

## Postprint of Modeling Methods for Refined Intersection Data Models

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### Abstract

To address the current deficiency of traffic network data models in describing the physical geometric form and traffic organization channelization at intersections, a road network data model for refined intersections is proposed, which characterizes information such as logical topology and marking rules from physical, logical, and geometric perspectives to meet the computational demands of traffic analysis. Concurrently, a modeling method for constructing intersection geometric topology is presented, leveraging physical and logical topologies through feature-based linear referencing techniques. Modeling experiments on at-grade intersections validate that the proposed method effectively supports the automatic generation of refined intersection geometric data.

### Full Text

### Preamble

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### Modeling Approach of Precise Intersection Data Model

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**Abstract:** Aiming at the current deficiency in describing the physical geometry and traffic organization channelization of intersections in traffic network data models, this paper proposes a road network data model oriented toward refined intersections. The model describes the logical topology, marking rules, and

other information of intersections from physical, logical, and geometric levels to support the computational requirements of traffic analysis. Simultaneously, a modeling method for intersection geometric topology is presented based on physical and logical topology using element-based linear referencing technology. Finally, modeling experiments were conducted on planar intersections, and the results demonstrate that the proposed method can effectively support the automatic generation of refined intersection geometric data.

**Keywords:** data model; planar intersection; layered topology; intelligent transportation

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## 0 Introduction

Computable GIS-T has emerged as a significant research direction in intelligent transportation in recent years [1]. The first step in constructing a computable GIS-T system is to achieve the representation and storage of transportation objects in computers, namely, building a data model. As a crucial component of urban road systems, road intersections serve as control points for managing and organizing road traffic. The traffic conditions at intersections largely reflect the traffic state of the entire road network. Therefore, a refined intersection data model is key to implementing computable GIS-T. On a computable GIS-T platform, various traffic analyses in the transportation field—including traffic capacity calculation, traffic state estimation, traffic demand analysis, and traffic simulation—all rely on the support of refined intersection data models.

Current research on intersection models, both domestically and internationally, predominantly treats intersections as part of the road network. Consequently, it is necessary to examine the research status through studies on road network data models. Present research on road network data models mainly falls into two categories: link-level road network data models and lane-level road network data models. In terms of link-level models, major studies include Sheffi's node-arc model, Li et al.'s directed link-based road network model, and the GDF model [2-4]. These models primarily target applications in transportation planning, traffic management, and link-level travel, focusing heavily on describing the logical connectivity between road segments. However, they abstract intersections merely as nodes and use them as the basis for determining traffic flow interruptions, describing the connectivity relationships of traffic flows in various directions at intersections. Moreover, these models provide only coarse descriptions of road physical geometry, failing to represent internal organization channelization and intersection widening scenarios.

In the realm of lane-level road network data models, various data models [5-7] describe road traffic down to the lane level, effectively supporting the expression of logical connectivity between lanes. Nevertheless, these models offer only rough descriptions of internal geometric information at intersections and cannot

describe the physical geometric forms and traffic organization channelization at intersection locations.

The aforementioned model studies all treat intersections as objects within the road network, emphasizing logical topology aspects such as traffic flow and lane connectivity during the modeling process. However, they lack adequate description of attributes related to internal geometric forms, organization channelization, and widening of intersection approaches. Consideration of internal objects such as left-turn waiting zones, right-turn channelization lanes, and left-turn guide lines is minimal. Even when some models address intersection geometric forms, they remain at a very coarse level of general 轮廓形态. Furthermore, many models lack standardized, unified, and accurate semantic expression, preventing holistic model representation and better support for external applications.

Therefore, this paper begins with the requirements of various computational analyses in the transportation field on a computable GIS-T platform for intersection data models and conducts separate modeling for intersections. Based on existing physical and logical topology, it explores systematic methods for constructing intersection geometric topology using linear referencing and linear offset techniques.

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## 1 Refined Intersection Data Model

Through analysis of various traffic computational requirements on a computable GIS-T platform, such as signal control optimization and traffic simulation [8-11], it is evident that the model needs to describe the internal geometric forms and logical relationships of intersections. Consequently, this study describes intersections as an integrated composition of physical topology, logical topology, and geometric topology. Physical topology describes the basic skeleton of intersections, including the physical fundamental attributes and connectivity relationships of road units in space. Logical topology, based on physical topology, achieves abstract expression of traffic rules conveyed by markings. Geometric topology reflects certain traffic rules by constructing markings that carry traffic regulations, utilizing the style, color, and other appearance information of these markings. The model employs unified semantic expression to achieve holistic model correlation and computational support. The schematic diagram of the three-layer topology model is shown in Figure 1.

[Figure 1: see original paper]

### 1.1 Physical Topology

Physical fundamental topology forms the basis of the refined intersection data model, comprising two components: road segment nodes and road segments. Let  $V$  denote the set of road segment nodes, where  $v_i$  represents a road segment node containing attributes such as the set of road segments connected to node  $v_i$ .

Let  $E$  denote the set of road segments, where  $e_i$  represents a road segment connecting road segment nodes  $v_m$  and  $v_n$ . To facilitate subsequent description of geometric topology, the concept of directed road segments is introduced. Define  $A$  as the set of directed road segments, where  $a_i$  is a directed road segment in road segment  $e_i$  with direction from  $v_m$  to  $v_n$ . The physical topology schematic diagram is shown in Figure 1(a).

## 1.2 Logical Topology

Logical topology represents the abstract expression of traffic rules within intersections, defined as  $L_G = \{A, L, L_C, L_L, C, V\}$ , where  $A$  is the set of directed road segments,  $a_i \in A$  is a directed road segment representing the traffic flow direction;  $L$  is the set of lanes,  $l_i \in L$  represents a lane, which is the smallest road unit located within directed sub-segments that regulates vehicle operation behavior;  $L_C$  represents the set of longitudinal lane connectivity relationships, where  $lcv_i = \langle l_f, l_t \rangle$  indicates the longitudinal passage from lane  $l_f$  to lane  $l_t$ ;  $L_L$  represents the set of lateral lane connectivity relationships, where  $lcl_i = \langle l_f, l_t \rangle$  indicates the lateral connectivity relationship from lane  $l_f$  to lane  $l_t$ . The schematic diagram and related ER diagram of logical topology are shown in Figures 2 and 3.

[Figure 2: see original paper]

[Figure 3: see original paper]

## 1.3 Geometric Topology

**1.3.1 Geometric Element Types and Positional Relationships** Geometric topology refers to the geometric expression and positional relationships of markings that carry traffic rules within intersections. The geometric expression includes the geometric element types, colors, styles, and specific types of markings, while positional relationships describe the actual location information of markings.

In this model, physical topology serves as the reference frame for constructing geometric topology. Directed road segments are selected as the reference line, and the positional relationships of markings belonging to road segment  $a_i$  are described using linear referencing and linear offset techniques.

Intersection markings belong to different geometric element types, including point elements, line elements, and surface elements. Line elements comprise line segments, arcs, parallel curves, and quadratic Bézier curves, while surface elements in this paper include only rectangles. Different types of geometric elements express geometric positions in the reference frame through linear referencing and linear offset techniques. Let  $fea$  denote any geometric element, i.e., point element  $p$ , line segment  $line$ , arc  $a$ , quadratic Bézier curve  $b$ , parallel curve  $pl$ , and rectangle  $sq$ . Then define  $fea.loc$  as the position of geometric element  $fea$  in reference frame  $G$ . The positional relationships of various geometric element types are described as follows:

- a) The geometric position of a point element is represented by a triple  $p.loc = \langle ver, la, t \rangle$ , where  $ver$  is the reference line in physical fundamental topology,  $la$  is the longitudinal offset distance, and  $t$  is the lateral offset distance (left-side offset along the reference line direction is positive, right-side offset is negative).
- b) The geometric position of a line segment  $line$  can be represented by a binary tuple  $line.loc = \langle p_1, p_2 \rangle$ , where  $p_1$  and  $p_2$  are point elements corresponding to the two endpoints of the segment.
- c) The geometric position of an arc  $a$  is described as a triple  $a.loc = \langle p_1, p_2, p_0 \rangle$ , where  $p_1$  and  $p_2$  correspond to the start and end points of the arc, and  $p_0$  corresponds to the arc's center point.
- d) The geometric position of a quadratic Bézier curve can be denoted as  $b.loc = \langle p_0, p_1, p_2 \rangle$ , where  $p_0$  and  $p_2$  are point elements representing the two endpoints of the quadratic Bézier curve, and  $p_1$  is the intermediate control point.
- e) The geometric position of a parallel curve  $pl$  is expressed as  $pl.loc = \langle p_1, p_2, line \rangle$ , where  $p_1$  and  $p_2$  are the two endpoints of the parallel curve, and  $line$  is the reference line for the parallel curve.
- f) The geometric position of a rectangle can be expressed as  $sq.loc = \langle p_1, p_2, p_3, p_4 \rangle$ , where  $p_1, p_2, p_3, p_4$  are the four endpoints of the rectangle in sequence, all being point elements.

**1.3.2 Marking Geometry Expression** The geometric topology of the road network is represented as  $G_G = \{LB, PC, SL, TA, GL, RTC\}$ , where  $LB$  denotes the set of lane boundaries,  $lb_i \in LB$  represents a single lane boundary;  $PC$  denotes the set of crosswalks,  $pc_i \in PC$  represents a single crosswalk;  $SL$  denotes the set of stop lines,  $sl_i \in SL$  represents a single stop line;  $TA$  denotes the set of guide arrows,  $ta_i \in TA$  represents a single guide arrow;  $GL$  denotes the set of guide lines,  $gl_i \in GL$  represents a single guide line;  $RTC$  denotes the set of right-turn curves,  $rtc_i \in RTC$  represents a single right-turn curve. It is stipulated here that when a right-turn channelization lane is installed at an intersection, the right-turn curve is incorporated into the lane boundary of the right-turn channelization lane for unified expression. The schematic diagram of markings is shown in Figure 4.

[Figure 4: see original paper]

### 1) Lane Boundaries

In this study, same-direction lane dividers, opposite-direction lane dividers, and road edge lines are collectively referred to as lane boundaries, as shown in Figure 5.

[Figure 5: see original paper]

A single lane boundary  $lb_i$  contains attributes  $\{lb_i.loc, lb_i.sty, lb_i.col, lb_i.typ, lb_i.pos\}$ , where  $lb_i.typ$  represents the type of lane boundary, with types including widened section lane boundary, transition section lane boundary, ordinary section lane boundary, right-turn channelization lane boundary, and left-turn waiting zone lane boundary.  $lb_i.sty$  represents the style of  $lb_i$ , with 5 types: single solid line and single dashed line.  $lb_i.col$  represents the color of  $lb_i$ , with options of white and yellow.  $lb_i.pos$  represents the order of  $lb_i$ , where each type of lane boundary is numbered separately according to its entrance and exit lanes following the rule of numbering from inside to outside along the traffic flow direction.

## 2) Crosswalks

In this study, the geometric element type of crosswalks is treated as a rectangle. A single crosswalk  $pc_i$  contains attributes  $\{pc_i.loc, pc_i.sty, pc_i.col, pc_i.typ\}$ , where  $pc_i.typ$  represents the type of crosswalk, including entrance lane crosswalk, exit lane crosswalk, and right-turn channelization lane crosswalk.  $pc_i.col$  describes the color of the crosswalk.  $pc_i.loc$  describes the geometric element position information of the crosswalk.

## 3) Stop Lines

Stop lines are set at intersection entrance lanes, with their geometric element type being a line segment. A single stop line  $sl_i$  contains attributes  $\{sl_i.sty, sl_i.col, sl_i.typ, sl_i.loc\}$ , where  $sl_i.sty$  represents the style of the stop line, generally a single solid line;  $sl_i.col$  represents the color of the stop line;  $sl_i.typ$  indicates the type of stop line; and  $sl_i.loc$  describes the geometric element position information of the stop line.

## 4) Guide Arrows

Guide arrows are set within lanes to specify permitted travel directions for vehicles. In this study, various types of guide arrows are treated as point elements. A single guide arrow  $ta_i$  contains attributes  $\{ta_i.loc, ta_i.typ, ta_i.pos, ta_i.seq\}$ , where  $ta_i.typ$  represents the type of guide arrow, with 11 types according to national standards;  $ta_i.loc$  represents the position information of the guide arrow. Guide arrows in the same group share consistent longitudinal order. For guide arrows on the same entrance (or exit) lane, numbering proceeds sequentially along the traffic flow direction. The lateral order of guide arrows in the same group is numbered from the road interior to the exterior. As shown in Figure 6,  $ta_i.pos$  and  $ta_i.seq$  represent longitudinal and lateral order respectively.

[Figure 6: see original paper]

## 5) Guide Lines

A single guide line  $gl_i$  contains attributes  $\{gl_i.loc, gl_i.typ, gl_i.sty, gl_i.col\}$ , where  $gl_i.typ$  indicates the type of guide line,  $gl_i.sty$  represents the style of the guide line,  $gl_i.col$  represents the color of the guide line, and  $gl_i.loc$  describes the geometric element position information of the guide line. Regarding the geometric element type of guide lines, numerous domestic and international scholars have indicated that design should be based on left-turn vehicle trajectories, yet none have provided specific channelization design schemes [12,13]. Therefore, this

paper adopts the commonly used quadratic Bézier curve in engineering as the geometric element type for guide lines.

## 6) Right-Turn Curves

Right-turn curves stipulate that right-turning traffic must not cross or drive over the line when turning right within the intersection. The geometric element type of right-turn curves is an arc. A single right-turn curve  $rtc_i$  contains attributes  $\{rtc_i.loc, rtc_i.sty, rtc_i.col\}$ , where  $rtc_i.col$  represents the color of the right-turn curve, generally white;  $rtc_i.sty$  represents the style of the right-turn curve, generally a single solid line; and  $rtc_i.loc$  describes the geometric element position information of the right-turn curve.

In summary, the ER diagram of the geometric topology layer is shown in Figure 7.

[Figure 7: see original paper]

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## 2 Geometric Topology Construction Method

As described in Section 1, logical topology is constructed based on physical topology through a cross-scale hierarchical modeling approach, focusing on describing abstract traffic rules at intersections. Geometric topology, however, emphasizes the geometric expression and positional relationships of markings that carry these traffic rules. Only the combination of physical topology, logical topology, and geometric topology constitutes a complete refined intersection data model. Existing road network models mostly contain physical and logical topology but lack geometric topology. Therefore, this section proposes a method for constructing intersection geometric topology based on existing physical and logical topology by introducing external geometric parameters (such as right-turn curve radius, crosswalk width, etc.) and employing linear referencing and linear offset techniques.

According to explicit specifications in national and local standards for intersection design, certain correlation relationships exist among geometric units during intersection construction. For example, crosswalk positions need to be determined based on curb extensions, while crosswalk lengths need to be determined based on guidance island positioning. Consequently, when constructing geometric topology from logical topology, various intersection markings must follow a specific derivation sequence.

Based on the correlation relationships among geometric units, geometric units within the intersection scope are sorted by construction order. For a topological model containing  $n$  geometric units that can be constructed sequentially, define  $Fea_k$  as the  $k$ -th geometric unit and  $G_k$  as the geometric topology model after constructing the  $k$ -th geometric unit. Then  $G_{k+1} = G_k \oplus Fea_k$ , where the symbol  $\oplus$  represents geometric unit superposition—importing external geometric parameters on the basis of  $G_k$  to construct  $G_{k+1}$ . Further, we can obtain the

fundamental  $G_0 = \emptyset$  and the final  $G_n = G_g$ . The specific steps for constructing geometric topology are as follows (the symbol  $\cdot$  is a left-associative operator):

- a) Calculate the curb position based on logical topology, introduce the right-turn curve radius  $rtc.rad$  as an external geometric parameter, and construct the right-turn curve  $rtc$ .
- b) Determine whether a right-turn channelization lane exists based on logical topology, identify the positions of entrance and exit endpoints and the number of lanes for the right-turn channelization lane boundary, and construct the right-turn channelization lane boundary.
- c) Introduce external geometric parameters including the offset distance  $pc.dis$  between the crosswalk's inner edge and the exit road segment, and the crosswalk width  $pc.wid$ , to construct the crosswalk  $pc$ .
- d) Introduce the offset distance  $sl.dis$  between the stop line and the road segment to construct the stop line  $sl$ .
- e) Introduce external geometric parameters including the widened section length  $len$ , transition section length  $tlen$ , and ordinary section length  $nlen$  to construct three types of lane boundaries: widened section, transition section, and ordinary section.
- f) Introduce the external geometric parameter  $ta.dis$  representing the distance between guide arrows and stop lines, assuming guide arrows are placed in the middle of lanes, to construct guide arrows  $ta$ .
- g) Introduce the lane boundary radius  $lb.rad$  as an external geometric parameter to construct left-turn waiting zone lane boundaries.
- h) Use the starting lane boundary endpoint, the outermost exit lane boundary endpoint, and the intersection point of their extensions as control points to construct guide lines.

The overall process of geometric topology construction is shown in Figure 8.

[Figure 8: see original paper]

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### 3 Case Application

This paper takes a simple planar four-way intersection as an example, using the intersection's physical and logical topology information as input data. On the C# platform, the construction of intersection geometric topology was implemented using ArcEngine secondary development components and a Microsoft Access relational database. The physical topology is shown in Figure 9, where road segments  $e_1, e_2, e_3, e_4$  connect to intersection  $v_1$ . Logical topology is automatically generated according to rules: road segment  $e_1$  has five entrance lanes (including one right-turn channelization lane) and five exit lanes, while road

segment  $e_3$  has four entrance lanes and three exit lanes. External geometric parameters are set according to national standards and planning design specifications, with the right-turn curve radius set according to curb radius standards for scenarios without non-motorized vehicle lanes. The constructed planar intersection geometric topology is shown in Figure 10.

[Figure 9: see original paper]

[Figure 10: see original paper]

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## 4 Conclusion

Based on the requirements of intersection-related research and grounded in physical and logical topology, this paper proposes a method for constructing intersection geometric topology by acquiring logical connectivity relationships and relevant attribute data (lane width, length, etc.) of directed road segments, lanes, longitudinal lane connectors, and lateral lane connectors from logical topology, combined with external geometric parameters including right-turn curve radius, crosswalk width, widened section length, and transition section length, referencing national standards and planning design specifications, and employing linear referencing and linear offset techniques with physical fundamental topology as the reference frame.

Practice has proven that the three-layer model and its modeling method proposed in this paper can effectively support automatic intersection modeling by computers. However, the current model has limited description of road traffic rules and does not consider traffic objects such as weather and environmental conditions, making it difficult to describe intersection scenarios under complex conditions. These limitations must be addressed in future research. Additionally, intersection modeling should be more tightly coupled with road segment modeling to achieve a refined road network data model.

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