Constructing a digital 3D road network in 3D city models by using open access data – MSc. Geomatics Thesis Graduate Plan

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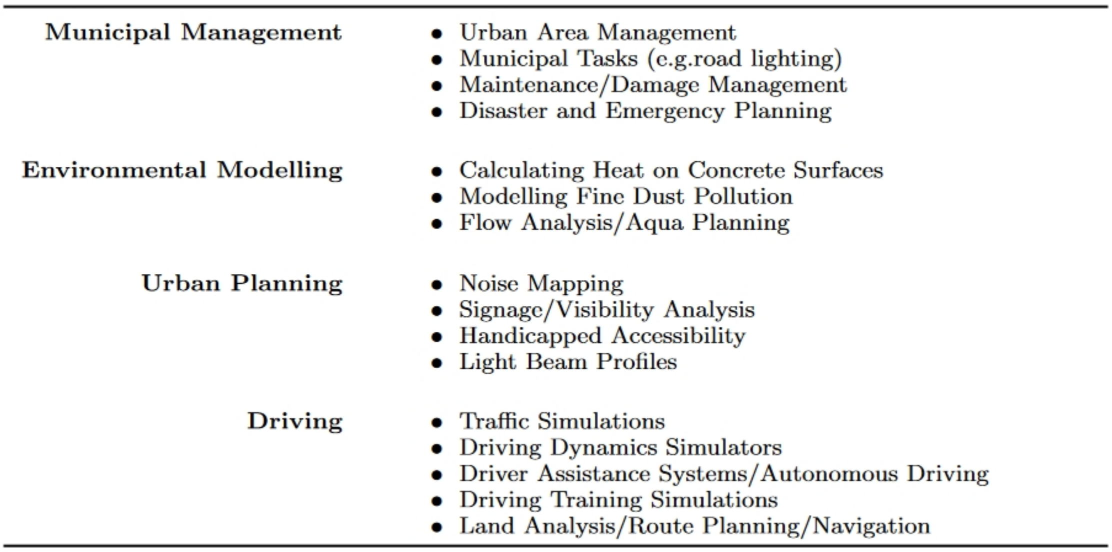
January 26th 2024

1 Introduction

Background: The evolution of urban modelling has witnessed a paradigm shift with the development and emerging trends of 3D city models. In response to the escalating complexity of urban environments, the demand for more sophisticated representations has led to the widespread adoption of three-dimensional spatial models. These 3D city models encapsulate a detailed and dynamic portrayal of urban landscapes, incorporating not only the horizontal layout but also the vertical dimension, offering a more comprehensive understanding of urban structures and topography.
The traditional 2D representations of road networks are inherently limited in capturing the complexity of urban environments. In contrast, the utilization of 3D road network models provides a more holistic and dynamic representation, offering a comprehensive understanding of spatial relationships, elevations, and connectivity. The incorporation of 3D Geographic Information Systems (GIS) allows for the visualization of intricate urban landscapes, facilitating more informed decision-making processes for civil engineers, urban planners, policymakers, and stakeholders. Moreover, when coupled with the concept of digital twins, these 3D road network models evolve into dynamic, real-time simulations of urban environments. This convergence enables stakeholders to monitor, analyze, and simulate the behavior of road networks, offering a predictive and responsive framework for optimizing traffic flow, enhancing urban mobility, and proactively addressing challenges in infrastructure development. To underscore the practical implications, notable examples of 3D road network model applications highlight their significance in municipal management, environmental modelling, urban planning, and driving field[Labetski (2017)](Figure 1). As urban planning and infrastructure management have become increasingly intertwined with advancements in technology, the integration of 3D road networks within these models has emerged as a crucial component.



Municipal Management	• Urban Area Management • Municipal Tasks (e.g.road lighting) • Maintenance/Damage Management • Disaster and Emergency Planning
Environmental Modelling	• Calculating Heat on Concrete Surfaces • Modelling Fine Dust Pollution • Flow Analysis/Aqua Planning
Urban Planning	• Noise Mapping • Signage/Visibility Analysis • Handicapped Accessibility • Light Beam Profiles
Driving	• Traffic Simulations • Driving Dynamics Simulators • Driver Assistance Systems/Autonomous Driving • Driving Training Simulations • Land Analysis/Route Planning/Navigation

Figure 1: 3D road applications. [Labetski (2017)]

Research Gap Identification: Roads are always modelled as networks in different representation levels: centrelines, carriageways and lanes[Labetski et al. (2018a)]. The desired representation methods and level of details may differ based on the requirements in various applications and user cases. Currently, the most securable datasets describe the road network as the 2D linear representation, it only represents the centrelines [Vitalis et al. (2022)]. Improved the road network model from 2D linear representation to 2D areal representation have attracted great scientific and commercial attention since the advent of digital cartography and satellite navigation. Since the detailed road network representation is crucial in some emerging applications as the fundamental technical information such as automated vehicle system and navigation system, the researchers and industry field have invested a lot on improving the accuracy and enriching the detailed attributes by collecting the data through LiDAR scans, satellite imagery. Those researches and commercial products are usually limited in the specific regions or have to be purchased as the detailed data for modelling high-resolution road network are not easy to acquire.
In terms of 3D road network models, as all the 3D models, they require elevation data, and the modelling process take the much more topological and geometric issues into consideration, a high-quality 3D model relies on the accuracy and

level of details of its 2D representation. As a result, 2D road models are common in terms of both public and private geospatial providers, whereas accurate 3D road models are rare in comparison. In 3D city models, buildings have the most elaborate data model, especially concerning the differentiation between the different LoDs. Also, most use cases identified for 3D city models seem to use mostly building data (see for example [Biljecki et al. (2015)]. Therefore, the modelling approach for obtaining a 3D road network model through easy available datasets is rare.

Thesis Objectives and Scope of the Research: The primary objective of this research is to construct a comprehensive 3D road network model within the context of 3D city models, leveraging open-access data sources. Utilizing OpenStreetMap (OSM) for 2D road geometry generation and Digital Surface Models (DSM) for elevation data, the scope encompasses the integration of these elements into a cohesive 3D road network model. The study delves into 2.5D road surface modelling techniques, combining geometric and elevation data to establish a more accurate representation of the real 3D road network. Moreover, the model will be enriched with semantic information, showcasing the versatility of the constructed model in addressing real-world challenges within urban environments.
It is essential to generate a three-dimensional depiction of road networks in order to present a more lifelike portrayal of road systems, which can assist in navigation, safety, urban planning, and decision-making. It also enables detailed analysis of critical elements like intersections and structures, enhancing our understanding of road infrastructure and its interactions with the surrounding environment.

Thesis Structure: The graduate plan is organized into four main sections. ”Related Work” reviews existing literature, ”Research Questions” outlines specific inquiries, ”Methodology” details the systematic approach, and ”Time Planning” establishes a timeline for successful execution. This structure guides readers through the construction and application of the 3D road network model.

2 Related work

Based on the differences of data sources and researches objectives, the related studies of 3D road network models in 3D city models can be categorized into following types:

1. **Generate 2D road network from OpenStreetMap(OSM) road centerline to 2D road network:** The studies and projects are focused on creating 2D road models and developing visualization software capable of generating digital maps using OSM road datasets.

2. **Enhanced 2D road network generation methods by integrating OSM data with other source datasets:** The researches focus on enhanced 2D road network generation methods by integrating OSM data with other source datasets can produce improved results with varying levels of detail, tailored to specific purposes. The outcomes differ according to the characteristics of the combined datasets.

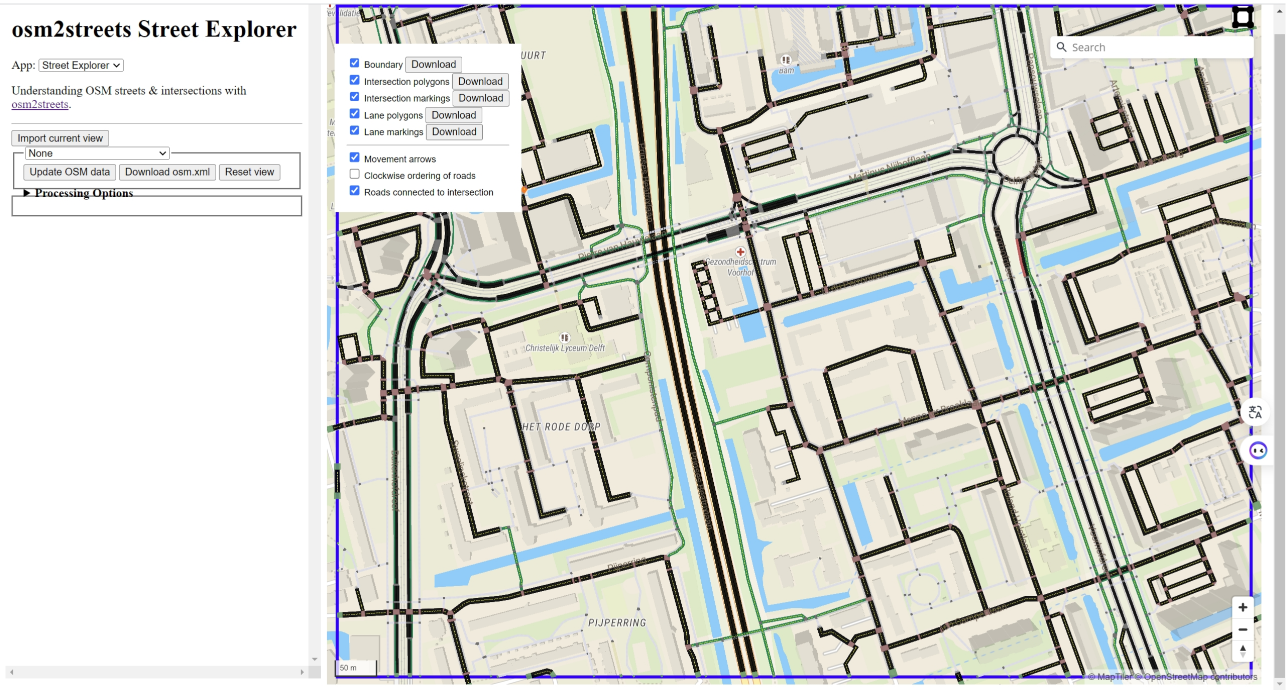
3. **Generate road data from satellite, aerial images and varioues sensors:** The realm of studies and corresponding goals encompass a wide range of scope, the majority of literature generating centrelines from road polygons, extracting the shape/boundary of roads, and lane detection, lane-level road extraction for autonomous vehicles. Some detailed components in the road networks are also be generated in high-definition map(HD-map) such as road signs, transportation funitures, etc[TomTom], those components are out of the scope in this research.

4. **Generate 2.5D or 3D road network models:** Due to the various sources of elevation data and their different traits, the approaches and outcomes of 2.5D or 3D road network models are diversity; and the studies of converting 2D road networks to 2.5D or 3D models are few comparing to the working on 2D scope.

5. **Improve the transportation model in CityGML:** Based on the CityGML v2.0 transportation module, some studies put forward the improved framework for achieving the potential application, mainly focus on the multi-LoD modelling, and using the existing datasets to model the multi-LoDs road network also be studied.

2.1 Generate 2D road network from OpenStreetMap(OSM) road centreline to 2D road network

Projects like **"abstreet"**[A/B Street] and **"osm2street"**[A/B Street/ osm2streets] contribute to the creation of detailed 2D road models and digital maps through OSM road datasets. The **"abstreet"**[] project serves as a comprehensive transportation planning and traffic simulation software for creating cities friendlier to walking, biking, and public transit, **"osm2street"** provides a simplified street network schema, emphasizes the creation of 2D road models from OSM road centrelines, (Figure 2), presents many challenges for rendering, routing, and analyzing done at the detail of lanes, especially in the presence of dual carriageways, separated cycletracks and footways, and complex intersections (Figure 3).



osm2streets Street Explorer

App: Street Explorer

Understanding OSM streets & intersections with osm2streets.

☑ Boundary Download
☑ Intersection polygons Download
☑ Intersection markings Download
☑ Lane polygons Download
☑ Lane markings Download
☑ Movement arrows
☐ Clockwise ordering of roads
☑ Roads connected to intersection

Figure 2: Screenshot of "osm2street", output the road polygons for a chosen region.

The project "The Neukölln street maps" focussed on showcasing how detailed mapping of urban environment and street lane infrastructure – especially for bike and foot traffic – can be done with OSM [OpenStreetMap Berlin], emphasizing the importance of detailed attributes in OSM when rendering for specific elements like bicycle lanes (Figure 4, 14). Furthermore, the paper titled "OSM-Based Automatic Road Network Geometry Generation in Unity" [Yu (2019)] presents a method for automatic road network geometry generation using OSM data in Unity, demonstrating the applicability of OSM for 2D road network creation in diverse contexts.
In summary, these projects and studies, while diverse in their specific focuses, converge on the common point of utilizing OSM data for the generation of 2D road networks. Whether developing toolkits, enhancing visualizations, or leveraging OSM for automatic geometry generation, these endeavors collectively underscore the significance of OSM as a foundational data source for 2D road modeling within 3D city environments. The results vary depending on the amount of information available and the method used to extract it for the final outcome.

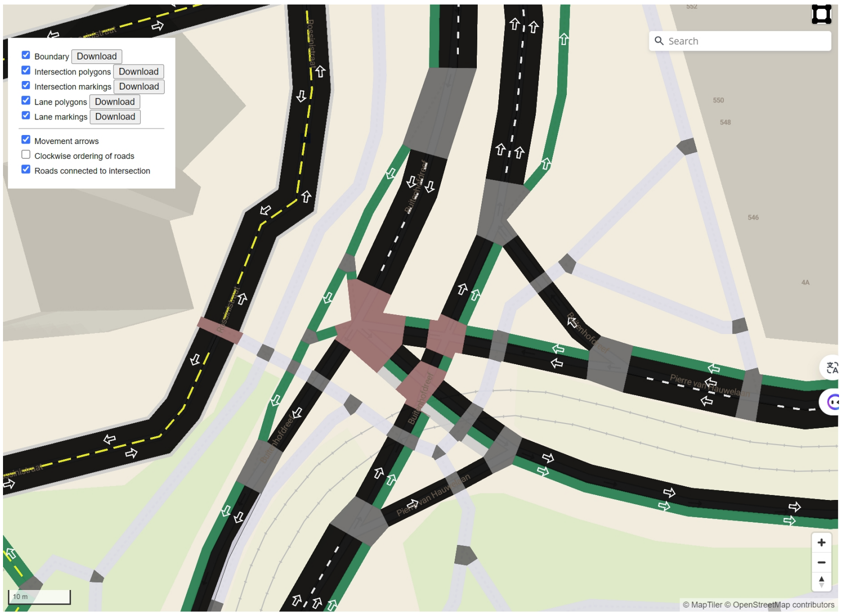


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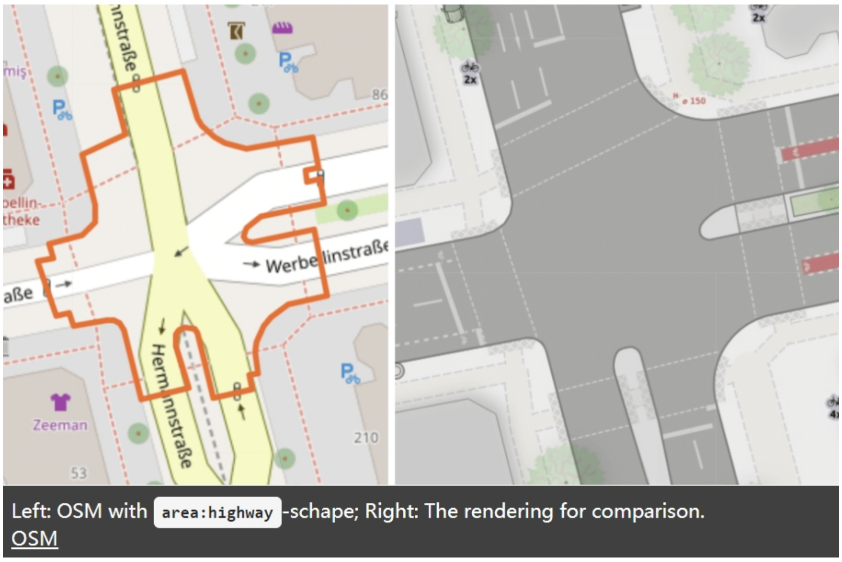
Figure 3: Details of lanes and intersection representation generated by ”osm2street”.

Figure 4: Screenshot of ”Detailed rendering of bicycle lanes and junctions as part of the OSM ’Straßenraumkarte’”.

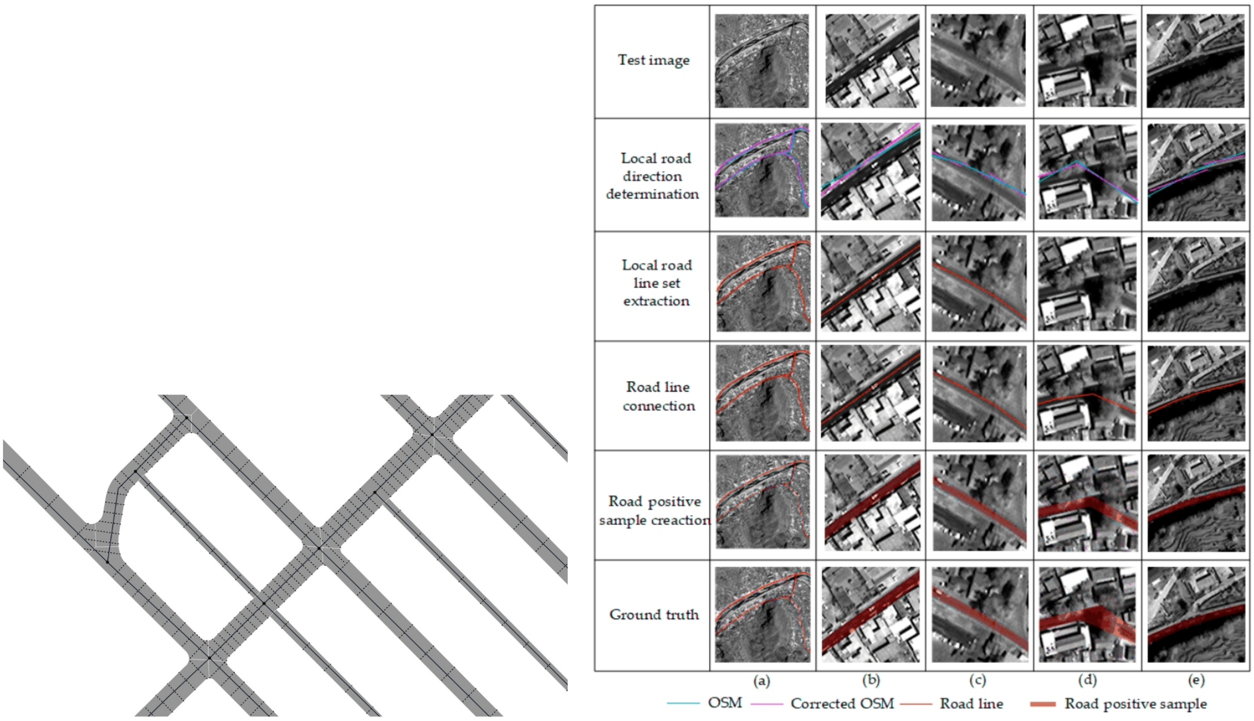


Left: OSM with `area:highway`-schape; Right: The rendering for comparison.
OSM

Figure 5: Using the ’area:highway’ tag to render detailed intersection. [OpenStreetMap Berlin]

2.2 Enhanced 2D road network generation methods by integrating OSM data with other source datasets

The paper titled ”From Road Centrelines to Carriageways—A Reconstruction Algorithm” introduces a methodology for creating carriageways based on OSM’s centrelines and open access areal representations (Figure 6a), showcasing the effectiveness of this approach for worldwide application[Vitalis et al. (2022)]. Another noteworthy work, ”An OSM Data-Driven Method for Road-Positive Sample Creation,” proposes a novel method for creating accurate road-positive samples for deep learning using OSM data and orthophoto images (Figure 6b), incorporating road homogeneity constraints and texture features[Dai et al. (2020)]. In ”Map Matching and Lanes Number Estimation with OpenStreetMap,” a new method for estimating the number of lanes using low-precision GPS data and OSM is presented[Kasmi et al. (2018)]. Additionally, the MSc. thesis on ”Safety-Driven Road Width Estimations from Vector Data” introduces a novel approach for estimating road width using vector data, emphasizing the significance of considering road width for road safety management applications[Chatzidiakos (2021)].
These studies advance 2D road network generation by improving accuracy and detail, addressing specific purposes, and utilizing diverse fusion datasets. The approaches collectively use OSM-based methods and emphasize to how to address the misalignment between OSM and additional datasets and modify the encountered errors. Overall, they demonstrate innovative approaches that integrate OSM data with other datasets to enhance 2D road network generation for improved detail and purpose-specific tailoring.



(a) OSM centrelines and road width calculation. [Vitalis et al. (2022)]

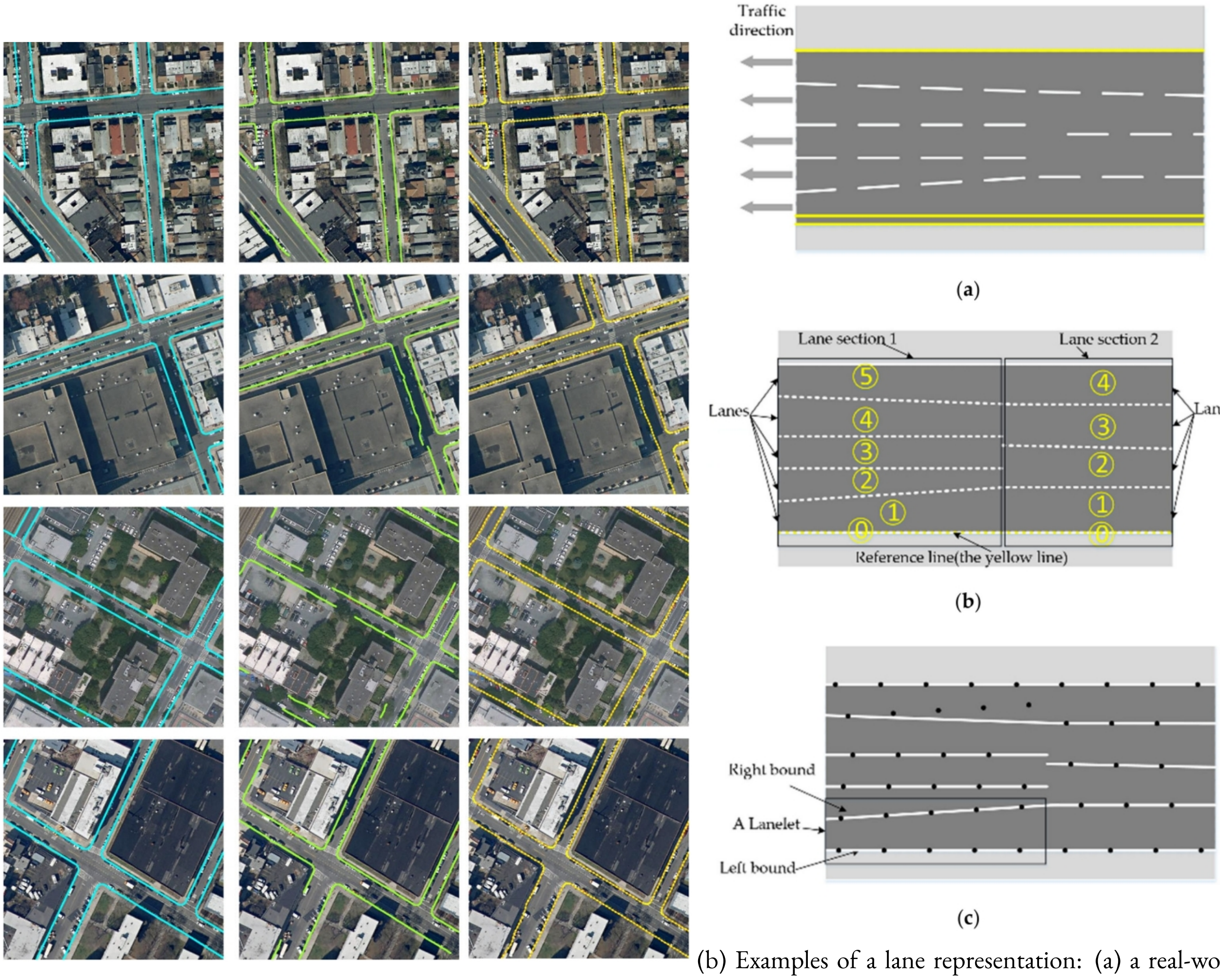
(b) OSM raw data, corrected OSM and road positive samples. [Dai et al. (2020)]

Figure 6: OSM-based researches

2.3 Generate road data from satellite, aerial images and various sensors

A hot research topic in remote sensing and geomatics focuses on road network extraction from satellite images using innovative approaches. One method employs a semantic segmentation neural network for road extraction from high resolution remote sensing images, that ResUnet combines residual learning and U-Net architecture for enhanced training efficiency and information propagation[Zhang et al. (2018)]. Another technique integrates a persistence-guided discrete Morse-based graph reconstruction algorithm into a machine learning framework, aiming for automatic road network extraction and algorithmic training sample production[Dey et al. (2019)]. A study addresses road-boundary detection for autonomous driving, highlighting the importance of offline detection using aerial images to overcome occlusion challenges. It introduces the Topo-boundary benchmark dataset, comprising 25,295*4-channel aerial images, filling a gap in publicly available datasets for offline topological road-boundary detection[Xu et al. (2021)] (Figure 7a). These studies collectively contribute to advancements in automated road boundary extraction, leveraging satellite imagery, point cloud, machine learning, and road network reconstruction.

There is also a large body of work on reconstructing road networks from the sensors' data, the majority of targeted applications is the autonomous driving. For improving the accuracy of navigation, a large amount of researches spotlight on lane-level road network(Figure 7b) generation based on various on-board systems. Collectively, the sensors for data collection and lane-level road geometry extraction methods are discussed. Based on the studies, each category of sensors had advantages and disadvantages for different on-board systems. They were all the available data sources for lane-level road network collection. The extraction methods were further divided into three categories: trajectory-based methods, 3D point-cloud-based methods, and vision-based methods. Point-cloud-based methods were the highest accuracy approaches, vision-based methods were the most economical, and trajectory-based methods were direct approaches for constructing centreline lane-level road networks. For the representation of lane-level road networks, mathematical modeling and logic formats are used in those studies. However, there is still room for improvement in the data collection and the production of the lane-level road network. In addition, lane-level maps have not reached a consensus state and neither have the formats of lane-level road networks[Zheng et al. (2019)].



(a) Offline topological road-boundary detection from aerial images. [Xu et al. (2021)]

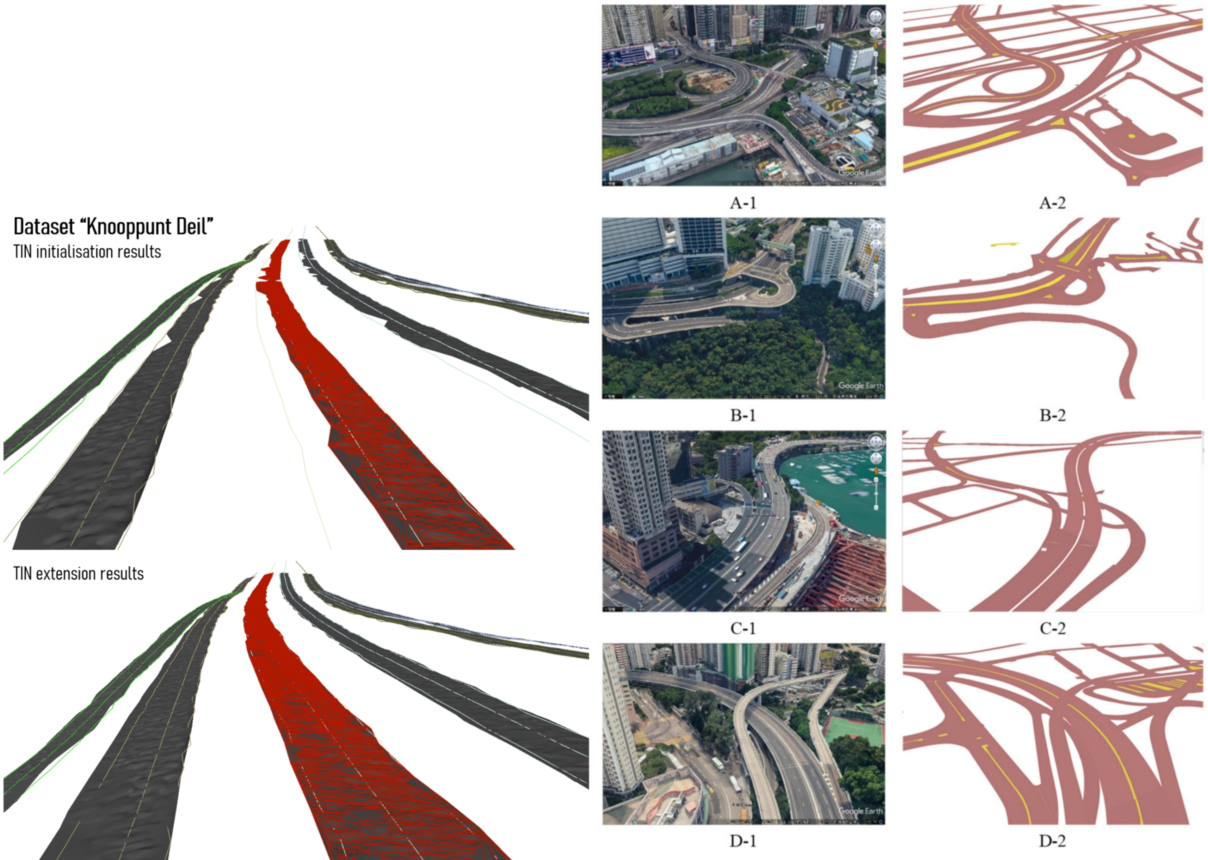
(b) Examples of a lane representation: (a) a real-world lane; (b) a lane representation by OpenDrive; and(c) a lane representation by lanelets. [Zheng et al. (2019)]

Figure 7: Road network models from satellite, aerial images and various sensors

2.4 Generate 2.5D or 3D road network models

In the domain of generating 2.5D or 3D road network models, diverse methodologies and applications have been explored, each leveraging distinct data sources and research objectives. Noteworthy studies include the work presented in "Constructing a digital 3D road network for The Netherlands," which focuses on the 3D conversion of a national road network(Figure 8a) using airborne Lidar data and 2D road network model[Kenesei (2021)]. Additionally, the project on ”Integrate and store 3D roads and terrain for navigation purposes” highlights the development of a comprehensive 3D road and terrain dataset for improved navigation, featuring methods for extracting 2D road polygons and enriching them with elevation data[Longxiang Xu and obben (2023)]. The ”Novel Framework for 3D Road Extraction Based on Airborne LiDAR and High-Resolution Remote Sensing Imagery” proposes an operational framework for extracting and reconstructing 3D road models (Figure 8b) by integrating multisource remote sensing data, including three stages: road extraction based on multisource data, road layering and point-cloud filtering, and road elevation interpolation, addressing challenges related to occlusion and topological complexity[Gao et al. (2021)]. Furthermore, some of studies work on delves into constructing high-precision digital elevation models for urban plots[Li et al. (2023)] and urban road DEMs[Tao et al. (2022), Yang et al. (2020)], respectively, emphasizing the importance of considering morphological characteristics for accurate representations.

Collectively, these studies contribute valuable insights into the development of 2.5D or 3D road network models, showcasing advancements in data acquisition, processing techniques, and their potential applications in urban environments. The studies also demonstrate the potential and possibilities of fusing multisource geospatial data in the field of 3D road network modeling, this topic is worth researching due to the emerging data trends.



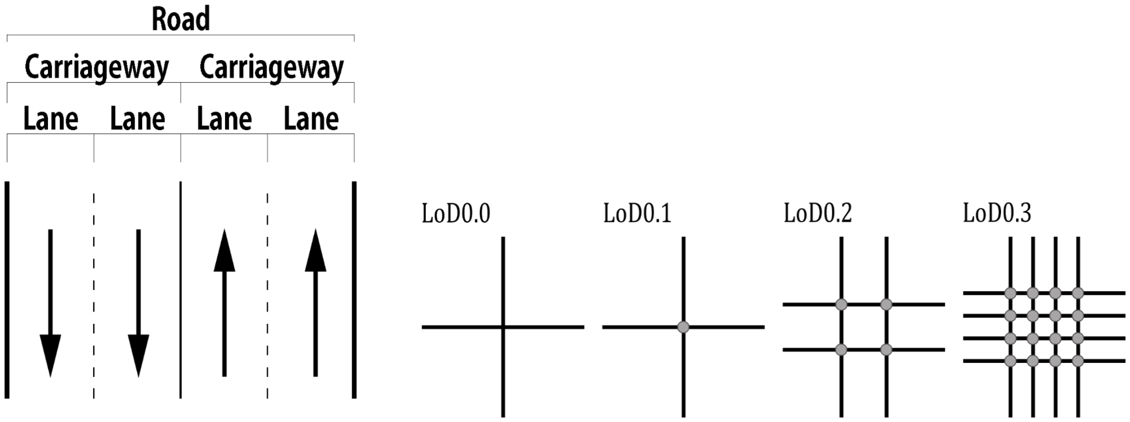
(a) Visualisations of TIN surfaces of 3D road models. [Kenesei (2021)]

(b) 3D road results from LiDAR point clouds and high-resolution remote sensing imagery and Google map images. [Gao et al. (2021)]

Figure 8: Start-of-the-art 3D Road network models

2.5 Improve the transportation model in CityGML

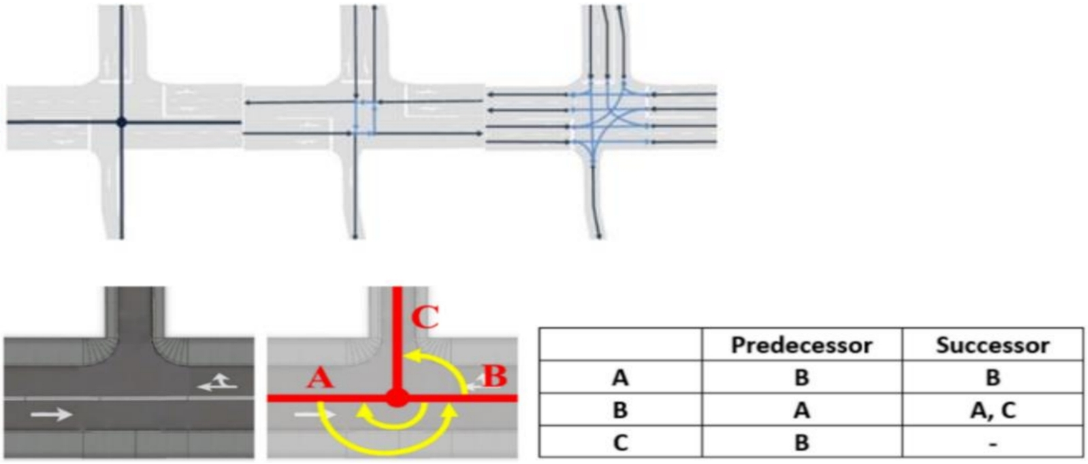
Several studies have proposed enhancements to the CityGML transportation model by focusing on multi-Level of Detail (LoD) modeling and semantic enrichment. These studies explore methods for semantically modeling various transportation modes and suggest enhancements like multi-LoD modeling and detailed intersection representation [Beil and Kolbe (2017)], facilitate the ability to describe roads as multi-LoD objects where the first value refers to its polygon representation (i.e. lane vs. carriageway, vs. road representation, see Figure 9a) and the second to its network representation (Figure 9b) [Labetski et al. (2018b)]. The proposed CityGML 3.0 Transportation Model aims to upgrade the current CityGML 2.0 Transportation Model to a detailed streetspace level, addresses key aspects and showcasing versatility in applications [Beil et al. (2020)],[Beil and Kolbe (2020)]. In the new model, each level of granularity can have a linear, areal, volumetric, and point cloud representation. In granularity settings, ”area” represents an undifferentiated streetspace, ”way” partitions surfaces into roadbeds and walkways, etc. to represent individual carriageways; and ”lane” separates individual driving lanes for enhanced navigation and detailed traffic simulations. It also introduces that an explicit representation of predecessor/successor relations (e.g., regarding turning restrictions) can be modelled in CityGML 3.0 as shown in Figure 10. Additionally, improvements in CityJSON are encoded to enhance the level of detail specification for roads within 3D city models, addressing CityGML's shortcomings and providing a structure for linking linear and areal road data [Boersma (2019)].



(a) The difference between a road, a carriageway and a lane. Arrows indicate the flow of traffic.

(b) Proposed refinement to the network representation of roads in CityGML.

Figure 9: Multi-LoDs representation in improved CityGML 2.0 transportation models. [Labetski et al. (2018b)



	Predecessor	Successor
A	B	B
B	A	A, C
C	B	-

Figure 10: Linear representations of predecessor/successor relations in proposed CityGML 3.0. [Boersma (2019)]

3 Research questions

3.1 Problem and Motivation

On the surface it would seem that constructing a 3D road network model from open access data would be preferred for facilitating various applications due to a closer resemblance to reality/“the real world”[Labetski (2017)], and that enables users and developers to reuse existing wide-spread datasets and/or extend it with new and innovative functionality[Tamminga and Hoogendoorn (2019)]. At the same time there are two major problems that contradict this way of thinking:

1. **No universal method and undefined standards:** Based on the analysis of various road applications and their representation level requirements[Boersma (2019)], the results of the analysis indicated that there is no "one size-fits-all" solution to road modelling[Vitalis et al. (2022)]. Therefore, an important aspect of designing as solution for a road model consists of selecting or preparing data at the appropriate representation level. The final outcome will highly rely on the accuracy, level of details, and completeness of the input datasets.

2. **The robustness and resemblance of reconstruction results:** The 3D road network represents real-world entities built according to engineering criteria. Available datasets are simplified digital versions of the real world and construction approaches must address errors in the 3D datasets while maintaining model accuracy. It is important to ensure the robustness of road models and minimize errors, such as topological errors and discrepancies with common sense, regardless of the input data quality. Then the level of details can be improved during the generation process.

3.2 Research Objective and Questions

3.2.1 Research questions

Based on the identified problems and guided by the preliminary research, the main research question is:

"How can we achieve a 3D conversion of road network model only using the open access geospatial datasets and enrich the its semantic information in 3D city models?"

3.2.2 Research objectives

The goal of this research is to:

Construct a comprehensive 3D road network model in 3D city models by utilizing open-access data sources.

The primary objective of this research is to construct a comprehensive 3D road network model within the context of 3D city models, leveraging open-access data sources. The research aims to achieve this overarching goal through a series of specific objectives. Firstly, it involves utilizing the most common open-access data sources to generate both 2D and 3D geometry, forming the foundational elements of the 3D road network model. Secondly, the research seeks to enhance the Level of Details (LoD) and enrich the semantic information embedded in the model by extracting secure information from open-access datasets. This process ensures that the 3D road network model not only exhibits geometric accuracy but also incorporates detailed and relevant semantic attributes. Lastly, the research focuses on the encoding aspect, intending to represent the constructed model in the CityJSON format, aligning with the CityGML models. This final step facilitates interoperability and integration with existing geospatial data standards, ensuring compatibility and accessibility in the broader domain of 3D city modeling. Together, these objectives form a comprehensive approach towards achieving the research goal of constructing an intricate 3D road network model within the framework of 3D city models, grounded in open-access data utilization and adherence to recognized data standards.

3.2.3 Sub-questions:

The accompanying research questions will guide the research in addressing the major issues and achieving the objectives:

- How to generate the 2D road geometry from OSM road centrelines?
  - How to calculate the road width according to the given attributes in the OSM?
  - How to address the most common intersections and even the complex intersections?
  - How can the normal road segments, various width road segments, and changeable intersections be aggregated to create a well-connected complete road network?
- How to generate the 3D road geometry from 2D road network and the corresponding elevation data?
  - How to distinguish the real 2D intersections with the 3D transportation modes(overpass, bridge, tunnel)?
  - How to extract the reliable elevation data from Digital Surface Models(DSM)/ Digital Terrain Models(DTM) and assign them to the right road segments?

    - How to detect and conquer the errors/outliers, and avoid the ”bumpy road surface” and ”unrealistic” bridges/tunnels?

- How to improve the models through enhancing the LoDs and adding semantic information?
    - What attributes and details in open datasets are essential for constructing a basic 3D road network model at the lowest LoDs? Also, what information is valid for improving the road models to LoD 2+ and how can they be utilized?
    - How can the current CityGML transportation schema be employed in the progress of road geometry generation?

- How to validate the completeness and accuracy of road network models?
    - How can the accuracy of road network models be evaluated?
    - How to validate and guarantee a error-less result?

- Output the results following CityGML road modelling rules and CityJSON encoding.

3.3 Scoping/Managing expectations: MoSCoW

The ”Must”, ”Should”, ”Could” and ”Won’t” demonstrate the hierarchy and the scope of this research:

3.3.1 Must:

1. Only use the open access data which can be found in most regions;
2. Construct the 3D road network models for driving way and cycleway;
3. Generate the 2D road network polygons from the OSM road centerline;
4. Extract elevation data from DSM and assign them to the corresponding road segments;
5. Generate the 2.5D road/bridge/tunnel surface for each road segments and aggregate them into the 3D road network models;
6. Distinguish the carriageway, cycleway, sidewalk(the sidewalks that exist in other types of road as an attached information in OSM) when the input data provides the sufficient information;
7. Address the most common intersection cases, including the 2D intersectiona and 3D intersections like bridges and tunnels;
8. Testing regions should encompass city urban environment, rural environment with various changeable terrain;
9. Compare the 2D road network polygons with the available official road areal representation data, such as the pre-existing open data 2D road model Nationaal Wegenbestand (NWB) (National Road Database) from the Netherlands;
10. Compare the road elevation data with the available official road elevation, such as the swissTLM3D[Swisstopo (Accessed 17 Jan. 2024)], the large-scale topographic landscape model of Switzerland which contains the elevation data for road centerlines.
11. Validate the correctness of the topological and geometric correspondence of the 3D models;
12. Use the CityGML transportation model and encoding the data, output as the CityJSON format file.

3.3.2 Should:

1. Construct the LoD2+ road network models, enhance the model to lane-level when the input data is sufficient to extract the lanes;
2. Address the complex intersection cases.

3.3.3 Could:

1. Construct the terrain adjacent or around the road network;
2. Genenrate the railway and tram surface and their 3D models, integrate into the road network;
3. Generate the vertical or inclined surfaces of tunnels and bridges that connect them to the intersected roads;
4. Construct the separated 3D footway network models;

3.3.4 Won't:

1. The connectivity issues of the road network would not be solved when the problems stem from the raw data rather than from topological issues;
2. Would not generate the tunnel body, only model for the tunnel entrances;
3. Would not guarantee the correctness of details such as the number of lanes, and the distribution of each lane within the road boundary;
4. Geometric issues will not be addressed if they only affect visualization and not the topology.

4 Methodology

The methodology employed for road network modeling is characterized by the absence of a standardized solution, prompting a focused investigation into various critical aspects. The primary objectives encompass the meticulous extraction of essential and valid information, both topological and semantic, from open datasets. The proposed methodology includes the design of solutions to generate comprehensive 2D and 2.5D road geometries, addressing the intricacies associated with 3D geometry for features such as bridges, tunnels, and overpasses. The execution of these objectives is structured into five distinct stages, ensuring a systematic and thorough approach to road network modeling. This methodological framework (Figure 11) is tailored to accommodate the unique challenges posed by diverse datasets, aiming to provide a robust and versatile solution for the construction of accurate and detailed road network models within 3D city models.

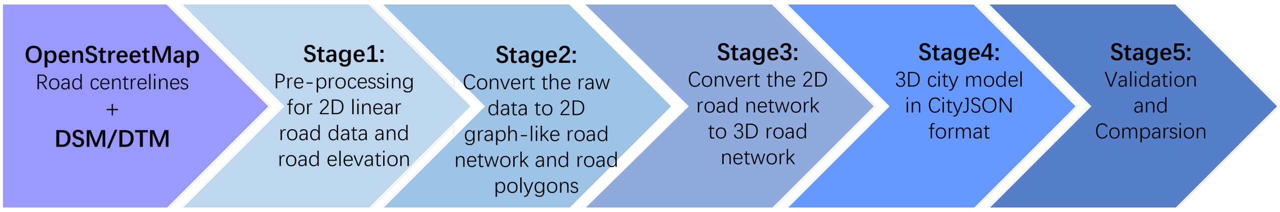


Figure 11: Illustration of the top-level stages of methodology pipeline.

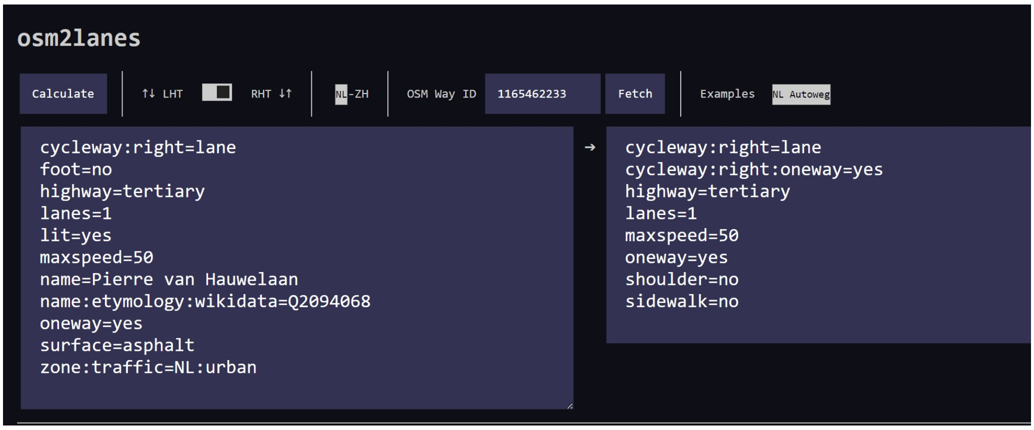
4.1 Stage1: Pre-processing for the 2D linear road data and road elevation

Goal: The first stage of methodology aims to extract the essential information from the raw data, determine the preliminary data for 2D and 3D road geometry.
Stage1 outcome: Number of lanes,types of lanes and roads, directions of lanes, 3D intersection marking tags, elevation data of road centreline vertices.
In the preprocessing of OSM raw data, key steps include filtering for essential details, specifically isolating lane centrelines, and distinguishing intersections as 2D or 3D structures. The subsequent assignment of road elevations involves extracting elevation data from DSM/DTM and assigning elevation values to road centreline vertices. These steps form the foundation for precise and detailed 3D road network modelling.

4.1.1 OSM raw data pre-processing

1) Filter raw data and extract the essential information lane centrelines:

1. Filter the OSM 2D road data according to the 'highway' tag;
2. Extracting the useful information from OSM data, such as the 'lanes', 'width', 'oneway', etc (Figure 12 as an example);
3. Save the direction of each lane, forward or backward;
4. Label the road segments with **'bridge', 'tunnel', 'embankment=yes'**, those tags indicate the road segments can be marked as one part of 3D intersections.



1165462233

```
cycleway:right=lane
foot=no
highway=tertiary
lanes=1
lit=yes
maxspeed=50
name=Pierre van Hauwelaan
name:etymology:wikidata=Q2094068
oneway=yes
surface=asphalt
zone:traffic=NL:urban
```

→

```
cycleway:right=lane
cycleway:right:oneway=yes
highway=tertiary
lanes=1
maxspeed=50
oneway=yes
shoulder=no
sidewalk=no
```

Figure 12: A screenshot from the 'osm2lane' repository[osm (Accessed 17 Jan. 2024)], a part of 'osm2street', displays the data extracted from OSM using the related tags.

2) Determine whether the intersection is a 2D intersection or 3D intersection(bridge/tunnel/overpass):

1. By using the **'bridge', 'tunnel', 'embankment=yes'** labels;
2. Check if the centrelines share the same start/end node, then save the real adjacent centrelines Linestring to each road segment:
    - True: likely to be a real 2D intersection;
    - False: no, only intersect and overlap when the centrelines show on the 2D, but not the real intersection.
3. Add additional tag for the road centrelines of 3D intersections.

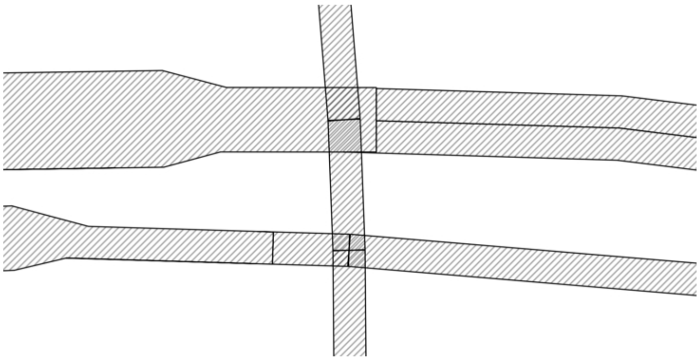


Figure 13: Marking 3D intersections for further processing, overlapping in 2D but cannot be joined together. (From Longxiang Xu and obben (2023))

4.1.2 Assign road elevation to the road centrelines

Extract the elevation data from DSM/DTM:

1. For the regions that cannot find DTM, firstly extract the DTM from the DSM;
2. Extract the start-point and end-point of each road centreline, and obtain the vertices every 0.5 meter along the road;
3. Extract the crossing points for the intersected centrelines;
4. Perform a spatial join or intersect operation between the road centerlines and the DTM/DSM. This operation associates each road vertices with the elevation information from the corresponding DTM/DSM cell;
5. Compare the elevation difference of specific road vertices from DTM and DSM:
   - the labelled road centrelines need to be compared, since they must have different elevation;
   - the crossing points shared by the multiple centrelines;

Assign the elevation value for the road vertices:

1. Based on the difference elevation from DSM and DTM, 3D intersections and the related road centrelines can be further detected, label all of them for the following processing;
2. Assign the DTM elevation information to the 'grounded' road segments which adhere to the terrain;
3. Assign the DSM elevation information to the 'lifted' road segments;

4.2 Stage2: 2D road geometry generation

Goal: Convert the raw data information to the 2D graph-like road network with good connectivity, and robust 2D road polygons.
Stage2 outcome: 2D linear representation of road network(lane-level); 2D areal representation of road network, including the road polygons of road segments and the intersections.
The first step of 2D road network modeling process involves transforming road centrelines to lane centrelines and uniting adjacent lane centrelines to create a **2D linear representation**. Calculations for lane and road width are performed, enabling the generation of lane and road polygons. In the end of stage2, this systematic approach ensures a comprehensive **2D areal representation**, incorporating road connector polygons, junction identification, and polygon construction for junctions.

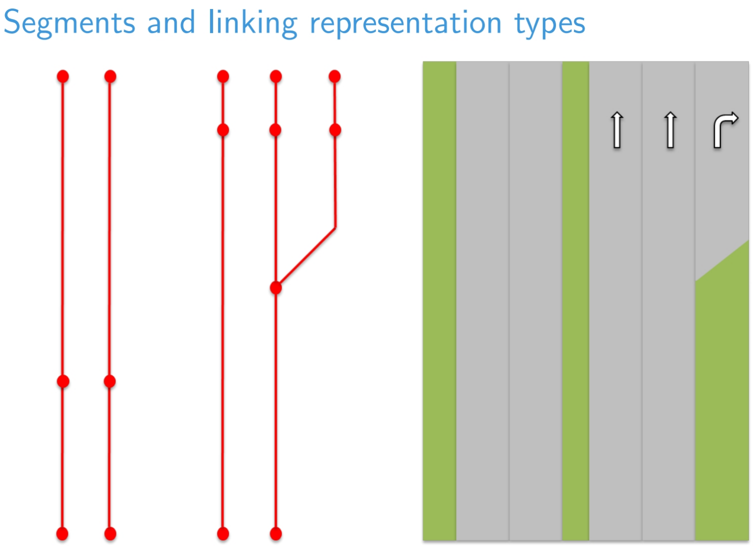
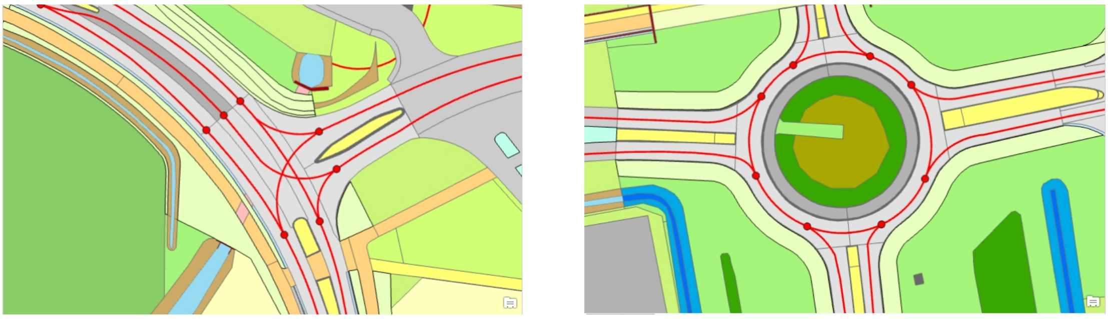


Figure 14: 2D representation schema, left: 2D linear representation, right: 2D areal representation.[Boersma (2019)]



- RoadNodeType: LaneSplit, Intersection and Roundabout
- RoadEdgeType: Connecting and Roundabout

Figure 15: Examples of the lane-level linear representation of road network intersection, LoD0.3[Boersma (2019))]

4.2.1 Linear representation of road network

1. Road width and lane width calculation, calculate lane width from the lane types (using road design criteria[Schoon (1994)] as reference), or the extract the 'width' value in OSM dataset then extrapolate the lane width;
2. Offset road centrelines according to the road types, number of lanes, corresponding width and other tags of them;
3. Join the lane centrelines of road segments based on the types, directions, labels, and adjacent tags of the lanes for non-intersecting lane segments;
4. For the intersected lanes, find the corresponding traffic lanes from the lanes which adjacent to the same intersections, and draw the virtual lane centrelines to truly connect them, the ideal model is shown as Figure 16; Further exploration of the detailed methods for constructing a lane graph will be conducted following the provided guidelines from Liu et al. (2013), Zhang et al. (2011), Zhang et al. (2016), Yang et al. (2011), Jiang et al. (2019), Homayounfar et al. (2019), etc;
5. Form the multilinestring clusters and each cluster can regard as the same lane in the real road network;

Result of Linear representation of road network is: for each lane, the centreline is clearly generated, the road network is graph-like structure with semantic information (example schema as shown in Figure 17a).

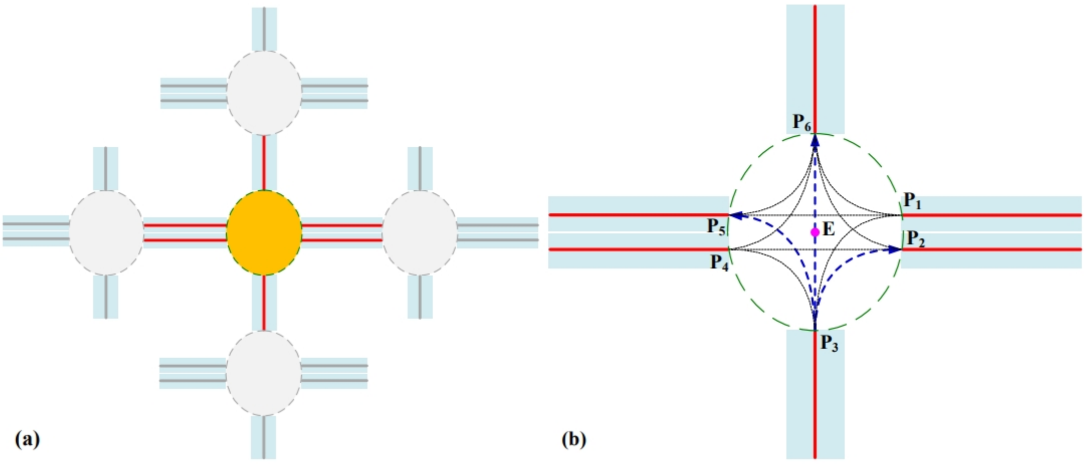
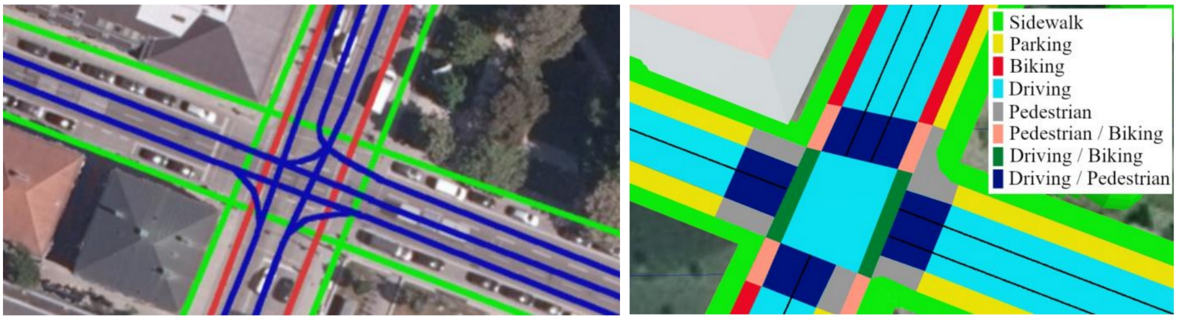


Figure 16: Desribe the intersection map model with respect to connectivity and virtual lanes (From Liu et al. (2013))



(a) Linear representation of TrafficSpaces colored by function attribute.

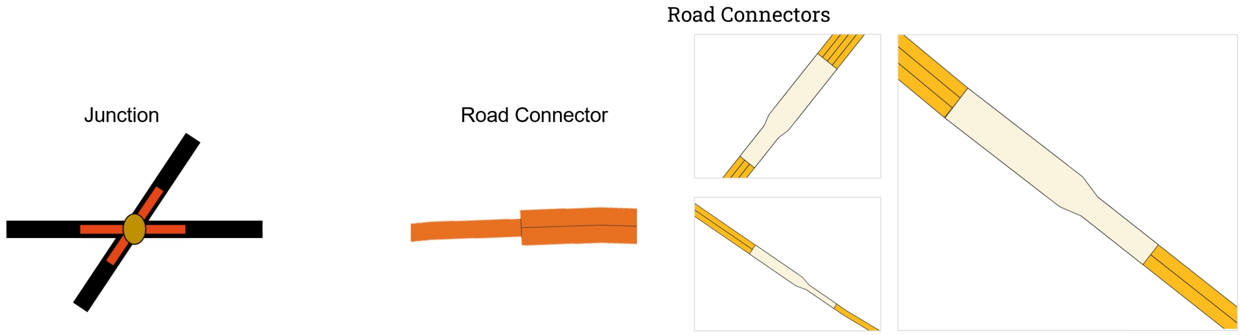
(b) Areal representation of TrafficSpaces colored by function attribute(s).

Figure 17: Ideal results in Stage2, schematic diagram from Beil and Kolbe (2020)

4.2.2 Areal representation of road network

1. Buffer the lane multilinestring and obtain the lane polygons, tackle the errors such as the gaps between lane polygons;
2. Address the junctions when the number of lanes in adjacent roads is different, see the similar implementations in Longxiang Xu and obben (2023) as shown in Figure 18;
3. **Address the common intersection types:** obtain the boundary of intersections and the nodes in the intersection boundary which connect to the lane centrelines and lane polygons (Figure 19);
    - Three-way intersection
    - Crossing intersection
    - intersection only contains driving lanes;
    - driving lanes, cycleway lanes combined intersection;
    - etc
4. Optimize the road corners following road design criteria, the methods can refer the illustration Figure 20;
5. Road polygons of bridges, tunnels and overpass will be generated following the same logic.

Areal representation result is: the polygons of lanes, the polygons of different types of roads, the polygons of intersections and roundabouts, with semantic information (example schema as shown in Figure 17b).



(a) connecting roads

(b) road connector polygons

Figure 18: Road connecting methods in Longxiang Xu and obben (2023).

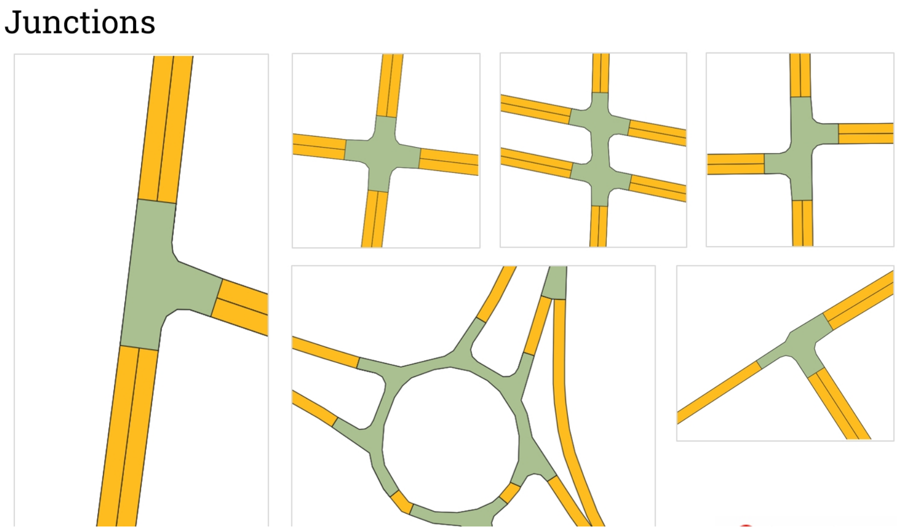


Figure 19: Intersection polygons visualization from Longxiang Xu and obben (2023).

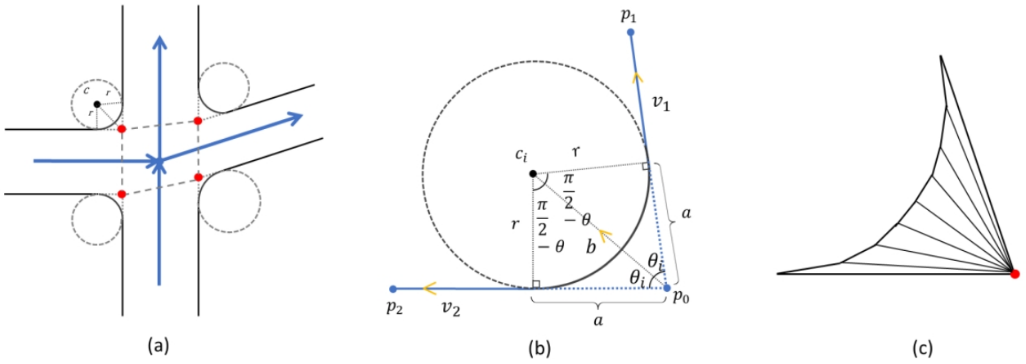


Figure 20: Describe the circles for buffer area generation, implemented in Yu (2019).

4.3 Stage3: Elevation interpolation and 3D road geometry generation

Goal: Convert the 2D road network to 3D road network.
Stage3 Outcome: 3D road geometry with corrected elevation.
The elevation data has been assigned to each vertex, but this value cannot be directly used to generate a robust and correct 2.5D road surface. Elevation data smoothing is necessary for constructing 'commonsensical' road surfaces. The final step of the 3D road network outcome is the generation of 3D geometry.

4.3.1 Modify and smooth the vertice elevation data

1. **Detecting the outliers**, such as incorrect data due to errors during interpolation, particularly on narrow roads, or issues with vegetation occlusion;

2. **Reassign the correct elevation data for the 'no data' vertices in DTM**, due to occlusion, there is no data in the DTM. In such cases, the true elevation data of those vertices will be determined based on the neighboring vertices of the lanes they belong to. It's important to consider the slope of the roads as well. Therefore, the approach would be to find the neighboring vertices and assign elevation values to the 'no-data' snippets of the road at the start and end points. Then, the elevation for each 'no-data' vertex within the snippets can be calculated.

3. **Smooth the vertex elevation**, divide the road centreline into multiple fragments with intervals of 0.5/1 meter, calculate the normal vector of the road fragments, establish a threshold for detecting uneven road elevations, and adjust the "bumpy vertex" accordingly (outliers illustration see Figure 21).

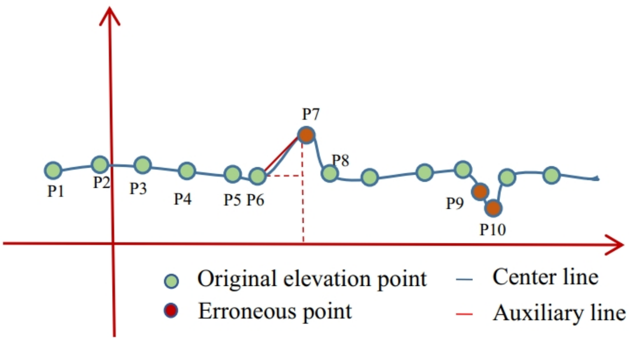


Figure 21: Detect the outliers and smooth the vertices' elevation data (diagram from Yang et al. (2020))

4.3.2 3D road polygons generation

1. **For road surface:** Find the 2D perpendicular lines of road centreline vertices to divide the road segment into multiple fragments. The crossing point of the 2D perpendicular line and the road polygon shares the same elevation value, this bidirectional interpolation of roads (Figure 22) allows for the construction of the road surface for each fragment. Finally, integrate the adjacent fragments to obtain the complete polygons.

2. **For intersection and roundabout:**
   - Storing the intersection polygon vertices by the sequence of coordinates of vertices (example in Figure 23);
   - For the vertices shared with road polygons, the elevation data can be directly assigned from road centreline vertices. For the other intersection vertices, elevation values can be obtained from the neighboring vertices in sequence;
   - Using Normal Delauny Triangulation to generate the polygons;

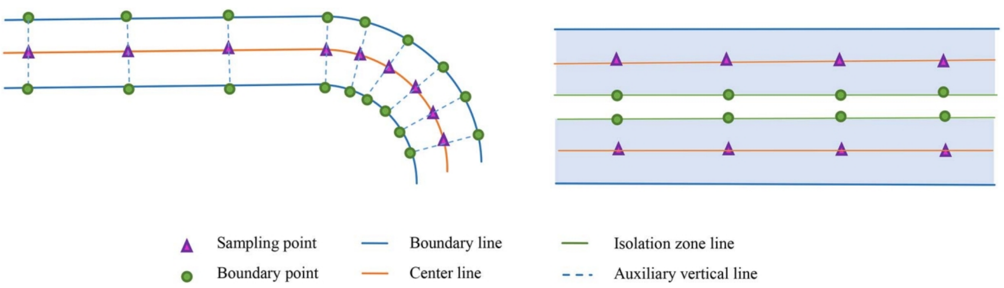


Figure 22: Assign the corrected elevation data to the vertices on the lane boundary, bidirectional interpolation of roads (diagram from Yang et al. (2023)).

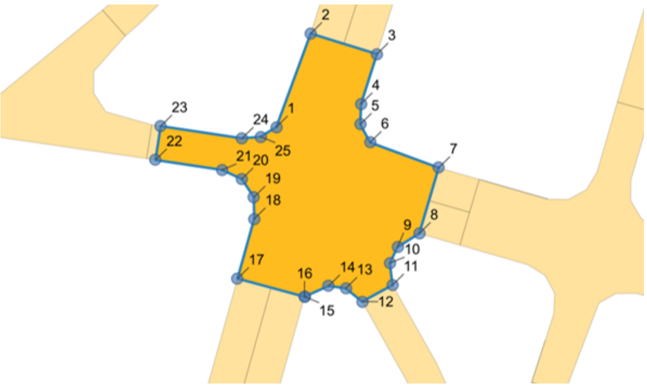


Figure 23: Intersection vertices and the sequence, from Longxiang Xu and obben (2023)

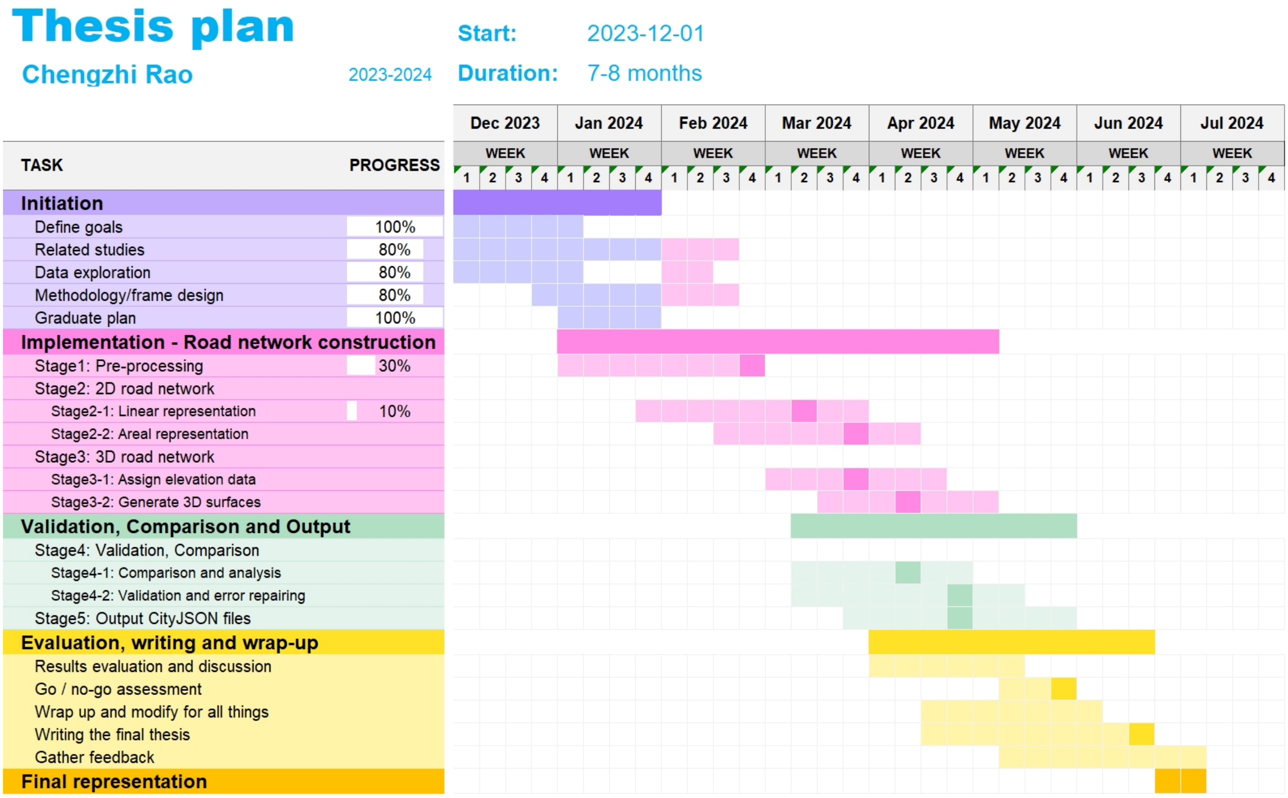
4.4 Stage4: Transforming the data to CityJSON

The 2D road geometry will be saved as a .geojson file, and the intermediate product of the 3D road geometry will be saved as a .obj file. The final output will be a 3D city model in CityJSON format, which includes semantic information encoding.

4.5 Validation and Comparsion

Using the validation tools to assess the quality of 3D road network models, validate 3D primitives according to the international standard ISO19107, and validate the syntax of CityJSON objects.
Due to the absence of state-of-the-art 3D road network models, the comparison work can only be carried out in 2D, by comparing the 2D road network generated from this research with the official road polygons available, or by using open access road centreline elevation for comparison.

5 Time planning



Thesis plan

Chengzhi Rao 2023-2024

Start: 2023-12-01

Duration: 7-8 months

TASK	PROGRESS
Initiation	
Define goals	100%
Related studies	80%
Data exploration	80%
Methodology/frame design	80%
Graduate plan	100%
Implementation - Road network construction	
Stage1: Pre-processing	30%
Stage2: 2D road network	
Stage2-1: Linear representation	10%
Stage2-2: Areal representation	
Stage3: 3D road network	
Stage3-1: Assign elevation data	
Stage3-2: Generate 3D surfaces	
Validation, Comparison and Output	
Stage4: Validation, Comparison	
Stage4-1: Comparison and analysis	
Stage4-2: Validation and error repairing	
Stage5: Output CityJSON files	
Evaluation, writing and wrap-up	
Results evaluation and discussion	
Go / no-go assessment	
Wrap up and modify for all things	
Writing the final thesis	
Gather feedback	
Final representation	

Figure 24: Gantt chart for thesis time management.

6 Tools and datasets used

6.1 Tools

6.1.1 Tools for data processing and generation

This research will mainly works in the realm of geometric data processing and generation, a diverse set of tools and technologies play a pivotal role in transforming raw data into meaningful insights. Leveraging the strengths of programming languages such as Python and C++, this toolkit encompasses a range of libraries and software designed to handle spatial information effectively. The tools I need to use are listed as:

- Programming languages: Python, C++;

- Library for geometry generation: (Geo)pandas, shapely, osm2lanes, osm2streets, CGAL, etc;
- Software: QGIS, MeshLab, etc;
- Visualization tools: Matplotlib(Python), Plotly(Python), Open3d(Python and C++), Geogram(C++), etc

6.1.2 Tools for validation

Using validation tools **val3dity** and **cjval** validate the quality of 3D road network models and the correctness of syntax of output CityJSON file respectively.

- val3dity: Validation tools of 3D primitives, it verifies whether a 3D primitive respects the definition as given in ISO19107 and GML[TUDelft3D (Accessed 17 Jan. 2024)].
- cjval: A library to validate the syntax of CityJSON objects (CityJSON + CityJSONFeatures). It validates against the CityJSON schemas and additional functions have been implemented (because these can't be expressed with JSON Schema)[CityJSON (Accessed 17 Jan. 2024)].

6.2 Data

6.2.1 OSM data: the 2D road vector data

Tested regions: Countries and cities such as the Netherlands, Switzerland, London, and Berlin should be explored, and the open access geospatial data - OSM and DSM - of these regions will be used in this research.

Official 2D road geometry and elevation data for comparison: For some regions like the cities in the Netherlands have released the official 2D road polygons, can be used as the validation data to assess the quality of my work:

- Netherlands: 2D road model Nationaal Wegenbestand (NWB) (National Road Database);
- Berlin: the detailed map based on the OSM Berlin project in one specific district;
- Switzerland: the elevation data for road centrelines.

It's worth noting that the OSM data must contain the fundamental attribute **'highway'**, and the direction of road centreline segments must be correct (backward and forward).

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