Spatio-Temporal Conceptual Data Modeling of Urban Road Based on Geographic Information System

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Abstract. The urban road is the foundation of smart city construction, and its successful management benefits the entire city. However, currently, the spatial characteristics of the urban road are relatively simple in a geographic information system (GIS), causing limitations in urban road management. This study analyses the contents and properties of the spatial and temporal objects of urban roads, such as road segments, bridges, tunnels, and road ancillary facilities, and determines their spatial and temporal relationships. Thus, this study constructs a spatio-temporal conceptual data model of the urban road using the unified modeling language. This model provides basic information for an urban road spatial and temporal data in GIS and is also the basis for constructing the urban road logical and physical model. An urban road example is used to demonstrate the model application.

1. Introduction
The urban fine management system has become an essential component of supporting the development of smart cities, with urban roads being one of the vital objects in fine management content. The urban road is an urban facility directly related to residents’ daily life, and its construction, operation, and maintenance will continually produce large-scale data. The current urban road management mode is mainly based on on-site records, manual processing, and experienced decision-making, which is difficult to satisfy the requirements of smart city fine management.

Geographic Information System (GIS) can build an urban road data model with the object being the space and time of an urban road. However, there are still flaws in the current model. For example, in some GIS spatio-temporal data models of urban roads, the spatial characteristics of roads are generally simplified as single or double line elements, and intersections are set as point elements, which are only used to describe simplified traffic conditions. Unfortunately, the road segment in the actual urban road management contains specific ancillary facilities such as roadway, sidewalk, and street lights. The space and time information, as well as the attributes of these facilities, are not reflected in the current spatio-temporal data model.

In this study, by considering urban road design and management specifications, the urban road objects are subdivided by classes and transformed into objects that can be recognized and expressed by GIS, and then the spatio-temporal relationship between the objects is analyzed, to build a conceptual spatio-temporal data model, which provides basic conditions for the informatization of urban road in GIS.

2. Research background
Some scholars have researched spatio-temporal data models based on GIS with respect to municipal facilities operation and urban traffic management.

Zhang Z [1] investigated an incremental spatio-temporal information expression and public municipal infrastructure spatio-temporal information integration technology. The investigation demonstrates that the current data model lacks the expression of time elements, and spatio-temporal data modeling can integrate time and space data generated during the operation of facilities, to reflect the historical and current situation of facilities.

Tang W [2] proposed a GIS data model for urban municipal roads (MRGISDM). The current manual management of urban roads is considered inefficient, thus the necessity to build a GIS data model and use GIS to organize and store urban road data. The data model mainly includes three aspects: conceptual, logical, and physical models. After research, Geodatabase data mode is selected to store the data model after the research, and a unified modeling language (UML) is used to describe it.

Xiao L et al. [3] summarized the main characteristics of common GIS models, analyzed each model’s advantages and disadvantages, and proposed the key principles of building an object-oriented GIS data model. The study reveals that the topological relationship data model emphasizes the relationship between geometric elements, and representing complex geographical entities is difficult, whereas the entity-oriented data model lacks the expression of topological relationship. Therefore, the study developed an object-oriented GIS data model, with the primary goal of expressing the geometric, topological, and semantic relationships between objects, such as time, space, and attributes.

Q. K. Harpham [4] studied a universal spatio-temporal data integration classification technology. It is considered that there are many auxiliary technologies for environment modeling, some of which are redundant. Thus, a universal structured theoretical framework is proposed, which describes the structure of space and time data by classifying spatio-temporal data, and supports the effective integration of entity object data in GIS.

The aforementioned studies have explored the data mapping problem of urban facility entities in GIS, and they all suggest that space and time data are important components of the urban facility. Based on the existing research, this study considers the urban road, which is a component of urban facilities, as the research object. A spatio-temporal data conceptual model should be built in GIS due to the complexity of urban road attributes, and then the logical relationship between the data information should be established.

3. Basic definition

The urban road concept includes not only the road itself but also its ancillary facilities. Based on the latest urban road management regulation [5], urban roads are defined as roadways, sidewalks, bridges, tunnels, and ancillary facilities with certain technical conditions for vehicles and pedestrians.

The main body of urban road construction can be government and enterprise. The urban roads management department can be further subdivided within its scope based on the types of ancillary facilities. The Gardening and Greening Bureau, for example, is responsible for the greenbelt, green island, and other greening facilities; Pipelines and their well covers are maintained and managed by several maintenance departments, depending on the type of pipeline. For example, the electric company (e.g., State Grid Corporation of China) is responsible for power and cable wells, whereas the communication department (e.g., China Unicom) is responsible for telecommunications. Therefore, ancillary facilities need to be included in the scope of urban roads.

3.1. Spatio-temporal information of urban road

The spatio-temporal information on urban roads includes two parts: space information and time information.

(1) Urban road ancillary facilities are managed by several maintenance departments. Therefore, it is necessary to divide the facilities into entities to manage their information. There are many types of
relationships among facilities in terms of spatial distribution, such as inclusion and parallel between ancillary facilities and road space.

(2) The urban road time information is the basis of an efficient urban road operation. Urban road data vary with time in the context of smart cities, and operation and management businesses have obvious time characteristics. For example, with the expansion of urban road scale, its spatial layout, spatial location, and attribute information changes with time; in the process of urban road construction and operation, the construction and completion progress changes with time; in the process of urban road maintenance and inspection, there is a stipulated time when the action is performed. All these reflect the importance of urban road time information.

3.2. Conceptual model of urban road spatio-temporal data

The urban road spatio-temporal data conceptual model is the expression of real space and time information in GIS. The space and time information of roads, bridges, and their ancillary facilities in urban roads must be understood and studied as real-world information, and then be abstracted and organized to map the spatio-temporal information into a data form that can be recognized and processed by GIS, to clarify the spatio-temporal entity objects and their network relationships.

4. The object and network of spatial-temporal data conceptual model

Entity objects can be abstracted as elements in GIS, and the same elements can form element classes; Nonentity objects, like time, can be abstracted into objects and object classes. The urban road includes several elements such as road, road segment, bridge, tunnel, and road ancillary facilities. A road segment class is made up of several elements with the same scale, such as road segments.

4.1. Spatial objects

The elements of an urban road system may be classified into three levels based on their inclusion: the first level of element is the road, the second level is road segments, and the third level includes bridges, tunnels, and ancillary facilities (see figure below). Bus stations, street lights, and road greenbelts are the ancillary facilities within the road segments. Each entity corresponds to a certain type, such as a road class, road segment class, bridge class, tunnel class, and many more.

![Figure 1. Urban road entity hierarchy](image)

Each entity’s attribute information should be provided in the spatial object. A goal of this study is to use GIS to subdivide the facility objects of urban roads, making it easier to record and interpret road facility data. Therefore, attribute fields must be added to each type. For example, the following are the attributes of road segment as a polygon element:
Road Length: a road is composed of segments of a certain scale, and the length of the road is the total length of the segments it contains;

Road Width: the width of the road investigated in this study should be the horizontal distance between the red lines on both sides of the road, which include sidewalk, road green belt, and other features;

Road Grade: urban roads can be divided into four grades: expressway, trunk road, secondary trunk road, and branch road;

Pavement Material: the roadway and sidewalk pavement materials are different. Roadway materials include cement concrete pavement, asphalt pavement, and others; pavement materials include color prefabricated brick pavement, natural stone pavement, and many more.

4.2. Time object

The time object of urban roads includes structure, density, and granularity. In terms of time structure, urban road facilities frequently undergo several timed events such as construction, completion, operation, and maintenance, thus a linear time structure should be adopted. The characteristic of urban road maintenance is the occurrence of an emergency in a certain stable state, so discrete-time can be used to describe its data density. Because the daily operation state of urban roads is relatively stable, the unit “day” can be used as its time granularity, i.e., the smallest time unit.

4.3. Spatial relationship

There are two major types of urban roads in a spatial relationship, based on spatial affiliation: one-to-one and one-to-many. One-to-one refers to elements that do not spatially contain each other, whereas one-to-many refers to an element that contains more than one other element. For example, if a road comprises multiple road segments, the relationship between road and road segments is one-to-many. When a road segment consists of multiple lanes, sidewalks, tunnels, and ancillary facilities, it has a one-to-many relationship with the elements it contains. The walkways and road greenbelts are segregated, thus having a one-to-one relationship. From the three levels of entity, the first and second-level elements exhibit a one-to-many relationship, the second and third-level elements also exhibit a one-to-many relationship, and the third-level elements exhibit a one-to-one relationship. In GIS, spatial relationships are used to correspond to the topological relationships among the elements, one-to-many can correspond to the relationships of “contains,” “points within a region,” whereas one-to-one can correspond to the relationships of “adjacent.”

4.4. Time relationship

Time relationship represents the distribution of entities over time. The time object of an urban road can be divided into two types: time and time period, as well as three types: time direction, time distance, and time topological relationship. Time direction describes the order in which events occur. Time distance describes the time interval between events. Time topological relationship describes the relationship between time and time period. Time point can be used to represent time and time edge to represent the time period. The topological relationships are shown in the following table.

| Relationship | Object |
|--------------|--------|
|              | time point/time point | time edge/time edge | time point/time edge |
| EQUALS       | ✓       | ✓                  | ✓                  |
| BEFORE       | ✓       | ✓                  | ✓                  |
| AFTER        | ✓       | ✓                  | ✓                  |
| DURING       | ✓       | ✓                  | ✓                  |
| STARTS       | ✓       | ✓                  | ✓                  |
| FINISHES     | ✓       | ✓                  | ✓                  |
| MEETS        | ✓       | ✓                  | ✓                  |

Table 1. Time topological relationship of urban road
5. Building spatial-temporal data conceptual model

This study builds an urban road spatio-temporal conceptual data model using UML, based on the aforementioned research. First, the conceptual model of spatial data is constructed. The spatial objects contain geometric features, topological relations, and attribute information. The geometric features of the road, for example, can be abstracted as “Line Element,” which represents the road’s centerline. The bridge, tunnel, roadway, sidewalk, and other items in the road segment must reflect their length, width, and other attributes in the road management, so the geometric characteristics of the objects in the road segment are “polygon element.” Ancillary facilities on urban roads, such as bus stations, take up limited space, and their management focuses more on data such as coordinates and ownership, so they can be used as “Point Element.” Object classes are made up of several objects, and their spatial relations are expressed in the model shown in the figure below.

Figure 2. Spatial conceptual data model of urban road

This study introduces temporal data into an urban road spatio-temporal data conceptual model. Using road segments as an example, temporal data are the state and operation information of road segments at a specific time. The urban road spatio-temporal data conceptual model after introducing temporal data is presented in the figure below.
6. Example

This study applies a spatio-temporal data conceptual model based on the information of urban road section, roadway, and sidewalk. Because the road section includes the bridge, tunnel, roadway, sidewalk, and other facilities, only the road section, roadway, and sidewalk are selected as the research object due to the limited space of this study, and their spatio-temporal data tables are listed as follows:

Table 2. Spatio-temporal data table of urban road

| Level | Attribute             | Code  | Field Type | Key Type  |
|-------|-----------------------|-------|------------|-----------|
| 1     | Urban Road ID         | DLBM  | VARCHAR    | PRIMARY   |
|       | Name                  | DLMC  | VARCHAR    |           |
|       | Location              | WZQY  | VARCHAR    | FOREIGN   |
|       | Record Date           | SJRQ  | DATE       |           |
|       | Class                 | DLDJ  | VARCHAR    | FOREIGN   |
|       | Origin                | DLQD  | VARCHAR    |           |
|       | Destination           | DLZD  | VARCHAR    |           |
|       | Length                | DLCD  | NUMBER     |           |
|       | Width                 | DLKD  | NUMBER     |           |
|       | Construction Time     | JSSJ  | DATE       |           |
|       | Construction Company  | JSDW  | VARCHAR    | FOREIGN   |
|       | Last Maintenance Time | YHSJ  | DATE       |           |
|       | Maintenance Company   | YHDW  | VARCHAR    | FOREIGN   |
|       | Maintenance Condition | YHQK  | VARCHAR    |           |

Table 3. Spatio-temporal data table of the road section

| Level | Attribute             | Code  | Field Type | Key Type  |
|-------|-----------------------|-------|------------|-----------|
| 2     | Road Section ID       | LDBM  | VARCHAR    | PRIMARY   |
|       | Name                  | LDMC  | VARCHAR    |           |
|       | Location              | WZQY  | VARCHAR    |           |
|       | Record Date           | SJRQ  | DATE       |           |
|       | Class                 | LDDJ  | VARCHAR    |           |
|       | Origin                | LDQD  | VARCHAR    |           |
|       | Destination           | LDZD  | VARCHAR    |           |
|       | Length                | LDCD  | NUMBER     |           |
|       | Width                 | LDKD  | NUMBER     |           |
Table 4. Spatio-temporal data table of roadway

| Level | Attribute                | Code   | Field Type | Key Type |
|-------|--------------------------|--------|------------|----------|
| 3     | Roadway ID               | CXDBM  | VARCHAR    | PRIMARY  |
|       | Record Date              | SJRQ   | DATE       |          |
|       | Length                   | CXDCD  | NUMBER     |          |
|       | Width                    | CXDKD  | NUMBER     |          |
|       | Direction                | CXDFX  | VARCHAR    |          |
|       | Number of Lanes          | CXDSL  | NUMBER     |          |
|       | Speed Limit              | CXDXS  | NUMBER     |          |
|       | Pavement Material        | LMCZ   | VARCHAR    | FOREIGN  |
|       | Last Maintenance Time    | YHSJ   | DATE       |          |
|       | Maintenance Company      | YHDW   | VARCHAR    | FOREIGN  |
|       | Maintenance Condition    | YHQK   | VARCHAR    |          |
|       | Road Section ID          | LDBM   | VARCHAR    | FOREIGN  |

Table 5. Spatio-temporal data table of sidewalk

| Level | Attribute                | Code   | Field Type | Key Type |
|-------|--------------------------|--------|------------|----------|
| 3     | Sidewalk ID              | RXDBM  | VARCHAR    | PRIMARY  |
|       | Record Date              | SJRQ   | DATE       |          |
|       | Length                   | RXDCD  | NUMBER     |          |
|       | Width                    | RXDKD  | NUMBER     |          |
|       | Direction                | RXDFX  | VARCHAR    |          |
|       | Pavement Material        | LMCZ   | VARCHAR    | FOREIGN  |
|       | Last Maintenance Time    | YHSJ   | DATE       |          |
|       | Maintenance Company      | YHDW   | VARCHAR    | FOREIGN  |
|       | Maintenance Condition    | YHQK   | VARCHAR    |          |
|       | Road Section ID          | LDBM   | VARCHAR    | FOREIGN  |

7. Conclusion
This study investigates and builds a spatio-temporal conceptual data model of an urban road, which provides basic information for urban fine management. The amount of spatio-temporal information of urban roads is enormous, including not only the spatial information of road segments, bridges, tunnels, and ancillary facilities, but also the time information of operating events. By abstracting the spatio-temporal information into a model, the urban road system can be recognized and managed by GIS. The model divides urban road entity space objects into elements and element classes, which include the attributes that the entity must manage, such as length, width, and grade. Several constructions, maintenance, and other events in urban roads are described by linear and discrete-time objects with “day” as the unit. Considering space–time relationships, there are one-to-one and one-to-many relationships in terms of space, and it mainly describes the topological relationship between time points and time periods in terms of time. This study builds a spatio-temporal conceptual data model of
urban roads, based on the above information, which provides the basis for the subsequent construction of logical and physical models. An urban road example is used to demonstrate the model application.

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