A Trajectory-Oriented Carriageway-Based Road Network Data Model, Part 1: Background

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ABSTRACT  This is the first of a three-part series of papers which introduces a general background of building trajectory-oriented road network data models, including motivation, related works, and basic concepts. The purpose of the series is to develop a trajectory-oriented road network data model, namely carriageway-based road network data model (CRNM). Part 1 deals with the modeling background. Part 2 proposes the principle and architecture of the CRNM. Part 3 investigates the implementation of the CRNM in a case study. In the present paper, the challenges of managing trajectory data are discussed. Then, developing trajectory-oriented road network data models is proposed as a solution and existing road network data models are reviewed. Basic representation approaches of a road network are introduced as well as its constitution.

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

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Introduction

With the dramatic development of positioning and telecommunication technologies, lots of trajectory data of moving vehicles can be calculated, collected, and transferred. In the meanwhile, this development and the availability of trajectory data have also motivated research efforts on disaggregate transportation modeling in GIS for transportation (GIS-T)[3-4]. As a result, vehicles' trajectory data can be applied to multiple purposes, such as fleet management, navigation, road pricing, or traffic flow analysis[3]. One fundamental requirement of these applications is to efficiently manage trajectory data.

However, the management of trajectory data inevitably is confronted with two challenges. One is the dramatically increasing trajectory data volume due to the frequent movement of vehicles and the requirement of keeping track of the movement, and the other challenge is the spatio-temporal characteristics inherent in trajectory data. One measure to solve both challenges is to reduce the spatial dimensionality of trajectory data based on the locational relationship between the trajectory coordinate system and the road network topology and geometry. The reason is that the lower spatial dimensionality definitely reduces data volume and simplifies the spatio-temporal complexity, the modeling, and the query processing of trajectory data[4].

Trajectory data of vehicles is usually collected and recorded as a sequence of points in 2D or 3D Euclidean space. The reducing of the spatial dimensionality of trajectory data can be achieved by changing the spatial reference of trajectory data from 2D or 3D Euclidean space to 1D linear network space. A linear network, such as a road network, is embedded in 2D or 3D Euclidean space, and the network is able to provide a 1D measurement framework for the spatial reference of objects, such as vehicles, whose activities are restricted to the network[5].

Fortunately, in GIS-T, a widely-applied approach, namely linear-referencing system...
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LRS, has been developed to provide 1D spatial reference for objects spatially related to a road network. The fundamental element of LRS is road network data model. Different road network data models will define different LRS. So far, a number of road network data models have been developed\[^6\,\,^1\,\,^2\,\,^7\,\,^1\,\,^2\,\,^8\,\,^9\,\,^1\,\,^0\]. However, because most of them except for Fohl’s model\[^1\,\,^1\,\,^2\] are not designed explicitly for vehicle trajectory data but for static points or sections such as a segment of pavement or a bus stop in a road network, it is not straightforward to apply them to the spatial reference of trajectory data with respect to the specific requirements from vehicle trajectory data. Fohl’s model\[^1\,\,^1\,\,^2\] does mention the spatial reference of vehicle locations, but it does not provide an operational LRS and its lane-based approach, which is also adopted in Lu’s model\[^9\], indeed causes the complexity of locating a vehicle. Instead of models for road networks, regarding general network models, the works of Vazirgiannis and Wolfson\[^1\,\,^3\], Guting, Almeida, et al.\[^4\], Jensen, Pedersen, et al.\[^1\,\,^4\], and Speicys, Jensen, et al.\[^1\,\,^5\] have proposed various network models. However, because they did not consider the physical constitution of a road network, it is difficult to represent a road network in the real world with their data models.

In view of the inadequacies of the support to trajectory data in existing road network data models, this paper presents a trajectory-oriented, carriageway-based road network data model, in short “CRNM”. The CRNM, as an extension to existing models, can not only provide trajectory data with spatial reference, but also facilitate trajectory data queries. The CRNM will be described in detail in the second part of the series.

### 1 Basic representation approaches for a road network

A road network, as a measure of conquering distance in space, is linear in nature. It consists of strip-shape roadway entities and intersections which are connected together physically. On the basis of a road network, the public transit network which consists of transit stops and in-transit or line-haul links is established\[^1\,\,^6\]. In view of the linear characteristics of road network and public transit network, the node-arc model is employed to represent them\[^1\,\,^7\]. In the node-arc model, an arc must start and end at two nodes, respectively, a node must be a starting point or an ending point of one or several arcs and different arcs can only intersect at nodes. For a road network, a node corresponds to an intersection while an arc corresponds to a roadway entity. For a public transit network, a node corresponds to a transit stop while an arc corresponds to an in-transit or line-haul link. In the present study, only the node-arc model for a road network is discussed.

The spatial extent of a road network divides the space into two parts, namely on-road space and off-road space. Since transportation features, which are really concerned, such as bus stops, road pavements, and vehicles are mostly located in or near the on-road space, it is reasonable to consider employing the underlying road network to provide spatial references for those transportation features. By this means, linear (or location) referencing systems (LRS) are developed. The principle of LRS is to provide spatial reference for an unknown location through the offset distance between the unknown location and a known location along a linear feature within a road network. Therefore, a LRS typically includes three parts, a road network, a location referencing method (LRM), and datum\[^1\,\,^8\,\,^9\,\,^1\,\,^0\]. The road network that is generally represented with the node-arc model is the foundation of LRS. The LRM determines how to locate an unknown location based on the above principle. The datum is the set of objects with known georeferenced locations\[^1\,\,^1\,\,^2\]. Both the road network and the datum are directly measured in the ubiquitous coordinate system. They jointly map unknown locations to the real world through the LRM.

Different representations of a road network affect the selection of LRM which usually determine the designations of datum. Three catego-
ries of LRM ascertained by Nyerges[18] are “road name and reference point”, “control section” and “link and node” approaches. A detailed discussion on these approaches can be found in Miller and Shaw[16]. In general, the first two approaches, i.e., “road name and reference point”, and “control section”, can only provide unknown location events with approximate spatial references, and thus they are not suitable to locate trajectory of a moving vehicle. On the other hand, the “link and node” LRM that utilizes the node-arc model to represent a road network doesn’t designate any fixed reference point along a road segment in advance but employs the nodes in the node-arc model directly as the datum. The link in the “link and node” LRM is a synonym for the arc in node-arc model. Spatial references are accurately calculated through the offset distance to a node along a link/arc. The “link and node” LRM is a straightforward approach to provide accurate spatial references for trajectories of moving vehicles.

The initial objective of developing LRS is to facilitate maintaining information of static transportation infrastructures which are related to or attached to a road network[14]. Introducing LRS as well as the node-arc model into the present study is in order to extend and apply them to trajectory data.

2 Geometric roadway entities

As mentioned in Section 1, loosely to say, a road network consists of linear roadway entities and intersections. However, to be exact, there are different types of roadway entities in the real world. From a geometric perspective, a roadway entity can be a road segment, carriageway, or lane. From a non-geometric (or, administrative) perspective, a roadway entity can be a street. Correspondingly, an intersection, which is determined by roadway entities, can be the point where streets, road segments, carriageways, or lanes start, end, or meet. Therefore, in order to represent a road network concisely, the different kinds of roadway entities and their relationships are analyzed as follows.

A road segment can be divided into two (or more) parallel strips by dividing (or median) strips, and the each parallel strip, which is a one-way roadway entity, is defined as a carriageway[20]. If there is no dividing strip on a road segment, then the road segment is also a carriageway, but the carriageway maybe is a one-way or two-way roadway entity. A carriageway can not include any dividing strip but it may include one or several traffic lanes with same or opposite moving directions. A lane is a strip of roadway entity for a single line of vehicles. In many cases, there is no physical dividing strip but double-line divider to prohibit U-turn at random points along a road segment[20]. Since both measures are used to divide directional traffic flow and drivers are not allowed to cross them in principle, we treat a double-line divider the same as a physical dividing strip.

Fig. 1 illustrates different compositions of road segments, carriageways, and lanes. Since a roadway entity usually is a strip-shape feature, it is easy to represent it with its centerline and width. In what follows, we will use the centerline of a roadway entity to refer to the entity if there is no explicit description, for example, roadway \( c_r \), which refers to the roadway whose centerline is \( c_r \). In Fig. 1 (a), \( c_i \) is the centerline of the horizontal road segment (also called dual carriageway) which includes two carriageways whose centerlines are \( c_4 \) and \( c_5 \), respectively. \( c_4 \) is also the centerline of the lane in the carriageway. The carriageway \( c_4 \) includes two lanes \( c_3 \) and \( c_5 \) which have the same traffic direction. In Fig. 1 (b), the horizontal road segment only includes one carriageway, and their centerlines are both \( c_1 \). The carriageway \( c_1 \) includes two opposite-direction lanes whose centerlines are \( c_5 \) and \( c_6 \), respectively.

According to the above definitions, there should be a one-to-many relationship between road segments and carriageways, and a one-to-many relationship between carriageways and lanes. The one-to-many relationship, as illustrated in Fig. 2 (a), between \( A \) and \( B \) means the ce-
Interline of each A parallels the centerlines of one or several Bs and all these centerlines have identical length if the small differences at curving parts can be ignored, and inversely, for each B, there must be one A that meets the above relationship with the B. The one-to-many relationship facilitates providing references for each other, or in other words, simplifying the relationships among roadway entities and eventually the road network data model. However, in the real world, different carriageways, which share one road segment, or different lanes, which share one carriageway, often have the separate intersection points that are used to determine the segmentation of roadway entities, and thus the carriageways and lanes maybe have different lengths. As a result, the one-to-many relationship can not be maintained, and instead, a many-to-many relationship, as illustrated in Fig. 2 (b) is formed.

For examples, if a segmentation is that a carriageway must start and end at the points where the carriageway intersects other carriageways, then, in Fig. 1 (a), two carriageways whose centerlines both parallel $c_3$ will be different in length. The carriageway whose centerline is $c_1$ intersects other carriageways from two roadway entities, i.e., $R_1$ and $R_2$, at point $A$ and $B$, and thus a carriageway can be segmented as a roadway entity between point $A$ and point $B$. On the other hand, because of the dividing strip $c_2$, the other carriageway whose centerline is $c_4$, doesn’t indeed intersect any other carriageway at either point $A$ or $B$, and thus it shouldn’t be segmented at the two points. As a result, the two carriageways are different in length. A similar case happens in Fig. 2 (b) if a similar assumption that a lane must start and end at the points where the lane intersects other lanes is adopted. Lane $c_9$ intersects lane $c_8$ at point $F$ and never intersects lane $c_6$. According to the segmentation assumption, point $F$ should be an end point of lanes $c_8$ but not lanes $c_6$, which makes the lengths of lanes $c_8$ and $c_6$ different. As a consequence of the above two cases, in one road segment / carriageway, there are several carriageways / lanes with different lengths, and these carriageways / lanes maybe cross several road segments / carriageways. The consequence leads to a typical many-to-many relationship between different roadway entities of a road network.

Many-to-many relationships make it complicated to providing references among different roadway entities and the road network data model. Introducing virtual intersection points (e.g., point $C$, $D$, and $E$) and using them to segment a
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3 Non-geometric roadway entities

Besides the aforementioned geometric features of a road network, another important attribute associated to roadway entities is the roadway’s identification. Generally, the identification is a unique name associated with one or several road segments. Therefore, another category of roadway entity is defined as street, a non-geometric feature, by this paper. One street, which consists of one or several contiguous road segments, must possess a unique identification, e.g., street name. Through road segments, the relationship between geometric features and non-geometric features can be built.

The streets in a road network usually have been designated (or segmented) already and are familiar to the general public, whereas there is no unified rule to designate road segments. Therefore, the relationship between streets and road segments is undetermined. However, if road segments are segmented short enough, a one-to-many relationship between streets and road segments can be maintained. The one-to-many relationship in this case means that each street consists of one or several road segments piecewise at the parallel direction of vehicle movement and each road segment must be only included in one street.

In most of trajectory data queries, street names always appear in query conditions. It is the reason why street is considered in the development of a trajectory-oriented road network data model. For example, in Fig. 1(a), consider a query “to calculate the average velocity of traveling from west to east in the segment of street R3 between the intersection points A and B”, where $R_3$ is the name of the street that includes the road segment $c_3$. Indeed, the query is to retrieve velocity information on the carriageway $c_i$ between points A and B. By this means, it is feasible to convert query conditions from non-geometric features (i.e., streets) to geometric features (i.e., road segments, carriageways, and lanes), and it is also necessary to convert them because network calculations must be conducted with geometric features eventually.

4 Conclusions

Conclusively, the constitution of a road network can be illustrated in Fig. 3. Four kinds of linear features (i.e., lanes, carriageways, road segments, and streets) and one kind of point feature (i.e., intersections) constitute a road network. Carriageway and lane are used in the network calculations to evaluate the queries with conditions expressed with streets. Road segments, as middle objects, translate street-specific query conditions into carriageway-and-lane-specific query conditions.

In the light of the above introduction and definition, the CRNM will be presented in the second of the series of papers.

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