A Trajectory-Oriented, Carriageway-Based Road Network Data Model, Part 2: Methodology

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ABSTRACT  This is the second of a three-part series of papers which presents the principle and architecture of the CRNM, a trajectory-oriented, carriageway-based road network data model. The first part of the series has introduced a general background of building trajectory-oriented road network data models, including motivation, related works, and basic concepts. Based on it, this paper describes the CRNM in detail. At first, the notion of basic roadway entity is proposed and discussed. Secondly, carriageway is selected as the basic roadway entity after compared with other kinds of roadway, and approaches to representing other roadways with carriageways are introduced. At last, an overall architecture of the CRNM is proposed.

KEYWORDS  trajectory; road network data model; carriageway; GIS; GIS-T

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Introduction

If let roadway entities be denoted by arcs and intersections be denoted by nodes, then a road network can be represented with node-arc model. Because the designation of nodes can be determined by arcs according to the definition of node-arc model, how to designate arcs becomes the key of representing a road network. As described in the first paper of the series, all four kinds of roadway entities (i.e., streets, road segments, carriageways, and lanes) can be represented by arcs. However, only one of the four kinds of roadway entities should be selected as basic roadway entities represented by arc because, otherwise, several networks covered by one another in space ought to be created and maintained separately.

The basic roadway entities can be used to provide references for other kinds of roadway entities based on the relationships between them. In the proposed model, carriageway is selected as the basic roadway entity according to the comparisons between carriageway and others in the reminder of this paper. Meanwhile, the disadvantages of applying existent road network models to trajectory data are discussed. Approaches to representing other roadways with carriageways are introduced. At last, an overall architecture of the CRNM is presented.

1 Selection of basic roadway entity

1.1 Street and road segment vs carriageway

Most existent road network models have not explicitly designated the basic roadway entities, but implicitly regarded street or road segment as the basic roadway entities and assigned them various names, such as “road elements” in GDF[11], “linear datum” in NCHRP[27], “linear event” in Dueker’s model[32] and Koncz’s model[4], and “feature-based route” in Zhou’s model[33]. One possible reason could be that most available road network maps only consist of the centerlines of road segments or streets. Another possible rea-
son could be that these models focus on the locations of static traffic infrastructures (e.g., pavement and bus stops) or discrete traffic events (e.g., traffic accident). For example, if one wants to locate a traffic accident, a straightforward order is to find the relevant street, then the road segment of this street, then the carriageway on this road segment, and finally the lanes on this carriageway. However, these street-based or road-segment-based models could be unsuitably applied to trajectory data as in the following discussion.

First, trajectory data usually consists of a great number of discrete points, and each point eventually is located on a certain lane or carriageway. Therefore, it is troublesome and will definitely increase trajectory data volume to locate so many points according to the order: street; road segment; carriageway; lane. Instead, a carriageway-based or lane-based model may locate these points faster and with less data volume.

Second, because trajectory data initially is located in Euclidean space, it is not straightforward to provide spatial reference for them in a network space, and a map-matching algorithm, which can distinguish the particular roadways on which a vehicle passes by, must be employed to conduct the transformation between two spaces. Road network data models are always associated with map-matching algorithms. Different data models will lead to different calculations and results. A major principle of the algorithm is based on the “shape” comparison between trajectories and possible routes consisting of roadway entities. For example, Fig. 1 illustrates different routes based on different road network data models, in which \( S_n \) is street; \( R_n \) is road segment; \( C_n \) is carriageway; \( L_n \) is lane. As shown in Fig. 1 (a), a route consisting of streets may include a part of a street, instead of a complete street, which definitely increases the complexity of shape comparison. Instead, a route consisting of road segments and carriageways, as shown in Fig. 1(b), includes only complete roadway entities, i.e. road segments and carriageways. Furthermore, carriageway-based routes can approach to trajectories closer than road-segment-based routes because carriageways limit the movement of vehicles in narrower strips than road segments. Therefore, carriageway-based model outperforms road-segment-based model in facilitating map-matching algorithms.

Third, according to the discussion in the first paper of the series, road segments are usually segmented very shortly in length in order to maintain the one-to-many relationship between streets and road segments. Continually, if road segments are selected as basic roadway entities and the one-to-many relationship between road segments and carriageways need to be maintained, then the number of carriageways will be very large, which must impair the performance of network calculation. Instead, for a carriageway-based model, because there is no fixed segmentation rule for carriageways, a well-designed rule will possibly keep a less number of carriageways as well as a simple relationship among roadway entities.

1.2 Lane vs carriageway

Lane-based road network models have been developed by Lu\(^7\) and Fohl and Curtin\(^4\). It
seems that lanes could be the best choice of basic roadway entities because vehicles must move on a certain lane at most travel time, and lane-based model can locate trajectories quickly and with the least data volume. However, it is not the case for the following reasons. First, the number of lanes is much more than that of carriageways in a road network, which definitely impairs the performance of network calculation. Second, lanes cannot limit vehicle movement as strictly as carriageways. A vehicle cannot move across a dividing strip and it can only move from the current carriageway to the next carriageway through a node, whereas, as shown in Fig. 1(d), vehicles may not only change from one lane to another lane at a designated node, but also change at any point when the two lanes lie alongside at the normal direction of movement. Therefore, it is really difficult to form a route consisting of lanes for map-matching algorithms. Third, the current positioning technologies cannot be accurate enough to locate a vehicle at the level of lane, which makes lane-specific spatial reference problematic. Although how to improve the positioning accuracy is beyond the focus of this paper, with the limitation of dividing strips and suitable map-matching algorithms, it is possible to locate a vehicle at the level of carriageway.

On the basis of above comparison, carriageways can be qualified as basic roadway entities and because of this the developed model is called CRNM.

2 Carriageways-based representation

2.1 Representing lanes

Two segmentation rules are adopted to determine the two end points of a carriageway and maintain the one-to-many relationship between carriageways and lanes. First, once a part or all of lanes from two or more carriageways intersect at a certain point, then the point must be one of two end points of each related carriageway. Second, if the number of lanes changes in a carriageway, then the carriageway will be split at the changing point. Fig. 2, where only centerlines of carriageways and lanes are drawn, illustrates the segmentation rules. In Fig. 2(a), a vertical one-lane carriageway intersect a horizontal two-lane carriageway. In Fig. 2(b), the number of lane changes from two to three.

In the CRNM, a carriageway is represented by an arc and its starting and ending points are represented by two nodes in terms of a node-arc model. All lanes in a carriageway and the carriageway itself have the same ends points at the normal direction of vehicles’ movement and parallel one another at the parallel direction of vehicles’ movement. The one-to-many relationship may help simply road network data model by use of several attributes of carriageways to depict lanes, instead of treating lanes as physical roadway entities. These attributes include the number of lanes and the distances between the centerlines of each lane and the concerned carriageway at the normal direction of traffic flow. Furthermore, we can define some patterns for typical combinations, such as 2-lane carriageway and 4-lane carriageway. And then we can further simply the model by replace those attributes with a simple pattern number.
2.2 Representing intersections

The status always becomes complicated in the area near a node where usually more than one intersection points exist; the centerlines of carriageways maybe meet at more than one point; and the centerlines of lanes maybe are distorted and are not parallel. In order to solve the problem, a simple measure is to designate a node (e.g. point A and B in Fig. 2) and then define an intersection zone for the node (e.g. two intersection zones in Fig. 2). The intersection zone should be able to cover all intersection points of lanes and carriageways associated with the node. The measure is reasonable because the interest of modeling a trajectory-oriented road network focuses on which roadway entity the vehicle will move onto from the current roadway entity, instead of how the vehicle changes the current roadway entity around a node. In some cases, a node is easy to be designated because carriageways’ centerlines can nicely meet at one point, for example, point A in Fig. 2 (a), while in other cases, all concerned carriageways may meet together at more than one point. For the latter cases, one solution is to chose a point for a node manually and lead all carriageways’ centerlines to this point, e.g., point B in Fig. 2 (b), or leave the carriageways as they were, provided the carriageways end points are within the intersection zone. Instead of geometrical attributes, other attributes of a carriageway can be used to record the connectivity information. Carriageways can be simply thought of meeting one another at a big “point”, i.e., an intersection zone.

The geometrical shape of an intersection zone could be of any type, provided it can meet the above requirements. In order to simplify the representation of an intersection zone, this paper employs a circle with the node as the center point to denote an intersection zone. The radius of a circle representing an intersection zone is not a constant, but varies from case to case.

2.3 Representing road segments and streets in CRNM

Streets of a road network are important factors included in practical network-related trajectory applications. Therefore, it is necessary to build relationship between streets and carriageways. However, the direct relationship between streets and carriageways is always complicated because streets are usually pre-designated and carriageways are determined by the proposed segmentation rules. Neither of them can adjust segmentation to maintain a one-to-many relationship between them. For example, as seen in Fig. 3, a street may include a complete carriageway (e.g. C1) or only a part of a carriageway (e.g. C2); a carriageway (e.g. C4) may span several streets; and carriageways (e.g. C1 and C3) may overlap each other partially at the parallel direction of the street.

![Fig. 3 Complicated relationship between carriageways and streets](image-url)

In order to solve the problem, road segments are employed as the middle objects between streets and carriageways. As above-mentioned, a street consists of one or several road segments piecewise. Therefore, it is easy to build the one-to-many relationship between streets and road segments. However, on the other hand, it is difficult to build the one-to-many relationship between road segments and carriageways because of the similar reason mentioned in the last paragraph. In view of this, a lookup table can be created to keep the complicated many-to-many relationship between road segments and carriageways. The segmentation rule of road segments is that a road segment will be split once there is an intersection point of the carriageways in the road segment. This rule not only maintains the one-to-many relationship between
streets and road segments because each road segment can be split short enough, but also simplifies the structure of the lookup table. Each record in this lookup table at least includes the following two elements: the identification of a road segment and the description of a part of a carriageway. Fig. 4 gives an example of the lookup table and a corresponding road network, in which \( P_4 \) is point on a carriageway; \( N_i \) is node; \( C_s \) is carriageway; \( R_s \) is road segment. A part of a carriageway is denoted by two points which can be end points or any other points on the carriageway, e.g., \([N_i, P_j]\) of \( C_s \). Although, with this rule, the number of road segments will increase, it does not matter because road segments are not included in the network calculations, which, instead, are conducted for carriageways and lanes.

In addition, introducing road segments to link up streets with basic roadway entities, e.g., carriageways, has the following two advantages. First, streets can change their designated names or ranges more frequent than physical features of a road network. If such changes happen, it is necessary only to update the relationship between streets and road segments and keep the relationships between physical features unchanged. Second, many network-related queries focus on particular segments of a street instead of the street as a whole. Therefore, it is easier to depict query conditions with road segments.

3 Architecture of CRNM

The above sections have discussed and presented CRNM at the conceptual level. In this section, the objects, their attributes and relationships among them are formalized with a UML (unified modeling language) diagram in Fig. 5 at the logical level. The UML is a graphic language for visualizing, specifying, constructing, and documenting the artifacts of a software-intensive system[12]. A specification on UML can be found in Reference [12].
As seen in Fig. 5, 5 objects and 5 associations are included in the UML diagram. According to the name of each object, it is easy to explain what they represent. According to Section 2.1, lane is not treated as an object but an attribute (i.e., Lanes) of object carriageway. The necessary attributes of each object are also listed. They can be grouped into the following categories for the convenience of discussion. Here, suppose that A, B refers to attribute B of object A, e.g., Carriageway, GeoLine.

1) The attributes RoadSegment.ID, Carriageway.ID, Node.ID, and Street.ID store the unique identifications of these objects, respectively, and they are numeric. Although Street.Name which stores the name of a street has the same function to Street.ID, it is easier to conduct calculation with numbers than with characters, and thus the ID is also included as an attribute of object Street.

2) Carriageway, GeoLine stores the spatial coordinates (e.g., latitude and longitude) of the centerline of a carriageway while Node, GeoPoint stores the spatial coordinates of the centerline's end points. Node.Radius is used to store the radius of the intersection zone of a node which is a circle.

3) Carriageway, FromNodeID and Carriageway, ToNodeID corresponding to attribute Node.ID denote two nodes which are respectively the starting and ending nodes of the carriageway. There is no concrete difference between the starting and ending nodes of a carriageway but their names. Although the direction indicated by the starting and ending nodes does not represent the directions of traffic flow on the carriageway, it can be used to provide references of direction for related features such as Carriageway, Lanes in the carriageway, Carriageway, Lanes. Lanes is an array and stores offset distances from the centerline of each lane to the carriageway's centerline at the normal direction of vehicle movement. The traffic flow directions on lanes may be different, in which some are the same to that of the carriageway, some are the opposite to it, and others are uncertain. It is possible to attach direction information to the attribute Carriageway, Lanes. The case study in the next paper of the series will propose a measure to realize it.

4) Node, InCarriagewaysID and Node, OutCarriagewaysID are two arrays that store the ID values of the carriageways that start and end at the node, respectively. Street, RoadSegmentsID restores the ID values of all road segments constituting the street and RoadSegment. StreetID stores the ID value of the street that includes the road segment.

5) There is no concrete entity corresponding to the object LookupRecord which, instead, is used to maintain the relationship between RoadSegment and Carriageway. LookupRecord, RoadSegmentID and LookupRecord, CarriagewayID denote the road segment and the carriageway that are related to each other at the particular part of the carriageway. The part can be described with LookupRecord, StartPosition and LookupRecord, EndPosition which record distances from the starting node of a carriageway to the two denoted positions along the carriageway, respectively.

4 Conclusions

This paper is the core of the series. The CRNM is introduced in detail. In this model, the carriageways of a road network are selected as basic roadway entities denoted by arcs of the node-arc model to represent a road network and provide references for other kinds of roadway entities and intersections.

The CRNM has several advantages. First, the carriageway-based feature of the CRNM facilitates matching of trajectory data. Second, the proposed concept, intersection zone, solves the difficulty in the representation of the complex movement of vehicles around nodes to a great extent. Third, as seen in the proposed architecture of the CRNM, two one-to-many relationships, i.e., carriageway-lane and street-road segment, can be maintained, and a lookup table is used to link road segments and carriageways.

(Continued on Page 150)