Reconstructing the topology of urban street intersections from a lines+lanes road model for improved generalization and representation on maps

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Abstract:

The road network in many urban areas today has to facilitate sustainable transport options such as cycling, walking or public transport in addition to conventional car-centric mobility, and climate adaption policies seek to incorporate more vegetation and green spaces into the urban landscape. The allocation of street "real estate" in the urban fabric is therefore evolving away from a simple monolithic and continuous road surface for (motorized) traffic, into a more complex and heterogeneous topology of dedicated functional lanes (e.g. for motorized traffic, bus lanes, cycle lanes, on-street parking, sidewalks, linear green spaces and barriers etc.), with additional features potentially interrupting the continuity of these lanes (e.g. trees and flowerbeds, driveways and gates, features designed to protect or support pedestrians and cyclists etc.). However, most online maps of urban areas have not yet evolved beyond representing urban street space as being composed of simple linear segments without much internal differentiation, with the possible exception of sidewalks and crosswalks, which sometimes are added without much regard for topological integrity with other map layers.

Researchers have acknowledged the need for more detailed representation of the complexity of (urban) street space and have proposed various concepts for improved modelling of the underlying phenomena. The project *OpenStreetMap Verkehrswende* has conducted a detailed grass-roots "micro-mapping" of urban street space of a part of Berlin, mostly as polygonal features (Seidel, 2022). Traffic management systems are making use of highly detailed 2D or 3D models of street space, so called HD maps, in which the properties of various road parts are modelled with centimetre-level precision and enriched with lane-level semantic information, mainly for the purpose of guiding (semi-)autonomous vehicles (Elghazaly et al., 2023; Rehrl et al., 2024). In addition to such approaches which require significant modelling and surveying efforts to create the detailed geometric and semantic models required, apps like *StreetComplete* have also made the casual mapping and refinement of details of the urban street space feasible (such as adding semantic information about parking, cycling or crosswalks to the existing OpenStreetMap road network) (Pühringer, 2025).

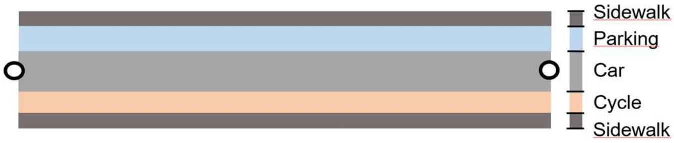

Figure 1. A "line+lanes" model of street space. The street segment is modeled as a simple linear feature, augmented with information about the width and properties of its lanes. This model can easily be integrated with or derived from existing data sets.

While novel and highly detailed geometric models of street spaces are required for applications such as routing or autonomous driving, and can certainly contribute to a better representation of street details on large-scale maps, it can be argued that such refined geometric models do not necessarily solve the fundamental *cartographic* problem of communicating the intricate details of today's urban road networks to human map viewers: at the map scale required to maintain an overview of e.g. an inner city cycling route, there is simply not enough space to keep lane-level or smaller geometric features legible if represented to scale. Thus, a generalization step is necessary to optimize the map for legibility of important details. However, fundamental generalization operators such as exaggeration or displacement may be challenging to apply to a polygon-based geometric model (Jones et al., 1995). Therefore, in this paper a different approach for modelling the urban street space is proposed: keep the simple model of a street network as a network of connected line segments (with each segment representing the entire lateral space logically "belonging" to that road segment, including curbs, sidewalks, linear green spaces etc.), and enrich the segment geometry with data about the lanes it is composed of (including each lane's width, its dedication, surface material, curbs or barriers etc.) (see Figure 1). Optionally, point features such as barriers, crossings or vegetation can be added to a lane by specifying its longitudinal position from the starting point of the segment. While such a "lines+lanes" model of streets obviously offers a less

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accurate representation of the exact geometry of each feature on the road, it has several advantages over a polygon-based geometric model: it can easily be integrated with existing line-based or network-based data on street networks, which are abundantly available; it can be assessed on-the-ground with little or no surveying equipment and little work effort, making a crowdsourced approach feasible; topological integrity can be assured more reliably because of the simple and well established underlying geometry model; and, last but not least, generalization of the resulting map, such as enlarging specific lanes, hiding irrelevant information, or highlighting obstacles or hazards for special purpose maps (such as cycling or walking maps) can be more easily achieved. The premise of this project is therefore that even with today's possibilities to create highly accurate geometric models of street space, investigation of the cartographic affordances of a simpler lines+lanes model seems worthwhile.

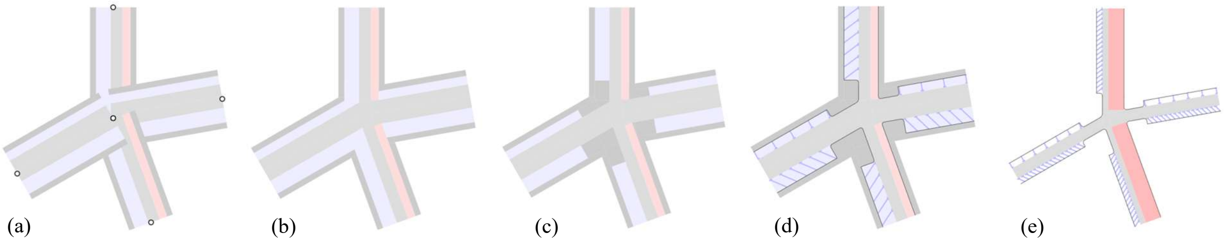

Figure 2. What happens at intersections of roads in the lines+lanes model? The presented algorithm derives from the raw input data (a) the connectedness and tessellation of lanes at the intersection (b), including features such as sidewalk expansions, crossings etc. (c). The results can then be rendered in a realistic yet highly stylized style (d) and open the possibility of cartographic generalization, e.g. by enlarging or shrinking details based on their relevance for the map user (e.g cycling lanes – e).

While creating a visual representation of a single street segment with multiple lanes from the lines+lanes model can be accomplished with simple geometric operations (displacing each segment appropriately from the centre line), a key question is how the multiple lanes should be visualized at intersections, in the absence of additional explicit information about the intersection geometry. Individual lanes do not all continue throughout the intersection, but establish a deterministic topology of connected lanes and interruptions throughout. To achieve realistic depictions of street intersections from the lines+lanes model which does support storing the geometry of intersections explicitly, this topology of lane connections at an intersection has to be reconstructed algorithmically from global assumptions about lane priorities, and potential semantic information assigned to the lanes or the intersection point. In the paper, an algorithmic approach for (re)constructing both the topology (lane connections and interruptions) as well as the geometry of the intersection (polygon geometry for graphical representation on the map) is presented (see Figure 2). It needs to be noted that the resulting geometry does not necessarily resemble accurately the geometrical situation on-the-ground, but is hoped to accurately depict the topological relationships of relevant elements of the street space to the viewer and, as mentioned above, supports generalization of the results by purposefully distorting the map representation to highlight relevant information (e.g.by exaggerating geometric dimensions of more relevant elements, highlighting crossings, obstacles or hazards etc.)

The development and testing of the algorithms for deriving the topological and geometric properties of street intersections of medium complexity from a lines+lanes model are currently ongoing, as well as the compilation of a gallery of test cases, both synthetically generated as well as extracted from OpenStreetMap data for several cities. The presentation will be completed by an initial assessment of the usability of the results in various urban navigation scenarios, as well as a detailed discussion of the applicability of the algorithm for varying intersection complexity, lane configurations and other limitations.

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