionally, volumetric *TrafficSpaces*

[22]https://creating-citygml-datasets.readthedocs.io/en/latest/
[23]https://www.3dis.de/cityeditor/

within the building are generated by vertically extruding corresponding *TrafficAreas*. Predecessor and successor relations between these *TrafficSpaces* are manually introduced and the resulting (true) 3D model is geo-referenced at a location in Grafing near Munich, which allows a connection of the 3D garage model with existing real-world road data available from the previously mentioned OpenDRIVE data conversion. Individual *TrafficAreas* and *AuxiliaryTrafficAreas* of the garage are modelled in level of granularity ’lane’ representing individual lanes and parking slots. To ensure the clarity of the illustration, volumetric or linear representations of *(Auxiliary)TrafficSpaces* are not visible in the given example. A version of this model was used by Olbrich et al. (2024) for demonstrating multi-modal navigational use cases (cf. chapter 7.5).

6.4.2 Road on a Bridge Deck

As described in sub-chapter 5.8.3, surfaces that represent the exact same area but are semantically different can be connected using *CityObjectRelations* (= equal). This applies for example to bridge decks that are part of *Roads* and *Bridges* simultaneously. A basic dataset demonstrating this concept is created using the 3D modelling software SketchUp with a corresponding CityEditor plugin and a FME post-process to convert the model to CityGML 3.0 compliant data. Figure 6.11 illustrates the resulting dataset of a CityGML 3.0 compliant *Road* consisting of three *Sections*. *TrafficSpaces* and corresponding *TrafficAreas* of the middle *Section* are simultaneously modelled as *RoofSurfaces* of a corresponding *Bridge* object. This is realized using the *CityObjectRelations* as discussed earlier. The resulting dataset is available for download in the previously mentioned repository[21].

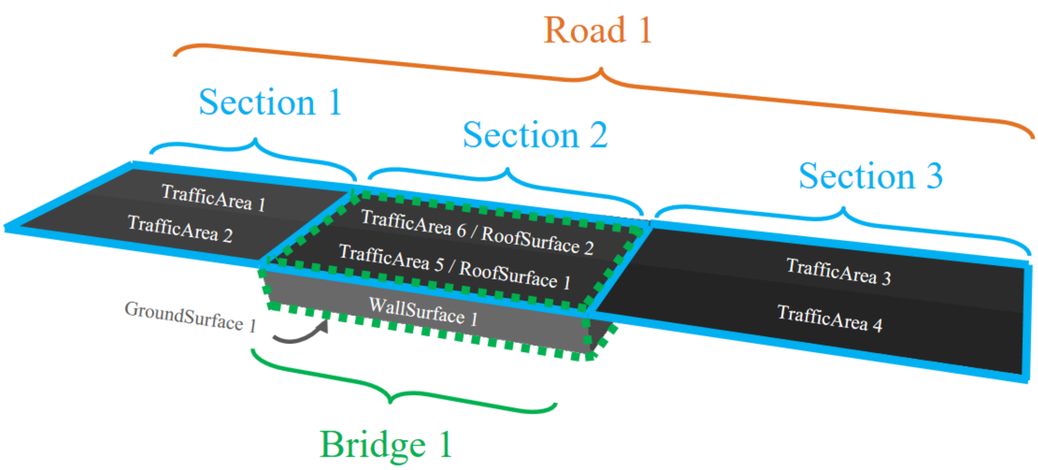


Figure 6.11: Generic CityGML 3.0 compliant 3D model demonstrating CityObjectRelation concepts for non-redundant representations of surfaces simultaneously part of a Road and a Bridge.

Chapter 7

Implemented Use Cases for semantic CityGML Streetspace Models

Some of the contents in this chapter have been presented in the following peer-reviewed and published papers:

Beil, C., Ruhdorfer, R., Coduro, T. and Kolbe, T. H. (2020). 'Detailed Streetspace Modelling for Multiple Applications: Discussions on the Proposed CityGML 3.0 Transportation Model'. In: *ISPRS International Journal of Geo-Information* 9(10), p. 603. URL: https://doi.org/10.3390/ijgi9100603

Schwab, B., Beil, C. and Kolbe, T. H. (2020). 'Spatio-Semantic Road Space Modeling for Vehicle – Pedestrian Simulation to Test Automated Driving Systems'. In: *Sustainability* 12(9), p. 3799. URL: https://doi.org/10.3390/su12093799

Beil, C., Kendir, M., Ruhdorfer, R. and Kolbe, T. H. (2022). 'Dynamic and web-based 4D visualization of streetspace activities derived from traffic simulations and semantic 3D city models'. In: *Proceedings of the 17th International 3D GeoInfo Conference 2022*. Vol. X-4/W2-2022. ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences. University of New South Wales. ISPRS: Sydney, pp. 29–36. URL: https://doi.org/10.5194/isprs-annals-X-4-W2-2022-29-2022

Beil, C., Ilic, M., Keler, A. and Kolbe, T. H. (2024). 'Automatically evaluating the service quality of bicycle paths based on semantic 3D city models'. In: *Lecture Notes in Geoinformation and Cartography - Recent Advances in 3D Geoinformation Science - Proceedings of the 18th 3D GeoInfo Conference*. Technical University of Munich, Chair of Geoinformatics. Springer Nature Switzerland: Cham, pp. 75–92. URL: https://doi.org/10.1007/978-3-031-43699-4_5

Olbrich, F., Beil, C., Nguyen, S. H. and Kolbe, T. H. (2024). 'Multimodale Navigationsanwendungen für CityGML 3.0 konforme 3D-Straßenraummodelle mittels Graphdatenbanken'. In: *44. Wissenschaftlich-Technische Jahrestagung der DGPF in Remagen – Publikationen der DGPF, Band 32*. Deutsche Gesellschaft für Photogrammetrie, Fernerkundung und Geoinformation e.V., pp. 357–369. URL: https://www.dgpf.de/src/tagung/jt2024/proceedings/paper/26_dgpf2024_Olbrich_et_al.pdf

In order to demonstrate the practicability of the developed concepts, several use cases from different application domains utilizing functionalities that require information provided by semantic 3D streetspace models are implemented and evaluated in the following chapters.

7.1 Road Pavement Rating Analysis

Z. Yao (2020) presents an extension to the WebGL-based Cesium Virtual Globe called 3DCityDB web-map client. The web client allows an efficient 3D visualization of multiple data layers and supports visualization formats such as glTF or 3D Tiles, which can be generated from original CityGML data. Each layer can be linked with corresponding semantic data stored in Google Spreadsheets. Attributive information provided in these tables can be linked via corresponding unique *gml:id* values contained within each object. This allows (combined) queries for these attributes and subsequent analysis of query results. In this context, an interesting application of semantic road models is the estimation of potential repair costs of transportation infrastructure. The streetspace model of New York contains a huge variety of semantic information, such as street names, number of driving lanes, street area in m^2 or attributive information on pavement ratings evaluated by the NYC Department of Transportation. These attributes can be queried in different combinations and thus be used for gaining additional information.

First, all traffic areas belonging to 5th Avenue are selected. This is done by selecting roadbed and intersection areas with the name '5 Avenue' (since this is the naming convention of roads contained within the source data) by querying the respective *gml:name* attribute. Intersection areas contain multiple *gml:name* attributes, thus using the query *like '%5 Avenue'*, intersections that contain this value will be selected. Figure 7.1 shows the result of this query in the web client with all roadbed and intersection areas of 5th Avenue highlighted in yellow.

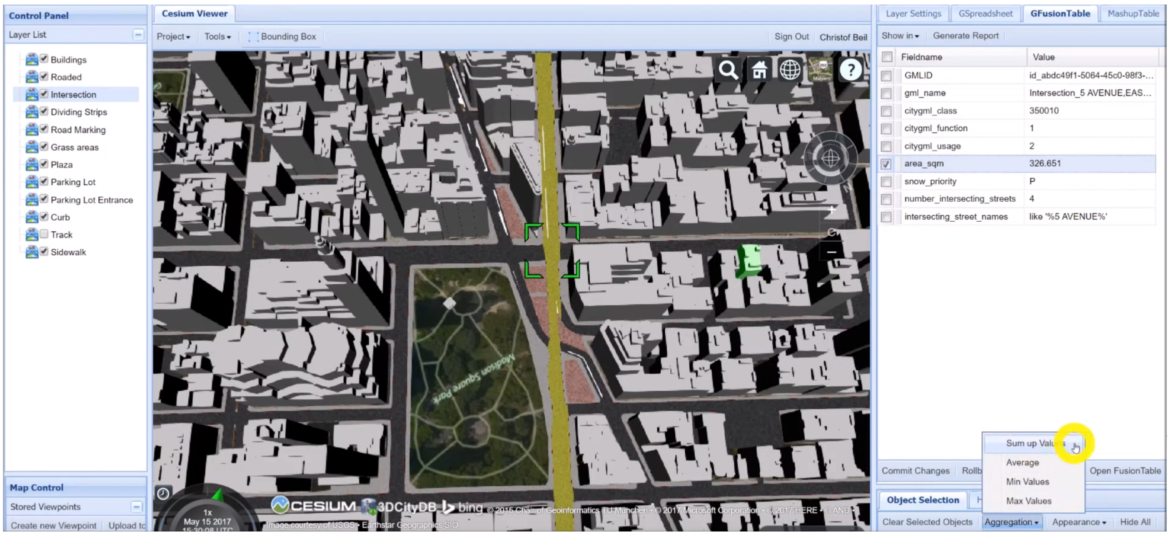


Figure 7.1: Query for all roadbed and intersection areas belonging to 5th Avenue using the 3DCityDB Web Client Pro.

A similar query is done for road surfaces of the famous Broadway in New York City[24]. Additionally, by summing up all corresponding 'area_sqm' values of the selected objects (providing information

[24]Note: Parts of Broadway extend beyond the borders of the created city model. The part of Broadway contained within the city model extends from Broadway Bridge to the very south of Manhattan (approx. length of 21.5 km).

on the surface area of individual objects in square meters), the total traffic area of roadbeds and intersections in m^2 of Broadway is calculated. Then, making use of information on street pavement conditions (rated with 1-3 = BAD, 4-7 = FAIR, 8-10 = GOOD), all roadbed objects (of Broadway) with a street pavement rating of 6 and 7 (lowest existing values) are selected. By calculating the total area in m^2 of the selected roadbed objects, assumptions on potential future repair costs can be made. Note that only some roadbed objects contain information on pavement ratings. Further evaluations such as the total area of roadbed and intersection areas of Broadway can be calculated. Some of the results of these calculations for Broadway are:

- Total area of roadbeds on Broadway: 357,060 m^2
- Total area of intersections on Broadway: 65,619 m^2
- Total area of roadbeds and intersections on Broadway: 422,679 m^2
- Total area of roadbeds on Broadway with a pavement rating of 6-7: 28,774 m^2
- Total area of roadbeds on Broadway with a pavement rating of 8-10: 109,326 m^2

Information on road surface areas, which are in a particular bad state can be used in order to estimate potential repair costs of the road parts. In addition, information on used or needed surface material can be included into these calculations. Similarly, information on road markings and corresponding surface areas is useful in order to estimate costs of renewing road marking paint. Figure 7.2 shows a visualization of roadbed pavement ratings of central Manhattan at the intersection of Broadway and 5th Avenue. Road surfaces are colored according to pavement rating values in order to give a quick and intuitive impression about road conditions.

Figure 7.2: Visualization of road pavement ratings of individual sections within a semantic 3D city model of New York City.

Similar queries can be used to derive other facts and numbers, such as number and total area of parking lots (large sealed surfaces intended for car parking) within the entire city:

- Number of parking lots in the entire city: 20,714
- Total area of parking lots in the entire city: 35,093,227 m^2
- Average parking lot area: 1,694 m^2

7.2 Local Heat Island Effect Analysis

The Urban Heat Island (UHI) effect refers to the phenomenon where urban areas experience higher temperatures compared to their surrounding rural areas. This difference is mostly due to buildings and large sealed surfaces with surface materials such as asphalt and concrete that tend to absorb and retain heat (Deilami et al., 2018). Bornstein (1968), for example, discusses the urban heat island effect in New York City showing significant differences in temperature in and around the urban area of the city. Lima Alves and Lopes (2017) show the influence of vegetation in reducing the negative impact of the UHI effect. While the UHI effect is usually evaluated on a larger (city) scale, local heating effects, e.g. for an area of a specific intersection or plaza, can be determined similarly. Detailed 3D streetspace models including vegetation objects such as individual trees allow a more microscopic analysis of this effect. Until now, solar irradiation analyses are mainly performed for buildings in order to estimate solar energy production potentials. However, this can also be used to automatically simulate urban or local heat island effects caused by solar irradiation on large sealed surfaces such as road infrastructure or public plazas.
Chaturvedi et al. (2017b) and Willenborg et al. (2018) presented a method for large-scale solar potential estimation based on semantic 3D city models given in CityGML. As depicted in figure 7.3, the position of the sun is calculated for an entire year. The temporal resolution can be adapted according to required detail and available computing power (usually a temporal resolution of 1 hour is used). Then, each point is associated with a radiation power and stored as a corresponding attribute. An approximation of a sky half dome is constructed, where each point represents a spherical segment. Semantic objects of a semantic 3D city model are then converted into a point-grid representation. While the developed tool originally only supports *Building Roof-* and *WallSurfaces*, *Road* and *Square* surfaces (such as *(Auxiliary)TrafficAreas*) can be prepared in such a way, that it is possible to do irradiation simulations on these surfaces as well. The points constructed from the semantic surfaces are used as reference points for the irradiated solar energy. Shadows cast by surrounding features such as buildings or vegetation objects or the surrounding terrain are considered by using a ray-tracing approach. Rays from the point-grid created from the semantic surfaces to all sun and hemisphere points are calculated and intersected with potential occluding objects. Results of this simulation include a Sky View Factor (SVF), direct, diffuse and global irradiation values for each simulated time period. These results are stored as attributes with the original semantic objects and used to create a texture showing color gradients.

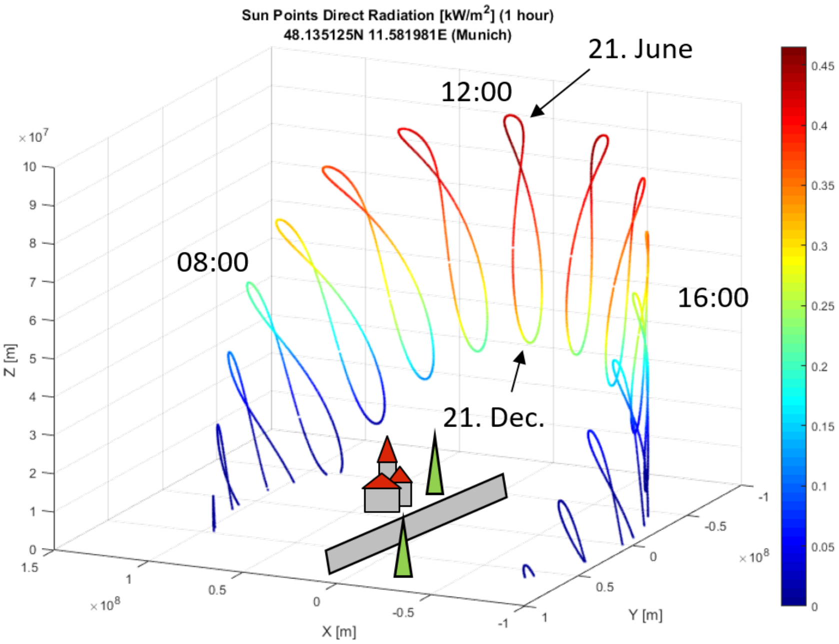


Figure 7.3: Hourly positions of the sun in the course of a year relative to objects such as buildings, roads or vegetation and corresponding direct radiation in [kWh/m^2] adapted from (Willenborg et al., 2019).

This solar-irradiation-analysis tool is now tested using LoD 2 *Buildings* in combination with areal streetspace objects, estimating global, diffuse, and direct irradiation. Figure 7.4 shows the result of this solar irradiation simulation. The city model is textured according to global irradiation values (kWh/a), ranging from blue (low irradiation values) over green to red (high irradiation values). This type of visualization is useful for quick and intuitive analyses of suitable areas to install photovoltaic systems or in the case, of roads to locate local heat islands or shady places (Chaturvedi et al., 2017b). In order to allow more profound analyses, all calculated irradiation values as well as attributes, such as a ‘Sky View Factor’ (SVF), are also stored as attributes for each individual city object. As an example, the maximum SVF for three selected locations (open plaza (1), roof of Flatiron Building (2), backyard parking lot (3)) is shown. Figure 7.5 shows similar results for a CityGML streetspace model of an intersection in Munich derived from the previously presented Munich Lane Model. In this example, vegetation objects such as trees were additionally considered in the simulation in order to estimate the influence of shading caused by vegetation on solar irradiation. Results are visualized in a Cesium based web-map client including multiple layers. The image on the left includes vegetation objects used in the simulation in order to evaluate shadowing effects. In the image on the right, these vegetation objects are hidden to clearly demonstrate their effect on irradiation values (and thus local heat development) in certain areas. Further information such as surface materials with specific heat radiation and thermal properties as well as air flow simulations could be included to further improve the results of these analyses. Sukma et al. (2024) demonstrate the usage of 3D building models in combination with sensor data to evaluate the UHI effect, which could be transferred to the streetspace and used to complement the presented evaluations.

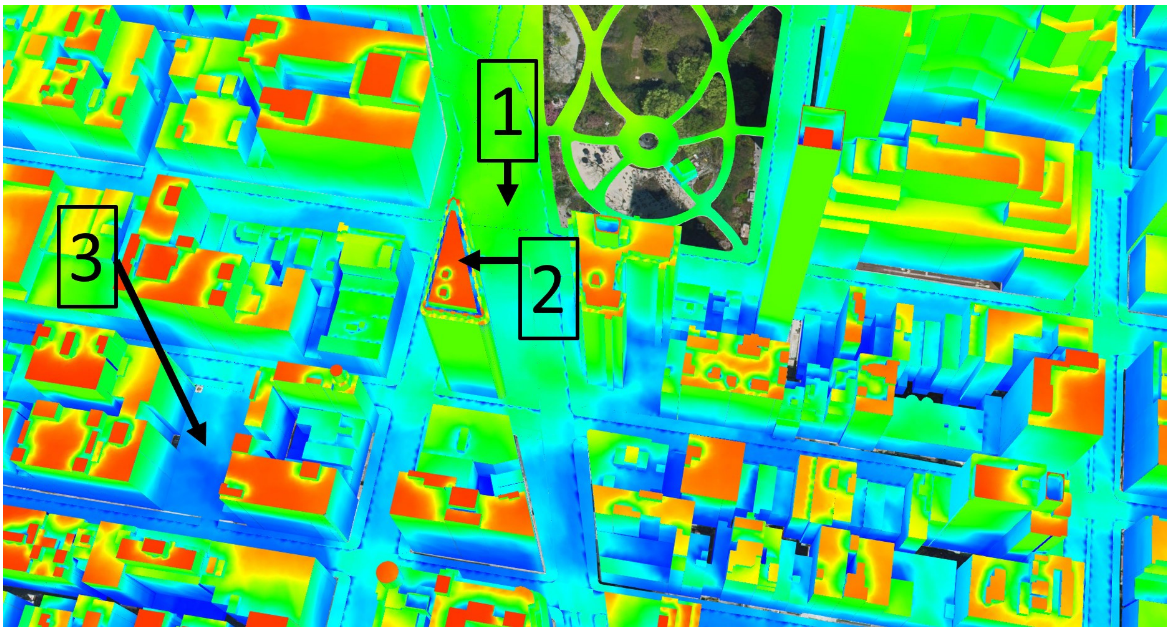


Figure 7.4: Visualization of a global irradiation estimation (kWh/m^2 per year) for buildings and street objects Maximum Sky View Factor: (1): 0.532, (2): 0.958, (3): 0.254 (Beil et al., 2020).

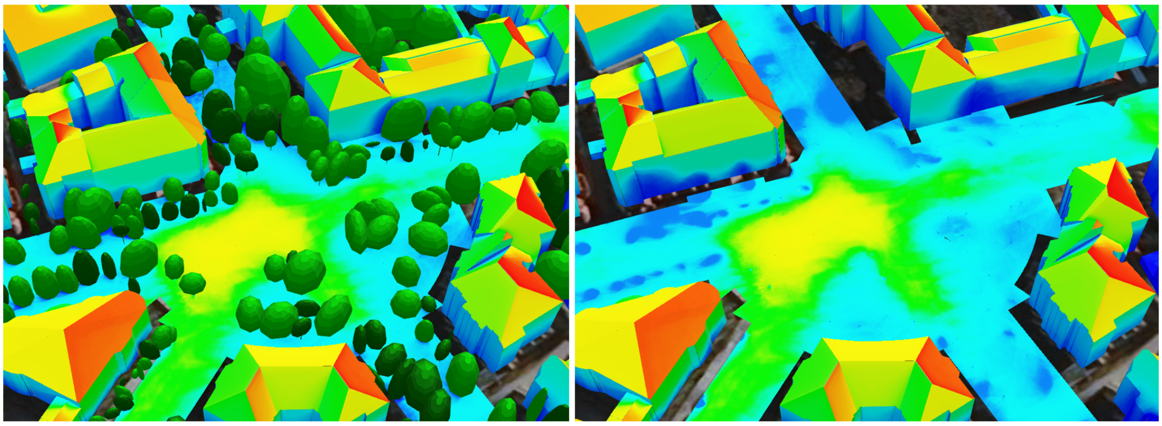


Figure 7.5: Effect of vegetation on solar irradiation (kWh/m^2 per year) on large sealed surfaces such as roads or plazas.

7.3 Web-based Visualization of Traffic Simulation Results

7.3.1 Related Work

There is some related work on web-based visualizations of time-dependent and city related processes in general. Murshed et al. (2018) present a web-based application for visualizing dynamic processes in smart cities such as changing irradiation data on buildings or changing cooling energy needs. Methods for representing time-evolving 3D city models using 3D Tiles, including different building states such as creation, modification or demolition, are described in Jaillot et al. (2020). Mao et al. (2020) present dynamic style animations of energy simulations using 3D Tiles. The integration of dynamic sensor data with city models plays a central role in the context of smart cities. Macura (2019) describes a method for visualizing time-dependent sensor data of buildings within a Cesium based 3D GIS application by coloring volumetric geometries representing individual rooms with colors according to temperature measurements at certain times. Chaturvedi (2021) presents dynamic visualizations of building energy demands in Cesium derived from live sensor data. Kurkcu et al. (2017) visualize bus time data, including color-coded speed-per-section representations and bus stop times. However, this visualization does not include individually moving objects. Schwab et al. (2020) show how pedestrian and vehicle simulation results can be coupled and visualized within simulation environments such as Virtual Test Drive (VTD).

Furthermore, there are some publications focusing specifically on the visualization of microscopic traffic simulations. W. Chen et al. (2015) give an overview and categorization of traffic data visualizations and describe different typical processing stages of generating visualizations from traffic data. Chao et al. (2020) present a survey on different approaches to animated visualizations of traffic simulations. H. Xu et al. (2022) present an application for managing and visualizing traffic simulation results. The application can work with both Vissim and SUMO simulation results and visualizes moving vehicles and static signals using colored dots overlayed with a 2D map, whereby the color of individual points depends on their current speed. Additionally, traffic densities can be represented using a heat-map visualization. Most of the traffic simulation visualizations mentioned so far mainly focus on representing vehicle movements using point geometries or more abstract representations of general traffic movement or traffic volume. However, a more realistic visualization of individual traffic participants as well as other streetspace activities could be achieved using 3D models. Keler et al. (2018) present a Virtual Reality (VR)-based, ego-perspective bicyclist visualization coupled with traffic simulation results. Artal-Villa et al. (2019) present methods for coupling traffic simulations with game engines such as Unity. Simulation tools such as 'Car Learning to Act' (CARLA) are coupled with game engines (the Unreal Engine in this case) and thus (in addition to realistic simulations) provide highly detailed visualizations Dosovitskiy et al. (2017). While this results in realistic and visually appealing visualizations, this also requires specific apps or software for viewing these representations.

Furthermore, game engines usually use a local reference system and do not support geo-referenced data. Thus, it is difficult to integrate other data sources (e.g. point clouds or city models) ad-hoc within a common visualization. A more accessible approach for visualizing traffic simulation results can be done by coupling these with semantic 3D city models and creating web-based visualizations using virtual globes, which also support geo-referencing. Ruhdorfer et al. (2018) derived input data for the micro-traffic simulation tool Vissim from semantic 3D streetspace models and then visualized traffic simulation results in GoogleEarth using KML. Z. Yao (2020) demonstrates methods for extending the Cesium virtual globe in order to visualize large city models and also briefly mentions the possibility to include data available in the Cesium Language (CZML) format. Chaturvedi et al. (2019) present how the concept of Dynamizers can be used for integrating and visualizing dynamic data within semantic 3D city models. Several publications present how CZML can be used for visualizing dynamic processes in the Cesium virtual globe L. Zhu et al. (2018a).

7.3.2 Introduction to the Cesium Language (CZML)

The current version 1.0 of CZML was developed by the company AGI and can be used for visualizing time-dependent data in the Cesium virtual globe. A documentation of the standard and its concepts is provided in the CZML Guide[25]. L. Zhu et al. (2018b) give a detailed explanation of the structure and content properties of CZML documents. In the following example, the most relevant parts of the structure and properties of CZML documents with respect to visualizing streetspace activities are described using an example derived from traffic simulation results. CZML documents (.czml) are based on the JavaScript Object Notation (JSON) data format and consist of multiple sequential JSON objects called packets as displayed in listing 7.1. The first packet in any CZML file is a document object defining an 'id', 'name' and 'version' of the CZML file. Information on the time interval (start and end time of the simulation) as well as the desired current (starting) time of the visualization can be contained within a 'clock' property. All properties are stored as a 'name : value' pair. Individual packets for each object are created. First, the 'id' of each traffic member and an optional 'name' property is stored. Then a 'model' property containing a relative path to a folder referencing different .gltf models depending on the type of traffic member (e.g. pedestrians, bicycles or trams) is included. In this example, a 3D model called '1.gltf' is referenced. A 'heightReference' property is set to 'NONE' since this allows the vertical position of models to correspond to their z-values. While it is also possible to set this value to 'CLAMP_TO_GROUND' or 'RELATIVE_TO_GROUND', this could cause problems when visualizing models at different height levels (e.g. vehicles on bridges). In order to hide models at a certain zoom-level, a 'distanceDisplayCondition' is set to a range of 1 to 800 meters indicating the visibility of objects based on camera distance. Within the position property the geographic coordinates and elevation values of objects are given for time steps (one second in this case) relative to the time defined within the respective 'epoch' property. Similarly, the orientation of objects is specified with a unit quaternion representation of angles for time steps relative to the 'epoch' property. CZML offers the opportunity to specify an interpolation algorithm, which is used to interpolate data between time-tagged values. If not further specified, a linear interpolation is used.

```
[
 {
  "id" : "document",
  "name" : "TrafficSimResults",
  "version" : "1.0",
  "clock" : {
   "interval" :
   "2024-10-18T09:03:49.449Z/2024-10-18T10:10:49.0489Z",
   "currentTime" : "2024-10-18T09:05:40.449Z",
   "multiplier" : 1
  }
```

[25] https://github.com/AnalyticalGraphicsInc/czml-writer/wiki/CZML-Guide

```
 },

 {
  "id" : "car01",
  "name" : "car01",
  "model" : {
  "gltf" : "./Modelle/1.gltf",
  "heightReference" : "NONE",
  "distanceDisplayCondition" : {
  "distanceDisplayCondition" : [ 1, 800 ]
  }
 },
  "position" : {
  "epoch" : "2024-10-18T09:03:49.449Z",
  "cartographicDegrees" :
  [ 0.0, "11.568003", "48.132709", 517.89,
    1.0, "11.567893", "48.132711", 518.00,
    ...
  ]
  },
  "orientation" : {
  "epoch" : "2024-10-18T09:03:49.449Z",
  "unitQuaternion" :
  [ 0.0, -0.21071101232792602, -0.3013600122118491,
         -0.6864276868642915, -0.6273755199476252,
    1.0 -0.21621932000480018, -0.2974324100898577,
         -0.6978521288546177, -0.6146426387242255,
    ...
  ]
  }
 }
]
```

Listing 7.1: Example CZML file derived from SUMO traffic simulation results.

7.3.3 Converting SUMO Simulation Results to CZML

"Simulation of Urban MObility" (SUMO)[26] is an open-source software package for microscopic traffic simulations developed by the German Aerospace Center (DLR) (Behrisch et al., 2011) capable of handling networks on a large scale. Simulations can include different traffic types such as vehicles, bicycles or pedestrians. A SUMO-Network is a directed graph, with junctions of a road network represented by nodes and linear connections represented by edges (Lopez et al., 2018). To create a SUMO-Network, different input files are needed. One file should contain the nodes, one should

[26] **https://sumo.dlr.de/docs/index.html**.

specify the edges and one should specify the connections between the edges. The connections define which lane of an origin edge is connected to the lane of a destination edge. While it is possible to include elevation data into the simulation, the SUMO network data in this example is given in cartesian 2D coordinates. OpenStreetMap (OSM) data is used as the foundation from which the SUMO network is built. Based on aerial images and other reference data, the OSM-based SUMO network is manually adjusted in order to be as accurate and up-to-date as possible. The SUMO network is calibrated using information on traffic signals as well as traffic counts and detector data for the relevant area. The accuracy of SUMO simulation results is limited by the accuracy of the underlying input data from which the simulation network is generated. Output lon/lat geo-coordinates are given with a precision of six decimal places. There are a range of output files available such as raw vehicle positions or emissions. Another file called 'Floating Car Data Output' (FCDOutput) contains information on location (longitude / latitude coordinates), orientation (angle), speed, vehicle types and other information for certain time steps. The angle describing the orientation of traffic members is given according to the navigational standard (0-360 degrees, going clockwise with 0 at the 12 o'clock position). The position given with lon/lat coordinates corresponds to the front of a vehicle. While different time-steps are possible, experiments showed, that a one second step between locations is sufficient to achieve a smooth visualization later on. It is also possible to include elevation data within the SUMO simulation directly. In this case slope values can also be part of the output file. However, for OSM data this is still experimental. The workflow for generating a CZML document from SUMO simulation results is illustrated in figure 7.6.

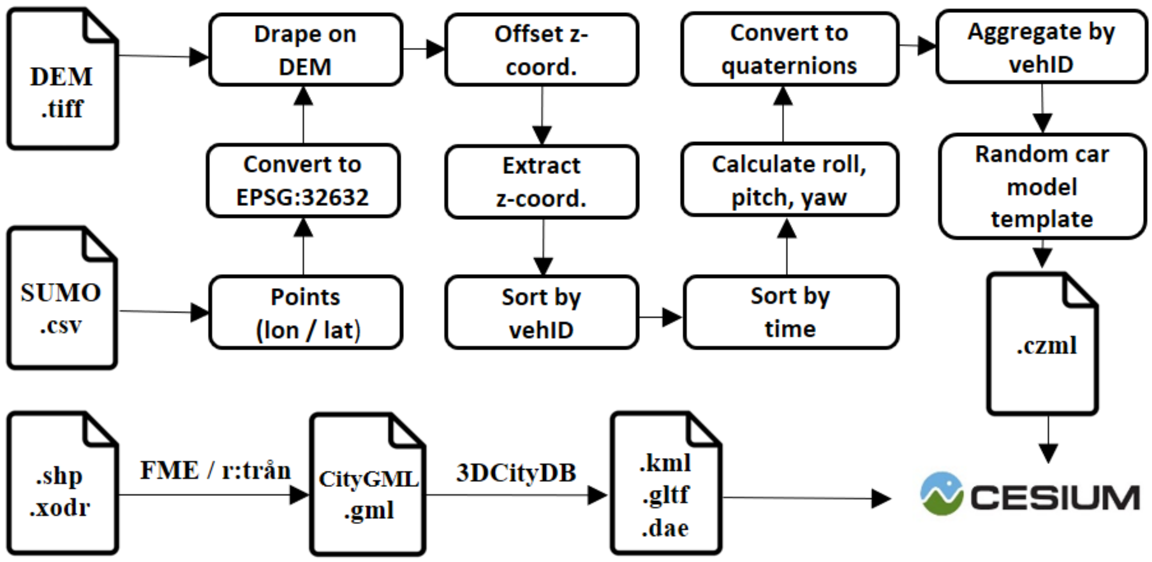


Figure 7.6: Workflow for generating and visualizing CZML documents from SUMO traffic simulation results (Beil et al., 2022).

The area of interest (approximately 0.5 km x 1 km) will be visualized later. In order to get realistic simulation results, the actual traffic simulation is conducted for a larger area in the center of Munich.

Multiple simulations with different traffic types and time-steps are conducted.
The SUMO simulation results are then converted to the CZML format with a conversion workflow created using the Feature Manipulation Engine (FME). While FME does not support CZML natively, it is possible to create and write text documents with a corresponding file structure. Input data for this conversion process are the CSV data of the SUMO FCDOutput as well as a digital elevation model with a resolution of one meter provided as GeoTIFF.
First, point geometries are created from the positional information in order to adapt the z-values of these points to the underlying terrain, the point geometries are transformed into the 'WGS 84 / UTM zone 32 N' (EPSG:32632) coordinate system and then draped on the digital elevation data. A vertical offset to each position can be included in order to avoid potential rendering problems due to multiple layers at the same height level. After storing the final z-coordinate of each point as a new attribute, all contents of the CSV file are sorted by their 'vehId' and 'time' attribute. Optionally, it is possible to filter for specific vehicle types, locations (bounding box) or time spans. Then, the orientation of traffic members given as roll, pitch and yaw values is calculated. 3D models are placed in their 'body frame' as shown in figure 7.7. The placement of models is offset from the center of gravity, so that reference points represent the front of vehicles. According to the CZML Guide, the orientation property in CZML is defined as a vector that represents the 'body axes' of an object transformed to the 'Earth fixed axes'. The transformation between the 'Earth Centered Earth Fixed' (ECEF) frame and the 'East-North-Up' (ENU) local tangent plane coordinate frame is depending on the location of models on the Earth's surface (longitude/ latitude coordinates). Some rotations need to be performed in order to align the vehicle roll, pitch, yaw axes with the East-North-Up axes. First, 3D models are rotated around the z-axis in order to point towards the North-axis. This depends on the local longitude as well as the orientation of the 3D model in its 'body frame'. Individual orientations of 3D models at a certain time then correspond to the angle value derived from the SUMO simulation. Then, the pitch and roll angles are adapted based on the local latitude and longitude coordinates, so that models are placed correctly on the local tangent plane. Also local slopes in driving direction are considered.

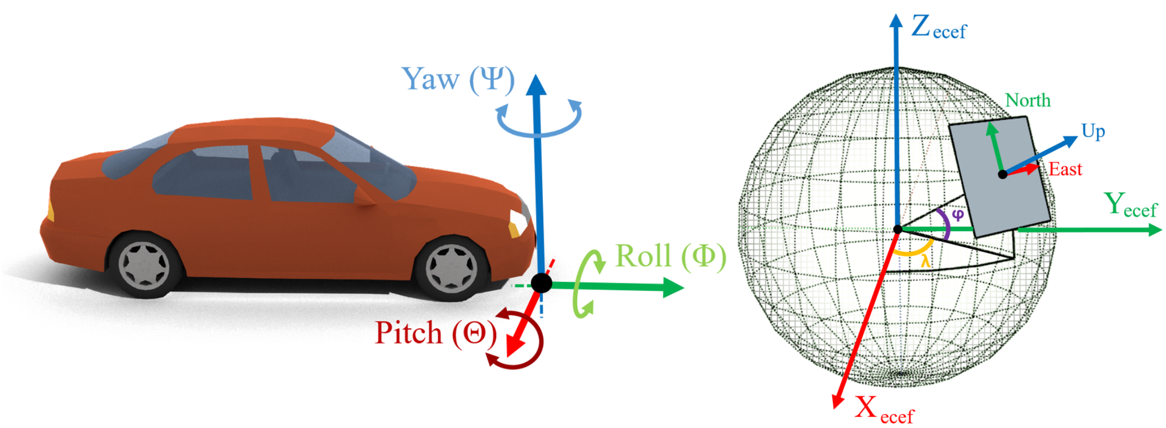


Figure 7.7: Left: Roll, pitch and yaw angles in the 'body frame' of the 3D model. Right: ECEF and ENU frames (Beil et al., 2022)

Every conversion and calculation step so far is done for each point individually. Now, information is aggregated based on corresponding 'vehId' attributes. In this process, individual CZML packets are created for each 'vehId'. Interval and epoch times are specified according to the time span of the simulated scenario. Time-step, position and orientation values are added to each packet iteratively. Relative paths to a folder containing a bibliography of different 3D models are created based on 'vehType' attributes. The 3D models used were downloaded from the SketchUp Warehouse and converted to .gltf using FME. The origin of 3D models is placed as shown in figure 7.7. This corresponds to the front of a vehicle, which is also the reference point of positions used in SUMO. This method also takes into account different heights of the used 3D models and places the models so that tires align with the ground (this is another reason, why the 'heightReference' is set to 'NONE'). Additionally, optional point geometry representations visible from a certain zoom-level can be added. Cesium offers an animated model called 'Cesium Man', which is used to represent pedestrians. In case the 'vehType' property is 'tram', 'person' or 'truck' corresponding model paths are set. For cars, 16 different 3D models are assigned semi-randomly by setting the relative path to a 3D model called [1-16].gltf. Models are assigned to vehicles sorted by 'vehId'. This is relevant in order to assign the same 3D model to vehicles each time the workflow is run. If the exact information on specific vehicle types were available, corresponding 3D models could be referenced. Finally, the resulting document is formatted and written using the FME 'Text File' writer with an output file extension set to '.czml'.

7.3.4 Results

The workflow described in section 7.3.3 was used for deriving CZML data from a SUMO traffic simulation conducted for an area of interest in central Munich and combined with the pole and traffic light models as well as with the 3D streetspace model. The available traffic simulation covered a time period of 1 hour and 20 minutes with over 300,000 individual data points corresponding to 1,359 vehicles, 21 trams, 245 pedestrians and 63 bicyclists. Additionally, an alternative simulation for another time period containing 2,623 vehicles and 682 trucks is conducted (approx. 1,500 polygons per car model). Individual CZML files are created per traffic type and integrated within web-based visualizations using the '3DCityDB Web-Map Client'[27]. 36 traffic signals and 23 poles were created for a selected intersection within the area of interest by considering their real-world coordinates and types. Each city object contains semantic information, which can be viewed interactively by clicking on individual features. Several CZML layers are integrated within the visualization.
Figure 7.8 illustrates two points in time, with car models stopping at a red light (left image) and moving after the light has changed to green (right image). The number of individual traffic members that can be included within a (performantly running) visualization mainly depends on the geometric complexity of individual models, the number of relevant objects and the total time-span of the simulation. Figure 7.9 shows a direct comparison between a real-world scenario of an intersection near Frankfurter Ring in Munich using a Google Street View image and the corresponding 3D visualization. Figure 7.10 illustrates several vehicle models driving on the terrain or on a bridge ramp with adapted inclinations according to respective slopes in driving direction.

[27] **http://go.tum.de/054180**.

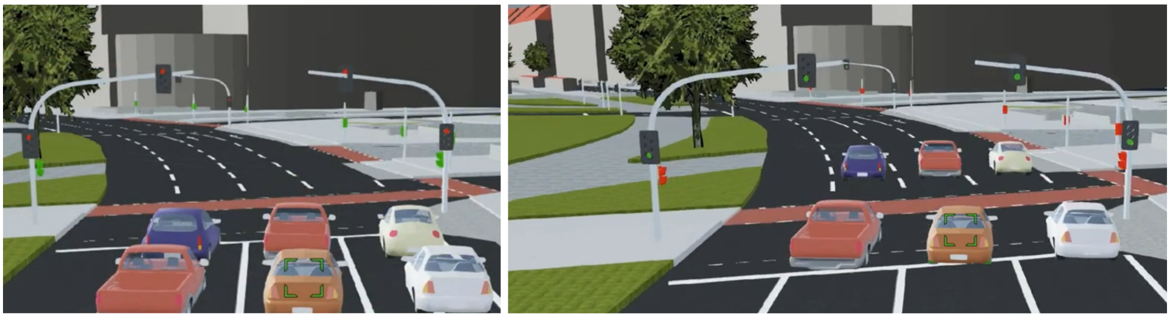


Figure 7.8: Vehicles and changing traffic signals with time. Left: Stopping cars and red traffic light; Right: Moving cars and green traffic light (Beil et al., 2022).

Figure 7.9: Web-based visualization of traffic simulation results for an area around the ’Frankfurter Ring’ in Munich with a direct comparison of a Google Street View image.

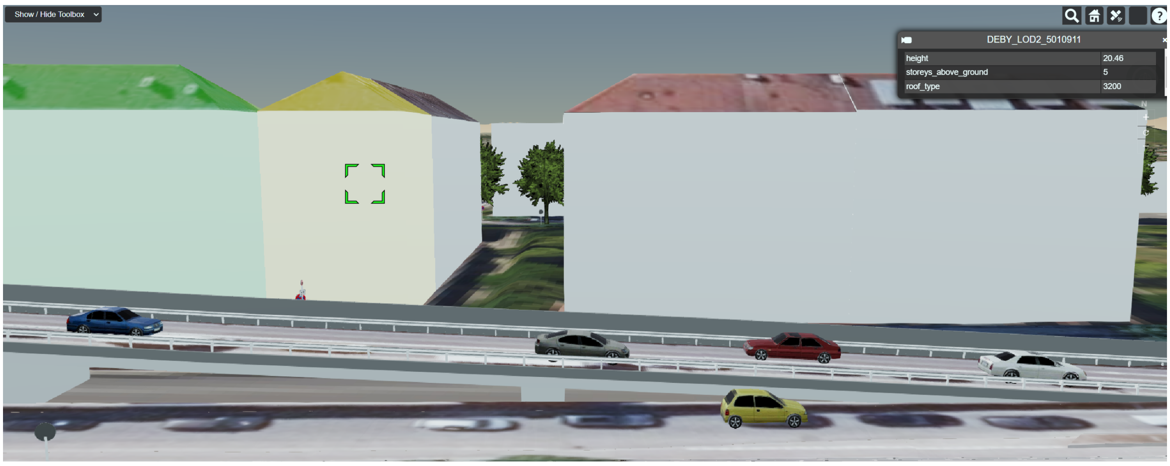


Figure 7.10: Web-based visualization of traffic simulation results within a semantic 3D city model including vehicles driving on a bridge ramp. The inclination of vehicle models is adapted to corresponding slopes of the underlying terrain and 3D models while considering respective driving directions.

7.3.5 Discussion of web-based Traffic Simulation Visualization Results

Due to the nature and level of detail of microscopic traffic simulations (as performed by tools such as SUMO), some 'unrealistic' lateral vehicle movements are visible within the visualization of their results. While sub-microscopic driving simulations also contain highly detailed vehicle behaviors, this is not considered within microscopic traffic simulations. However, more detailed simulation results could also be transferred to CZML using the process described in this chapter. While the method for deriving CZML documents from traffic simulations is demonstrated using SUMO, results from other tools (e.g. Vissim) could be processed similarly as long as relevant simulation outputs (position, orientation, vehicle type etc.) are available. The 3D models of vehicles used in this scenario do not contain additional animations such as rotating tires. Animated models could be easily included if available. While the used models of pedestrians do provide a walking animation, this animation also continues when pedestrians are stopping at a certain location. CZML provides a property called 'runAnimation'. This can be used to create different packets for moving and standing pedestrians with this property set to 'true' or 'false' respectively. The used tram model is relatively long, but does not bend when driving around corners. Within the web-based visualization it is possible to lock the current view to a specific traffic member, which then is followed in the continuing visualization. This could be further developed by creating an ego-perspective from the inside of vehicles. In the future, aerial mobility may play an increasing role within urban transportation. The visualization of drone or UAV flights could be integrated within 3D city model environments, too. In this context, the CityGML concept of *TrafficSpaces* representing the space where traffic actually takes place are relevant for aerial spaces as well. Traffic members currently not included (due to no information contained in the SUMO simulation) such as taxis, buses or cargo bikes could easily be integrated by extending the bibliography of referenced 3D models accordingly. In the future, it might be possible to couple simulation and visualization at run-time. This might also be relevant when including dynamic real-time data such as sensor information. Based on work presented in this chapter, the integration of static as well as time-dependent aspects of urban digital twins within a common representation can be improved.

7.4 Pedestrian Simulation

7.4.1 Creating Pedestrian Scenery Map Layouts from CityGML Data

The CityGML data available for Ingolstadt generated from OpenDRIVE contains information on Roads, CityFurniture, SolitaryVegetationObjects and Generic objects represented with 3D geometries. Furthermore, it comprises LOD 1 building models that were generated based on building layouts and height values included in the OpenDRIVE dataset. The CityGML dataset is used to create an XML document defining the geometrical map layout of the simulation scenery, which can be consumed by the pedestrian simulation software momenTUM (Kielar et al., 2016). This requires areal (polygonal) information on areas used by pedestrians such as sidewalks or crosswalks. The workflow used to generate an XML momenTUM scenery description from CityGML data is shown in figure 7.11[28].

[28]**https://github.com/tum-gis/momenTUM-layout-from-citygml**.

First, some pre-processing of the CityGML data needs to be done to have the right geometric and semantic structure required by the pedestrian simulator momenTUM. This includes projecting each object onto the two-dimensional plane as simulations are conducted in 2D. The original data is provided within the UTM zone 32N (EPSG:32632) coordinate system. To make coordinate values more easily manageable, systematic offsets are applied (East: -674000, North: -5405000). Then, the convex hull of each object is created, and the orientation of each polygonal feature is adjusted to ensure a counterclockwise vertex winding, as this is expected by momenTUM. All objects are aggregated to calculate a 2D bounding box of the scenery. Next, coordinates of each geometry are extracted, objects are sorted, counted and new attributes are created to be used for the assignment of CityGML objects to corresponding momenTUM scenery elements. These elements are obstacles, areas (origin, intermediate, destination) and 'taggedAreas' (sidewalks, crosswalks). Buildings, CityFurniture objects and Vegetation objects are directly assigned to obstacle elements. Suitable areas are defined as origins (locations where pedestrians enter the scenery), intermediates (locations pedestrians should interact with) and destinations (locations where pedestrians leave the scenery). Road and Generic objects are filtered using the CityGML function attribute to identify sidewalks, crosswalks or traffic islands (assigned to momenTUM crosswalks). The coordinate system of the two-dimensional spatial domain is defined by a bounding box and stored in the scenery data tag, which serves as a hierarchical root object to all scenery elements within the XML layout document.

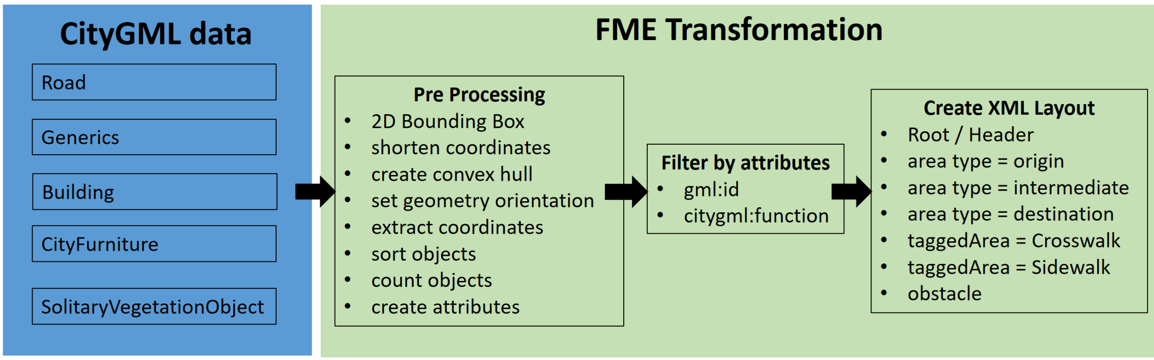


Figure 7.11: Workflow for generating a momenTUM scenery layout from CityGML using FME (Schwab et al., 2020)

7.4.2 Results

Listing 7.2 shows an example of the resulting XML momentTUM scenery description. The resulting simulation scenery layout is shown in figure 7.12. While obstacles generated from CityGML like Buildings, Vegetation and CityFurniture objects (red) cannot be entered, sidewalks (green) and crosswalks (yellow) are preferably used by pedestrians. As an intermediate solution, origins (dark blue), intermediates (pink) and destinations (light blue) are created manually. Here, CityGML building models in LOD 3 could be used from other data sources, since OpenDRIVE does not support the modelling of doors, for instance. This information in combination with other city objects such as public plazas or bus stations could easily be integrated within the workflow to generate a simulation layout.

```xml
<simulator version="MomenTumV2.0.0"
    simulationName="TUM_Layout_from_CityGML">
  <layouts>
    <scenario id="0" name="pedSim_TUM"
      maxX="21199.0626539188" maxY="16209.480080016"
      minX="20810.6720472456" minY="15649.1286034081">
      <area id="0" name="Origin" type="Origin">
        <point x="21043.242946836166" y="16009.957191649824"/>
        <point x="21044.415482939221" y="16009.647645104676"/>
        <!-- ... -->
      </area>
      <area id="1" name="Intermediate" type="Intermediate">
        <point x="20924.347566412762" y="15937.21406888403"/>
        <point x="20930.773944705725" y="15934.75292866677"/>
         <!-- ... -->
      </area>
      <area id="2" name="Destination" type="Destination">
        <point x="20896.12493518088" y="16199.675366044044"/>
        <point x="20897.363270128146" y="16198.927134675905"/>
         <!-- ... -->
      </area>
      <taggedArea id="0" name="Sidewalk" type="Sidewalk">
        <point x="21075.573558032513" y="16042.266192510724"/>
        <point x="21078.339263913222" y="16041.542930634692"/>
         <!-- ... -->
      </taggedArea>
      <taggedArea id="29" name="Crosswalk" type="Crosswalk">
        <point x="21005.17621501442" y="15903.497433401644"/>
        <point x="21007.044528313912" y="15903.055170617998"/>
        <!-- ... -->
      </taggedArea>
      <obstacle id="0" name="Solid" type="Solid">
        <point x="21165.532933952287" y="15829.52257222496"/>
        <point x="21185.400104395114" y="15821.701374722645"/>
        <!-- ... -->
      </obstacle>
    </scenario>
  </layouts>
</simulator>
```

Listing 7.2: Exemplary XML momenTUM scenery description derived from CityGML data.

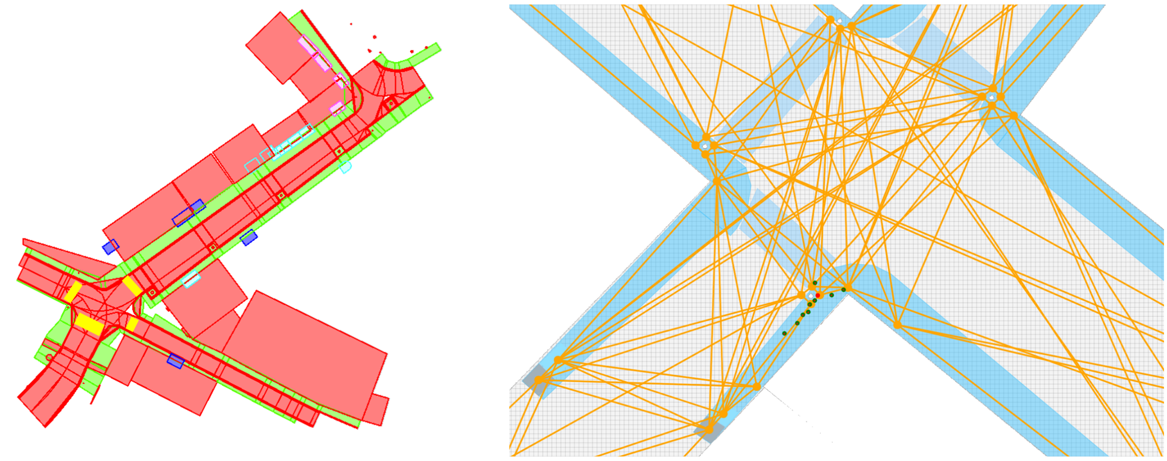


Figure 7.12: Simulation scenery generated from CityGML data with walkable areas such as sidewalks (green) and crosswalks (yellow) and obstacles such as buildings or road surfaces (red) (left). Corresponding pedestrian graph-network generated in momenTUM (right).

The pedestrian simulation results created using momenTUM with the described process are then coupled with the virtual driving simulation environment software VirtualTestDrive (VTD). In the scenario illustrated in figure 7.13, several pedestrians are moving from right to left. A detailed description on the generation process as well as the workflow for linking the pedestrian simulation with VTD is given in Schwab et al. (2020).

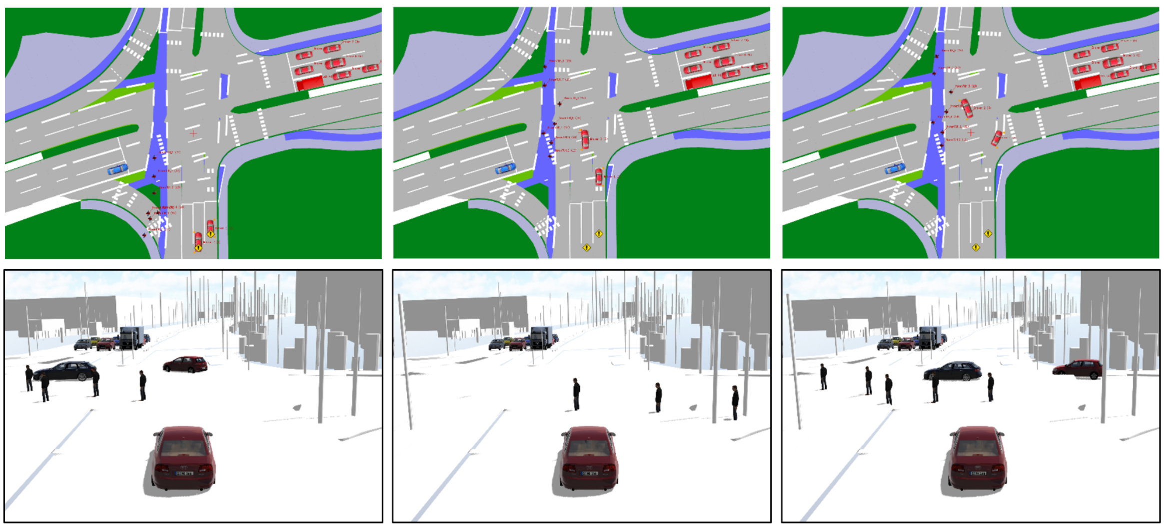


Figure 7.13: Simulation scenario visualized in the VTD editor (top images) and corresponding 3D visualization (bottom images) illustrating several time steps progressing from right to left (Schwab et al., 2020).

7.5 Multi-modal Routing and Navigation

While navigational use cases based on (linear or graph-based) representations of roads are commonly done (e.g. using OSM or GDF data), using CityGML-compliant 3D streetspace models as a data source for such purposes has several advantages. First, multi-modal routing functionalities require information on multiple transportation types such as driving lanes, footpaths or bicycle lanes as well as potential areas for switching between these modes of transportation such as parking slots. While there are routing applications considering public and private transport as well as pedestrian routes, they typically do not consider parking facilities required for making recommendations on optimal routes including points of transfer between different modes of transportation. Second, additional provided by three-dimensional models of roads and their environment can be useful to consider further aspects such as slope, road width, obstacles or raised / lowered curbs which are useful e.g. in the context of routing for people with limited mobility. Third, three-dimensional models allow routing use cases to be done on multiple levels within a true 3D environment, which is relevant for example within multi-story parking garages. A fourth aspect in this regards is the potential for linking indoor and outdoor routing applications, making use of the introduced space concept of CityGML, which is valid for both indoor (rooms) and outdoor (traffic) spaces.

7.5.1 Methodology

Concepts, object hierarchies and relations of CityGML can be mapped to a graph-based structure within the graph-database Neo4j[29] including objects (nodes) and their relations (edges) using the software citymodel-compare[30] (Nguyen et al., 2017). Due to the representation of links between objects (e.g. via XLinks) and the existing hierarchical structure of CityGML, relationships between the CityGML elements can be directly traced and graphically displayed in the graph database. This allows the representation of *TrafficSpaces* and corresponding predecessor / successor relations in a graph-structure. Using the Cypher query language, Neo4j makes it possible to examine this network for certain patterns such as shortest-path analysis relevant for routing and navigational use cases. Detailed information on this process is given in (Olbrich et al., 2024). In order to create a routable network from the CityGML structure mapped in the graph database, an abstracted network must be derived. Individual sub-graphs for each transportation type are created. Transfer-points between these sub-graphs need to be introduced in order to be able to switch between them. Furthermore, options for switching between adjacent lanes need to be introduced with additional edges between nodes representing relevant *TrafficSpaces*. These pre-processing steps slightly increase the size of the graph-database but are necessary in order to achieve realistic results. The transfer of a CityGML-compliant streetspace model consisting of individual *TrafficSpace* objects to a graph-based structure is illustrated in figure 7.14.

[29]https://neo4j.com/
[30]https://github.com/tum-gis/citymodel-compare

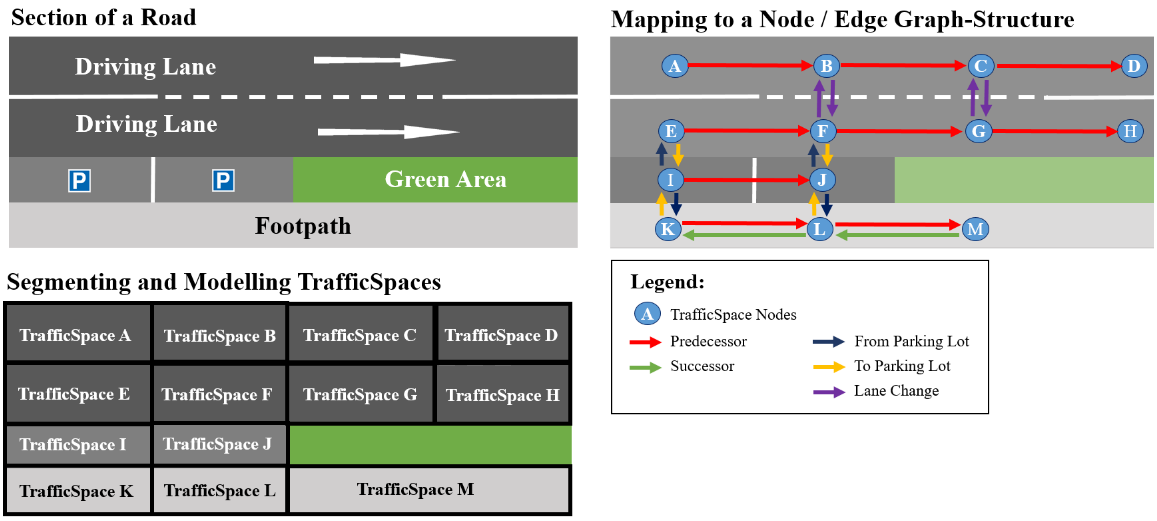


Figure 7.14: Mapping TrafficSpaces and their relations to a graph-based structure.

Driving lanes, sidewalks, parking areas and other relevant parts of roads are represented with *TrafficSpaces*. These *TrafficSpaces* are transferred to individual nodes within a graph-structure. Relations between these *TrafficSpaces* relevant for navigational and routing purposes such as predecessor (red arrows) or successor (green arrows) relations, a switch to (yellow arrows) or from (blue arrows) parking slots and possible lane changes between different lanes within a road (purple arrows) are represented with respective directed edges in the graph structure. Information on traffic directions is derived from the corresponding CityGML attribute *TrafficDirection*, which provides this information with respect to the underlying geometry (forwards, backwards or both). Furthermore, information on predecessors and successors of individual *TrafficSpaces* are translated to the respective graph-representation. Different edge weights such as distance or travel time can be applied depending on the focus of the routing application. Further weights correlating with road slopes, widths or road safety are possible. Since, all required information for a basic routing can be provided by *TrafficSpaces* represented with linear, areal, volumetric or even point cloud geometries, different geometric representations can be combined and transferred to a common graph-based structure.

7.5.2 Results

The described process of deriving a routable graph-structure from 3D CityGML streetspace models within a graph-database is done for several real-world examples. Several CityGML 3.0-compliant datasets derived from OpenDRIVE data using the open-source converter r:tron (as described in sub-chapter 6.1.3) are available. Since these datasets contain all relevant information for the proposed use case, they are suitable for implementing the described workflow. Additionally, the 3D model of a parking garage described in sub-chapter 6.4.1 is combined with the streetspace model of Grafing. This is achieved by manually georeferencing the 3D model at a suitable location and linking *TrafficSpaces* of the garage model with nearby *TrafficSpaces* of the Grafing road model. This is done for both driving lanes and walkable areas such as footpaths. The same process is applied to the CityGML 3.0-compliant dataset of some selected roads in Hamburg. Table 7.1 gives an overview on both datasets and the respective derived graph-databases. While all CityGML objects and relations are mapped to a corresponding graph-database-structure, only a subset of this graph is relevant for routing use cases, thus reducing the size of the database actually required for the presented task.

Table 7.1: Objects and file sizes of CityGML datasets and derived graph-databases.

	Grafing near Munich	**Hamburg (selected roads)**
Geographic bounding box	Height: 1.76 km Width: 2.45 km	Height: 2.44 km Width: 1.58 km
Nr. of CityGML features	TrafficSpaces: 9,103 TrafficAreas: 10,015 CityFurniture: 5,625 Markings: 6,608 Buildings: 1	TrafficSpaces: 1,641 TrafficAreas: 1,797 CityFurniture: 7,185 Markings: 3,317 Buildings: 218
Total nr. of nodes / edges	6,428,260 / 6,574,711	1,653,029 / 1,662,887
Nr. of nodes / edges relevant for routing use cases	9,103 / 13,920	1,583 / 2,455
CityGML file size	535 MB	132 MB
Size of Neo4j DB before / after pre-processing	1.64 GB / 1.83 GB	0.98 GB / 1.12 GB

The Grafing scenario combines several of the advantages of three-dimensional streetspace models for multi-modal routing. This is tested by selecting an arbitrary location in Grafing as a starting point for a routing request. A parking slot on the roof of the 3D garage building is defined as a switching point and an end point outside of the building, which is part of the pedestrian network is selected as destination. In order to demonstrate the usability of the implemented process to CityGML-compliant datasets from different sources and regions, routing requests are also performed on the streetspace model of Hamburg.

7.6 Evaluating the Service Quality of Bicycle Paths

The growing demand for sustainable mobility has led to an increased focus on the development and improvement of bicycle infrastructure, especially within cities. However, evaluating the quality of existing or planned bicycle paths is a complex task mostly done manually. In this chapter, a novel approach for automatically evaluating the Bicycle Level of Service (BLOS) using parameters derived from semantic 3D city and streetspace models compliant with concepts developed in this thesis is presented. The general workflow of the implemented process is illustrated in figure 7.15 and explained in detail in the following sub-chapters.

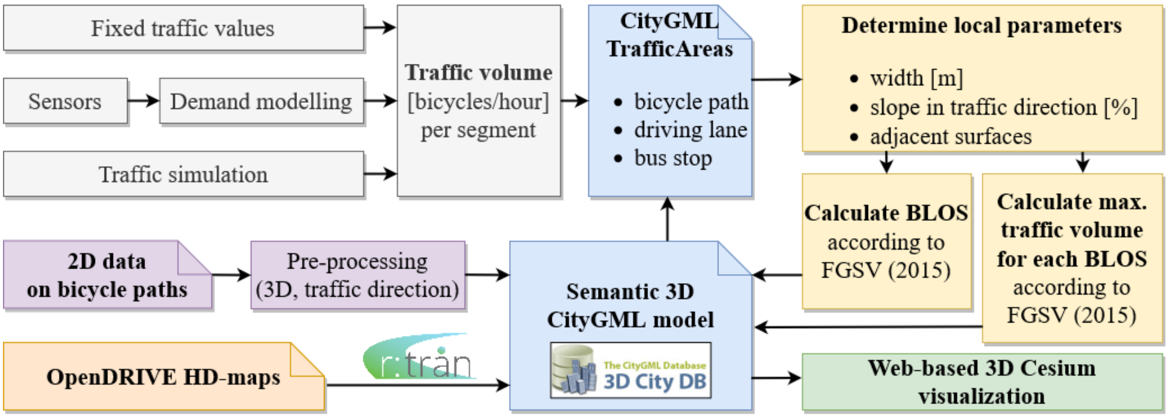


Figure 7.15: General workflow for determining the Bicycle Level of Service using parameters derived from semantic 3D city models (Beil et al., 2024).

7.6.1 Methods and Concepts for determining the Quality of Bicycle Paths

Several methods have been proposed to assess the quality of bicycle infrastructure that all differ in the type, amount and weighting of considered impact factors. In general, existing methods can be classified into seven overarching categories clustered according to their specific focus of assessment. While each of the categories and methods provides a unique perspective on the quality of bicycle infrastructure, they can all help to guide investments in bicycle infrastructure to promote a safe, convenient and comfortable cycling experience for all types of cyclists. The choice of the specific method applied may depend on the specific context and goals of the assessment, as well as the availability of data and resources. Table 7.2 summarizes common methods to assess the quality of bicycle infrastructure, clustered into seven overarching categories and selected exemplary methods are referenced.

The calculation of a BLOS is a commonly used method to assess the quality of bicycle infrastructure and is incorporated in a wide range of national standards and guidelines and thus provides a clear and standardized grading system that can be easily understood by stakeholders. It is a quantitative method that assigns a level of service of the transportation system based on the level of comfort, safety and the quality of traffic flow for cyclists. Similar to all methods presented in table 7.2, it is considered a macroscopic assessment method so far, since it mostly focuses on entire links or link segments of the transportation network, that stretch over a relatively long distance, or entire intersections. However, this macroscopic focus does not provide a detailed understanding of the quality of smaller elements of the transportation network or bottlenecks within longer sections, disturbing an otherwise continuously safe and comfortable cycling experience. Thus, an adapted method for analyzing the service quality of bicycle paths on a microscopic level is proposed.

Table 7.2: Comparison of common methods to assess the quality of bicycle infrastructure (Beil et al., 2024).

Category	Description	Exemplary Methods
Bicycle Level of Service (BLOS)	Evaluation of the quality of cycling facilities based on quantitative factors, similar to the Level of Service (LOS) approach used for motorized traffic.	Technical regulation / Handbook for Road Infrastructure Design (HBS) (FGSV, 2015) Highway Capacity Manual (HCM) (TRB, 2022)
Safety Analysis or Safety Audits	Evaluation of the safety of cycling infrastructure by conducting a systematic review of potential hazards and safety issues.	Bicycle Interaction Hazard Score (IHS) (Landis, 1994) Bicycle Intersection Safety Index (ISI) (Carter et al. 2007)
Connectivity Analysis	Evaluation of the extent to which cycling networks provide access to key destinations, in terms of the network connectivity.	Cyclist Routing Algorithm for Network Connectivity (CRANC) (Gehrke et al., 2020)
Accessibility Analysis	Evaluation of the extent to which cycling networks provide access to different user groups, such as people with disabilities or elderlies.	TUM Accessibility Atlas (Büttner et al. 2018) Gravity-Based Accessibility Measures for Integrated Transport-Land Use Planning (GraBAM) (Papa & Coppola, 2012)
Multi-Criteria Analysis (MCA)	Evaluation of the quality of cycling networks based on a set of pre-determined criteria related to safety, connectivity and accessibility.	Multiple Criteria Decision Analysis (MCDA) (Belton & Stewart, 2002) Explanatory Spatial Data Analysis (ESDA) (Osama & Sayed, 2016)
Stress Level Analysis or Comfort Analysis	Evaluation of the perceived level of stress, based on quantitative factors such as traffic volume and speed or the presence of bike lanes.	Bicycle Compatibility Index (BCI) (Harkey et al., 1988) Bicycle Stress Map (BSM) (Mekuria et al., 2012)
Bikeability Index	Evaluation of a range of factors that affect the quality of the bicycle experience in urban areas, taking into account both physical and social factors.	Bikeability evaluation using street view imagery and computer vision (Ito & Biljecki, 2021) Munich Bikeability Index (Schmid-Querg et al. 2021)

7.6.2 Implemented Method for evaluating the Bicycle Level of Service (BLOS)

The method implemented to determine the service quality of bicycle paths is described in a national technical regulation called "Handbook for Road Infrastructure Design" issued by the German "Research Association for Roads and Traffic" (FGSV, 2015). The method is based on the calculation of a Bicycle Level of Service (BLOS) depending on a disturbance rate *DR* of cyclists. This disturbance rate is evaluated based on the local width and slope of bicycle paths, bicycle traffic volume, amount of wide bicycles and influence of adjacent disturbances such as bus stops. The method is applicable to stretches of dedicated bicycle paths with high traffic volumes. Bicycle paths need to be divided into segments as soon as one of the parameters necessary for calculating the BLOS changes significantly. The method distinguishes between one-way and two-way bicycle paths. This chapter focuses on concepts for the evaluation of one-way bicycle paths, as these are generally by far the most common types of bicycle paths. This method is chosen since an increasing availability of high-resolution data allows an automated evaluation of bicycle paths based on geometric and semantic features. Limitations of this method and possibilities to extend it with additional concepts and information are discussed in sub-chapter 7.6.8. Slopes increase the width requirement of a cyclist due to lateral swaying or the need to get off the bicycle. Thus, a fictional width w_{f1} of bicycle paths due to local slope (eq. 7.1) results from the actual width w minus the additional width w_{A1} required due to the local slope according to table 7.3.

$$w_{f1} = w - w_{A1} \tag{7.1}$$

Table 7.3: Additional width required due to the local slope according to FGSV (2015).

slope [%]	w_{A1} [m]
> 6	0.45
$4 <$ slope ≤ 6	0.30
≤ 4	0

The fictional width w_{f2} of bicycle paths due to the amount of wide bicycles such as cargo bikes (required if more than 15 % of all bicycles are wide bicycles) results from the actual width w minus the additionally required width w_{A2} set at 0.3 meters (eq. 7.2).

$$w_{f2} = w - w_{A2} \tag{7.2}$$

The smallest fictional width w_f (due to slope or wide bicycles) is chosen (eq. 7.3).

$$w_f = min \begin{cases} w_{f1} \\ w_{f2} \end{cases} \tag{7.3}$$

The overtake rate *OR* is evaluated with respect to traffic volume *qB*, mean speed of bicycles *V* and corresponding standard deviation σ according to equation 7.4.

$$OR = \frac{2 \cdot qB \cdot \sigma}{V^2 \cdot \sqrt{\pi}} \tag{7.4}$$

The disturbance rate for one-way bicycle paths DR_O (eq. 7.5) results from the overtake rate *OR* (based on number of bicycles per hour *qB* times the factor for disturbances due to overtakes f_{DO} according to table 7.4.

$$DR_O = OR \cdot f_{DO} \tag{7.5}$$

Table 7.4: Factor for disturbances depending on local fictional width according to FGSV (2015).

$w_f[m]$	f_{DO}	$qB[b/h]$
	0	≤ 100
≥ 2.0	0.25·(0.01 · qB-1)	100 < qB < 300
	0.5	≥ 300
$1.80 \leq w_f < 2.00$	1.0	-
$1.60 \leq w_f < 1.80$	2.0	-
< 1.60	4.0	

Punctual, local disturbances due to bus stops near bicycle paths DR_P are set at 1 for all segments within a certain proximity of bus stops. The disturbance rate *DR* for each segment then results from the addition of the disturbance rate of punctual disturbances DR_P (if available) plus the disturbance rate from overtakes DR_O (eq. 7.6).

$$DR = DR_O + DR_P \tag{7.6}$$

The mean disturbance rate DR_m for the length *L* of an entire bicycle path then can be calculated as mean of the disturbance rates DR_i of all segments weighted according to respective segment lengths L_i (Eq. 7.7). Both values (eq. 7.6 and eq. 7.7) can be translated to BLOS scores (cf. table 7.5). Values of eq. 7.6 give BLOS scores for each (high-resolution) segment, while eq. 7.7 gives an aggregated (mean) value over an entire bicycle path.

$$DR_m = \frac{\sum_{i=1}^{n} L_i \cdot DR_i}{L} \tag{7.7}$$

Table 7.5: Bicycle Levels of Service (BLOS) of one-way bicycle paths depending on disturbance rates *DR* (for each segment) or DR_m (for an entire bicycle path) according to FGSV (2015).

BLOS	Disturbance rate (*DR* or DR_m)
A	< 1
B	< 3
C	< 5
D	< 10
E	≥ 10

The values in table 7.5 correspond to the following definitions specified within the technical regulation FGSV (2015):

- A: All cyclists have unrestricted freedom of movement. Changes in the line of travel within the cross-section or changes in speed are not required.
- B: Freedom of movement is hardly restricted. Changes in the line of travel within the cross-section or changes in speed are rare.
- C: Freedom of movement is repeatedly restricted by other cyclists. Changes in the line of travel within the cross-section or changes in speed are regularly required.
- D: Freedom of movement is significantly restricted by other cyclists. Changes in the line of travel within the cross-section or changes in speed are often required.
- E: Freedom of movement is constantly restricted by other cyclists. Constant changes in the line of travel within the cross-section or changes in speed are required.

In order to calculate the maximum traffic volume [bicycles per hour] of bicycle path segments acceptable to reach a certain BLOS, equations 7.5 and 7.4 are combined and rearranged to form equation 7.8. Where DR_{max} is the maximum disturbance rate per BLOS (cf. table 7.5) and f_{DO} depends on the local fictional width w_f. For $w_f \geq 2.0$ the corresponding f_{DO} is set at 0.5. The mean speed of bicycles V and corresponding standard deviation σ are considered. Potential punctual disturbances are not considered in this evaluation. Resulting maximum traffic volume values are rounded down to give whole numbers.

$$qB_{max} = \frac{DR_{max} \cdot V^2 \cdot \sqrt{\pi}}{2 \cdot \sigma \cdot f_{DO}} \tag{7.8}$$

Until now this method has mostly been used manually, which is labor and time intensive both for gathering relevant input information on bicycle paths and calculating BLOS values from this information. Thus, so far this method is mostly used for limited spatial extends of specifically relevant segments. In order to automate this process and to be able to calculate BLOS values for bicycle paths of entire cities, information provided by semantic 3D streetspace models are beneficial. Table 7.6 lists parameters required for this method and compares available information provided by such models.

Table 7.6: Parameters considered by the implemented method and availability of information in CityGML streetspace models.

Parameter	Considered by the used method	Available in 3D CityGML model
width [m]	yes	is calculated
slope [%]	yes	is calculated
traffic direction	indirectly	yes
traffic volume [b/h]	yes	is linked
wide bicycles [> 15%]	yes	is assumed
adjacent bus stops	are derived	yes
other influences	no	could be derived
shared usage	no	yes
change of direction	no	could be derived
change of slopes	no	could be derived
speed limit [km/h]	no	yes
surface material	no	yes
surface smoothness	no	no
perceived comfort	no	no

7.6.3 Deriving Width, Slope and adjacent Surfaces of Bicycle Paths from 3D Streetspace Models

Key variables necessary for this method are the width and slope of bicycle paths. Since these parameters can change rapidly and potentially just over a short distance in the course of a bicycle path, it is essential to be able to calculate lane widths and slopes at short intervals. Vitalis et al. (2022) use a method developed by Hoffmanns (2020) for deriving road widths from polygonal representations and corresponding centerlines. A similar approach is chosen in order to calculate the width of bicycle paths at a high resolution as illustrated in figures 7.16.

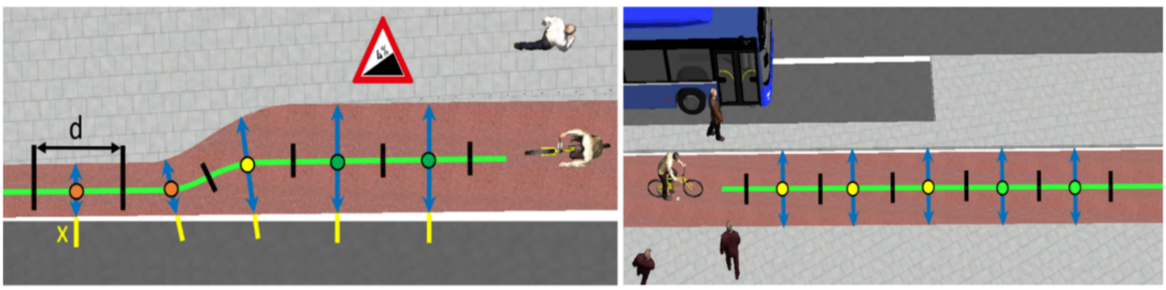


Figure 7.16: Width calculation of bicycle paths at short intervals and determining adjacent surfaces (Beil et al., 2024).

The following processing steps are implemented using FME in order to derive the width and slope of bicycle paths at short intervals as well as information on adjacent surfaces.

1) Filter TrafficAreas with "function = bicycle path or combined foot-/cyclepath" (CityGML codelist values = 3 or 4) or "usage = bicycle" (CityGML codelist value = 6).
2) Calculate centerline (green) and its length and assign an ID per centerline using respective FME transformers. Alternatively, directly use linear TrafficSpace representations, which correspond to lane centerlines and are available in CityGML 3.0 data derived from OpenDRIVE data using the OpenDRIVE to CityGML converter r:trån.
3) Split each centerline into segments of length d (indicated with black dashes) and assign IDs per segment.
4) Calculate the slope of each segment using start and end elevation and length of each segment (the length of segments at the start or end may be shorter than d). If the original geometry already contains 3D information (which is the case for datasets given in OpenDRIVE and converted to CityGML), the slope can be directly derived. Otherwise, information from a corresponding digital terrain model can be incorporated. Information on the traffic direction is required (and also available) to evaluate the slope in traffic direction, since the method considers additional space needed by cyclists at positive inclines greater than 4 % (cf. table 7.3).
5) Create centerpoint of each segment.
6) Create orthogonal lines (blue) in each centerpoint and extend to boundary of bicycle path polygons.
7) Calculate length of each orthogonal line (equal to width w of bicycle path at each centerpoint)
8) Extend orthogonal lines by x meters and test for overlap with adjacent surfaces (yellow extensions of orthogonal lines indicate, that an adjacent driving lane is detected). This method ensures, that driving lanes are detected even if they are not directly adjacent to bicycle paths, but within a range of x meters. Similarly, other relevant adjacent surfaces such as pedestrian sidewalks or parking lanes can be determined.
9) Buffer bus stop polygons by y meters and intersect with adjacent centerpoints (yellow points in the right image of figure 7.16).

Each centerpoint now contains information on local width, slope in traffic direction, adjacent surfaces and nearby bus stops (if available), a segment ID and the ID of the original CityGML TrafficArea. These parameters are then used to calculate BLOS values and corresponding maximum traffic volumes for each centerpoint as well as aggregated mean BLOS values for each CityGML TrafficArea according to the method presented in section 7.6.2.

7.6.4 Including Bicycle Traffic Volumes and evaluating the Amount of Wide Bicycles (e.g. Cargo Bikes)

Information on bicycle traffic volumes (bicycles per hour) can be included in different ways. In every case, these values are assigned to corresponding city objects in order to be used as input data for the presented method.

1) Fixed bicycle traffic volumes
   In case there is no information on actual bicycle traffic volumes available, the method can be applied multiple times using various fixed values (e.g. 50, 100, 250 bicycles/h). In this context, it needs to be stated, that bicycle traffic volumes and traffic flow differ between section and intersection areas. This means results calculated using fixed traffic volumes for an entire network often do not reflect reality. However, in this way it can be determined up to which capacity the quality of individual bicycle path segments are of a certain level of service.

2) Individual bicycle traffic volumes derived from sensors
   Alternatively, detailed information on actual traffic volumes can be derived from sensors such as bicycle counting stations, which are available in several cities. Usually, the location of these sensors is known, which allows a direct relation of counting results to specific bicycle lanes in the semantic 3D city model. Even if not every bicycle lane may be linked with real-world sensor information, exemplary stations can give information on the general scale and magnitude of bicycle traffic volumes in certain parts of a city, which then can be used as input for the presented bicycle path quality analysis. Typical averages or maximum capacity utilization can be derived from such analysis and linked with corresponding semantic city objects. Information derived from sensors distributed in a city can also be used as input for demand modelling techniques to estimate bicycle traffic volumes. Cities such as Hamburg provide open-access to IoT servers of bicycle counting sensors via a standardized OGC SensorThings API[31].

3) Individual bicycle traffic volumes derived from simulations
   Bicycle traffic volumes derived from real-world counting sensors may not be available for every bicycle path (segment). However, approximate numbers can be simulated using traffic simulation software and then linked to semantic bicycle path objects.

Accurate information on the percentage of wide bicycles might often not be available. However, since there are only two options that can be taken into account (share of wide bicycles over or under 15 %), the method can be applied for both cases to compare results.

7.6.5 Linking Results with semantic 3D City Objects

CityGML provides the concept of generic attributes for storing information not considered within the definitions of the original standard. Alternatively, a built-in mechanism called Application Domain Extension (ADE) to extend the data model of the standard with application-specific concepts is available, which could be developed for the presented application. In this study, results on the quality of bicycle paths (BLOS) determined using the method described in this chapter, are stored as generic CityGML attributes with corresponding CityGML TrafficAreas (bicycle lanes). Furthermore, segments are colored according to quality categories (cf. table 7.5) as depicted in figure 7.17, using the possibility of CityGML features to have appearances. This is done by transferring BLOS values of individual centerpoints to corresponding surface representations of bicycle path segments.

[31] https://iot.hamburg.de

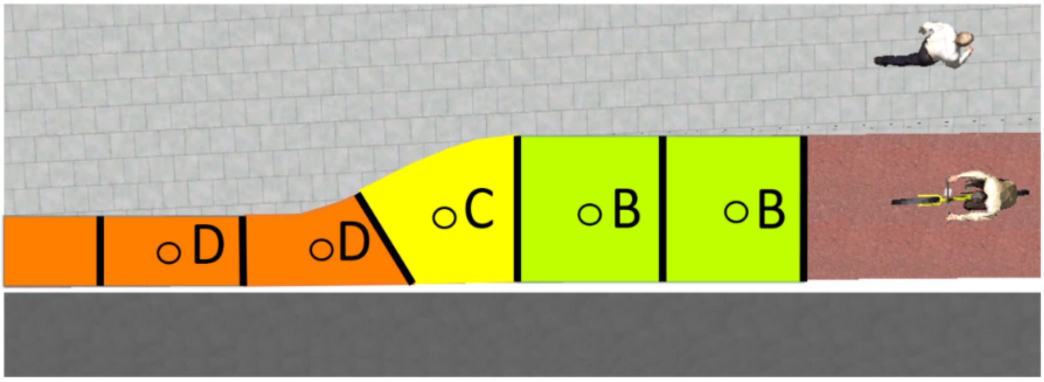


Figure 7.17: Coloring bicycle path segments according to quality results of corresponding center-points.

7.6.6 Web-based Visualization of Results in Combination with 3D City Models

The 3DCityDatabase (3DCityDB) is a CityGML compliant open-source solution for importing, managing, analyzing, visualizing, and exporting virtual 3D city models (Z. Yao et al., 2018). The corresponding 3DCityDB Web-Map-Client is an application for web-based visualization of 3D city models using the Cesium virtual globe, which additionally offers the possibility to link city objects with semantic data for interactive exploration. Multiple layers (e.g. buildings, vegetation, road infrastructure, etc.) can be included and an incorporated tiling mechanism allows the visualization of large 3D city models. A web-based visualization is created using the 3DCityDB Importer/Exporter tool and its corresponding visualization export capabilities. This includes bicycle paths colored according to individual BLOS values (cf. table 7.5). Since at the time of creating the visualization, only CityGML version 2.0 data is supported by the 3DCityDB v4.3, results are provided in CityGML versions 2.0 and 3.0. The possibility to communicate analysis results for existing or planned scenarios in an interactive and openly accessible web-based visualization has potential for improved public participation. However, resulting BLOS values need to be interpreted correctly and can be misleading. Bicycle paths, for example, are usually constructed in such a way, that at peak traffic volumes, a BLOS of category D is reached. Without this knowledge, analysis results may give a wrong impression on the actual service quality of bicycle paths to the public.

7.6.7 Results

The method and process described in sub-chapter 7.6.2 is applied to data available for multiple cities including Hamburg and Munich. Since streetspace and bicycle path data according to CityGML 3.0 is available for all of these examples, the method is easily transferable.

1) Different bicycle traffic volumes for the same scenario
   Figure 7.18 shows results of the presented method in a web-based Cesium visualization combined with a corresponding semantic 3D city model. Information on bicycle paths available in the

CityGML format is used to calculate BLOS scores of the same scenario for different traffic volumes. This is done using different fixed values (e.g. 50, 100, 150, 200, 250 bicycles per hour).

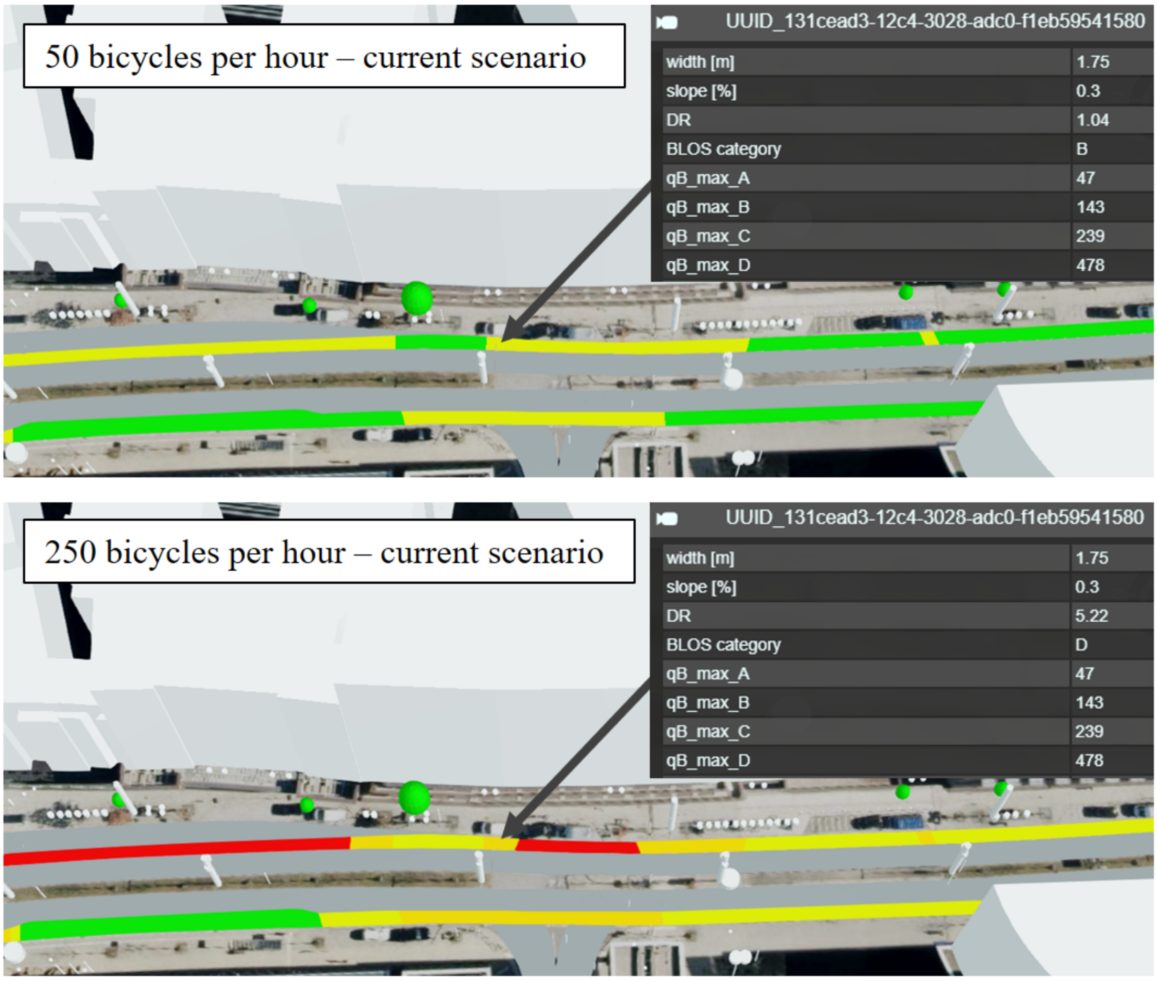


Figure 7.18: Web-based Cesium visualization of BLOS results for different bicycle traffic volumes combined with a corresponding 3D city model. Green blobs represent trees (Beil et al., 2024).

Additionally, bicycle traffic volumes provided by bicycle counting sensors are available in the research area, providing information on typical average and peak bicycle traffic volumes. Multiple layers colored according to those results are integrated within this visualization. In this example, bicycle paths are split into 2 meter segments, resulting in a high resolution of calculated BLOS scores. The top image in figure 7.18 shows results for a traffic volume of 50 bicycles per hour, while the bottom image shows results of the same bicycle paths for 250 bicycles per hour.

2) Same bicycle traffic volume for current and planned scenario
Figure 7.19 shows a direct comparison of BLOS scores of existing bicycle paths with a planned scenario in the same area with increased bicycle path widths. Both scenarios are calculated with

the same traffic volume (150 bicycles per hour in this example), showing the improved BLOS for wider bicycle paths. Visualizations of these analyses can be useful in order to present the impact of planned scenarios to the public, demonstrating improved bicycle path qualities according to the presented method.

Figure 7.19: Comparison of BLOS values at 150 bicycles per hour of the current state of bicycle paths with a planned scenario (Beil et al., 2024).

3) Maximum traffic volume capacity for each BLOS
Using equation 7.8, maximum traffic volumes can be determined with which a bicycle path segment of a certain (fictional) width is still categorized within a specific BLOS category. For example: Assuming a typical mean speed of cyclists V of 18 km/h with a standard deviation σ of 3 km/h and a local (fictional) width of a segment of 1.75 meters (corresponding to a factor for disturbances due to overtakes f_{DO} of 2.0, cf. table 7.4), a disturbance rate DR of under 1 (equal to category A, cf. table 7.5) can be achieved for a bicycle traffic volume of up to 47 bicycles per hour. Similarly, maximum capacities for all other BLOS categories are calculated (exemplary results are visible in figure 7.18). These values can be calculated per bicycle path segment. Additionally, the minimum value of all segments can be determined in order to evaluate the maximum capacity of an entire bicycle path.

4) Comparison of calculated bicycle path widths with recommended minimum widths
   Most countries have guidelines on the design of bicycle paths with regard to mini-mum widths that should be available in order to ensure usability and safety. In addition to evaluating BLOS values, calculated widths of bicycle paths can be compared with such standard widths specified within infrastructure design guidelines and regulations. This allows to determine the percentage of cycle paths (in relation to length) that adhere to these guidelines and to identify segments that do not fulfill them. Typically, bicycle path widths of at least 1.5 meters for one-way lanes are required with a recommended minimum width of 2 meters. Within the research area, over 28 km of bicycle path data is available. Widths are calculated at an interval of 0.6 meters resulting in 47,655 individual bicycle path segments. Segments are categorized by width ranges as summarized in table 7.7, showing that most of the evaluated bicycle paths are within the recommended ranges. Widths of under 1 meter mostly result from tapered geometries of start and end segments of bicycle paths (as visible in figure 7.19) and are thus filtered from this evaluation. Alternatively, start and end segments can be filtered with topological information on neighboring segments. Similar metrics can be used to compare bicycle infrastructure of different cities.

Table 7.7: Percentage of bicycle path widths within a certain range in a citywide research area (Beil et al., 2024).

Width range [m]	Nr. of segments	Length [km]	Percentage [%]
≥ 2	16,227	9,74	34.1
$1.5 \leq w < 2.0$	20,658	12.39	43.4
$1.0 \leq w < 1.5$	9,642	5.79	20.3
< 1.0	1,128	0.62	2.2

7.6.8 Discussion of BLOS Evaluation Results

The implemented method is chosen due to its potential for automated evaluations of bicycle path qualities for large areas. Parameters relevant for other methods such as the perceived level of comfort of cyclists are not considered. Thus, this method should be combined with other approaches (such as MCA, connectivity analysis, bikeability, etc.) for evaluating the quality of bicycle paths in order to have a holistic result. While the presented method is based on detailed studies (FGSV, 2015), there are some limitations. BLOS is primarily focused on physical attributes of the transportation system and does not take into account social or cultural factors that may affect the perceived quality of bicycle infrastructure. It also does not consider the quality of the connections between different parts of the network or the accessibility of certain destinations that can be reached by bicycle. Results of this method highly depend on accurate calculations of bicycle path widths and slopes. Thus, in order to be able to evaluate accurate BLOS scores, the used input data must be available in great geo-metric detail and with explicit geometry representations. The 3D streetspace models used in this example are derived from highly accurate OpenDRIVE data converted to explicit geometries according to CityGML 3.0 and thus provide this information with the required detail. Results of width and slope calculations additionally depend on chosen distance intervals (sampling rates) for which these evaluations are calculated. In this context, a step size of at most 2 meters is recommended. Since BLOS values are categorized based on disturbance rates calculated from bicycle path widths, a difference in width of only a few centimeters may already result in a different BLOS score. While this results in high-resolution evaluations, it can be beneficial to compare results of adjacent segments in order to identify very short segments with results differing from those of neighboring segments and considering a smoothing mechanism. In case no information on elevation or traffic directions is available, the method can still be used in relatively flat areas with slopes of less than 4 % (since this is the threshold for which slopes have an influence on the calculation of a fictional width, cf. table 7.3). As discussed earlier, semantic 3D streetspace models can provide additional information that could be relevant for the estimation of bicycle path qualities, which are not considered by the implemented method. This includes information on surface smoothness, changes of slopes and directions, surface material or speed limits. Additionally, the method only considers bus stops as sources of local disturbances. As presented in this chapter, information on adjacent surfaces can easily be determined and thus be extended to influences of adjacent pedestrian paths, driving and parking lanes or structures separating bicycle paths from other traffic members.

Information on bicycle paths and 3D city models can also be used for visibility analysis (Bassani et al., 2015). Either to determine which parts of a city are visible for cyclists (e.g. in an intersection area) or to evaluate the visibility of cyclists for other traffic members such as car drivers. This is relevant for evaluating the safety of cyclists and to identify potentially dangerous areas. Known positions of cyclists and driving lanes, in addition with information on traffic directions (and thus view direction of cyclists), can be used to calculate lines of sight, which then can be intersected with other city objects such as buildings, vegetation or parking cars. In the context of urban digital twins, an increasing availability of detailed information on the streetspace will allow these evaluations to be used for a number of cities and regions.

Chapter 8

Conclusion and Outlook

8.1 Key Findings and Discussion of Results

In this chapter, key findings and answers to the research questions and hypotheses stated in chapter 1.3 of this thesis are presented and discussed.

Question 1.1: What geometric, semantic, topological, temporal and visual requirements do existing and potential applications and use cases impose upon digital models of the streetspace?

A number of use cases, functionalities and data requirements are defined and evaluated in chapter 2. Concrete requirements for 3D streetspace models cannot be evaluated directly for specific use cases as (a) several different functionalities of software applications are typically required and used to fulfill the goal(s) of individual use cases and (b) the specific requirements for the data and its form of representation and properties only ever result from the respective functionalities. Thus, individual requirements of functionalities are identified and evaluated in detail. This is achieved by first conducting a literature review for 36 identified use cases categorized according to their main application domain: (1) Infrastructure Planning, Construction and Management, (2) Automotive, Transportation and Navigation, (3) Environmental Simulations and Analyses and (4) Land Administration and Topographic Mapping. Then, required functionalities to achieve the respective goals are linked with those use cases. In order to allow a structured evaluation, geometric, semantic, topological, temporal and visual requirement categories are defined and evaluated in detail for each functionality. The results of this evaluation are discussed in chapter 2.5.2 and summarized in the tables 2.1, 2.2 and 2.3.

Question 1.2: How are roads and the streetspace represented in relevant standards, conceptual data models and data formats and do these concepts adequately address the determined requirements?

Depending on the intended main application domain, standards, conceptual data models and data formats relevant for road and streetspace modelling have different foci with respect to geometric, semantic, topological, temporal and visual concepts and capabilities. Chapter 3 provides an evaluation of 12 of the most relevant standards and data formats in the field of semantic road and streetspace modelling grouped according to application domains. Capabilities of these specifications are summarized in multiple tables (c.f. tables 3.2 and 3.3) in order to evaluate the mentioned aspects. These capabilities can be compared to requirements of functionalities and respective use cases previously

identified and discussed in chapter 2. Since the evaluated standards are tailored towards specific main application domains, no single standard fully covers all aspects of the identified data requirements. Main shortcomings are a focus on linear (graph-based) geometric representations, parametric geometry definitions not directly usable by many GIS related functionalities and use cases, a lack of concepts defining how to model surface-based and non-redundant 3D representations of roads as well as few concepts for the integrated representation of multiple transportation modes within a common 3D city model.
Modelling principles and available geometric, semantic, topological, temporal or visual capabilities of individual standards, conceptual models and data formats heavily depend on their intended field of application. Standards commonly used in the automobile industry such as OpenDRIVE, GDF or RoadXML focus on a referenceline-based parametric representation of roads. While the newest version of GDF also includes concepts for surface-based representations, there are no openly available data examples making use of this concept yet. Furthermore, these standards are not intended for integrated representations with other city objects such as buildings, bridges, city furniture or vegetation. Additionally, the focus of these standards and data formats such as Lanelet or the Vissim representation is more on modelling traffic logic required by respective use cases and less on accurate surface-based representations.
Standards used for infrastructure planning and management such as LandInfra or IFC have recently been revised in order to provide more concepts for road representations. However, concepts required for use cases from other domains (e.g. traffic logic) are not provided. Additionally, limited georeferencing capabilities and a focus on spatially limited models e.g. (individual sites as opposed to an entire city) present limitations to data provided according to these standards.
Other specifications and data formats such as OSM (generalized linear representation of roads only), INSPIRE specifications or administrate data (GeoInfoDok) similarly lack lane-level surface-based concepts, combined non-redundant representations of multiple transportation modes and/or concepts for representing information such as traffic logic. CityGML version 2.0 also has limited capabilities to address many of the previously determined requirements of potential and existing use cases. Results of detailed evaluations of these standards, conceptual models and data formats are comprised with in the tables 3.2 and 3.3. Additionally, deficits of CityGML 2.0 for modelling transportation infrastructure are discussed in chapter 5.1.

Question 1.3: How should the streetspace be modelled in the context of semantic 3D city models in order to meet requirements of intended applications and use cases?

The concepts for modelling the streetspace as part of semantic 3D city models presented in chapter 5 are developed based on the previously evaluated requirements of software functionalities and use cases. This means, that different geometric representations such as linear (graph-based), areal (surface-based) and volumetric geometries as well as point clouds with explicit geo-referenced 3D coordinates of roads are required. For a number of functionalities and use cases it is also required to provide non-redundant representations of multiple transportation infrastructure within one consistent model. Not only objects representing roads should be considered but also the space above these surfaces, which is used by traffic members, needs to be represented explicitly. Other components of a city such as vegetation, city furniture or buildings can interact with this space and thus needs to be considered in order to represent a complete 3D city model. Different levels of semantic decomposition, object hierarchies and a number of thematic attributes are identified and should be modelled accordingly using standardized concepts and attribute codelists. Topological information such as incidence, adjacency or a predecessor / successor concept to represent traffic logic are required for graph- and surface-based as well as volumetric representations of individual objects. Concerning capabilities for representing temporal information, sensor information such as traffic volumes or air pollution information needs to be associated with corresponding streetspace objects. Additionally, different versions of road and other infrastructure models should be re presentable in order to model different planning options, stages or to allow the historization of previous scenarios. (Photo-)Realistic visualizations of streetspace models are required for a number of use cases and thus should be possible.

Question 1.4: How should urban spaces (including roads, railways and other transportation infrastructure) be segmented into well-defined 3D objects in order to achieve non-redundant geometric and semantic representations?

A concept for segmenting transportation infrastructure into three levels of granularity is developed and presented in chapter 5. Roads, for example, can be represented either with their entire width (granularity = area), by individual carriageways and traffic modes (granularity = way) or with lane-level accuracy (granularity = lane). A number of required objects such as individual driving lanes, sidewalks or bicycle paths, etc. are identified and specified with corresponding codelists. The developed concept for segmenting transportation networks into Sections and Intersections is applicable to different modalities, such as Roads, Railways or Waterways and thus allows an integrated representation of multiple interacting transportation types (cf. chapter 5.8). A level crossing of a Road and Railway network, for example, can be represented non-redundantly with one Intersection object linked to both top-level features. Individual surfaces can contain multiple function or usage attributes in order to further express this relationship. Further concepts for non-redundant representations of Roads within Buildings, on Bridges or within Tunnels are developed and explained. These concepts allow an integrated, non-redundant and consistent representation of the streetspace within a standardized semantic 3D city model.

Hypothesis 1.5: The international OGC standard CityGML version 2.0 can be extended and revised in order to be suitable for representing the streetspace in such a way, that requirements imposed by most use cases are met.

General modelling principles introduced to the newest version 3.0 of CityGML such as the space concept and new possible geometric representations are used in this dissertation work as a foundation for developing revised concepts for modelling transportation infrastructure, which were adopted by the CityGML 3.0 standard. Existing concepts of the CityGML 2.0 Transportation module are evaluated and limitations with respect to fulfilling previously defined requirements of software func-

tionalities and use cases are identified in chapter 5.1. While CityGML version 2.0 already contained a Transportation module for modelling road or railway networks, concepts were unclear in many cases and not sufficient for a number of use cases. However, the basic concept of hierarchically structured city objects with spatio-semantic properties provided the basis for developing extended and revised concepts presented in this thesis. The data model developed in this dissertation work was adopted and published as part of the newest version of the international OGC standard CityGML 3.0.
Existing concepts of the CityGML 2.0 Transportation module are extended by introducing Sections and Intersection segmenting Roads and other transportation networks into smaller objects (cf. chapter 5.3). This also allows an integrated representation for multiple transportation infrastructure (roads, railways, level crossings, footpaths, waterways, etc.) within a common and non-redundant 3D city model (cf. chapter 5.8). The newly introduced space concept is adopted by further segmenting objects into spaces (e.g. TrafficSpaces) and space boundaries (e.g. TrafficAreas). Three levels of granularity (area, way and lane) are introduced, which can be represented geometrically using linear, areal, volumetric or point cloud geometries. New classes such as Markings, Holes and ClearanceSpaces are defined. A predecessor/ successor concept for TrafficSpaces in combination with information on traffic directions enables the storage of information required by routing, navigational and other related use cases. In sub-chapter 5.10 it is shown, that these newly introduced concepts are capable of meeting most of the requirements defined by the presented software functionalities and use cases. Potential limitations (such as a missing linear referencing system) or other specific information can be added by using extension capabilities of CityGML by introducing generic classes and attributes or defining Application Domain Extensions (ADEs).

Hypothesis 1.6: Interoperability of CityGML with existing standards for road modelling can be improved by extending and revising modelling concepts.

The newly introduced semantic concepts, developed in the course of this dissertation work, such as segmenting transportation networks into Sections and Intersections increases interoperability with a number of (recent versions of) standards that utilize a similar decomposition strategy (e.g. OpenDRIVE 1.8, GDF 5.1 or IFC 4.3). Specifically improved interoperability between CityGML 3.0 and OpenDRIVE 1.8 is demonstrated in chapter 6.1 by explaining how concepts of OpenDRIVE can be mapped to CityGML 3.0, making use of several new capabilities such as the section / intersection segmentation, predecessor / successor relations, information on traffic directions, multiple geometric representations including linear and surface-based geometries as well as clear lane-level definitions of roads. While these newly introduced concepts of CityGML 3.0 significantly improve interoperability between these two standards, missing concepts such as linear referencing or parametric representations of geometries would need to be added in the form of a CityGML OpenDRIVE ADE.

Question 1.7: What data sources are available and suitable for generating streetspace models according to the developed concepts and which levels of granularity can be achieved?

Semantically unstructured data such as 3D point clouds or meshes are increasingly available e.g. from mobile mapping campaigns and in combination with geospatial data such digital terrain models, digital surface models or aerial images can be used as source information to derive semantic (3D) models of roads and the streetspace. Additionally, cadastral data on land cover and 2D topographic landscape models are often available. Several cities including Melbourne, New York City, Vienna or Washington D.C. provide GIS data such as land cover information or planimetric data on roads, sidewalks, etc. on their open data platforms. All of the mentioned cities provide information on roads in level of granularity 'way' often including information on sidewalks and other surface types and sometimes segmented according to section and intersection areas. However, this data is typically provided in the form of ESRI Shapefiles, which are not structured according to a conceptual model and thus differ with respect to semantic and geometric segmentation and information. The provided data contains enough information in order to convert it into a common data structure following the concepts of CityGML 3.0. This is explicitly demonstrated in chapter 6.3.2 using open data provided by the city of Melbourne.
The city of Munich is creating a so-called Lane Model based on the Road2Simulation guideline. Data with a level of granularity equal to 'lane' is produced in the course of this project and converted to CityGML 3.0 using ETL processes (cf. 6.3.1). There are companies producing 3D lane-level data on roads including traffic logic in the OpenDRIVE format. This data can be converted to CityGML version 3.0 directly using the open source converter r:tron. In some cities and regions, such as Singapore, London or Japan, data on roads compliant to CityGML version 2.0 is available. This data can be upgraded to CityGML 3.0 using the mapping strategies presented in chapter 6.2. Plugins for 3D modelling software such as SketchUp (currently) provide possibilities for generating CityGML 2.0 compliant data, which can be upgraded similarly in order to benefit from the newly available concepts.

Question 1.8: How can selected use cases from different application domains be implemented in order to benefit from the newly available concepts?

Selected use cases from different application domains identified in chapter 2 are implemented in order to demonstrate the benefits of 3D streetspace models generated according to the concepts of CityGML 3.0 developed in chapter 5. The importance of non-redundant and surface-based representations using explicit geometries in combination with semantic information on surface types, surface area and pavement condition is demonstrated in sub-chapter 7.1 by making combined queries for this information on a semantic 3D streetspace model of New York City. In order to manage the large amount of data, road networks are decomposed into sections and intersections, which can be aggregated.
Similarly, a solar irradiation and urban heat island analysis is conducted and presented in sub-chapter 7.2, which also requires explicit surface-based road geometries as well as other components of semantic 3D city models such as information on buildings, vegetation or the terrain.
A semantic 3D streetspace model used to calibrate input data for a microscopic traffic simulation and to represent simulation results within a web-based 4D visualization using the Cesium virtual globe is presented in sub-chapter 7.3. This requires non-redundant and lane-level information on

road networks and their surroundings. Resulting visualizations are used for public information and participation processes in the context of redesigning a central boulevard in Munich.
In sub-chapter 7.4, it is demonstrated, how surface-based representations of sidewalks, crosswalks and other areas not intended to be used by pedestrian, can be utilized to create scenery layouts for pedestrian simulations.
Multi-modal routing and navigation use cases require a graph-based and topologically connected representation of various transportation networks. Using the possibility to map CityGML transportation networks to a graph database, multi-modal routing is possible as demonstrated in sub-chapter 7.5. This use case is extended by incorporating 3D road networks within a parking garage, connected to an outside road and pedestrian network, showcasing the benefit of an integrated and standardized 3D road and streetspace model as part of a coherent semantic 3D city model.
A method for automatically deriving parameters required for evaluating the service quality of bicycle paths from semantic models is presented in sub-chapter 7.6. This requires surface-based 3D information in order to evaluate information such as bicycle path width, slope and adjacent surfaces. Information on traffic volumes is connected with the semantic model and evaluation results are visualized within a web-based Cesium visualization in combination with a 3D city model.
The implemented use cases demonstrate the usability and benefits of semantic 3D road and streetspace models represented according to concepts developed within this thesis.

8.2 Contributions of the Thesis

Contributions achieved in the course of this doctorate and presented in this thesis are summarized in this chapter.

1) Contributions to scientific research
Research conducted in the course of this dissertation work resulted in the publication of multiple peer-reviewed journal and conference papers listed in the original publications section at the end of this thesis. The results of this work contribute to scientific research in a number of ways:

- The newly developed concepts allow a geometrically and semantically non-redundant, topological and temporally consistent as well as visual appealing representation of semantic 3D road and streetspace models as part of an integrated and standardized 3D city model. The introduced level of granularity concept allows the modelling of roads and other transportation infrastructure in multiple levels of semantic decomposition. Clear definitions and concepts for decomposing large transportation networks into individual objects (both geometrically and semantically) improve modelling strategies in this area and enhance interoperability with other commonly used standards. Newly introduced concepts of non-redundant representations of multiple transportation infrastructure provide a framework for a consistent and integrated representation of such models. These modelling principles are also beneficial for further developing technologies for gathering detailed data on the streetspace and producing data structured according to the developed concepts from semantically unstructured sources such as point clouds.

- The introduction of a space concept for representing transportation spaces with linear, areal, volumetric or point cloud geometries enables further research in fields such as combined 3D indoor-outdoor navigation or usage conflict detection and increases interoperability of CityGML 3.0 with standards such as IFC.
- Clear and unambiguous definitions of terms such as ’application domain’, ’use case’, ’functionality’ or ’software application’ presented in this thesis, allow a structured evaluation and discussion of semantic 3D streetspaces models and their requirements, which can be transferred to other aspects of urban digital twins in order to conduct similar evaluations. Similarly, the definition of requirement categories and individual requirements can be transferred to other fields of research in the context of 3D city modelling, e.g. in order to identify capabilities of modelling concepts for buildings, vegetation or other types of infrastructure such as railways.
- The comprehensive review and evaluation of capabilities of the most relevant standards, conceptual models and guidelines provides the foundation for identifying respective strengths and limitations. The evaluation of these specifications with respect to the identified requirements is valuable to both researchers and practitioners working with data provided according to these concepts.
- The created datasets, which are provided as open data, are useful for different fields of research. The data on the streetspace containing detailed semantic, geometric and topological information standardized according to the developed concepts can serve as ground truth for other fields of research such as developing automated driving systems or processes for automatic 3D streetspace model reconstruction (e.g. using machine learning techniques). Additional research on emerging use cases such as lane free traffic or urban air mobility can benefit from information provided by detailed 3D city and streetspace models.
- The presented research includes examples for practical use cases utilizing the developed concepts of representing roads and the streetspace (e.g. multi-modal navigation in 3D). This not only validates the research but also provides the foundation for future research e.g in the context of emerging fields of application such as urban digital twins or automated driving.

These contributions collectively advance the field of 3D city modelling, particularly in the accurate and detailed representation of transportation infrastructure within urban environments. Furthermore, the provided concepts are beneficial to related fields of research such as urban planning, transportation engineering or environmental sciences.

2) **Contributions to international standardization**
Concepts developed in this doctorate for modelling roads and the streetspace in the context of semantic 3D city models are included in the international OGC standard *CityGML version 3.0 Conceptual Model* (Kolbe et al., 2021) as well as the corresponding *CityGML version 3.0 GML Encoding* (Kutzner et al., 2023). Concepts are further explained and illustrated in the modelling guideline *Road2CityGML3 version 1.0* (Beil et al., 2023). Several organizations such as the Geodataservice of Munich or members of the Japanese PLATEAU project (Ministry of Land, Infrastructure, Transport and Tourism (MLIT) of Japan) are already adopting concepts defined in

these standards and guidelines.
Concepts developed in the course of this dissertation work were also presented to and discussed with members of other standardization organizations such as the Association for Standardization of Automation and Measuring Systems (ASAM), which is responsible for further developing the standard OpenDRIVE. Currently, there are discussions for future concepts to link OpenDRIVE data with environment and streetspace models provided according to CityGML 3.0.

3) **Contributions to generation processes and applications of semantic 3D streetspace models**
There are several cities and regions, which already have detailed information on roads and the streetspace available. Usually, however, this data is provided within an ArcGIS or QGIS environment and structured in different ways both semantically and geometrically. Thus, modelling new (and potentially re-structuring already available) data according to concepts developed in this doctorate and adopted by the CityGML 3.0 standard within a common representations framework will provide an increased harmonization of data sources immediately usable by the same tools for a number of use cases.
The strategies for mapping the Munich Lane Model to CityGML 3.0 concepts, were implemented in the course of the projects *Digital Twin Munich* and *Connected Urban Twins* and will serve as a foundation for operational usage to create semantic 3D streetspace models from administrative data in the city of Munich. Both, identified requirements as well as evaluated standards are valuable for any organization interested in developing and using a digital twin of roads and the streetspace. Newly introduced concepts such as levels of granularity in combination with geometric levels of detail are presented. The approach of modelling transportation spaces can be the foundation for a number of further developments making use of this concept. The presented concepts for a non-redundant representations of multiple transportation infrastructure (e.g. combined representations of roads and railways) enable a realistic representation of the streetspace within digital models. Findings of this research, including mapping strategies of OpenDRIVE concepts to CityGML 3.0, also contributed to the conceptual development of the open-source OpenDRIVE to CityGML converter r:tron implemented by Benedikt Schwab (Schwab et al., 2020). This tool enables the direct conversion any available OpenDRIVE data to the CityGML 3.0 data structure developed in this doctorate.
Overall, the introduced concepts significantly advance possibilities for modelling the streetspace in the context of semantic 3D city models and subsequently utilizing these models.

8.3 Outlook and Future Research

Concepts and implementations presented in this thesis can be the foundation for several topics of future research, which are described in this chapter. In the context of urban digital twins, developments such as the Japanese PLATEAU project are in the process of adopting concepts of the CityGML 3.0 standard to existing and newly gathered data. As already described in this thesis, other cities and regions such as Munich are also interested in utilizing concepts developed in the course of this thesis to represent road and streetspace information within their 3D city models. In this context, the

modelling and reconstruction of three-dimensional road and streetspace models, including underpasses or complex intersections on multiple levels, requires future research.
The increased availability of highly detailed data gathered with mobile mapping or laser scanning methods will provide source information for deriving semantic 3D models structured according to concepts developed in this thesis. So far, the data gathering process of geometric, semantic and especially topological information (e.g. traffic logic) is a process mostly done manually. Developing (semi)automatic 3D reconstruction methods capable of producing geometrically detailed and semantically accurate 3D road and streetspace models from unstructured data such as point clouds remains a challenge. Concepts of structuring and segmenting road objects in a standardized way, as presented in this thesis, can serve as a foundation for developing such methods. Furthermore, data provided according to these concepts can serve as ground truth or training data for developing reconstruction or object classification methods based on machine learning principles.
In the context of artificial intelligence (AI), large language models (LLM) have recently gained widespread attention. Initial research on utilizing such models for deriving information from semantic 3D models using prompts in order to gain insight on the available information can be performed on the basis of semantic 3D city models including road and streetspace representations. Furthermore, research on utilizing artificial intelligence for automatic scene generation of road infrastructure according to the presented concepts can be done. For example, planning and designing a roundabout to replace an existing intersection is manually intensive and time consuming work, which could be done more efficiently in the future using AI methods.
The extension capabilities of CityGML can be used to develop application specific ADEs building on the presented concepts. A proposal for extending CityGML with concepts such as linear referencing or explicitly modelling road material layers could further increase the interoperability of CityGML with standards such as OpenDRIVE or IFC. Currently, there are discussions in the ASAM community proposing a linking mechanism of OpenDRIVE and CityGML data, utilizing respective strengths of both standards.
The data examples implementing concepts presented in this thesis are (mainly) based on the GML encoding of CityGML. Datasets in further encodings could be derived in the future. In this context, the newest version 5.0 of the 3DCityDB already supports the conceptual specifications of CityGML 3.0, including the transportation module. First investigations for implementing the conceptual model of the CityGML 3.0 transportation module in CityJSON are available (Yarroudh et al., 2023). Similar to CityGML concepts presented in this thesis, the newest version 4.3.2.0 of IFC provides revised concepts for modelling road infrastructure. While questions in the field of BIM-GIS integration have so far mostly been investigated using building models, the newly developed concepts for the representation of road infrastructure offer the possibility of similar investigations using models of roads and the streetspace relevant in both domains.
Concepts such as modelling traffic spaces can be useful to new fields of transportation such as urban air mobility. Research on requirements of a standardized representation of air spaces in combination with 3D city models, e.g. for flight path planning of transportation drones, is an interesting topic for future research.

Appendix A - Proposed Codelists for the CityGML 3.0 Transportation Module

Codelists for defining attributes available for classes in the CityGML 2.0 Transportation module were defined by the Special Interest Group 3D (SIG3D) and included in the CityGML 2.0 specification. In order to ensure compatibility with the previous version of the standard, attributes and corresponding values defined in these codelists that remain valid for the Transportation Module in the CityGML 3.0 specification or that can be transferred to new attributes remain the same (indicated with black fonts in the following tables A1-A10). Some attribute values are moved to different newly available attributes (indicated in red). E.g. road markings were modelled using *TrafficAreas* in CityGML 2.0 , while in CityGML 3.0 a new *Marking* class is introduced. Additionally, codelists and attributes with corresponding values that are relevant but were not specified in CityGML 2.0 are introduced (indicated in blue).

Codelist of the *Road, Railway, Track and Waterway* attribute *class*	
1000 private	1050 air_traffic
1010 common	1060 rail_traffic
1020 civil	1070 waterway
1030 military	1080 subway
1040 road_traffic	1090 others

Table A1: Codelist of the *Road, Railway, Track* and *Waterway* attribute *class*.

Codelist of the *Section* attribute *class*	
1 road_section	4 track_section
2 railway_section	5 dead_end
3 waterway_section	9999 other

Table A2: Codelist of the *Section* attribute *class*.

Codelist of the *Intersection* attribute *class*	
1 road_intersection	8 X_intersection
2 level_crossing	9 lane_merge_intersection
3 three_way_intersection	10 roundabout
4 four_way_intersection	11 ford
5 five_or _more_way_intersection	12 tram_intersection
6 Y_intersection	13 pedestrian_intersection
7 T_intersection	9999 other

Table A3: Codelist of the *Intersection* attribute *class*.

Codelist of the *TrafficArea* and *TrafficSpace* attribute *function*	
1 driving_lane	21 barrier
2 footpath	22 stairs
3 cyclepath	23 escalator
4 combined foot-/cyclepath	24 filtering_lane
5 square	25 airport_runway
6 car_park	26 airport_taxiway
7 parking_lay_by	27 airport_apron
8 rail	28 airport_heliport
9 rail_road_combined	29 moved to *Marking class*
10 moved to *Marking class*	30 green_spaces
11 moved to *Marking class*	31 recreation
12 moved to *Marking class*	32 bus_lay_by
13 moved to *Marking class*	33 motorway
14 moved to *Marking class*	34 motoway_entry
15 moved to *Marking class*	35 motorway_exit
16 moved to *Marking class*	36 motorway_emergancy_lane
17 moved to *Marking class*	37 private_area
18 overhead_wire	38 parking_slot
19 train_platform	39 roadside
20 crosswalk	9999 unknown

Table A4: Codelist of the *TrafficArea* and *TrafficSpace* attribute *function*.

Codelist of the *TrafficArea* and *TrafficSpace* attribute *usage*	
1 pedestrian	10 teleferic
2 car	11 aeroplane
3 truck	12 helicopter
4 bus, taxi	13 taxi
5 train	14 horse
6 bicycle	15 emergency
7 motorcycle	16 e-scooter
8 tram, streetcar	17 e-bike
9 boat, ferry, ship	9999 unknown

Table A5: Codelist of the *TrafficArea* and *TrafficSpace* attribute *usage*.

Codelist of the *AuxiliaryTrafficArea* and *AuxiliaryTrafficSpace* attribute *function*	
1000 soft shoulder	1230 flower_tub
1010 hard shoulder	1240 restricted
1020 green area	1300 traffic_island
1030 middle lane	1310 raised_median
1040 lay_by	1400 bank
1050 border	1410 embankment, dike
1060 road_channel	1420 railroad_Embankment
1100 parking_bay	1440 noise_protection
1200 ditch	1500 noise_guard_bar
1210 moved to *Hole class*	1600 towpath
1220 kerbstone	1610 road_works
1221 low_kerbstone	1700 others

Table A6: Codelist of the *AuxiliaryTrafficArea* and *AuxiliaryTrafficSpace* attribute *function*.

Codelist of the *Square* attribute *class*	
1 plaza	3 parking_lot
2 gas_station	9999 other

Table A7: Codelist of the *Square* attribute *class*.

Codelist of the *TrafficArea* and *AuxiliaryTrafficArea* attribute *surfaceMaterial*	
1 asphalt	8 soil
2 concrete	9 sand
3 pavement	10 grass
4 cobblestone	11 wood
5 gravel	12 steel
6 rail_with_bed	13 marble
7 rail_without_bed	9999 unknown

Table A8: Codelist of the *TrafficArea* and *AuxiliaryTrafficArea* attribute *surfaceMaterial*.

Codelist of the *Marking* attribute *class*	
11 road_marking	121 arrow_straight
12 road_marikng_direction	122 arrow_straight_right
13 road_marking_lane	123 arrow_straight_left
14 road_marking_restricted	124 road_marking_lane_broken
15 road_marking_crosswalk	125 road_marking_lane_solid
16 road_marking_stop	126 symbol_bicycle
17 road_marking_other	127 symbol_bus_stop
29 airport_runway_marking	128 symbol_other

Table A9: Codelist of the *Marking* attribute *class*.

Codelist of the *Hole* attribute *class*	
1210 drainage	1230 road_damage
1220 manhole	1240 subway_entry

Table A10: Codelist of the *Hole* attribute *class*.

Appendix B - Mapping Tables: Munich Lane Model to CityGML 3.0

Mapping rules for converting data provided by the Munich Lane Model to concepts of the CityGML 3.0 Transportation module are given in the following table B1.

Table B1: Mapping Lane Model attributes to CityGML 3.0 attributes and codelist values.

Lane model attribute	**CityGML attribute**	**CityGML attribute name**	**CityGML codelist value**	**CityGML feature type**
LaneArea attribute: type				
driving	citygml_function	driving_lane	1	TrafficArea
biking	citygml_function	cyclepath	3	TrafficArea
sidewalk	citygml_function	footpath	2	TrafficArea
parking	citygml_function / citygml_usage	parking_lay_by / car	7 / 2	TrafficArea
roadside	citygml_function	generic attribute: roadside	—	TrafficArea
bus	citygml_function / citygml_usage	driving_lane / bus, taxi	1 / 4	TrafficArea
bus; parking	citygml_function / citygml_usage	parking_lay_by / bus, taxi	7 / 4	TrafficArea
sidewalk; biking	citygml_function	combied foot-/ cyclepath	4	TrafficArea
walkingArea	citygml_function	footpath	2	TrafficArea
driving;tram	citygml_function / citygml_usage	driving_lane / tram, streetcar	1 / 8	TrafficArea
tram	citygml_function	generic attribute: tram	—	TrafficArea
taxi	citygml_function / citygml_usage	driving_lane / bus, taxi	1 / 4	TrafficArea
shoulder	citygml_function	soft shoulder	1000	AuxiliaryTrafficArea
specialArea	citygml_function	generic attribute: specialArea	—	AuxiliaryTrafficArea
restricted	citygml_function	generic attribute: restricted	—	AuxiliaryTrafficArea
median	citygml_function	generic atribute: median	—	AuxiliaryTrafficArea
none	citygml_function	generic attribute: none	—	AuxiliaryTrafficArea
LaneArea attribute: material				
asphalt	citygml_surface_material	asphalt	1	TrafficArea or AuxiliaryTrafficArea
cobble	citygml_surface_material	cobblestone	4	TrafficArea or AuxiliaryTrafficArea
concrete	citygml_surface_material	concrete	2	TrafficArea or AuxiliaryTrafficArea
soil	citygml_surface_material	soil	8	TrafficArea or AuxiliaryTrafficArea
vegetation	citygml_surface_material	grass	10	TrafficArea or AuxiliaryTrafficArea
gravel	citygml_surface_material	gravel	5	TrafficArea or AuxiliaryTrafficArea
pavement	citygml_surface_material	pavement	3	TrafficArea or AuxiliaryTrafficArea

Table B2: Mapping Lane Model objects to the CityGML 3.0 data structure.

Lane model object	CityGML feature type	CityGML parent feature type	CityGML parent top-level-feature type
LaneAreas within Junctions	TrafficArea or AuxiliaryTrafficArea	TrafficSpace or AuxiliaryTrafficSpace	Intersection
LaneAreas outside of Junctions	TrafficArea or AuxiliaryTrafficArea	TrafficSpace or AuxiliaryTrafficSpace	Section
WalkingAreas within Junctions	TrafficArea or AuxiliaryTrafficArea	TrafficSpace or AuxiliaryTrafficSpace	Intersection
WalkingAreas outside of Junctions	TrafficArea or AuxiliaryTrafficArea	TrafficSpace or AuxiliaryTrafficSpace	Section
SpecialAreas within Junctions	TrafficArea or AuxiliaryTrafficArea	TrafficSpace or AuxiliaryTrafficSpace	Intersection
SpecialAreas outside of Junctions	TrafficArea or AuxiliaryTrafficArea	TrafficSpace or AuxiliaryTrafficSpace	Section
Junctions	Intersection	—	Road
Referencelines type StandardLine	Section	—	Road
Referencelines type ConnectionLine	Generic	—	—
Referencelines type NetworkLine	Generic	—	—
NetworkNodes	Generic	—	—
LaneBorders	Generic	—	—

Acronyms

AAA	AFIS-ALKIS-ATKIS
ADE	CityGML Application Domain Extension
AdV	Working Committee of the Surveying Authorities of the States of the Federal Republic of Germany (Arbeitsgemeinschaft der Vermessungsverwaltungen der Länder der Bundesrepublik Deutschland)
AFIS	Amtliches Festpunktinformationssystem (German Official Geodetic Control Stations Information System)
ALKIS	Amtliches Liegenschaftskatasterinformationssystem (German Official Real Estate Cadastre Information System)
AR	Augmented Reality
ASAM	Association for Standardization of Automation and Measuring Systems
ATKIS	Amtliches Topographisch-Kartographisches Informationssystem (German Official Topographic Cartographic Information System)
B-rep	Boundary Representation
CityGML	City Geography Markup Language
CommonRoad	Composable benchmarks for motion planning on roads
CZML	Cesium Language
DEM	Digital Elevation Model
DLM	Digital Landscape Model
DSM	Digital Surface Model
DTM	Digital Terrain Model
ETL	Extract, Transform, Load
EU	European Union
FME	Feature Manipulation Engine
FZI	Forschungszentrum Informatik
GDF	Geographic Data Files

GeoInfoDok	Dokumentation zur Modellierung der Geoinformationen des amtlichen Vermessungswesens (Documentation on the Modelling of Geoinformation of Official Surveying and Mapping in Germany)
GML	Geography Markup Language
IFC	Industry Foundation Classes
IMU	Inertial Measuring Unit
INSPIRE	Infrastructure for Spatial Information in Europe
ISO	International Organization for Standardization
JSON	JavaScript Object Notation
KML	Keyhole Markup Language
LDBV	Landesamt für Digitalisierung, Breitband und Vermessung (Bavarian Agency for Digitisation, High-Speed Internet and Surveying)
LOD	Level of Detail
MMS	Mobile Mapping Systems
OGC	Open Geospatial Consortium
OKSTRA	Objektkatalog für das Straßen- und Verkehrswesen (Object catalog for the road and traffic sector)
OSM	OpenStreetMap
OWL	Web Ontology Language
PBF	ProtocolBufBinary
STEP	Standard for the Exchange of Product model data
TC	Technical Committee
TLM	Topographisches Landschaftsmodell
TUM	Technische Universität München
TWG	Technical Working Group
UDT	Urban Digital Twin
UHI	Urban Heat Island
UIM	Urban Information Models
UML	Unified Modeling Language

VR	Virtual Reality
XML	Extensible Markup Language
XSD	XML Schema Definition

Bibliography

Abdollahi, A., Pradhan, B., Shukla, N., Chakraborty, S. and Alamri, A. (2020). 'Deep Learning Approaches Applied to Remote Sensing Datasets for Road Extraction: A State-Of-The-Art Review'. In: *Remote Sensing* 12(9), p. 1444. URL: https://www.mdpi.com/2072-4292/12/9/1444.

Abou-Senna, H., Radwan, E., Westerlund, K. and Cooper, C. D. (2013). 'Using a traffic simulation model (VISSIM) with an emissions model (MOVES) to predict emissions from vehicles on a limited-access highway'. In: *Journal of the Air & Waste Management Association* 63(7), pp. 819–831. eprint: https://doi.org/10.1080/10962247.2013.795918. URL: https://doi.org/10.1080/10962247.2013.795918.

Aboushal, E. A. (2021). 'Regenerative design of a defined urban space using CityGML model'. In: *Journal of Urban Planning and Development* 147(3), p. 04021035.

Abualdenien, J. and Borrmann, A. (2022). 'Levels of detail, development, definition, and information need: a critical literature review'. In: *Journal of Information Technology in Construction* 27, pp. 363–392. URL: https://www.itcon.org/paper/2022/18.

AdV (2022). *GeoInfoDok-Version 7.1*. URL: https://www.adv-online.de/GeoInfoDok/Aktuelle-Anwendungsschemata/AAA-Anwendungsschema-7.1.2-Referenz-7.1/.

Agugiaro, G., González, F. G. G. and Cavallo, R. (2020). 'The City of Tomorrow from… the Data of Today'. In: *ISPRS International Journal of Geo-Information* 9(9), p. 554.

Aleksandrov, M., Zlatanova, S., Kimmel, L., Barton, J. and Gorte, B. (2019). 'Voxel-based visibility analysis for safety assessment of urban environments'. In: *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences* IV-4/W8, pp. 11–17.

Althoff, M., Koschi, M. and Manzinger, S. (2017). 'CommonRoad: Composable benchmarks for motion planning on roads'. In: *2017 IEEE Intelligent Vehicles Symposium (IV)*, pp. 719–726.

Althoff, M., Urban, S. and Koschi, M. (2018). 'Automatic conversion of road networks from OpenDRIVE to lanelets'. In: *2018 IEEE International Conference on Service Operations and Logistics, and Informatics (SOLI)*. IEEE, pp. 157–162.

Amann, J., Borrmann, A., Center, L. O. and Gladbach, B. (2015). *Creating a 3D-BIM-compliant road design based on IFC alignment originating from an OKSTRA-accordant 2D road design using the TUM Open Infra Platform and the OKSTRA class library*. Tech. rep.

Amirebrahimi, S., Rajabifard, A., Mendis, P. and Ngo, T. (2015). 'A data model for integrating GIS and BIM for assessment and 3D visualisation of flood damage to building'. In: *Locate* 15(2015), pp. 10–12.

Ariffin, M. M., Downe, A. G. and Abd Aziz, I. A. (2010). 'Developing a simulation game to facilitate the acquisition and transfer of road safety knowledge'. In: *2010 International Symposium on Information Technology*. Vol. 2. IEEE, pp. 924–929.

Artal-Villa, L., Hussein, A. and Olaverri-Monreal, C. (2019). 'Extension of the 3DCoAutoSim to simulate vehicle and pedestrian interaction based on SUMO and unity 3D'. In: *2019 IEEE Intelligent Vehicles Symposium (IV)*. IEEE, pp. 885–890.

ASAM (2020a). *ASAM OpenCRG Version 1.2.0*. Association for Standardisation of Automation and Measuring Systems e.V. (ASAM). URL: https://www.asam.net/standards/detail/opencrg/.

ASAM (2020b). *OpenDRIVE: Concept Document Version 1.0*.

ASAM (2023). *ASAM OpenDRIVE — Open Dynamic Road Information for Vehicle Environment, Version. 1.8*. Association for Standardisation of Automation and Measuring Systems e.V. (ASAM). URL: https://www.asam.net/standards/detail/opendrive/.

ASPRS (2018). 'LAS Specification Version 1.4 - 17-030rl'. In: American Society for Photogrammetry & Remote Sensing. URL: https://www.ogc.org/standard/las/.

Balado, J., Martinez-Sanchez, J., Arias, P. and Novo, A. (2019). 'Road Environment Semantic Segmentation with Deep Learning from MLS Point Cloud Data'. In: *Sensors* 19(16), p. 3466. URL: https://www.mdpi.com/1424-8220/19/16/3466.

Bandrova, T., Zlatanova, S. and Konecny, M. (2012). 'Three-Dimensional Maps for Disaster Management'. In: *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences* I-4, pp. 245–250. URL: https://isprs-annals.copernicus.org/articles/I-4/245/2012/.

Barazzetti, L., Previtali, M. and Scaioni, M. (2020). 'Roads Detection and Parametrization in Integrated BIM-GIS Using LiDAR'. In: *Infrastructures* 5(7), p. 55. URL: https://www.mdpi.com/2412-3811/5/7/55.

Barsi, A., Poto, V. and Tihanyi, V. (2018). 'Creating OpenCRG Road Surface Model from Terrestrial Laser Scanning Data for Autonomous Vehicles'. In: *Vehicle and Automotive Engineering 2*. Ed. by Jármai, K. and Bolló, B. Springer International Publishing: Cham, pp. 361–369.

Barz, A., Conrad, J. and Wallach, D. (2020). 'Advantages of Using Runtime Procedural Generation of Virtual Environments Based on Real World Data for Conducting Empirical Automotive Research'. In: *HCI International 2020 – Late Breaking Papers: Digital Human Modeling and Ergonomics, Mobility and Intelligent Environments*. Ed. by Stephanidis, C., Duffy, V. G., Streitz, N., Konomi, S. and Krömker, H. Springer International Publishing: Cham, pp. 14–23.

Bassani, M., Grasso, N. and Piras, M. (2015). '3D GIS based evaluation of the available sight distance to assess safety of urban roads'. In: *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci* XL-3/W3, pp. 137–143. URL: https://isprs-archives.copernicus.org/articles/XL-3-W3/137/2015/.

BASt. (2021). *Objektkatalog für das Straßen-und Verkehrswesen, Version 2.021*. Bundesanstalt für Straßenwesen.

BASt. (2024). *Anweisung StraßeninformationsBank (ASB), Version 2.05*. Bundesanstalt für Straßenwesen.

Batty, M. (2018). 'Digital twins'. In: *Environment and Planning B: Urban Analytics and City Science* 45(5), pp. 817–820. eprint: https://doi.org/10.1177/2399808318796416. URL: https://doi.org/10.1177/2399808318796416.

Batty, M., Chapman, D., Evans, S., Haklay, M., Kueppers, S., Shiode, N., Smith, A. and Torrens, P. M. (2001). *Visualizing the city: communicating urban design to planners and decision-makers*. Tech. rep. Technical Report Paper 26. London, UK: Centre for Advanced Spatial Analysis (UCL).

Bauranov, A. and Rakas, J. (2021). 'Designing airspace for urban air mobility: A review of concepts and approaches'. In: *Progress in Aerospace Sciences* 125, p. 100726. URL: https://www.sciencedirect.com/science/article/pii/S0376042121000312.

Becker, T., Nagel, C. and Kolbe, T. H. (2013). 'Semantic 3D Modeling of Multi-Utility Networks in Cities for Analysis and 3D Visualization'. In: *Progress and New Trends in 3D Geoinformation Sciences*. Ed. by Pouliot, J., Daniel, S., Hubert, F. and Zamyadi, A. Springer: Berlin, Heidelberg, pp. 41–62.

Behley, J., Garbade, M., Milioto, A., Quenzel, J., Behnke, S., Gall, J. and Stachniss, C. (Mar. 2024). 'Towards 3D LiDAR-based semantic scene understanding of 3D point cloud sequences: The SemanticKITTI Dataset'. In: *The International Journal of Robotics Research* 40(8-9), pp. 959–967. URL: https://doi.org/10.1177/02783649211006735.

Behrens, R., Kleine-Besten, T., Pöchmüller, W. and Engelsberg, A. (2015). 'Digitale Karten im Navigation Data Standard Format'. In: *Handbuch Fahrerassistenzsysteme: Grundlagen, Komponenten und Systeme für aktive Sicherheit und Komfort*. Ed. by Winner, H., Hakuli, S., Lotz, F. and Singer, C. Springer Fachmedien Wiesbaden: Wiesbaden, pp. 513–523. URL: https://doi.org/10.1007/978-3-658-05734-3_27.

Behrisch, M., Bieker, L., Erdmann, J. and Krajzewicz, D. (2011). 'SUMO – Simulation of Urban MObility: An Overview'. In: *SIMUL 2011*. ThinkMind. URL: https://elib.dlr.de/71460/.

Beil, C., Ilic, M., Keler, A. and Kolbe, T. H. (2024). 'Automatically evaluating the service quality of bicycle paths based on semantic 3D city models'. In: *Lecture Notes in Geoinformation and Cartography - Recent Advances in 3D Geoinformation Science - Proceedings of the 18th 3D GeoInfo Conference*. Technical University of Munich, Chair of Geoinformatics. Springer Nature Switzerland: Cham, pp. 75–92. URL: https://doi.org/10.1007/978-3-031-43699-4_5.

Beil, C., Kendir, M., Ruhdorfer, R. and Kolbe, T. H. (2022). 'Dynamic and web-based 4D visualization of streetspace activities derived from traffic simulations and semantic 3D city models'. In: *Proceedings of the 17th International 3D GeoInfo Conference 2022*. Vol. X-4/W2-2022. ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences. University of New South Wales. ISPRS: Sydney, pp. 29–36. URL: https://doi.org/10.5194/isprs-annals-X-4-W2-2022-29-2022.

Beil, C. and Kolbe, T. H. (2017). 'CityGML and the streets of New York - A proposal for detailed street space modelling'. In: *Proceedings of the 12th International 3D GeoInfo Conference 2017*. Ed. by Kalantari, M. and Rajabifard, A. Vol. IV-4/W5. ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences. This paper has received the 2nd Best Paper Award. University of Melbourne. ISPRS: Melbourne, Australia, pp. 9–16. URL: https://doi.org/10.5194/isprs-annals-IV-4-W5-9-2017.

Beil, C. and Kolbe, T. H. (2024). 'Applications for Semantic 3D Streetspace Models and Their Requirements - A Review and Look at the Road Ahead'. In: *ISPRS International Journal of Geo-Information* 13(10), p. 363. URL: https://doi.org/10.3390/ijgi13100363.

Beil, C., Kutzner, T., Schwab, B. and Kolbe, T. H. (2023). *Road2CityGML3 Version 1.0*. https://tum-gis.github.io/road2citygml3. URL: https://tum-gis.github.io/road2citygml3.

Beil, C., Kutzner, T., Schwab, B., Willenborg, B., Gawronski, A. and Kolbe, T. H. (2021). 'Integration of 3D Point Clouds with semantic 3D City Models - Providing semantic information beyond classification'. In: *Proceedings of the 16th International 3D GeoInfo Conference 2021*. Vol. VIII-4/W2. ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences. New York University. ISPRS: New York City, USA, pp. 105–112. URL: https://www.isprs-ann-photogramm-remote-sens-spatial-inf-sci.net/VIII-4-W2-2021/105/2021/.

Belton, V. and Stewart, T. J. (2002). 'An Integrated Approach to MCDA'. In: *Multiple Criteria Decision Analysis: An Integrated Approach*. Springer US: Boston, MA, pp. 331–343. URL: https://doi.org/10.1007/978-1-4615-1495-4_11.

Bender, P., Ziegler, J. and Stiller, C. (2014). 'Lanelets: Efficient map representation for autonomous driving'. In: *2014 IEEE Intelligent Vehicles Symposium Proceedings*. IEEE, pp. 420–425.

Biancardo, S. A., Capano, A., Oliveira, S. G. de and Tibaut, A. (2020). 'Integration of BIM and procedural modeling tools for road design'. In: *Infrastructures* 5(4), p. 37.

Biljecki, F. (2017). 'Level of detail in 3D city models'. PhD Thesis. Delft University of Technology. URL: https://doi.org/10.4233/uuid:f12931b7-5113-47ef-bfd4-688aae3be248.

Biljecki, F., Kumar, K. and Nagel, C. (2018). 'CityGML application domain extension (ADE): overview of developments'. In: *Open Geospatial Data, Software and Standards* 3(1), pp. 1–17.

Biljecki, F., Stoter, J., Ledoux, H., Zlatanova, S. and Çöltekin, A. (2015). 'Applications of 3D city models: State of the art review'. In: *ISPRS International Journal of Geo-Information* 4(4), pp. 2842–2889.

Board, T. R., National Academies of Sciences, E. and Medicine (2022). *Highway Capacity Manual 7th Edition: A Guide for Multimodal Mobility Analysis*. The National Academies Press: Washington, DC. URL: https://nap.nationalacademies.org/catalog/26432/highway-capacity-manual-7th-edition-a-guide-for-multimodal-mobility.

Bock, F. and Sester, M. (2016). 'Improving Parking Availability Maps using Information from Nearby Roads'. In: *Transportation Research Procedia* 19. Transforming Urban Mobility. mobil.TUM 2016. International Scientific Conference on Mobility and Transport. Conference Proceedings, pp. 207–214. URL: https://www.sciencedirect.com/science/article/pii/S2352146516308675.

Boersma, F. (2019). 'Modelling different levels of detail of roads and intersections in 3D city models'. Master's Thesis. Delft University of Technology.

Boffi, M., Piga, B. E. A., Mussone, L. and Caruso, G. (2022). 'Investigating objective and perceived safety in road mobility'. In: *Transportation Research Procedia* 60. New scenarios for safe mobility in urban areasProceedings of the XXV International Conference Living and Walking in Cities (LWC 2021), September 9-10, 2021, Brescia, Italy, pp. 600–607. URL: https://www.sciencedirect.com/science/article/pii/S2352146521009789.

Booch, G., Rumbaugh, J. and Jacobson, I. (2005). *Unified Modeling Language User Guide, The (2nd Edition)*. URL: https://dl.acm.org/doi/book/10.5555/1088874.

Bornstein, R. D. (1968). 'Observations of the urban heat island effect in New York City'. In: *Journal of Applied Meteorology and Climatology* 7(4), pp. 575–582.

Borrmann, A., Esser, S., Jaud, Š., König, M. and Liebich, T. (2020). *Begleitung der internationalen Standardisierungsprojekte IFC-Road & IFC-Rail: Abschlussbericht Gesamtprojekt*. Tech. rep. Technische Universität München.

Borrmann, A., Forster, C., Liebich, T., König, M. and Tulke, J. (2021). 'Germany's Governmental BIM Initiative – The BIM4INFRA2020 Project Implementing the BIM Roadmap'. In: *Proceedings of the 18th International Conference on Computing in Civil and Building Engineering*. Ed. by Toledo Santos, E. and Scheer, S. Vol. 98. Springer International Publishing: Cham, pp. 452–465.

Brand, L. and Löwner, M.-O. (2014). 'Parametrisierung und Identifikation urbaner Straßenkreuzungen im Kontext der Feinstaubmodellierung.' In: *DGPF Tagungsband, Gemeinsame Jahrestagung der DGfK, der DGPF, der GfGI und des GiN* 23, pp. 26–28.

Büttner, B., Kinigadner, J., Ji, C., Wright, B. and Wulfhorst, G. (2018). 'The TUM accessibility atlas: Visualizing spatial and socioeconomic disparities in accessibility to support regional land-use and transport planning'. In: *Networks and Spatial Economics* 18. Publisher: Springer, pp. 385–414.

Butz, T., Ehmann, M., Stryk, O. von and Wolter, T.-M. (2004). 'Realistic road modelling for the real-time simulation of vehicle dynamics'. In: *ATZ worldwide* 106(2), pp. 11–13.

Buuveibaatar, M., Lee, K. and Lee, W. (2022). 'Development of a Conceptual Data Model for 3D Geospatial Road Management Based on LandInfra Standard: A Case Study of Korea'. In: *ISPRS International Journal of Geo-Information* 11(5). URL: https://www.mdpi.com/2220-9964/11/5/316.

Buyuksalih, I., Bayburt, S., Buyuksalih, G., Baskaraca, A. P., Karim, H. and Rahman, A. A. (2017). '3D Modelling and Visualization based on the Unity Game Engine – Advantages and Challenges'. In: *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences* IV-4/W4, pp. 161–166. URL: https://isprs-annals.copernicus.org/articles/IV-4-W4/161/2017/.

Cabo, C., Ordoñez, C., García-Cortés, S. and Martínez, J. (2014). 'An algorithm for automatic detection of pole-like street furniture objects from Mobile Laser Scanner point clouds'. In: *ISPRS Journal of Photogrammetry and Remote Sensing* 87, pp. 47–56. URL: https://www.sciencedirect.com/science/article/pii/S092427161300230X.

Campos, C., Leitão, J. M. and Coelho, A. F. (2015). 'Integrated Modeling of Road Environments for Driving Simulation'. In: *Proceedings of the 10th International Conference on Computer Graphics Theory and Applications - Volume 1: GRAPP, (VISIGRAPP 2015)*. INSTICC. SciTePress, pp. 70–80.

Carrera-Rivera, A., Ochoa, W., Larrinaga, F. and Lasa, G. (2022). 'How-to conduct a systematic literature review: A quick guide for computer science research'. In: *MethodsX* 9, p. 101895. URL: https://www.sciencedirect.com/science/article/pii/S2215016122002746.

Carter, D. L., Hunter, W. W., Zegeer, C. V., Stewart, J. R. and Huang, H. (2007). 'Bicyclist intersection safety index'. In: *Transportation Research Record* 2031(1). Publisher: SAGE Publications Sage CA: Los Angeles, CA, pp. 18–24.

Chao, Q., Bi, H., Li, W., Mao, T., Wang, Z., Lin, M. C. and Deng, Z. (2020). 'A survey on visual traffic simulation: Models, evaluations, and applications in autonomous driving'. In: *Computer Graphics Forum*. Vol. 39. 1. Wiley Online Library, pp. 287–308.

Chaturvedi, K. and Kolbe, T. H. (2016). 'Integrating dynamic data and sensors with semantic 3D city models in the context of smart cities'. In: *ISPRS Annals of the Photogrammetry, Remote Sensing* *and Spatial Information Sciences* IV-2/W1, pp. 31–38. URL: https://www.isprs-ann-photogramm-remote-sens-spatial-inf-sci.net/IV-2-W1/31/2016/.

Chaturvedi, K. (2021). 'Integration and Management of Time-dependent Properties with Semantic 3D City Models'. PhD thesis. Chair of Geoinformatics, Technical University of Munich. URL: https://mediatum.ub.tum.de/node?id=1542959.

Chaturvedi, K., Smyth, C. S., Gesquière, G., Kutzner, T. and Kolbe, T. H. (2017a). 'Managing versions and history within semantic 3D city models for the next generation of CityGML'. In: *Advances in 3D geoinformation*. Springer, pp. 191–206.

Chaturvedi, K., Willenborg, B., Sindram, M. and Kolbe, T. H. (2017b). 'Solar potential analysis and integration of the time-dependent simulation results for semantic 3D city models using Dynamizers'. In: *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*. Vol. IV-4/W5, pp. 25–32. URL: https://isprs-annals.copernicus.org/articles/IV-4-W5/25/2017/.

Chaturvedi, K., Yao, Z. and Kolbe, T. H. (2019). 'Integrated management and visualization of static and dynamic properties of semantic 3D city models'. In: *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences* XLII-4/W17, pp. 7–14. URL: https://doi.org/10.5194/isprs-archives-XLII-4-W17-7-2019.

Chen, A., Ramanandan, A. and Farrell, J. A. (2010). 'High-precision lane-level road map building for vehicle navigation'. In: *IEEE/ION Position, Location and Navigation Symposium*, pp. 1035–1042.

Chen, G., Xiong, Q., Morris, P. J., Paterson, E. G., Sergeev, A. and Wang, Y. (2014). 'OpenFOAM for computational fluid dynamics'. In: *Notices of the AMS* 61(4), pp. 354–363.

Chen, J., Huang, X., Zheng, B., Zhao, R., Liu, X., Cao, Q. and Zhu, S. (2019). 'Real-time identification system of asphalt pavement texture based on the close-range photogrammetry'. In: *Construction and Building Materials* 226, pp. 910–919. URL: https://www.sciencedirect.com/science/article/pii/S0950061819319956.

Chen, L.-C. and Lo, C.-Y. (2009). '3D road modeling via the integration of large-scale topomaps and airborne LIDAR data'. In: *Journal of the Chinese Institute of Engineers* 32(6), pp. 811–823.

Chen, S., Truong-Hong, L., Laefer, D. and Mangina, E. (2018). 'Automated bridge deck evaluation through UAV derived point cloud'. In: *CERI-ITRN2018*. Dublin, Ireland, pp. 735–740.

Chen, W., Guo, F. and Wang, F.-Y. (2015). 'A survey of traffic data visualization'. In: *IEEE Transactions on Intelligent Transportation Systems* 16(6), pp. 2970–2984.

Chiang, K.-W. et al. (2023). 'Establishment of HD Maps Verification and Validation Procedure with OpenDRIVE and Autoware (Lanelet2) Formats'. In: *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences* X-1/W1-2023, pp. 621–627. URL: https://isprs-annals.copernicus.org/articles/X-1-W1-2023/621/2023/.

Constantin, A., Ding, J.-J. and Lee, Y.-C. (2018). 'Accurate Road Detection from Satellite Images Using Modified U-net'. In: *2018 IEEE Asia Pacific Conference on Circuits and Systems (APCCAS)*, pp. 423–426.

Crampen, D., Hein, M. and Blankenbach, J. (2024a). 'RoadGen4Twins: A Modular Approach for Generating Multi-Purpose Geometric-Semantic Models for Digital Twins of Roads'. In: *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences* X-4/W5-2024, pp. 103–110. URL: https://isprs-annals.copernicus.org/articles/X-4-W5-2024/103/2024/.

Crampen, D. and Blankenbach, J. (2023). ‘LOADt: Towards a Concept of Level of as-is Detail for Digital Twins of Roads’. In: *30th International Workshop on Intelligent Computing in Engineering (EG-ICE)*.

Crampen, D., Hein, M. and Blankenbach, J. (2024b). ‘A Level of As-Is Detail Concept for Digital Twins of Roads—A Case Study’. In: *Lecture Notes in Geoinformation and Cartography - Recent Advances in 3D Geoinformation Science - Proceedings of the 18th 3D GeoInfo Conference*. Springer Nature Switzerland: Cham, pp. 499–515.

Czerwinski, A., Gröger, G., Reichert, S. and Plümer, L. (2013). ‘Qualitätssicherung einer 3D-GDI EU-Umgebungslärmkartierung Stufe 2 in NRW’. In: *zfv* 138.

Czerwinski, A., Kolbe, T. H., Plümer, L. and Stöcker-Meier, E. (2006). ‘Interoperability and accuracy requirements for EU environmental noise mapping’. In: *Proceedings of the International Conference on GIS and Sustainable Development (InterCarto—InterGIS 12), Berlin, Germany*, pp. 28–30.

Deilami, K., Kamruzzaman, M. and Liu, Y. (2018). ‘Urban heat island effect: A systematic review of spatio-temporal factors, data, methods, and mitigation measures’. In: *International Journal of Applied Earth Observation and Geoinformation* 67, pp. 30–42. URL: https://www.sciencedirect.com/science/article/pii/S0303243417302994.

Dembski, F., Wössner, U., Letzgus, M., Ruddat, M. and Yamu, C. (2020). ‘Urban digital twins for smart cities and citizens: The case study of Herrenberg, Germany’. In: *Sustainability* 12(6), p. 2307.

Depretre, A. and Jacquinod, F. (2021). ‘Evaluating Urban Intensity through a City Information Model – Intermediate results from an action research project’. In: *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences* VIII-4/W2-2021, pp. 153–160. URL: https://www.isprs-ann-photogramm-remote-sens-spatial-inf-sci.net/VIII-4-W2-2021/153/2021/.

Dosovitskiy, A., Ros, G., Codevilla, F., Lopez, A. and Koltun, V. (2017). ‘CARLA: An open urban driving simulator’. In: *Conference on robot learning*. PMLR, pp. 1–16.

Drazkiewicz, A., Challies, E. and Newig, J. (2015). ‘Public participation and local environmental planning: Testing factors influencing decision quality and implementation in four case studies from Germany’. In: *Land Use Policy* 46, pp. 211–222. URL: https://www.sciencedirect.com/science/article/pii/S0264837715000496.

Elfouly, M., Kutzner, T. and Kolbe, T. H. (2015). ‘General Indicator Modeling for Decision Support based on 3D City and Landscape Models using Model Driven Engineering’. In: *Peer Reviewed Proceedings of Digital Landscape Architecture 2015 at Anhalt University of Applied Sciences*. Ed. by Buhmann, E., Ervin, S. M. and Pietsch, M. Wichmann: Dessau, pp. 256–267.

Elhashash, M., Albanwan, H. and Qin, R. (2022). ‘A Review of Mobile Mapping Systems: From Sensors to Applications’. In: *Sensors* 22(11), p. 4262. URL: https://www.mdpi.com/1424-8220/22/11/4262.

Engel, J. and Döllner, J. (2012). ‘Immersive visualization of virtual 3D City models and its applications in E-Planning’. In: *International Journal of E-Planning Research (IJEPR)* 1(4), pp. 17–34.

Fellendorf, M. (2013). ‘Digital Terrain Models for Road Design and Traffic Simulation’. English. In: *Photogrammetric Week ´13*. 1st ed. Wichmann Verlag, VDE Verlag GmbH, pp. 309–317.

Fellendorf, M. and Vortisch, P. (2010). ‘Microscopic traffic flow simulator VISSIM’. In: *Fundamentals of traffic simulation*. Vol. 145. Springer, pp. 63–93.

FGSV (2015). *Handbuch für die Bemessung von Straßenverkehrsanlagen [Manual for the design of road traffic facilities]*. Forschungsgesellschaft für Straßen-und Verkehrswesen e.V. [Research Association for Roads and Traffic e.V.] (in German), accessed on 20.01.2023. Forschungsgesellschaft für Straßen-und Verkehrswesen e.V. URL: https://www.fgsv-verlag.de/hbs-fgsv-reader.

Fischer, P., Azimi, S. M., Roschlaub, R. and Krauß, T. (2018). 'Towards HD Maps from Aerial Imagery: Robust Lane Marking Segmentation Using Country-Scale Imagery'. In: *ISPRS International Journal of Geo-Information* 7(12), p. 458. URL: https://www.mdpi.com/2220-9964/7/12/458.

Fiutak, G., Marx, C., Donaubauer, A. and Philipp, W. (2018a). *Projekt 3D Digitales Landschaftsmodell (3D-DLM) am Runden Tisch GIS e.V.* Tech. rep. Runder Tisch GIS e.V. URL: https://www.rundertischgis.de/projektarbeit/3d-digitales-landschaftsmodell/.

Fiutak, G., Marx, C., Willkomm, P., Donaubauer, A. and Kolbe, T. H. (2018b). 'Automatisierte Generierung eines digitalen Landschaftsmodells in 3D'. de. In: *PFGK18 - Photogrammetrie - Fernerkundung - Geoinformatik - Kartographie, 37. Jahrestagung in München 2018*. Ed. by Kersten, T. P., Gülch, E., Schiewe, J., Kolbe, T. H. and Stilla, U. 27. Deutsche Gesellschaft für Photogrammetrie, Fernerkundung und Geoinformation e.V.: München, pp. 888–902. URL: https://www.dgpf.de/src/tagung/jt2018/proceedings/proceedings/papers/77_PFGK18_Fiutak_et_al.pdf.

Florio, P., Peronato, G., Perera, A., Di Blasi, A., Poon, K. H. and Kaempf, J. H. (2021). 'Designing and assessing solar energy neighborhoods from visual impact'. In: *Sustainable Cities and Society* 71, p. 102959.

Floros, G., Boyes, G., Owens, D. and Ellul, C. (2019). 'Developing IFC for infrastructure: A case study of three highway entities'. In: *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*. Vol. 4. 4/W8. International Society for Photogrammetry and Remote Sensing, pp. 59–66.

Freese, M., Lukosch, H., Wegener, J. and König, A. (2020). 'Serious games as research instruments – Do's and don'ts from a cross-case-analysis in transportation'. In: *European Journal of Transport and Infrastructure Research* 20(4), pp. 103–126.

Fukada, H., Maita, N. and Abe, A. (2008). 'Proposal and Field Experiment of Road Facility Management Support System by RFID and GIS'. In: *Innovations and Advanced Techniques in Systems, Computing Sciences and Software Engineering*. Ed. by Elleithy, K. Springer Netherlands: Dordrecht, pp. 207–212.

Fuller, A., Fan, Z., Day, C. and Barlow, C. (2020). 'Digital Twin: Enabling Technologies, Challenges and Open Research'. In: *IEEE Access* 8, pp. 108952–108971.

Furda, A. and Vlacic, L. (2010). 'An object-oriented design of a world model for autonomous city vehicles'. In: *2010 IEEE Intelligent Vehicles Symposium*. IEEE. San Diego, CA, USA, pp. 1054–1059.

Gargoum, S. and El-Basyouny, K. (2017). 'Automated extraction of road features using LiDAR data: A review of LiDAR applications in transportation'. In: *2017 4th International Conference on Transportation Information and Safety (ICTIS)*, pp. 563–574.

Gehrke, S. R., Akhavan, A., Furth, P. G., Wang, Q. and Reardon, T. G. (2020). 'A cycling-focused accessibility tool to support regional bike network connectivity'. In: *Transportation research part D: transport and environment* 85. Publisher: Elsevier, p. 102388.

Ghassoun, Y. and Löwner, M.-O. (2017). 'Comparison of 2D & 3D parameter-based models in urban fine dust distribution modelling'. In: *Advances in 3D Geoinformation*. Springer, pp. 231–246.

Ghassoun, Y., Löwner, M.-O. and Weber, S. (2015). 'Exploring the benefits of 3D city models in the field of urban particles distribution modelling - A comparison of model results'. In: *3D Geoinformation Science*. Springer: Cham, pp. 193–205.

Gilbert, T., Rönsdorf, C., Plume, J., Simmons, S., Nisbet, N., Gruler, H.-C., Kolbe, T. H., Berlo, L. van, Mercer, A. et al. (2020). *Built environment data standards and their integration: an analysis of IFC, CityGML and LandInfra*. Tech. rep. OGC Document 19-091r1, bSI TR1012. Open Geospatial Consortium. URL: https://portal.ogc.org/files/?artifact_id=92634.

Gitahi, J. and Kolbe, T. H. (2024). 'Requirements for Web-Based 4D Visualisation of Integrated 3D City Models and Sensor Data in Urban Digital Twins'. In: *Lecture Notes in Geoinformation and Cartography - Recent Advances in 3D Geoinformation Science - Proceedings of the 18th 3D GeoInfo Conference*. Springer Nature Switzerland: Cham, pp. 707–725.

Gnatz, S. (2018). 'Automatisierte Generierung hochdetaillierter 3D-Verkehrswegemodelle für Straßenbahnsimulatoren'. Master's Thesis. Technical University Munich, Chair of Geoinformatics.

Godavarthy, R. P., Russell, E. and Landman, D. (2016). 'Using vehicle simulations to understand strategies for accommodating oversize, overweight vehicles at roundabouts'. In: *Transportation Research Part A: Policy and Practice* 87, pp. 41–50. URL: https://www.sciencedirect.com/science/article/pii/S096585641530015X.

Goebbels, S. (2021). '3D Reconstruction of Bridges from Airborne Laser Scanning Data and Cadastral Footprints'. In: *Journal of Geovisualization and Spatial Analysis* 5(1), pp. 1–15.

Gonzalez-Collazo, S. M., Rio-Barral, P. del, Balado, J. and Gonzalez, E. (2022). 'Detection of Direct Sun Glare on Drivers from Point Clouds'. In: *Remote Sensing* 14(6), p. 1456. URL: https://www.mdpi.com/2072-4292/14/6/1456.

Grigoropoulos, G., Keler, A., Kaths, H., Spangler, M. and Busch, F. (2019). 'Using Geodata for Simulating Urban Traffic–Current Research in the Field of Traffic Engineering and Control'. In: *Geoinformationssysteme 2019–Beiträge Zur 6. Münchner GI-Runde*, pp. 44–49.

Gristina, S., Ellul, C. and Scianna, A. (2016). 'Developing A 3D Road Cadastral System: Comparing Legal Requirements And User Needs'. In: *ISPRS Annals*. Vol. IV-2/W1. International Society for Photogrammetry and Remote Sensing, pp. 223–231.

Gröger, G., Kolbe, T. H., Nagel, C. and Häfele, K.-H. (2012). *OGC City Geography Markup Language (CityGML) Encoding Standard, Version 2.0.0*. OGC Document 12-019. Open Geospatial Consortium. URL: https://www.ogc.org/standard/citygml/.

Gröger, G. and Plümer, L. (2011). 'How to achieve consistency for 3D city models'. In: *GeoInformatica* 15(1), pp. 137–165. URL: https://link.springer.com/article/10.1007/s10707-009-0091-6.

Großmann, A., Scheller, S., Reiterer, A. and Stoerk, D. (2023). *Analyse von Straßenbestandsobjekten aus Laserpunktwolken durch Mustererkennung Objekterkennung einschließlich der Georeferenzierung*. Tech. rep. Bundesanstalt für Straßenwesen, p. 127.

Gruler, H.-C., Stubkjaer, E., Axelsson, P. and Wikstrom, L. (2016). *OGC® Land and Infrastructure Conceptual Model Standard (LandInfra)*.

Guarnaccia, C. (2010). 'Acoustical noise analysis in road intersections: a case study'. In: *11th WSEAS International Conference on "Acoustics & Music: Theory & Applications"(AMTA'10), Iasi, Romania*, pp. 208–215.

Haklay, M. and Weber, P. (2008). 'OpenStreetMap: User-generated street maps'. In: *IEEE Pervasive Computing* 7(4), pp. 12–18.

Harkey, D. L., Reinfurt, D. W. and Sorton, A. (1st Dec. 1998). 'The Bicycle Compatibility Index: A Level of Service Concept, Implementation Manual'. In: (FHWA-RD-98-095). Ed. by University of North Carolina at Chapel Hill. URL: https://rosap.ntl.bts.gov/view/dot/14487.

Harrie, L., Oucheikh, R., Nilsson, A., Oxenstierna, A., Cederholm, P., Wei, L., Richter, K.-F. and Olsson, P. (May 2022). 'Label Placement Challenges in City Wayfinding Map Production–Identification and Possible Solutions'. In: *Journal of Geovisualization and Spatial Analysis* 6(1), p. 16. URL: https://doi.org/10.1007/s41651-022-00115-z.

Harshit, Chaurasia, P., Zlatanova, S. and Jain, K. (2024). 'Low-Cost Data, High-Quality Models: A Semi-Automated Approach to LOD3 Creation'. In: *ISPRS International Journal of Geo-Information* 13(4), p. 119. URL: https://www.mdpi.com/2220-9964/13/4/119.

Heipke, C. (2016). 'Herausforderungen bei der Erstellung von 3D-DLMs'. In: *Geoinformationssysteme*. Ed. by Kolbe, T. H., Bill, R. and Donaubauer, A. Wichmann.

Helbich, M., Amelunxen, C., Neis, P. and Zipf, A. (2012). 'Comparative spatial analysis of positional accuracy of OpenStreetMap and proprietary geodata'. In: *Proceedings of GI_Forum* 4, p. 24.

Henningsson, M., Blicharska, M., Antonson, H., Mikusiński, G., Göransson, G., Angelstam, P., Folkeson, L. and Jönsson, S. (2015). 'Perceived landscape values and public participation in a road-planning process – a case study in Sweden'. In: *Journal of Environmental Planning and Management* 58(4), pp. 631–653. URL: https://doi.org/10.1080/09640568.2013.876391.

Hexagon (2023). *Virtual Test Drive (VTD)*. URL: https://hexagon.com/de/products/virtual-test-drive.

Hirt, P.-R., Holtkamp, J., Hoegner, L., Xu, Y. and Stilla, U. (2022). 'Occlusion detection of traffic signs by voxel-based ray tracing using highly detailed models and MLS point clouds of vegetation'. In: *International Journal of Applied Earth Observation and Geoinformation* 114, p. 103017. URL: https://www.sciencedirect.com/science/article/pii/S1569843222002059.

Hoffmanns, W. (2020). *Breedtescript BGT wegdelen*. URL: https://github.com/willemhoffmans/bgt_wegbreedte/.

Holland, D., Hurst, I., Heathcote, G., Horgan, J. and Capstick, D. (Aug. 2020). 'The Changing Nature of Geospatial Data – Challenges for a National Mapping Agency'. In: *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* XLIII-B5-2020, pp. 179–183.

Huang, P., Cheng, M., Chen, Y., Luo, H., Wang, C. and Li, J. (2017). 'Traffic sign occlusion detection using mobile laser scanning point clouds'. In: *IEEE Transactions on Intelligent Transportation Systems* 18(9), pp. 2364–2376.

Huo, Y., Yang, A., Jia, Q., Chen, Y., He, B. and Li, J. (2021). 'Efficient Visualization of Large-Scale Oblique Photogrammetry Models in Unreal Engine'. In: *ISPRS International Journal of Geo-Information* 10(10), p. 643. URL: https://www.mdpi.com/2220-9964/10/10/643.

INSPIRE Thematic Working Group Transport Networks (2014). *D2.8.I.7 Data Specification on Transport Networks – Technical Guidelines*. Ed. by Centre, E. C. J. R. URL: https://joinup.ec.europa.eu/collection/inspire/solution/inspire-data-specification-transport-networks-guidelines-v301.

IPG Automotive (2024). *IPG CarMaker*. https://ipg-automotive.com/en/products-solutions/software/carmaker/.

ISO (2012a). *ISO 19148:2012 Geographic information — Linear referencing*.

ISO (2012b). *ISO/IEC 19505-1:2012 Information technology — Object Management Group Unified Modeling Language (OMG UML) — Part 1: Infrastructure*.

ISO (2013). *ISO 8855:2013 Road vehicles — Vehicle dynamics and road-holding ability*.

ISO (2018). *ISO 16739-1:2018 Industry Foundation Classes (IFC) für den Datenaustausch in der Bauwirtschaft und im Anlagenmanagement*.

ISO (2020a). *ISO 20524-1:2020 Intelligent transport systems — Geographic Data Files (GDF) GDF5.1 — Part 1: Application independent map data shared between multiple sources*.

ISO (2020b). *ISO 20524-2:2020 Intelligent transport systems — Geographic Data Files (GDF) GDF5.1 — Part 2: Map data used in automated driving systems, Cooperative ITS, and multi-modal transport*.

ISO (2024a). *Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries - Part 1: Data Schema*.

ISO (2024b). *ISO 19152-1:2024 Geographic information — Land Administration Domain Model (LADM) Part 1: Generic conceptual model*.

ISO 19103 (2015). *ISO/TS 19103:2015 Geographic information — Conceptual schema language*.

ISO 19107 (2019). *ISO 19107:2019 Geographic information — Spatial schema*.

ISO 19109 (2015). *ISO 19109:2015 Geographic information — Rules for application schema*.

ISO 19111 (2019). *ISO 19111:2019 Geographic information - Referencing by coordinates*.

ISO 19136 (2020). *ISO 19136:2020 Geographic information - Geography Markup Language (GML)*.

Ito, K. and Biljecki, F. (2021). 'Assessing bikeability with street view imagery and computer vision'. In: *Transportation Research Part C: Emerging Technologies* 132, p. 103371. URL: https://www.sciencedirect.com/science/article/pii/S0968090X21003739.

Jaillot, V., Servigne, S. and Gesquière, G. (2020). 'Delivering time-evolving 3D city models for web visualization'. In: *International Journal of Geographical Information Science* 34(10), pp. 2030–2052.

Jaud, Š., Clemen, C., Muhič, S. and Borrmann, A. (2022). 'Georeferencing in IFC: Meeting the Requirements of Infrastructure and Building Industries'. In: *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences* X-4/W2-2022, pp. 145–152. URL: https://www.isprs-ann-photogramm-remote-sens-spatial-inf-sci.net/X-4-W2-2022/145/2022/.

Jaud, Š., Donaubauer, A. and Borrmann, A. (2019). 'Georeferencing within IFC: A Novel Approach for Infrastructure Objects'. In: *Computing in Civil Engineering 2019: Visualization, Information Modeling, and Simulation*. American Society of Civil Engineers Reston, VA: Atlanta, Georgia, pp. 377–384.

Jaud, Š., Esser, S., Muhic, S. and Borrmann, A. (2020). 'Development of IFC schema for Infrastructure'. In: *Proceedings of the 6th International Conference siBIM:* Online, pp. 27–35.

Javanmardi, M., Javanmardi, E., Gu, Y. and Kamijo, S. (2017). 'Towards High-Definition 3D Urban Mapping: Road Feature-Based Registration of Mobile Mapping Systems and Aerial Imagery'. In: *Remote Sensing* 9(10), p. 975. URL: https://www.mdpi.com/2072-4292/9/10/975.

Jeong, N.-R., Han, S.-W. and Kim, J.-H. (2022). 'Evaluation of Vegetation Configuration Models for Managing Particulate Matter along the Urban Street Environment'. In: *Forests* 13(1), p. 46. URL: https://www.mdpi.com/1999-4907/13/1/46.

Jiang, X., Ma, J., Xiao, G., Shao, Z. and Guo, X. (2021). 'A review of multimodal image matching: Methods and applications'. In: *Information Fusion* 73, pp. 22–71. URL: https://www.sciencedirect.com/science/article/pii/S156625352100035X.

Jones, D., Snider, C., Nassehi, A., Yon, J. and Hicks, B. (2020). 'Characterising the Digital Twin: A systematic literature review'. In: *CIRP Journal of Manufacturing Science and Technology* 29, pp. 36–52. URL: https://www.sciencedirect.com/science/article/pii/S1755581720300110.

Jose, R. S. and Perez-Camanyo, J. L. (2023). 'High-Performance Computing Urban Air Pollution 3D Simulation with CFD PALM4U'. In: *Environment and Sustainable Development*. Ed. by Ujikawa, K., Ishiwatari, M. and Hullebusch, E. v. Springer Nature Singapore: Singapore, pp. 239–251.

Justo, A., Soilan, M., Sanchez-Rodriguez, A. and Riveiro, B. (2021). 'Scan-to-BIM for the infrastructure domain: Generation of IFC-compliant models of road infrastructure assets and semantics using 3D point cloud data'. In: *Automation in Construction* 127, p. 103703.

Kaden, R. (2014). 'Berechnung der Energiebedarfe von Wohngebäuden und Modellierung energiebezogener Kennwerte auf der Basis semantischer 3D-Stadtmodelle'. PhD thesis. Technical University of Munich, Chair of Geoinformatics. URL: https://mediatum.ub.tum.de/doc/1210304/1210304.pdf.

Kasemsuppakorn, P. and Karimi, H. A. (2008). 'Data requirements and a spatial database for personalized wheelchair navigation'. In: *2nd international convention on rehabilitation engineering & assistive technology*, pp. 31–34.

Kato, S., Tokunaga, S., Maruyama, Y., Maeda, S., Hirabayashi, M., Kitsukawa, Y., Monrroy, A., Ando, T., Fujii, Y. and Azumi, T. (2018). 'Autoware on Board: Enabling Autonomous Vehicles with Embedded Systems'. In: *2018 ACM/IEEE 9th International Conference on Cyber-Physical Systems (ICCPS)*, pp. 287–296.

Keler, A., Amini, S., Lindner, J. and Bogenberger, K. (Apr. 2023). 'Introducing Data-Format-Dependent Road Network Conversion Techniques – Lessons Learned from the Digital Twin Munich'. In: *31st Geographical Information Science Research UK (GISRUK) Conference*. Glasgow, Scotland.

Keler, A., Kaths, J., Chucholowski, F., Chucholowski, M., Grigoropoulos, G., Spangler, M., Kaths, H. and Busch, F. (2018). 'A bicycle simulator for experiencing microscopic traffic flow simulation in urban environments'. In: *2018 21st International Conference on Intelligent Transportation Systems (ITSC)*. IEEE, pp. 3020–3023.

Khan, J., Ketzel, M., Kakosimos, K., Sørensen, M. and Jensen, S. S. (2018). 'Road traffic air and noise pollution exposure assessment – A review of tools and techniques'. In: *Science of The Total Environment* 634, pp. 661–676. URL: https://www.sciencedirect.com/science/article/pii/S0048969718311343.

Kielar, P. M., Biedermann, D. H. and Borrmann, A. (2016). *MomenTUMv2: A modular, extensible, and generic agent-based pedestrian behavior simulation framework*. Tech. rep. TUM-I1643. Munich, Germany: Technical University Munich.

Knezevic, M., Donaubauer, A., Moshrefzadeh, M. and Kolbe, T. H. (2022). 'Managing Urban Digital Twins with an Extended Catalog Service'. In: *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences* X-4/W3-2022, pp. 119–126. URL: https://isprs-annals.copernicus.org/articles/X-4-W3-2022/119/2022/.

Kolbe, T. H. (2009). 'Representing and exchanging 3D city models with CityGML'. In: *3D geo-information sciences*. Springer, pp. 15–31. URL: https://mediatum.ub.tum.de/doc/1145752/947446.pdf.

Kolbe, T. H. and Donaubauer, A. (2021). 'Semantic 3D City Modeling and BIM'. In: *Urban Informatics*. Springer, pp. 609–636. URL: https://doi.org/10.1007/978-981-15-8983-6_34.

Kolbe, T. H., Gröger, G. and Plümer, L. (2008). 'CityGML–3D city models and their potential for emergency response'. In: *Geospatial information technology for emergency response*, pp. 257–274.

Kolbe, T. H., Nagel, C. and Stadler, A. (2009). 'CityGML–OGC Standard for Photogrammetry?' In: *Photogrammetric week*. Vol. 9, pp. 265–277.

Kolbe, T. H., Donaubauer, A. and Beil, C., eds. (2024). *Recent Advances in 3D Geoinformation Science*. en. Lecture Notes in Geoinformation and Cartography. Springer, p. 861. URL: https://doi.org/10.1007/978-3-031-43699-4.

Kolbe, T. H., Kutzner, T., Smyth, C. S., Nagel, C., Roensdorf, C. and Heazel, C. (2021). *OGC City Geography Markup Language (CityGML) Part 1: Conceptual Model Standard*. https://docs.ogc.org/is/20-010/20-010.html.

Kollarits, S. (2011). 'GIP – ein Ansatz zur integrierten Modellierung von Verkehrsnetzen'. In: *HMD Praxis der Wirtschaftsinformatik* 48(4), pp. 104–113. URL: https://doi.org/10.1007/BF03340610.

Kölle, M., Laupheimer, D., Schmohl, S., Haala, N., Rottensteiner, F., Wegner, J. D. and Ledoux, H. (2021). 'The Hessigheim 3D (H3D) benchmark on semantic segmentation of high-resolution 3D point clouds and textured meshes from UAV LiDAR and Multi-View-Stereo'. In: *ISPRS Open Journal of Photogrammetry and Remote Sensing* 1, p. 100001. URL: https://www.sciencedirect.com/science/article/pii/S2667393221000016.

Konde, A. and Saran, S. (2017). 'Web enabled spatio-temporal semantic analysis of traffic noise using CityGML'. In: *J Geomatics* 11(2), pp. 248–59.

Krausz, N., Potó, V., Lógó, J. M. and Barsi, Á. (2022). 'Comparison of Complex Traffic Junction Descriptions in Automotive Standard Formats'. In: *Periodica Polytechnica Civil Engineering* 66(1), pp. 282–290. URL: https://pp.bme.hu/ci/article/view/18616.

Kumar, K., Ledoux, H., Commandeur, T. J. F. and Stoter, J. E. (2017). 'Modelling urban noise in CityGML ADE: Case of the Netherlands'. In: *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences* IV-4/W5, pp. 73–81. URL: https://www.isprs-ann-photogramm-remote-sens-spatial-inf-sci.net/IV-4-W5/73/2017/.

Kumar, K., Labetski, A., Ohori, K., Ledoux, H. and Stoter, J. (July 2019). 'The LandInfra standard and its role in solving the BIM-GIS quagmire'. In: *Open Geospatial Data, Software and Standards* 4, p. 5.

Kurkcu, A., Miranda, F., Ozbay, K. and Silva, C. T. (2017). 'Data visualization tool for monitoring transit operation and performance'. In: *2017 5th IEEE International Conference on Models and Technologies for Intelligent Transportation Systems (MT-ITS)*. IEEE, pp. 598–603.

Kutsch, A., Margreiter, M., Stueger, P. N., Fehn, F., Metzger, B., Hamm, L., Engelhardt, R., Ilic, M. and Bogenberger, K. (2022). 'TEMPUS - Test Field Munich - Pilot Test for Urban Automated Road Traffic'. In: *2022 IEEE 25th International Conference on Intelligent Transportation Systems (ITSC)*, pp. 2514–2519.

Kutzner, T., Chaturvedi, K. and Kolbe, T. H. (2020). 'CityGML 3.0: New Functions Open Up New Applications'. In: *PFG – Journal of Photogrammetry, Remote Sensing and Geoinformation Science* 88, pp. 43–61. URL: https://doi.org/10.1007/s41064-020-00095-z.

Kutzner, T., Hijazi, I. and Kolbe, T. H. (2018). 'Semantic modelling of 3D multi-utility networks for urban analyses and simulations: The CityGML utility network ADE'. In: *International Journal of 3-D Information Modeling (IJ3DIM)* 7(2), pp. 1–34. URL: http://doi.org/10.4018/IJ3DIM.2018040101.

Kutzner, T., Smyth, C. S., Nagel, C., Coors, V., Vinasco-Alvarez, D., Ishimaru, N., Yao, Z., Heazel, C. and Kolbe, T. H. (2023). *OGC City Geography Markup Language (CityGML) Part 2: GML Encoding Standard*. https://docs.ogc.org/is/21-006r2/21-006r2.html.

Kwan, M.-P. and Lee, J. (2005). 'Emergency response after 9/11: the potential of real-time 3D GIS for quick emergency response in micro-spatial environments'. In: *Computers, Environment and Urban Systems* 29(2), pp. 93–113. URL: https://www.sciencedirect.com/science/article/pii/S0198971503000796.

Labetski, A., Gerwen, S. van, Tamminga, G., Ledoux, H. and Stoter, J. (2018). 'A Proposal for an improved Transportation Model in CityGML'. In: *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* XLII-4/W10, pp. 89–96. URL: https://isprs-archives.copernicus.org/articles/XLII-4-W10/89/2018/.

Laksono, D. and Aditya, T. (2019). 'Utilizing A Game Engine for Interactive 3D Topographic Data Visualization'. In: *ISPRS International Journal of Geo-Information* 8(8), p. 361. URL: https://www.mdpi.com/2220-9964/8/8/361.

Lamas, D., Justo, A., Soila, M. and Riveiro, B. (2022). '3D Point Cloud to BIM: Automated Application to define IFC Alignment and Roadway width entities from MLS-acquired LiDAR data of mountain Roads'. In: *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences* X-4/W2-2022, pp. 169–176. URL: https://www.isprs-ann-photogramm-remote-sens-spatial-inf-sci.net/X-4-W2-2022/169/2022/.

Landis, B. W. (1994). 'Bicycle Interaction Hazard Score: A Theoretical Model'. In: *Transportation Research Record* 1438(1438), pp. 3–8.

Ledoux, H., Arroyo Ohori, K., Kumar, K., Dukai, B., Labetski, A. and Vitalis, S. (2019). 'CityJSON: a compact and easy-to-use encoding of the CityGML data model'. In: *Open Geospatial Data, Software and Standards* 4(1), p. 4. URL: https://doi.org/10.1186/s40965-019-0064-0.

Ledoux, H., Biljecki, F., Dukai, B., Kumar, K., Peters, R., Stoter, J. and Commandeur, T. (2021). '3dfier: automatic reconstruction of 3D city models'. In: *Journal of Open Source Software* 6(57), p. 2866.

Ledoux, H. and Dukai, B. (2023). *CityJSON Specifications 2.0.1*. URL: https://cityjson.org/specs/.

Lee, J. and Zlatanova, S. (2008). 'A 3D data model and topological analyses for emergency response in urban areas'. In: *Geospatial information technology for emergency response*, pp. 159–184.

Lehner, H., Kordasch, S. L., Glatz, C. and Agugiaro, G. (2024). 'Digital geoTwin: A CityGML-Based Data Model for the Virtual Replica of the City of Vienna'. In: *Recent Advances in 3D Geoinformation Science*. Ed. by Kolbe, T. H., Donaubauer, A. and Beil, C. Springer Nature Switzerland, pp. 517–541.

Lemmen, C., Van Oosterom, P. and Bennett, R. (2015). 'The land administration domain model'. In: *Land use policy* 49, pp. 535–545.

Li, X., Wang, M., Liu, X., Wang, Z. and Bian, Y. (2022). 'Representing dynamic lanes in road network models'. In: *International Journal of Geographical Information Science* 36(7), pp. 1467–1483. eprint: https://doi.org/10.1080/13658816.2022.2060981. URL: https://doi.org/10.1080/13658816.2022.2060981.

Lian, R., Wang, W., Mustafa, N. and Huang, L. (2020). 'Road Extraction Methods in High-Resolution Remote Sensing Images: A Comprehensive Review'. In: *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* 13, pp. 5489–5507.

Lima Alves, E. D. and Lopes, A. (2017). 'The Urban Heat Island Effect and the Role of Vegetation to Address the Negative Impacts of Local Climate Changes in a Small Brazilian City'. In: *Atmosphere* 8(2). URL: https://www.mdpi.com/2073-4433/8/2/18.

Liu, Z., Yang, A., Gao, M., Jiang, H., Kang, Y., Zhang, F. and Fei, T. (2019). 'Towards feasibility of photovoltaic road for urban traffic-solar energy estimation using street view image'. In: *Journal of Cleaner Production* 228, pp. 303–318. URL: https://www.sciencedirect.com/science/article/pii/S0959652619313538.

Lopez, P. A., Behrisch, M., Bieker-Walz, L., Erdmann, J., Flötteröd, Y.-P., Hilbrich, R., Lücken, L., Rummel, J., Wagner, P. and Wießner, E. (2018). 'Microscopic traffic simulation using SUMO'. In: *2018 21st international conference on intelligent transportation systems (ITSC)*. IEEE, pp. 2575–2582.

Lovas, T., Ormandi, T., Somogyi, A. J., Baranyai, D., Tihanyi, V. and Tettamanti, T. (2022). 'Open-CRG Models From Different Data Sources to Support Vehicle Simulations'. In: *IEEE Access* 10, pp. 42690–42698.

Löwner, M.-O., Gröger, G., Benner, J., Biljecki, F. and Nagel, C. (2016). 'Proposal for a new LoD and multi-representation concept for CiityGML'. In: *ISPRS Annals of Photogrammetry, Remote Sensing & Spatial Information Sciences* 4, pp. 3–12.

Lu, L., Becker, T. and Löwner, M.-O. (2017). '3D Complete Traffic Noise Analysis based on CityGML'. In: *Advances in 3D Geoinformation*. Ed. by Abdul-Rahman, A. Springer International Publishing: Cham, pp. 265–283. URL: https://link.springer.com/chapter/10.1007/978-3-319-25691-7_15.

Luiten, B., Böhms, M., Alsem, D. and O'Keeffe, A. (2019). *Asset information management using Linked Data for the life-cycle of Roads*. Delft: CRC Press/Balkema, p. 8. URL: https://repository.tno.nl//islandora/object/uuid:1f844e74-8ac3-472b-aef6-2ea332c4e207.

Macura, J. (2019). ‘Time-variable Visualization from Sensor Data Inside Building in a 3D GIS Environment’. MA thesis. Department of Geomatics, University of West Bohemia.

Mao, B., Ban, Y. and Laumert, B. (2020). ‘Dynamic online 3D visualization framework for real-time energy simulation based on 3D tiles’. In: *ISPRS International Journal of Geo-Information* 9(3), p. 166.

Marnat, L., Gautier, C., Colin, C. and Gesquière, G. (2022). ‘py3dtilers: An Open Source Toolkit for Creating and Managing 2D/3D Geospatial Data’. In: *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences* X-4/W3-2022, pp. 165–172. URL: https://isprs-annals.copernicus.org/articles/X-4-W3-2022/165/2022/.

Martens, K., Benenson, I. and Levy, N. (2010). ‘The Dilemma of On-Street Parking Policy: Exploring Cruising for Parking Using an Agent-Based Model’. In: *Geospatial Analysis and Modelling of Urban Structure and Dynamics*. Ed. by Jiang, B. and Yao, X. Springer Netherlands: Dordrecht, pp. 121–138.

MathWorks, Inc. (2023). *MatLab - RoadRunner*.

Mekuria, M. C., Furth, P. G. and Nixon, H. (2012). ‘Low-stress bicycling and network connectivity’. In: *Mineta Transportation Institute Publications. https://transweb.sjsu.edu/research/Low-Stress-Bicycling-and-Network-Connectivity*. Mineta Transportation Institute Publications. Publisher: Mineta Transportation Institute. URL: https://scholarworks.sjsu.edu/mti_publications/74/.

Meyer, T. and Brunn, A. (2019). ‘3D Point Clouds in PostgreSQL/PostGIS for Applications in GIS and Geodesy.’ In: *GISTAM*, pp. 154–163.

Miranda, F., Doraiswamy, H., Lage, M., Wilson, L., Hsieh, M. and Silva, C. T. (2019). ‘Shadow Accrual Maps: Efficient Accumulation of City-Scale Shadows Over Time’. In: *IEEE Transactions on Visualization and Computer Graphics* 25(3), pp. 1559–1574.

Moon, H. et al. (2019). *Conceptual Model Report - Annex I – Example instance diagrams V1.0 - IFC Road WP3*.

Moradi, M. and Assaf, G. J. (2023). ‘Designing and Building an Intelligent Pavement Management System for Urban Road Networks’. In: *Sustainability* 15(2), p. 1157. URL: https://www.mdpi.com/2071-1050/15/2/1157.

Mueller, F. (2021). *Development of a CityGML OpenDRIVE ADE*. Technical Report. Technical University of Munich, Chair of Geoinformatics.

Murshed, S. M., Al-Hyari, A. M., Wendel, J. and Ansart, L. (2018). ‘Design and implementation of a 4D web application for analytical visualization of smart city applications’. In: *ISPRS International Journal of Geo-Information* 7(7), p. 276.

Nakasone, A., Prendinger, H., Miska, M., Lindner, M., Horiguchi, R. and Kuwahara, M. (2011). ‘OpenEnergySim: A 3D internet based experimental framework for integrating traffic simulation and multi-user immersive driving’. In: *4th International ICST Conference on Simulation Tools and Techniques*, pp. 490–498.

Nedkov, S. (2012). ‘Knowledge-based optimisation of 3D city models for car navigation devices’. MA thesis. Delft University of Technology, Delft, The Netherlands.

New York City Department of Transportation (2020). *New York City Street Design Manual -Third Edition*. URL: https://www.nycstreetdesign.info/.

Nguyen, S. H., Yao, Z. and Kolbe, T. H. (2017). 'Spatio-Semantic Comparison of Large 3D City Models In CityGML Using a Graph Database'. In: *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences* IV-4/W5, pp. 99–106. URL: https://isprs-annals.copernicus.org/articles/IV-4-W5/99/2017/.

Niestroj, M. G., McMeekin, D. A. and Helmholz, P. (2018). 'Overview of standards towards road asset information exchange'. In: *International Archives of the Photogrammetry, Remote Sensing & Spatial Information Sciences* XLII-4, pp. 443–450.

Noardo, F. et al. (2021). 'Reference study of IFC software support: The GeoBIM benchmark 2019 - Part I'. In: *Transactions in GIS* 25(2), pp. 805–841. eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1111/tgis.12709. URL: https://onlinelibrary.wiley.com/doi/abs/10.1111/tgis.12709.

Object Management Group (OMG) (2017). *Unified Modeling Language v2.5.1*. URL: https://www.omg.org/spec/UML/2.5.1.

Olbrich, F., Beil, C., Nguyen, S. H. and Kolbe, T. H. (2024). 'Multimodale Navigationsanwendungen für CityGML 3.0 konforme 3D-Straßenraummodelle mittels Graphdatenbanken'. In: *44. Wissenschaftlich-Technische Jahrestagung der DGPF in Remagen – Publikationen der DGPF, Band 32*. Deutsche Gesellschaft für Photogrammetrie, Fernerkundung und Geoinformation e.V., pp. 357–369. URL: https://www.dgpf.de/src/tagung/jt2024/proceedings/paper/26_dgpf2024_Olbrich_et_al.pdf.

Osama, A. and Sayed, T. (2016). 'Evaluating the impact of bike network indicators on cyclist safety using macro-level collision prediction models'. In: *Accident Analysis & Prevention* 97, pp. 28–37. URL: https://www.sciencedirect.com/science/article/pii/S0001457516302883.

Oude Elberink, S. (2010). 'Acquisition of 3D topography: Automated 3D road and building reconstruction using airborne laser scanner data and topographic maps'. PhD Thesis. International Institute for Geo-information Science and Earth Observation, Enschede, The Netherlands.

Oude Elberink, S., Stoter, J., Ledoux, H. and Commandeur, T. (2013). 'Generation and dissemination of a national virtual 3D city and landscape model for the Netherlands'. In: *Photogrammetric Engineering & Remote Sensing* 79(2), pp. 147–158.

Padsala, R., Valger, S., Santhanavanich, T., Voss, U. and Coors, V. (2024). 'Geo-visualisation of Air-Pollutant Dispersion in Complex Urban Environments using 3D City Models: Insights from High-Resolution Street Canyon Simulation - Concept and First Results'. In: *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* XLVIII-4/W11-2024, pp. 89–95. URL: https://isprs-archives.copernicus.org/articles/XLVIII-4-W11-2024/89/2024/.

Pan, Y., Wang, M., Lu, L., Wei, R., Cavazzi, S., Peck, M. and Brilakis, I. (2024). 'Scan-to-graph: Automatic generation and representation of highway geometric digital twins from point cloud data'. In: *Automation in Construction* 166, p. 105654.

Pantazatou, K., Kanters, J., Mattisson, K., Olsson, P.-O. and Harrie, L. (2024). 'Recommendation for Vegetation Information in Semantic 3D City Models Used in Urban Planning Applications'. In: *Recent Advances in 3D Geoinformation Science*. Ed. by Kolbe, T. H., Donaubauer, A. and Beil, C. Springer Nature Switzerland: Cham, pp. 3–30. URL: https://link.springer.com/chapter/10.1007/978-3-031-43699-4_1.

Papa, E. and Coppola, P. (2012). 'Gravity-based accessibility measures for integrated transport-land use planning (GraBAM)'. In: *Accessibility instruments for planning practice* 117. Publisher: COST Office Porto, p. 124.

Parish, Y. I. and Müller, P. (2001). 'Procedural modeling of cities'. In: *Proceedings of the 28th annual conference on Computer graphics and interactive techniques*, pp. 301–308.

Park, S. H., Jang, Y.-H., Geem, Z. W. and Lee, S.-H. (2019). 'CityGML-Based Road Information Model for Route Optimization of Snow-Removal Vehicle'. In: *ISPRS International Journal of Geo-Information* 8(12), p. 588.

Pauleit, S., Hansen, R., Rall, E. and Rolf, W. (Jan. 2020). 'Urban Green Infrastructure: Strategic planning of urban green and blue for multiple benefits'. English. In: *The Routledge Handbook of Urban Ecology*. Taylor and Francis, pp. 931–942.

Pechinger, M. (2023). 'Collective Perception using Roadside ITS Stations: Simulations on Traffic Safety and Efficiency of Urban Automated Driving'. en. PhD thesis. Technische Universität München, Lehrstuhl für Verkehrstechnik, p. 161.

Pena Acosta, M., Vahdatikhaki, F., Santos, J. and Doree, A. G. (2020). 'A conceptual framework for more efficient simulation of the interplay between road pavements and the Urban Heat Island phenomenon'. In: *EG-ICE 2020 Workshop on Intelligent Computing in Engineering*. Ed. by Ungureanu, L.-C. and Hartmann, T. Berlin University Press, pp. 264–274.

Petrova-Antonova, D., Malinov, S., Mrosla, L. and Petrov, A. (2024). 'Towards a Conceptual Model of CityGML 3.0 Vegetation ADE'. In: *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* XLVIII-4/W10-2024, pp. 155–161. URL: https://isprs-archives.copernicus.org/articles/XLVIII-4-W10-2024/155/2024/.

Piga, B., Caruso, G., Ferraioli, A. and Mussone, L. (2020). 'Modeling Virtual Road Scenarios for Driving Simulators: A Comparison of 3D Models with Different Level of Details'. In: *International Conference of Representation Disciplines Teachers.* Pp. 792–802.

Poggenhans, F. and Janosovits, J. (2020). 'Pathfinding and Routing for Automated Driving in the Lanelet2 Map Framework'. In: *2020 IEEE 23rd International Conference on Intelligent Transportation Systems (ITSC)*, pp. 1–7.

Poggenhans, F., Pauls, J.-H., Janosovits, J., Orf, S., Naumann, M., Kuhnt, F. and Mayr, M. (2018). 'Lanelet2: A high-definition map framework for the future of automated driving'. In: *2018 21st International Conference on Intelligent Transportation Systems (ITSC)*. IEEE, pp. 1672–1679.

Prandi, F., De Amicis, R., Piffer, S., Soave, M., Cadzow, S., Gonzalez Boix, E. and D'Hont, E. (2013). 'Using CityGML to deploy Smart-City Services for urban ecosystems'. In: *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* XL-4/W1, pp. 87–92. URL: https://www.int-arch-photogramm-remote-sens-spatial-inf-sci.net/XL-4-W1/87/2013/.

PTV Group (2021). *PTV VISUM*. URL: https://www.ptvgroup.com/en-us/products/ptv-visum.

Pu, S., Rutzinger, M., Vosselman, G. and Sander, O. E. (2011). 'Recognizing basic structures from mobile laser scanning data for road inventory studies'. In: *ISPRS Journal of Photogrammetry and Remote Sensing* 66(6, Supplement). Advances in LIDAR Data Processing and Applications, 28–S39. URL: https://www.sciencedirect.com/science/article/pii/S0924271611000955.

Puente, I., González-Jorge, H., Martínez-Sánchez, J. and Arias, P. (2013). 'Review of mobile mapping and surveying technologies'. In: *Measurement* 46(7), pp. 2127–2145. URL: https://www.sciencedirect.com/science/article/pii/S0263224113000730.

QGIS Development Team (2023). *QGIS Geographic Information System*. QGIS Association.

Quartieri, J., Mastorakis, N., Guarnaccia, C., Troisi, A., D'Ambrosio, S. and Iannone, G. (2009). 'Road intersections noise impact on urban environment quality'. In: *5th WSEAS International Conference on "Applied and Theoretical Mechanics"(MECHANICS'09), Puerto de la Cruz, Tenerife, Spain*, pp. 162–171.

Rahman, M. A., Franceschi, E., Pattnaik, N., Moser-Reischl, A., Hartmann, C., Paeth, H., Pretzsch, H., Rötzer, T. and Pauleit, S. (2022). 'Spatial and temporal changes of outdoor thermal stress: influence of urban land cover types.' eng. In: *Scientific reports* 12 (1), p. 671.

Randt, B., Bildstein, F. and Kolbe, T. H. (2007). 'Use of virtual 3D landscapes for emergency driver training'. In: *Proc. of the Int. Conference on Visual Simulation IMAGE*. Vol. 2. Scottsdale, Arizona.

Rashidan, H., Musliman, I. A., Abdul Rahman, A., Coors, V. and Buyuksalih, G. (2024). 'Semantic Segmentation of Building Models with Deep Learning in CityGML'. In: *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* XLVIII-4/W11-2024, pp. 97–102. URL: https://isprs-archives.copernicus.org/articles/XLVIII-4-W11-2024/97/2024/.

Raubal, M. and Winter, S. (2002). 'Enriching Wayfinding Instructions with Local Landmarks'. In: *Geographic Information Science*. Ed. by Egenhofer, M. J. and Mark, D. M. Vol. 2478. Springer Berlin Heidelberg: Berlin, Heidelberg, pp. 243–259.

Redweik, R. (2016). *CO2 Monitoring und Reporting auf Basis von 3D-Stadtmodellen*. Accessed on 20.07.2022. URL: https://www.3d-stadtmodelle.org/3d-stadtmodelle_2016/vortraege/01_Redweik_CO2-Monitoring.pdf.

Reichler, M., Taher, J., Manninen, P., Kaartinen, H., Hyyppä, J. and Kukko, A. (2024). 'Semantic segmentation of raw multispectral laser scanning data from urban environments with deep neural networks'. In: *ISPRS Open Journal of Photogrammetry and Remote Sensing* 12, p. 100061. URL: https://www.sciencedirect.com/science/article/pii/S2667393224000048.

Rezaee, M. and Zhang, Y. (2017). 'Road detection using Deep Neural Network in high spatial resolution images'. In: *2017 Joint Urban Remote Sensing Event (JURSE)*, pp. 1–4.

Richter, A., Löwner, M.-O., Ebendt, R. and Scholz, M. (2020). 'Towards an integrated urban development considering novel intelligent transportation systems: Urban Development Considering Novel Transport'. In: *Technological Forecasting and Social Change* 155, p. 119970.

Richter, A. and Scholz, M. (Sept. 2019). *Road2Simulation-Guideline*. https://doi.org/10.5281/zenodo.3375525. Version 1.2.1. URL: https://doi.org/10.5281/zenodo.3375550.

RoadXML (2020). *RoadXML - Road Network Description, XML Format Specification, Version 3.0.0. 2020.*

Robinson, D., Haldi, F., Leroux, P., Perez, D., Rasheed, A. and Wilke, U. (2009). 'CitySim: Comprehensive micro-simulation of resource flows for sustainable urban planning'. In: *Proceedings of the Eleventh International IBPSA Conference*, pp. 1083–1090.

Robles-Ortega, M. D., Ortega, L., Coelho, A., Feito, F. and Sousa, A. de (2013). 'Automatic street surface modeling for web-based urban information systems'. In: *Journal of urban planning and development* 139(1), pp. 40–48.

Ross, L. (2010). 'Virtual 3D City Models in Urban Land Management - Technologies and Applications'. PhD thesis. Technical University of Berlin.

Rua, E., Nunez-Seoane, A., Arias, P. and Martinez-Sanchez, J. (2023). 'Automatic detection to inventory road slopes using open LiDAR point clouds'. In: *International Journal of Applied Earth Observation and Geoinformation* 118, p. 103225.

Ruhdorfer, R., Willenborg, B. and Sindram, M. (2018). 'Coupling of Traffic Simulations and semantic 3D City Models'. In: *gis.Science* 2018(3), pp. 101–109.

Rui, M., Jiayu, C., Chendi, Y. and Li, X. (2024). 'OSMsc: a framework for semantic 3D city modeling using OpenStreetMap'. In: *International Journal of Geographical Information Science* 38(1), pp. 1–26. eprint: https://doi.org/10.1080/13658816.2023.2266824. URL: https://doi.org/10.1080/13658816.2023.2266824.

Rupprecht, T., Klingsch, W. and Seyfried, A. (2011). 'Influence of geometry parameters on pedestrian flow through bottleneck'. In: *Pedestrian and Evacuation Dynamics*. Springer, pp. 71–80.

Sabato, E., D'Amico, F., Tripodi, A. and Tiberi, P. (2023). 'BIM & Road safety – Applications of digitals models from in-built safety evaluations to asset management'. In: *Transportation Research Procedia* 69. AIIT 3rd International Conference on Transport Infrastructure and Systems (TIS ROMA 2022), 15th-16th September 2022, Rome, Italy, pp. 815–822.

Santhanavanich, T., Wuerstle, P., Silberer, J., Loidl, V., Rodrigues, P. and Coors, V. (2020). '3D Safe Routing Navigation Application for Pedestrians and Cyclists based on Open Source Tools'. In: *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences* VI-4/W2-2020, pp. 143–147. URL: https://www.isprs-ann-photogramm-remote-sens-spatial-inf-sci.net/VI-4-W2-2020/143/2020/.

Saran, S., Oberai, K., Wate, P., Konde, A., Dutta, A., Kumar, K. and Senthil Kumar, A. (2018). 'Utilities of virtual 3D city models based on CityGML: Various use cases'. In: *Journal of the indian society of remote sensing* 46(6), pp. 957–972.

Schmid-Querg, J., Keler, A. and Grigoropoulos, G. (2021). 'The Munich Bikeability Index: A Practical Approach for Measuring Urban Bikeability'. In: *Sustainability* 13(1), p. 428. URL: https://www.mdpi.com/2071-1050/13/1/428.

Schonowski, J. et al. (2024). *DIN SPEC 91607 Digitale Zwillinge für Städte und Kommunen*. de. DIN Deutsches Institut für Normung e. V., p. 131. URL: https://www.dinmedia.de/de/technische-regel/din-spec-91607/384414386.

Schrotter, G. and Hürzeler, C. (Feb. 2020). 'The Digital Twin of the City of Zurich for Urban Planning'. In: *PFG - Journal of Photogrammetry, Remote Sensing and Geoinformation Science* 88(1), pp. 99–112. URL: https://doi.org/10.1007/s41064-020-00092-2.

Schulte, C. and Coors, V. (2008). 'Development of a CityGML ADE for dynamic 3D flood information'. In: *Joint ISCRAM-CHINA and GI4DM Conference on Information Systems for Crisis Management*. Vol. 103. Harbin, China, p. 10.

Schwab, B. and Kolbe, T. H. (2022). 'Validation of parametric OpenDRIVE Road Space Models'. In: *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences* X-4/W2-2022, pp. 257–264. URL: https://www.isprs-ann-photogramm-remote-sens-spatial-inf-sci.net/X-4-W2-2022/257/2022/.

Schwab, B., Beil, C. and Kolbe, T. H. (2020). 'Spatio-semantic road space modeling for vehicle–pedestrian simulation to test automated driving systems'. In: *Sustainability* 12(9), p. 3799. URL: https://doi.org/10.3390/su12093799.

Schwab, B. and Kolbe, T. H. (2019). 'Requirement Analysis of 3D Road Space Models for Automated Driving'. en. In: *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences* IV-4/W8, pp. 99–106. URL: https://doi.org/10.5194/isprs-annals-IV-4-W8-99-2019.

Scorpio, M., Laffi, R., Masullo, M., Ciampi, G., Rosato, A., Maffei, L. and Sibilio, S. (2020). 'Virtual reality for smart urban lighting design: Review, applications and opportunities'. In: *Energies* 13(15), p. 3809.

Seif, H. G. and Hu, X. (2016). 'Autonomous Driving in the iCity - HD Maps as a Key Challenge of the Automotive Industry'. In: *Engineering* 2(2), pp. 159–162. URL: https://www.sciencedirect.com/science/article/pii/S2095809916309432.

Sekeran, M., Rostami-Shahrbabaki, M., Syed, A. A., Margreiter, M. and Bogenberger, K. (2022). 'Lane-Free Traffic: History and State of the Art'. In: *2022 IEEE 25th International Conference on Intelligent Transportation Systems (ITSC)*, pp. 1037–1042.

Seto, T., Furuhashi, T. and Uchiyama, Y. (June 2023). 'Role of 3D City Model Data as Open Digital Commons: A Case Study of Openness in Japan's Digital Twin "Project Plateau"'. In: *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* XLVIII-4/W7-2023, pp. 201–208.

Shahat, E., Hyun, C. T. and Yeom, C. (2021). 'City Digital Twin Potentials: A Review and Research Agenda'. In: *Sustainability* 13(6), p. 3386. URL: https://www.mdpi.com/2071-1050/13/6/3386.

Shen, J., Zhou, J., Zhou, J., Herman, L. and Reznik, T. (2020). 'Constructing the CityGML ADE for the Multi-Source Data Integration of Urban Flooding'. In: *ISPRS International Journal of Geo-Information* 9(6), p. 359.

Shi, Y., Boffi, M., Piga, B. E. A., Mussone, L. and Caruso, G. (2022). 'Perception of Driving Simulations: Can the Level of Detail of Virtual Scenarios Affect the Driver's Behavior and Emotions?' In: *IEEE Transactions on Vehicular Technology* 71(4), pp. 3429–3442.

Sindram, M. and Kolbe, T. H. (2014). 'Modeling of urban planning actions by complex transactions on semantic 3D city models'. In: *Proceedings of the International Environmental Modelling and Software Society (iEMSs)*. San Diego, California, pp. 848–855.

Slingsby, A. and Raper, J. (2008). 'Navigable space in 3D city models for pedestrians'. In: *Advances in 3D geoinformation systems*. Springer, pp. 49–64.

Soon, K. H. and Khoo, V. H. S. (2017). 'CityGML modelling for Singapore 3D national mapping'. In: *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences* XLII-4/W7, pp. 37–42.

Stadler, A. and Kolbe, T. H. (2007). ‘Spatio-semantic coherence in the integration of 3D city models’. In: *Proceedings of the 5th International ISPRS Symposium on Spatial Data Quality ISSDQ*. Archives. ISPRS: Enschede, The Netherlands.

Stoter, J., Kluijver, H. de and Kurakula, V. (2008). ‘3D noise mapping in urban areas’. In: *International Journal of Geographical Information Science* 22(8), pp. 907–924.

Stoter, J. E. (2004). ‘3D Cadastre’. PhD Thesis. TU Delft, The Netherlands.

Stoter, J. E., Vallet, B., Lithen, T., Pla, M., Wozniak, P., Kellenberger, T., Streilein, A., Ilves, R. and Ledoux, H. (2016). ‘State-of-the-art of 3D national mapping in 2016’. In: *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences* 41, p. 653.

Strassenburg Kleciak, M. (Aug. 2016). ‘OpenStreetMap - Capturing streets as areas OpenStreetMap - Straßen als Flächen erfassen’. In: *GIS Business* 11, pp. 26–29.

Strosahl, J., Sichermann, J., Jesch, M. and Spieler, D. (2022). ‘Perspective-Corrected Extraction of Trajectories from Urban Traffic Camera Using CNN’. In: *2022 International Conference on Connected Vehicle and Expo (ICCVE)*, pp. 1–7.

Sukma, A. I., Koeva, M. N., Reckien, D., Bockarjova, M., Silva Mano, A. da, Canili, G., Vicentini, G. and Kerle, N. (2024). ‘3D City Digital Twin Simulation to Mitigate Heat Risk of Urban Heat Islands’. In: *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* XLVIII-4/W11-2024, pp. 129–136. URL: https://isprs-archives.copernicus.org/articles/XLVIII-4-W11-2024/129/2024/.

Susi, T., Johannesson, M. and Backlund, P. (2007). *Serious games: An overview*. Technical Report HS- IKI -TR-07-001.

Tamminga, G. (2019). ‘A Novel Design of the Transport Infrastructure for Traffic Simulation Models’. PhD thesis. Delft, The Netherlands: Delft University of Technology.

Tamminga, G., Brink, L. van den, Van Lint, H., Stoter, J. and Hoogendoorn, S. (2013). ‘Toward GIS-Compliant Data Structures for Traffic and Transportation Models’. In: *TRB 92nd Annual Meeting Compendium of Papers*. Washington DC, United State, pp. 1–18.

Toma-Danila, D. (2013). ‘Transport network vulnerability assessment methodology, based on the cost-distance method and GIS Integration’. In: *Intelligent Systems for Crisis Management: Geo-information for Disaster Management (Gi4DM) 2012*, pp. 199–213.

Tong, X.-Y., Xia, G.-S. and Zhu, X. X. (2023). ‘Enabling country-scale land cover mapping with meter-resolution satellite imagery’. In: *ISPRS Journal of Photogrammetry and Remote Sensing* 196, pp. 178–196. URL: https://www.sciencedirect.com/science/article/pii/S0924271622003264.

TrianGraphics (2024). *Train3DBuilder*. URL: https://trian3dbuilder.de/.

Uggla, M. et al. (2023). ‘Future Swedish 3D City Models—Specifications, Test Data, and Evaluation’. In: *ISPRS International Journal of Geo-Information* 12(2), p. 47. URL: https://www.mdpi.com/2220-9964/12/2/47.

Ullmann, D., Kreimeier, J., Götzelmann, T. and Kipke, H. (2020). ‘BikeVR: a virtual reality bicycle simulator towards sustainable urban space and traffic planning’. In: *Conference on Mensch und Computer*, pp. 511–514.

Valls, F. and Clua, A. (July 2023). ‘Modeling Barcelona sidewalks: A high resolution urban scale assessment of the geometric attributes of the walkable network’. In: *PLOS ONE* 18(7), pp. 1–30. URL: https://doi.org/10.1371/journal.pone.0284630.

Varela-Gonzalez, M., Riveiro, B., Arias-Sanchez, P., Gonzalez-Jorge, H. and Martinez-Sanchez, J. (2014). ‘A CityGML extension for traffic-sign objects that guides the automatic processing of data collected using mobile mapping technology’. In: *International Archives of the Photogrammetry, Remote Sensing & Spatial Information Sciences* XL-1, pp. 415–420.

Vignali, V., Acerra, E. M., Lantieri, C., Di Vincenzo, F., Piacentini, G. and Pancaldi, S. (2021). ‘Building information Modelling (BIM) application for an existing road infrastructure’. In: *Automation in Construction* 128, p. 103752. URL: https://www.sciencedirect.com/science/article/pii/S092658052100203X.

Visconti, E., Tsigkanos, C., Hu, Z. and Ghezzi, C. (1st Dec. 2021). ‘Model-driven engineering city spaces via bidirectional model transformations’. In: *Software and Systems Modeling* 20(6), pp. 2003–2022. URL: https://doi.org/10.1007/s10270-020-00851-0.

Vishnu, E. and Sameer, S. (2021). ‘OGC CityGML 3D City Models Enriched with Utility Infrastructures for Developing Countries’. In: *Journal of the Indian Society of Remote Sensing* 49(4), pp. 813–826.

Vishnu, E. and Saran, S. (Nov. 2018). ‘Semantic Modeling of Utility Networks Implementation of Use Cases for Dehradun City’. In: *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* XLII-5, pp. 139–145.

Vitalis, S., Labetski, A., Ledoux, H. and Stoter, J. (2022). ‘From road centrelines to carriageways — A reconstruction algorithm’. In: *PLOS ONE* 17(2), e0262801. URL: https://app.dimensions.ai/details/publication/pub.1145738823.

Vo, A.-V. (2017). ‘Spatial data storage and processing strategies for urban laser scanning’. PhD thesis. University College Dublin (Ireland), School of Civil Engineering.

W3C (2008). *Extensible Markup Language (XML) 1.0 (Fifth Edition)*.

Wagener, N., Beckmann, J. and Eckstein, L. (2022). ‘Efficient Creation of 3D-Virtual Environments for Driving Simulators’. In: *2022 International Conference on Electrical, Computer, Communications and Mechatronics Engineering (ICECCME)*, pp. 1–6.

Wang, R., Peethambaran, J. and Chen, D. (2018). ‘Lidar point clouds to 3-D urban models : A review’. In: *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* 11(2), pp. 606–627.

Wang, Y., Chen, Q., Zhu, Q., Liu, L., Li, C. and Zheng, D. (2019). ‘A Survey of Mobile Laser Scanning Applications and Key Techniques over Urban Areas’. In: *Remote Sensing* 11(13), p. 1540. URL: https://www.mdpi.com/2072-4292/11/13/1540.

Wei, Y. and Ji, S. (2022). ‘Scribble-Based Weakly Supervised Deep Learning for Road Surface Extraction From Remote Sensing Images’. In: *IEEE Transactions on Geoscience and Remote Sensing* 60, pp. 1–12.

Weise, I. M., Schmidt, I. and Hettwer, I. J. (2018). ‘OKSTRA®, IFC und BIM: Neue Wege im Umgang mit Straßeninfrastrukturdaten’. In: *7. OKSTRA-SymposiumForschungsgesellschaft fuer Strassen- und Verkehrswesen (FGSV)(DEU)-German Road and Transportation Research Association*.

Weißmann, M., Edler, D., Keil, J. and Dickmann, F. (May 2023). 'Creating an Interactive Urban Traffic System for the Simulation of Different Traffic Scenarios'. In: *Applied Sciences* 13, p. 6020.

Wen, D., Huang, X., Bovolo, F., Li, J., Ke, X., Zhang, A. and Benediktsson, J. A. (2021). 'Change Detection From Very-High-Spatial-Resolution Optical Remote Sensing Images: Methods, applications, and future directions'. In: *IEEE Geoscience and Remote Sensing Magazine* 9(4), pp. 68–101.

Wheeler, B., Syzdykbayev, M., Karimi, H. A., Gurewitsch, R. and Wang, Y. (2020). 'Personalized accessible wayfinding for people with disabilities through standards and open geospatial platforms in smart cities'. In: *Open Geospatial Data, Software and Standards* 5(1), pp. 1–15.

Wierbos, M. J., Knoop, V. L., Haenseler, F. S. and Hoogendoorn, S. P. (2019). 'Capacity, Capacity Drop, and Relation of Capacity to the Path Width in Bicycle Traffic'. In: *Transportation Research Record* 2673(5), pp. 693–702.

Wilkie, D., Sewall, J. and Lin, M. C. (2011). 'Transforming GIS data into functional road models for large-scale traffic simulation'. In: *IEEE Transactions on Visualization and Computer Graphics* 18(6), pp. 890–901.

Willenborg, B., Behnisch, M., Muenzinger, M. and Poglitsch, H. (15th Nov. 2019). *Towards the Estimation of PV Potentials for all Buildings in Germany*. Presentation at Leonard Obermeyer Center (LOC) Day 2019. Technical University of Munich (TUM), Chair of Geoinformatics.

Willenborg, B., Sindram, M. and Kolbe, T. H. (2018). 'Applications of 3D city models for a better understanding of the built environment'. In: *Trends in Spatial Analysis and Modelling*. Springer International Publishing: Cham, pp. 167–191. URL: https://doi.org/10.1007/978-3-319-52522-8_9.

Winiwarter, L., Mandlburger, G., Schmohl, S. and Pfeifer, N. (Sept. 2019). 'Classification of ALS Point Clouds Using End-to-End Deep Learning'. In: *PFG - Journal of Photogrammetry, Remote Sensing and Geoinformation Science* 87(3), pp. 75–90. URL: https://doi.org/10.1007/s41064-019-00073-0.

Wong, K. and Ellul, C. (2018). 'User requirements gathering for a national 3D mapping product in the United Kingdom'. In: *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences* IV-4/W6, pp. 89–96. URL: https://www.isprs-ann-photogramm-remote-sens-spatial-inf-sci.net/IV-4-W6/89/2018/.

Wysocki, O., Hoegner, L. and Stilla, U. (2022). 'Refinement of semantic 3D building models by reconstructing underpasses from MLS point clouds'. In: *International Journal of Applied Earth Observation and Geoinformation* 111, p. 102841.

Wysocki, O., Schwab, B., Beil, C., Holst, C. and Kolbe, T. H. (2024). 'Reviewing Open Data Semantic 3D City Models to Develop Novel 3D Reconstruction Methods'. In: *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*. ISPRS TC IV Mid-term Symposium "Spatial Information to Empower the Metaverse" XLVIII-4-2024, pp. 493–500. URL: https://doi.org/10.5194/isprs-archives-XLVIII-4-2024-493-2024.

Xu, H., Wang, C. (, Berres, A., LaClair, T. and Sanyal, J. (2022). 'Interactive Web Application for Traffic Simulation Data Management and Visualization'. In: *Transportation Research Record* 2676(1), pp. 274–292.

Xu, Y. and Stilla, U. (2021). 'Towards Building and Civil Infrastructure Reconstruction from Point Clouds: A Review on Data and Key Techniques'. In: *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* 14, pp. 2857–2885.

Yan, J., Zlatanova, S. and Diakité, A. (2021). 'A unified 3D space-based navigation model for seamless navigation in indoor and outdoor'. In: *International Journal of Digital Earth* 14(8), pp. 985–1003.

Yao, H., Qin, R. and Chen, X. (2019). 'Unmanned Aerial Vehicle for Remote Sensing Applications—A Review'. In: *Remote Sensing* 11(12), p. 1443. URL: https://www.mdpi.com/2072-4292/11/12/1443.

Yao, Z. (2020). 'Domain Extendable 3D City Models – Management, Visualization, and Interaction'. PhD thesis. Chair of Geoinformatics, Technical University of Munich. URL: https://mediatum.ub.tum.de/doc/1454692/1454692.pdf.

Yao, Z., Nagel, C., Kunde, F., Hudra, G., Willkomm, P., Donaubauer, A., Adolphi, T. and Kolbe, T. H. (2018). '3DCityDB - a 3D geodatabase solution for the management, analysis, and visualization of semantic 3D city models based on CityGML'. en. In: *Open Geospatial Data, Software and Standards* 3(5), pp. 1–26. URL: https://doi.org/10.1186/s40965-018-0046-7.

Yarroudh, A., Nys, G.-A. and Hajji, R. (2023). '3D Modeling of Road Infrastructures according to CityGML 3.0 and its CityJSON Encoding'. In: *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* XLVIII-1/W2-2023, pp. 63–70. URL: https://isprs-archives.copernicus.org/articles/XLVIII-1-W2-2023/63/2023/.

Ye, C., Zhao, H., Ma, L., Jiang, H., Li, H., Wang, R., Chapman, M. A., Junior, J. M. and Li, J. (2022). 'Robust Lane Extraction From MLS Point Clouds Towards HD Maps Especially in Curve Road'. In: *IEEE Transactions on Intelligent Transportation Systems* 23(2), pp. 1505–1518.

Zhang, J., Zhao, X., Chen, Z. and Lu, Z. (2019). 'A Review of Deep Learning-Based Semantic Segmentation for Point Cloud'. In: *IEEE Access* 7, pp. 179118–179133.

Zhao, B., Silva, E. and Soga, K. (2018). 'Pavement degradation: a city-scale model for San Francisco, USA'. In: *Proceedings of the Institution of Civil Engineers-Smart Infrastructure and Construction* 171(3), pp. 93–109.

Zhu, L., Li, Z. and Wang, Z. (2018a). 'Representing time-dynamic geospatial objects on virtual globes using CZML — Part II: Impact, comparison, and future developments'. In: *ISPRS International Journal of Geo-Information* 7(3), p. 102.

Zhu, L., Wang, Z. and Li, Z. (2018b). 'Representing time-dynamic geospatial objects on virtual globes using CZML — Part I: Overview and key issues'. In: *ISPRS International Journal of Geo-Information* 7(3), p. 97.

Zhu, W., Simons, A., Wursthorn, S. and Nichersu, A. (2016). 'Integration of CityGML and Air Quality Spatio-Temporal Data Series via OGC SOS'. In: *Geospatial Sensor Webs Conference (GSW), Munster, Germany*, pp. 29–31.

Zlatanova, S., Yan, J., Wang, Y., Diakité, A., Isikdag, U., Sithole, G. and Barton, J. (2020). 'Spaces in spatial science and urban applications—state of the art review'. In: *ISPRS International Journal of Geo-Information* 9(1), p. 58.

All URLs in this thesis were checked on 7th of February 2025.

Original publications

The contents of this thesis are based on a number of publications, which were published in the course of this doctorate and are listed in this chapter in the order of publication dates.

1) Beil, C. and Kolbe, T. H. (2017). ‘CityGML and the streets of New York - A proposal for detailed street space modelling’. In: *Proceedings of the 12th International 3D GeoInfo Conference 2017*. Ed. by Kalantari, M. and Rajabifard, A. Vol. IV-4/W5. ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences. This paper has received the 2nd Best Paper Award. University of Melbourne. ISPRS: Melbourne, Australia, pp. 9–16. URL: https://doi.org/10.5194/isprs-annals-IV-4-W5-9-2017

2) Beil, C. and Kolbe, T. H. (2018). ‘Detaillierte Repräsentation des Straßenraums in 3D Stadtmodellen’. In: *PFGK18 - Photogrammetrie - Fernerkundung - Geoinformatik - Kartographie, 37. Jahrestagung in München 2018*. Ed. by Kersten, T. P., Gülch, E., Schiewe, J., Kolbe, T. H. and Stilla, U. Vol. 27. Deutsche Gesellschaft für Photogrammetrie, Fernerkundung und Geoinformation e.V.: München, pp. 717–728. URL: http://www.dgpf.de/src/tagung/jt2018/proceedings/proceedings/papers/30_PFGK18_KKN_03_Beil_Kolbe.pdf

3) Schwab, B., Beil, C. and Kolbe, T. H. (2020). ‘Spatio-Semantic Road Space Modeling for Vehicle – Pedestrian Simulation to Test Automated Driving Systems’. In: *Sustainability* 12(9), p. 3799. URL: https://doi.org/10.3390/su12093799

4) Beil, C. and Kolbe, T. H. (2020). ‘Combined modelling of multiple transportation infrastructure within 3D city models and its implementation in CityGML 3.0’. In: *Proceedings of the 15th International 3D GeoInfo Conference 2020*. Vol. VI-4/W1-2020. University College London. ISPRS: London, UK, pp. 29–36. URL: https://doi.org/10.5194/isprs-annals-VI-4-W1-2020-29-2020

5) Beil, C., Ruhdorfer, R., Coduro, T. and Kolbe, T. H. (2020). ‘Detailed Streetspace Modelling for Multiple Applications: Discussions on the Proposed CityGML 3.0 Transportation Model’. In: *ISPRS International Journal of Geo-Information* 9(10), p. 603. URL: https://doi.org/10.3390/ijgi9100603

6) Beil, C., Kutzner, T., Schwab, B., Willenborg, B., Gawronski, A. and Kolbe, T. H. (2021). ‘Integration of 3D Point Clouds with semantic 3D City Models - Providing semantic information beyond classification’. In: *Proceedings of the 16th International 3D GeoInfo Conference 2021*. Vol. VIII-

4/W2. ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences. New York University. ISPRS: New York City, USA, pp. 105–112. URL: https://www.isprs-ann-photogramm-remote-sens-spatial-inf-sci.net/VIII-4-W2-2021/105/2021/

7) Beil, C., Kendir, M., Ruhdorfer, R. and Kolbe, T. H. (2022). 'Dynamic and web-based 4D visualization of streetspace activities derived from traffic simulations and semantic 3D city models'. In: *Proceedings of the 17th International 3D GeoInfo Conference 2022*. Vol. X-4/W2-2022. ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences. University of New South Wales. ISPRS: Sydney, pp. 29–36. URL: https://doi.org/10.5194/isprs-annals-X-4-W2-2022-29-2022

8) Beil, C., Kutzner, T., Schwab, B. and Kolbe, T. H. (2023). *Road2CityGML3*. Version 1.0. Zenodo. URL: https://doi.org/10.5281/zenodo.7919560

9) Amini, S., Orlich, C., Beil, C., Keler, A. and Bogenberger, K. (2023). *Integrating SUMO in an urban digital twin - a case study from Munich*. http://dx.doi.org/10.13140/RG.2.2.30752.15364. SUMO User Conference 2023 - German Aerospace Center (DLR) - Berlin

10) Kolbe, T. H., Donaubauer, A. and Beil, C., eds. (2024). *Recent Advances in 3D Geoinformation Science*. en. Lecture Notes in Geoinformation and Cartography. Springer, p. 861. URL: https://doi.org/10.1007/978-3-031-43699-4

11) Beil, C., Ilic, M., Keler, A. and Kolbe, T. H. (2024). 'Automatically evaluating the service quality of bicycle paths based on semantic 3D city models'. In: *Lecture Notes in Geoinformation and Cartography - Recent Advances in 3D Geoinformation Science - Proceedings of the 18th 3D GeoInfo Conference*. Technical University of Munich, Chair of Geoinformatics. Springer Nature Switzerland: Cham, pp. 75–92. URL: https://doi.org/10.1007/978-3-031-43699-4_5

12) Olbrich, F., Beil, C., Nguyen, S. H. and Kolbe, T. H. (2024). 'Multimodale Navigationsanwendungen für CityGML 3.0 konforme 3D-Straßenraummodelle mittels Graphdatenbanken'. In: *44. Wissenschaftlich-Technische Jahrestagung der DGPF in Remagen – Publikationen der DGPF, Band 32*. Deutsche Gesellschaft für Photogrammetrie, Fernerkundung und Geoinformation e.V., pp. 357–369. URL: https://www.dgpf.de/src/tagung/jt2024/proceedings/paper/26_dgpf2024_Olbrich_et_al.pdf

13) Beil, C. and Kolbe, T. H. (2024). 'Applications for Semantic 3D Streetspace Models and Their Requirements - A Review and Look at the Road Ahead'. In: *ISPRS International Journal of Geo-Information* 13(10), p. 363. URL: https://doi.org/10.3390/ijgi13100363

14) Wysocki, O., Schwab, B., Beil, C., Holst, C. and Kolbe, T. H. (2024). ‘Reviewing Open Data Semantic 3D City Models to Develop Novel 3D Reconstruction Methods’. In: *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*. ISPRS TC IV Mid-term Symposium “Spatial Information to Empower the Metaverse” XLVIII-4-2024, pp. 493–500. URL: https://doi.org/10.5194/isprs-archives-XLVIII-4-2024-493-2024