Hierarchical lane-oriented 3D road-network model

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Research Article

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The existing road-network models based on the 2D link-node of roadway centrelines have inhibited lane-oriented network flow analysis and multi-dimensional inventory management in complicated 3D urban environments. This paper proposes a hierarchical lane-oriented 3D road-network model (HL-3DRNM), with a unified modelling language (UML) diagram. HL-3DRNM is a non-planar topological model with the support of a 3D lane ribbon cartographic display, which is characterized by: (1) multiple topological and cartographic representations and various abstraction levels (street, road segment, carriageway and lane); and (2) referenced multi-dimensional road information (point, line, area and volume) at lane level. HL-3DRNM provides solid mathematical foundations for a more detailed inventory management, effective network analysis and realistic navigation in the increasingly complicated 3D urban transportation systems.

Keywords: 3D GIS; Lane; Road-network model; Dynamic segmentation; GIS-T

1. Introduction: from 2D to 3D road networks

Roads are one of the most important elements related to urban life. With the rapid process of urbanization, more and more complicated transportation infrastructures are built in the third dimension, both upwards and downwards, such as flyovers, tunnels, and over-/underpasses (Zhou and Zhang 2003). Because of these changes, people's recognition of road networks is no longer constrained to the 2D planar world. On the other hand, in order to facilitate effective and efficient traffic management and logistics, more detailed traffic rules are under development; for example, multi-lanes, no turn lanes, bus-exclusive lanes, speed-limited lanes, temporal closed lanes, no oversize/overweight lanes, auxiliary lanes, etc. The speedy development of transportation systems, as well as the need for advanced transportation applications (i.e. emergency response, automated navigation, and lane-oriented road management), calls for suitable road-network models to describe the real 3D situation and to provide more detailed information on the road network of a city.

The rich 3D information of a road network can be summarized from three aspects: cartographic representations, attributes and semantic relationships. Taking a flyover as an example, 3D information involved in the cartographic representation

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includes two aspects: texture and geometry, and the important 3D attributes, such as slopes, 3D distances, and curved angles have been closely attached to the 3D cartography. Modelling a road network in 3D can also explicitly represent the 3D semantic relationships, such as above and below.

As shown in figure 1, a flyover can be modelled as a junction in a 2D roadway centreline-based network, or as a series of links in a 2D carriageway-based network model, each leading to a totally different result in the network analysis. The rich 3D information involved in 3D road networks has challenged the traditional 2D model because: (1) the visualization of 3D structures and 3D operations (such as 3D distance measurement) cannot be obtained from 2D models; (2) 2D models simplify the complicated transportation system to a single line network and even treat flyovers as points, which will be problematic in a real transportation application at a very large scale; and (3) 3D objects presented as 2D projections in GIS may lose some of their properties (texture, graphic, height, etc.) and their spatial relationships to other objects.

Besides the rich 3D information, road networks are usually abstracted as hierarchical or multi-level structures in order to facilitate database management as well as to better reflect the regulation of human cognition. GDF 4.0 (ISO 14285:2004) gives an example for the modelling of flyovers in a three-level structure, where Level 0 is the cartographic representation, Level 1 is the simple element representation, and Level 2 is the complex element representation.

In figure 2, two flyovers are physically connected by a short road segment S104, consisting of two directional carriageways L703 and L704. In the Level 1 model of GDF 4.0, each directional main road and ramp is represented by a single element; however, in the Level 2 model, the directional main roads and ramps are aggregated into two points, N901 and N902, and each point consists of the related main roads and ramps. In reality, the intersection point does not exist, and the linkage between the points is virtually represented. For example, L101~L106, L501~L506, and L601~L608 logically link with point N901, and the virtual links between the virtual point and the end-points of other roadways have been built correspondingly, such as S102 and S103.

Figure 1.   From 2D to 3D road networks.

Level 0
Cartography

Level 1
Carriageway

Level2
Roadway Centreline

Figure 2.   Abstraction of a flyover in a three-level network model.

It is obvious that the rich 3D information cannot be explicitly represented in the highly aggregated Level 2 model of GDF 4.0. Since the Level 1 model for the flyover provides a more detailed abstraction, however, the 3D information can only be located, reported, and analysed at the carriageway level, rather than at the lane level. In this paper, a new hierarchical structure—a 'roadway centreline-carriageway-lane'—is proposed (figure 3). This hierarchical structure is adopted in order to reveal fully the real features of 3D road networks and support both 3D visualization and hierarchical network analysis; in addition, the factors of human cognition knowledge are also considered. The characteristics of each hierarchical structure are illustrated as follows:

- Level 1: Roadway centreline (R). This provides macro-scale abstraction for road networks by using a single line to depict the road's general configuration and treats a complicated flyover as a node. Roadway centrelines are aggregated into streets with one direction or bi-direction, commonly used in applications such as transportation planning, street naming, and digital mapping.

Classification	Characteristics	Applicability	
Level 1: Roadway Centreline (R)	One-way or bi-directional; Aggregated into Street	Transportation planning; Street Naming; Digital Mapping	Macro-
Level 2: Carriageway (C)	Divided by physical dividing strips or double-line divider; One-way or bi-directional;	Trajectory data analysis; Traffic flow analysis	
Level 3: Lane (L)	Linked with lane ribbon; Only one direction	Traffic management; Auto navigation; Emergency response	Micro-

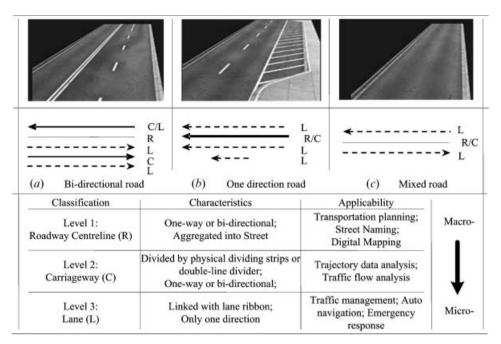Figure 3.   Hierarchical structure of road networks.

- Level 2: Carriageway (C). This is a collection of lanes with the same (in most cases) or different traffic flow directions, without physical dividing strips or a double line divider between the lanes (Church and Noronha 2003). The carriageway provides meso-scale abstraction for road networks. In a carriageway-based network model, a flyover is depicted as a series of links; therefore, it can serve for more advanced applications such as trajectory data analysis and traffic-flow analysis.
- Level 3: Lane (C). This provides micro-scale abstraction for road networks by using multiple lines with unique directions to reflect real vehicle movement and true transportation phenomena. Lane can be subdivided into physical lanes and virtual lanes. A physical lane is linked with a lane ribbon, which is represented as an elongated region with clear boundaries on a road surface, to allow the representation of the photorealistic geometric configuration of individual lanes. Virtual lanes are dynamically added at intersections or among physical lanes.

The remainder of this paper is organized as follows. Section 2 introduces the state of the art of road-network models. Section 3 discusses the structure of the hierarchical lane-oriented 3D road-network model by means of a unified modelling language (UML) diagram. Section 4 covers the implementation issues. Finally, concluding remarks are presented in section 5.

2.   State of the art of road-network models

A road network used to be universally represented as a node-arc model by a set of nodes and a set of links. In the past two decades, some classic road-network models were reported in the publications of transportation societies. Even though those models were given different names, such as the linear data model (Guo 2001), the

GIS-T data model (Miller and Shaw 2001), or the transportation data model (Curtin *et al.* 2003), the basic meanings were the same, but with the emphasis on different parts. In this paper, the concept of 'road-network model' (Oracle 2005) is adopted in order to show its emphasis on the data management and traffic-flow analysis related to the road-network system. Three groups of road-network models, namely, basic network models, process models, and object models, have been categorized by Curtin *et al.* (2003). It is believed that this classification has shown the evolutionary history of the road-network model; however, in this paper, another classification schema is given (table 1) in order to emphasize the application characteristics, such as anchoring to 2D navigation, lane-oriented analysis, 3D measurement and visualization, cross-enterprise application, and business implementation. In each group, several typical and prevailing models (Gottsegen *et al.* 1994, Fohl *et al.* 1996, Bespalko *et al.* 1998, Dueker and Butler 1998, Adams *et al.* 2001, Koncz and Adams 2002, Curtin *et al.* 2003, Demirel 2004a, Liu *et al.* 2005, Malaikrisanachalee and Adams 2005, Zuo *et al.* 2005, Li and Lin 2006) are discussed further.

A 2D navigation model is proposed to facilitate the calculation of the best route and to allow navigation by considering the driving habits and the use of trajectory data, mainly in a 2D GIS. Li's carriageway-based road-network model (CRNM) (Li and Lin 2006) facilitated mutual references among different levels of road entities. The basic modelling entity was the carriageway, which could approach the actual trajectory of a vehicle more feasibly and concisely than the roadway centreline. However, the size and the central location of the zone were difficult to determine in real applications of the proposed 'intersection zone'. Liu *et al.* (2005) proposed a feature-based, two-level structure road-network model for navigation. Level 1 was a feature-oriented geometry network used for showing the map, while level 2 was a node-link based logical network for route planning. In their model, a two-layer network topological structure was also presented, which was better for the driver than the traditional method of treating the entire road network as one graph. However, the proposed two-layer topology, considering the hierarchy of the transportation network and the division of transportation zones, was only suited for macro-scale routing because there was no lane-oriented information represented in the model.

A lane-based model is set to represent the appearance/disappearance of lanes, giving connectivity among parallel lanes and at turns. The non-planar, lane-based model of Fohl *et al.* (1996) utilized lanes as the primary element for analysis, and streets as the primary feature for display. Lanes were referenced to roadways through the linear offsets of the start and end locations of the lanes from the roadway centreline. Connectivity between lanes at interchanges was managed by the use of the point turntable, while continuous lateral connectivity between parallel lanes was maintained separately in the linear turntable. However, this procedure added to the complexity of encoding lane topology and restricted the model to specific GIS platforms that supported the use of turntables. Besides, there was no consideration of semantic information, which is very important in efficient transportation applications, especially in urban areas. In view of the above problems, Malaikrisanachalee and Adams (2005) proposed a solution that built the lane topology but eliminated the use of any 'turntable'. In their model, the lane was populated through the roadway centreline; the concepts of 'lateral sequence' and 'virtual lane' were added to maintain the lateral connectivity among the parallel lanes. In addition, the added lateral dimension allowed business data to be

Table 1. Comparison of existing road-network models.

Classification	Analysis	
	Main strengths	Main weaknesses
2D navigation models		
CRNM (Li and Lin 2006)	Mutual references among different kinds of entities; carriageway-based geometry	Intersection zone is hard to determine; never provides lane-level datum; hard to support lane-level navigation
Feature-based (Liu *et al.* 2005)	Feature-based approach; two-level structure; two-layer topology	Two-layer topology only suits macro-scale network analysis
Lane-based models		
Non-planar lane-based (Fohl *et al.* 1996)	Treat lane as independent entity for analysis; Non-planar concept	Turntable adds complexity to the system; no 3D and semantic consideration
Lane-based (Malaikrisanachalee and Adams 2005)	Add lane sequence; eliminates the use of turntable; modelling polygon feature	No multi-scale representation and 3D consideration; dynamic segmentation derived from roadway centreline
3D models		
Formal GIS-T (Bespalko *et al.* 1996)	3D geometry; lane-based; topologically correct	Only a conceptual model
Multi-dimensional (Demirel 2004b)	Conceptual decomposition of topological, geometric and thematic information; non-planar and two levels of topology; 3D geometry	The proposed two-level topology only suits macro-scale network analysis
3D data model (Zuo *et al.* 2005)	3D linear referencing system; support 3D visualization; synthesized lane topology	No attempt to consider lane-level topology; dynamic segmentation has not located at lane level
Enterprise LRS models		
NCHPR 20–27 (2), (3) (Adams *et al.* 2001)	Solid foundation; across one, two, three, and four dimensions	Datum is difficult to maintain; model is difficult to implement
GIS-T Enterprise (Dueker and Butler 1998)	Supports areal transportation facilities and events; event-centric	More complex and no 3D and temporal considerations
Business models		
UNETRANS (Curtin *et al.* 2003)	Object-oriented; seven object packages	No 3D and lane-level topology considerations
GeoTrans (Hardy 2005)	Multiple and intersection referencing method	Only LRS function at present; 2D analysis

maintained as polygon features. However, the model was derived from a 2D reference network, and so no multi-scale representations or 3D factors were considered.

A 3D model aims to resolve problems such as: (1) true distance measurement across hilly terrain; (2) representation of 3D structures, such as overpasses and on-ramps, and (3) assigning multiple routes over a single arc (Miller and Shaw 2001). Bespalko *et al.* (1996) discussed the characteristics of a 3D GIS-T data model. It was

believed that a formal 3D GIS-T model (Bespalko *et al.* 1997) should be three-dimensional, lane-based, and topologically correct. However, the model remained at the conceptual level; moreover, the implementation issues were still confusing. Demirel (2004b) proposed a dynamic multi-dimensional (3D geometry and time) data model that involved multi-dimensional location referencing and multi-scale representation. This model aimed to decompose geometry, topology and non-spatial data. The basic component—geometry—was defined fully in 3D, while topology, being non-planar, had two abstraction levels. Non-spatial information was introduced into the system as the 'Road Event' component. However, the proposed two-level topology, although different from Liu's two-layer topology (Liu *et al.* 2005) in content, was also derived from the visualization perspective and failed to consider the lane attributes and lane topology. Zuo *et al.* (2005) developed Lu's non-planar, feature-based model (Lu *et al.* 2002) by having the network topology built directly on the 3D geometry network. However, the 3D model took the synthesized lane as its basic entity. Like many other 3D models, there were no attempts to involve lane topology and the decomposition of geometry and topology.

An enterprise LRS model supports applications across an entire enterprise (e.g. agency, corporation or MPO) or across several enterprises with the use of linear referencing and dynamic segmentation techniques (Miller and Shaw 2001). The National Cooperative Highway Research Program (NCHRP) and Enterprise GIS-T model have supported such an effort. More recently, the Multi-Dimensional Multi-Modal Location Referencing System data model (MDLRS, also called the NCHRP 20–27 (3) model) was developed to integrate and effectively use data across one, two, three, and four dimensions, and among linear and nonlinear referencing systems (Adams *et al.* 2001, Koncz and Adams 2002). However, the maintenance of the linear datum is difficult and the model is too complicated to implement. The enterprise GIS-T model (Dueker and Butler 1998) is event-data-centric (Guo 2001) and object-oriented, more inclusive, and consequently more complex. The model is reported to accommodate areal inventory management; however, the areal events are managed by areal features instead of by dynamic attributes. Besides, the model provides limited 3D and temporal support.

A few business models focus on the implementation issues that incorporate existing GIS systems, such as UNETRANS (Curtin *et al.* 2003) and GeoTrans (Hardy 2005). The UNETRANS data model is object-oriented and can be regarded as a logical data model of GDF. The model provides templates for transportation-based entities based on ESRI's Geodatabase, including the following 10 packages: reference network; routing; location referencing; asset; activities; incidents; mobile objects; domain; street and address; and relationships. Another business model, the GeoTrans data model, is designed to satisfy the transportation information needs based on Intergraph products, characterized by its multiple linear reference methods and its typical 'intersection reference method' that enlarges the common LRS application in urban transportation systems. However, the current data structure of the GeoTrans data model is limited to linear reference systems, and both the UNETRANS and GeoTrans are system-dependent and therefore only support 2D analysis.

In addition to the aforementioned road-network models proposed by individuals or enterprises, there are also standards at the international level (ISO), the regional level (CEN) and the national level (i.e. GB/T 19711-2005) with particular importance to the construction of road networks. A major standardization

milestone in 2004 was the publication of the first internationalized version of the Geographic Data Files (GDF) standard, referred to as GDF 4.0 (ISO 14285:2004). The continuation of the GDF work, called X-GDF, is now under development. Its reported goals are to ensure: (1) harmonization with ISO/TC211 standards; (2) improvement of the physical record layout in terms of XML, GML and SQL; and (3) new content requirements, including the introduction of a spatio-temporal definition of a geographic object; support of safety applications; support of multi-modal transport; and support of 2D and 3D map display (Essena and Hiestermann 2005). The Chinese ITS community has actively participated in the development of X-GDF. Based on this experience, the Chinese national data model and data-exchange format for navigable spatial databases have been published and came into use in 2005 (GB/T19711-2005 2005).

The historical development of the road-network model is shown in figure 4. There are several novel concepts reported in each stage; for example, the linear referencing system (LRS) adopted in the NCHRP 20–27 model (Adams *et al.* 2001), non-planar concept proposed in the feature-based model (Zhou *et al.* 2000), lane-based (Fohl *et al.* 1996), carriageway-based (Li and Lin 2006) and a 3D road-network model (Bespalko *et al.* 1997) suggested in order to strengthen the importance of the horizontal and vertical dimensions of road-network systems. The tendency is now for road-network models to be anchored to the hierarchical lane-oriented 3D road-network model, where multi-dimensional and adaptive routing and lane-based inventory management become increasingly important and operational with the development of 3D and dynamic data-apturing technologies, such as Differential Global Positioning System (DGPS), Three Line Scanner (TLS) (Shi *et al.* 2004), etc.

3. HL-3DRNM: Hierarchical lane-oriented 3D road-network model

3.1 *Conceptual model*

The hierarchical lane-oriented 3D road-network model, HL-3DRNM for short, is the extension of a lane-based road-network model and a 3D road-network model, with the merits of other kinds of road-network models, such as the 2D navigation model, the enterprise LRS model and the business model, also being considered.
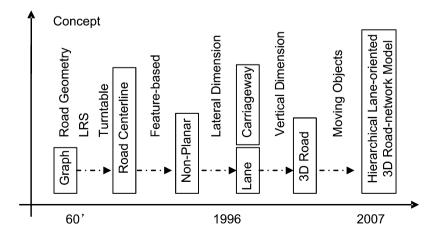

Figure 4.   Development of road-network models.

HL-3DRNM is a non-planar topological model with the support of 3D lane ribbon cartographic display and lane-oriented application. It maintains the integrity of the network data and provides better compatibility with the general hierarchical view of roads. The basic functionality of HL-3DRNM can be denoted simply by equation (1):

$$HL - 3DRNM = [\text{Geometry (3D Lane ribbon), Topology (Lane), Temporal}$$
$$\text{(Lane), Theme (Lane), Dynamic\_Segmentation} \tag{1}$$
$$\text{(3D Lane ribbon) Semantic\_Query (Street} - \text{Carriageway} - \text{Lane)]}$$

- The 3D lane ribbon provides the most accurate spatial location information, being better than the traditional 2D single roadway centreline, and also better than the 3D centreline of the lane, because the shape of the 3D lane ribbon is explicitly encoded in the real world, while the centreline of a roadway or lane is only a logical concept, and there is no corresponding physical configuration in the real world to depict the location of the roadway/lane centreline. The 3D lane ribbon is regarded as the minimum geometry feature of the road network and therefore can be aggregated into other modelling features such as carriageway surfaces or street surfaces.
- Lane topology provides the most realistic description of vehicle movement, including turns at points and movement among parallel lanes. Temporal and thematic attributes should also be associated with lanes instead of the roadway centreline, because transportation and traffic constraints, such as curve angles, vertical and lateral clearances, barriers, traffic rules, navigation signals, etc., are all referenced to single lanes rather than an entire road. Lane-oriented topology and lane-oriented temporal and thematic attributes enlarge the traditional roadway centreline model into microscopic transportation applications, for example, traffic simulation and lane-oriented traffic flow analysis.
- Dynamic segmentation is based on the lane ribbon instead of the roadway centreline. Traditionally, linear referencing systems (LRS) and dynamic segmentation are naturally combined and widely used in inventory management, because: (1) many transportation features are linear in nature; (2) it is easy to report on-road attributes; (3) they can be easily understood by users (e.g. ambulance drivers); and (4) the logical consistency of business data can be maintained. Various GIS professionals, including highway and street management organizations, utility companies, oil and gas exploration industries, pipeline industries, fleet management, automatic vehicle location systems, police and emergency management, etc., use the linear referencing functionality to maintain, analyse and plan events (assets, activities, accidents, mobile objects) that occur along their linear networks. The use of lane ribbon for dynamic segmentation enables the area or volume representation of events on the level of the lane, which widens the traditional linear referencing system.
- Semantic querying is set to retrieve the semantic relationships among streets, road segments, carriageways, and lanes. Street is a logical concept, being bi-directional or unidirectional. Road segment is an abstraction of street, dividing street into several small parts by different modelling rules. Carriageway and lane are more detailed description elements of a road network.

The relationships between the geometry, topology, and attributes of a road network have been relaxed in HL-3DRNM. The decomposition of geometry and topology facilitates the multi-model representation of the road network. Some other merits will also be derived: (1) the direct and explicit manipulation of logical networks is possible; and (2) the many-to-many relationships between cartographic representation and the logical network are facilitated. That is, it is possible to handle the network topology when the road network is decentralized, and it is also possible to build the combination of multi-scale geometry with multi-scale topology. On the other hand, the decomposition of the geometry and attributes eliminates the dependency of thematic information on a spatial component. As such, dynamic attributes of road information can be managed flexibly, and the geometry of the road network can be maintained as completely as possible.

As shown in figure 5, the simplified conceptual data model of HL-3DRNM includes four components, namely, geometry, topology, attribute, and metadata. The basic geometry component has three hierarchies. Geometry I refers to the macroscopic hierarchy, linking with road segments. Geometry II refers to the mesoscopic hierarchy, linking with carriageway, while Geometry III refers to the microscopic hierarchy, linking with the lane. Each hierarchy of geometry has been further divided into four categories, namely, point geometry, line geometry, area geometry, and volume geometry. Correspondingly, the topology component also includes three hierarchies. Topology 1 means a roadway centreline-based network, Topology II means a carriageway-based network, while Topology III refers to a lane-based network. In HL-3DRNM, road attributes have been managed by events, covering three categories, namely, assets, activities, and incidents. Assets, such as traffic signs, are represented as static physical features; activities, such as construction projects, are generally planned in advance and limited in duration; incidents are unplanned, short-term occurrences. As with the geometry components, road attributes may also have one of several spatial representations, such as point, line, area, or volume.

Transferring the simplified conceptual data model into a logical and physical model needs the identification of the main features and objects (figure 6). Features store information that has a spatial representation, while objects can only contain attributes that are related to a feature, but do not have an explicit spatial representation of their own (Curtin *et al.* 2003). The basic modelling features are points, lines, and polygons, with 3D coordinates. In order to model effectively the multi-scale road network and minimize the data storage, as well as facilitate the network analysis at the microscopic lane-level, three kinds of point feature are used: road segment node, intersection node, and carriageway node. Correspondingly, the two kinds of line feature are road segment and carriageway. An intersection zone is a kind of polygon feature, linked with an intersection node for map display. The

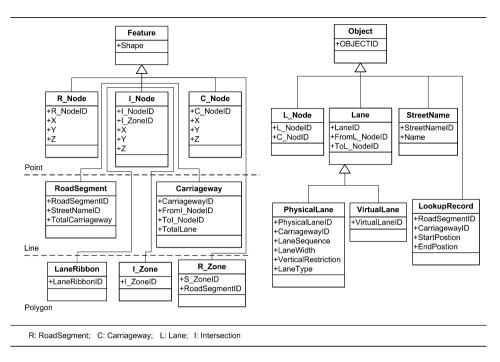Figure 5.   Simplified conceptual data model of HL-3DRNM.

Figure 6.   Main objects and features of HL-3DRNM.

other two polygon features are lane ribbon and road segment zone. Intersection zone and segment zone are used for texturing and true 3D visualization, while lane ribbon is used for lane-based inventory and lane-based route display. Objects defined in the HL-3DRNM model are of four kinds, namely, lane, lane node, street name, and look-up table. The lane object is used for topology analysis, including two sub-objects, namely, the physical lane and the virtual lane. The physical lane object is derived from the carriageway, but its cartographic representation relates to the lane ribbon. The virtual lane object is a connective element, and there is no corresponding feature. The street name object is defined for street addressing, and its cartographic representation can be derived from the road segment feature. The look-up table object is created to hold the complicated many-to-many relationships between road segments and carriageways.

The conceptual model of HL-3DRNM is further depicted as a UML diagram in figure 7. Four kinds of functional package are grouped, namely, 'Querying', 'Street centreline-based Network', 'Carriageway-based Network', and 'Lane-based Network'. In each package, several objects and features are involved, and their inner-relationships are built.

- Because of the complicated relationships between carriageways and road segments, the 'LookupRecord' object is used in the 'Querying' package. Each record in the 'LookupRecord' object includes four elements: 'RoadSegmentID', 'CarriagewayID', 'StartPosition' and 'EndPostion'. 'StartPosition' and 'EndPostion' denote the spatial relationship of one road segment and a part of a carriageway. The complicated relationship is then transferred into two simple one-to-many relationships: a one-to-many
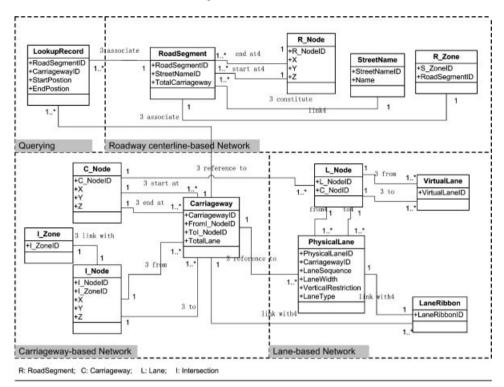
Figure 7.   UML diagram of HL-3DRNM.

relationship between 'RoadSegment' and 'LookupRecord' and a one-to-many relationship between 'Carriageway' and 'LookupRecord'.

- The features 'RoadSegment', 'R_Node', 'R_Zone' and object 'StreetName' are adopted in the 'Roadway centreline-based Network' package. 'RoadSegment' starts and ends at a roadway segment node and one 'R_Node' connects with one or more 'RoadSegment' edges. One 'RoadSegment' links to one 'R_Zone', and several 'RoadSegment' comprise a 'StreetName'. 'R_Zone' is used to support cartographic representation with texture for a road segment.

- The package 'Carriageway-based Network' comprises four features. 'Carriageway' starts at and ends at the carriageway node in its geometric network; however, in the logical network, 'Carriageway' starts from an intersection node and ends at another intersection node. As such, it is easy to build a connected network with the use of carriageway ID and intersection node ID. In order to support cartographic representation of carriageway-based network analysis and support for texturing at the intersection, the feature intersection zone is adopted and links with 'I_ Node'; the relationship is one to one.

- The package 'Lane-based Network' includes three objects and one polygon feature. 'PhysicalLane' and 'L_Node' are logically connected, and they reference to 'Carriageway' and 'C_Node', respectively. There is a one-to-many relationship between the 'Carriageway' and 'PhysicalLane'. An important variable in 'PhysicalLane' is the 'LaneSequence', which is used to denote the relative position among the parallel lanes. Some other important variables, such as lane type, lane width, and vertical restriction, can also be added to the

attributes of 'PhysicalLane'. 'VisualLane' is treated as a virtual object to facilitate the connectivity at turns and among parallel lanes. 'LaneRibbon' is used for supporting cartographic representation of the lane-based network and carriageway-based network. The relation between 'PhysicalLane' and 'LaneRibbon' is one to one; the relationship between 'Carriageway' and 'LaneRibbon' is one to many.

3.2 *Topology structure*

Lane-based road-network models had been developed by Fohl *et al.* (1996) on a conceptual level. Based on that work, Malaikrisanachalee and Adams (2005) proposed a solution by building the lane topology without the use of any 'turntable'. However, some limitations involved in the model inhibited its wide application. First, there was no consideration of multi-scale topologic and cartographic representation. Second, there was no lane geometry for lane-oriented navigation, and third, the encoding of lane topology was derived from the roadway centreline with linear offsets; however, the relation between a lane and the roadway centreline is complicated and therefore not easy to capture.

In the proposed HL-3DRNM model, lane is referenced to the 3D carriageway instead of the 2D roadway centreline. The introduction of carriageway facilitates the easy data organization of a lane-based network, and multi-scale geometrical and topologic representations can also be achieved. The elements of a lane-based network include lane and lane node that can be populated from its parent carriageway and carriageway node. The relationship between lane-based network and carriageway-based network has been depicted in figure 8. The lane-based topological network model is modelled as a simple directed graph, where network
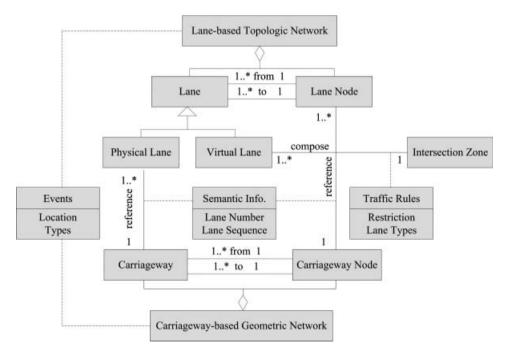

Figure 8.   Topology structure of a lane-oriented network.

connectivity between lanes is defined by nodal adjacency. Lane connectivity can be manually and explicitly encoded with the use of a lane connectivity table and the extra semantic information on the sequence number of the lane. Virtual lane is added into the intersection zone by considering the traffic rules, such as turning restriction or lane-type restriction. The events are reported at the carriageway-based geometric network, and the lane-based topology is dynamically updated with extra information such as event types and location.

Lane topology includes two parts: connectivity at turns and among parallel lanes. Encoding the connectivity at turns is done with the use of an extra virtual lane, which can be designed by on-site survey, transportation rules and traffic control systems. As shown in figure 9, two different kinds of lane topology can be encoded with the selection of different virtual lanes. In emergency routing, it is critical to control the lane connectivity at turns dynamically in response to the changing situation, such as avoiding specific points and disabling the use of specific lanes. The virtual lane created at turns can be added and updated in the lane connectivity table dynamically in order to adapt to the routing environment.

The continuous lateral connectivity between parallel lanes precludes the use of existing routing algorithms for navigation. Fohl *et al.* (1996) suggested one way, namely 'discretization', of adapting the lane-based network to work with the existing algorithm by representing a lane segment by a series of small edges, so that lane changing could be made at any vertex along the series. Malaikrisanachalee and Adams (2005) proposed a critical point approach in which virtual lanes occurred at points where the attributes of a lane changed. However, the rules in the real world that affect the choice of critical points are far more complicated than can be expressed by one unique criterion, and the implementation issues are still confused.

In figure 10, four kinds of discretization samples related to lane topology encoding among parallel lanes are summarized. It is believed that it is unnecessary to discretize along the entire lane, but only at some critical points, which can be determined by the changing attributes along the parallel lane, such as designed travel speed, designed lane changing point at interchanges and U-turns, and barriers. For example, a car might wish to move from a 40 mph lane to a 50 mph lane; a car on the left lane will make a right turn at an interchange; the connectivity between parallel lanes is to be maintained at a certain distance from the interchange; a car will avoid impedances such as barriers and will avoid occupying exclusive lanes, such as High Occupancy Vehicle (HOV) lanes, bus lanes, or emergency lanes.
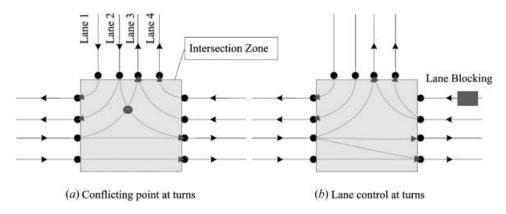

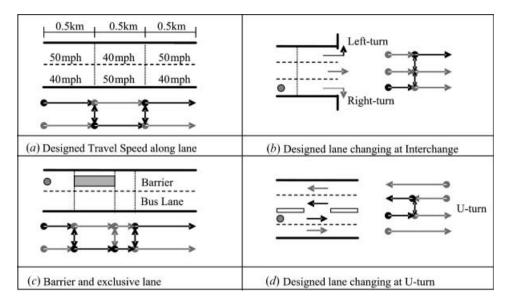Figure 9.   Encoding the lane topology at turns.

Figure 10.   Encoding the lane topology among parallel lanes.

The method of locating the critical points can be determined by performing network overlay between the impedance data and the lane-based network. Another way of determining the critical points comes from on-site surveys or from aerial images.

Temporal factors will impact on the construction of the lane topology, both at turns and among parallel lanes. Modelling the reversible lane with temporal constraints is an example. In this paper, the reversible lane is modelled as two topological lane objects; one is for certain times of the day, with the other for the remaining times of the day. As shown in figure 11, the daily rush hours, for example, are from 08:01 to 11:00, and from 17:01 to 20:00. In these periods, the lane from Node 100 to Node 200 will be active and be used for analysis, while outside these times, this lane will be replaced by the lane from Node 200 to Node 100. For the reversible lane, the two lane objects share the same cartographic representation, and the lane ribbon is regarded as their underlying cartography. Modelling lane changing costs at turns in different periods of time is another example of the use of time data. The solution can be achieve by assigning multiple lane-changing costs with associated time data; for example, from 08:01 to 11:00, the changing cost might be 5 s; however, in other periods of time, the changing cost might be only 3 s.

3.3   *Cartography structure*

3D cartographic structure is necessary for navigation and inventory management at the lane level. As mentioned earlier, road attributes have been manipulated by events, where a linear referencing system (LRS) and dynamic segmentation methods

LaneID	F_NodeID	T_NodeID	Effective Time	Cartographic Representation
1	100	200	08:01~11:00; 17:01~20:00	Lane Ribbon 100
2	200	100	11:01~17:00; 20:01~08:00	Lane Ribbon 100

Figure 11.   Modelling reversible lanes with temporal constraints.

are usually adopted to enable their cartographic representation. However, the datum of traditional LRS is populated from the 2D roadway centreline, and only point and linear events can be processed with the 2D offsetting approach. In HL-3DRNM, lane-oriented 3D LRS is extended to give references of 3D point, line, area and volume features. Being different from the traditional 2D LRS, the lane-oriented 3D LRS is built on the basis of 3D lane ribbon geometry, where each node of the underlying referencing network contains a 3D geographic coordinate (X, Y, Z), depicted by equations (2) and (3).

In Formula 2, the transformation is given between linear coordinates (provided by the road name and reference point method) and geographic coordinates in 2D space. Three key parameters are needed, namely, Route ID (RouteID), Reference Point ID (RPID) and Measure with linear offset (Measure_linear). In the proposed lane-oriented 3D LRS, the link-node reference method does not require any reference points, but link ID (LinkID), measure with linear offset (Measure_linear), lateral offset (Measure_lateral), and vertical offset (Measure_vertical) are added (Formula 3). The basic transformation schema from link-node linear reference coordinates to 3D geographic coordinates is illustrated in figure 12.

$$(\text{RouteID, RPID, Measure\_linear}) \rightarrow (X, Y) \qquad (2)$$

$$(\text{LinkID, Measure\_linear, Measure\_lateral, Measure\_vertical}) \rightarrow (X, Y, Z) \quad (3)$$

In the proposed lane-oriented 3D LRS, there is no lane line feature, only a polygon feature, i.e. the lane ribbon for cartographic representation of the lane. One alternative is to transfer the shape of the lane ribbon to the shape of the lane centreline by some graph algorithm such as the Medial Axis Transformation (Lee 2001), as shown in figure 13. However, this is an indirect approach and will add to the complexity of computation. In fact, the shape of the lane is regular, its centreline parallels the side boundary of the lane ribbon, and thus another possibility is to use one of the boundaries directly to replace the lane centreline as the underlying referencing geometry for lane-oriented 3D LRS. If the numbering sequence for the corner of the lane ribbon is properly designed, it is easy to query the first several corners as the nodes of the lane-oriented reference network. In the example, the numbering sequence is from the left-lower corner and anti-clockwise, the total number of corners is six, and the first three corners (Node 1, 2, 3) are used as the nodes for the reference network.
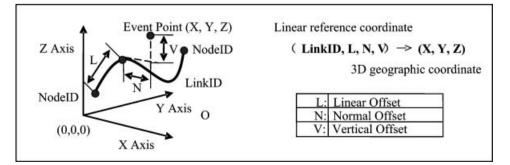

Figure 12.   Transferring linear reference coordinates to 3D geographic coordinates.
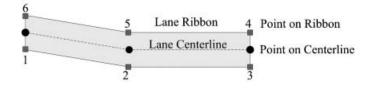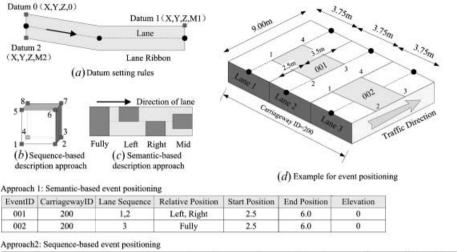
Figure 13.   Transferring lane ribbon to lane centreline.

The availability of the lateral dimension from the relative lane sequence and its semantics allows event data to be maintained as lane-oriented polygon or volume features in a flexible way, which has broken through the restricted linear domain of the existing linear referencing methods. With the extra semantic information such as 'left, middle, right, fully', it is possible to design the event's geometric location on any part of the lane ribbon. The rules for numbering the lane sequence and semantic description for location can be different, such as left-to-right or south-to-east, clockwise or anti-clockwise. In this paper, the numbering rules and semantic information are set as follows:

- If the traffic flow abides by right-driving regulations, e.g. in Asian and American countries, the numbering sequence is left to right. In such a way, lanes 1 and 2 have an adjacent relationship. The last number in the lane sequence usually denotes an exclusive lane, such as a bus lane or carpool lane.
- Relative positions are divided into four categories: left, right, middle, and fully. The relative position is measured on the basis of lane ribbon and starts from the right side boundary. The semantic 'Left' or 'Right' means that the events occupy the left or right side of the lane ribbon, 'Middle' means that the events occupy the middle part of the lane ribbon, while 'Fully' means that the lane ribbon is wholly occupied. The geometric position can be implicitly calculated with the support of lane ribbon coordinates.

Now, the events (figure 14), taking Event 002 as an example, can be reported as 'locates on carriageway 200, from 2.5 metres to 6 metres, on lane sequence 3, fully occupied', or reported as 'made up with four points, all on carriageway 200 and lane 3; for the first and last corner, linear offsets are 2.5 and 6, respectively, normal offsets are 0; for the second and third corner, linear offsets are 2.5 and 6, respectively, normal offsets are 3.75'. The datum setting rule for this sample case is illustrated in figure 14(*a*); the Datum 0 is the original datum with both linear and geographic coordinates (X, Y, Z, O), and the other two points are located on the corners of the lane ribbon (Datum 1 and Datum 2). Approach 1 is a line-based linear referencing method with the support of semantic information, namely a 'semantic-based event positioning approach'; the polygon event can be automatically generated through the normal extension to the other side of the lane boundary. Approach 2 is a corner-based referencing method with the support of point sequence information, namely a 'sequence-based event positioning approach'; each corner point needs to be individually represented by the three spatial offsets, namely, linear, normal and vertical. In the example, there is no vertical offset given, and the corner points are only four; however, volume events can be generated with more corner points and with extra vertical offsets.

By comparison, approach 1 is suitable for providing area features with a regular shape; the semantic information helps to provide flexible position description;

Approach 1: Semantic-based event positioning

EventID	CarriagewayID	Lane Sequence	Relative Position	Start Position	End Position	Elevation
001	200	1,2	Left, Right	2.5	6.0	0
002	200	3	Fully	2.5	6.0	0

Approach2: Sequence-based event positioning

EventID	Corner 1					Corner 2					Corner 3					Corner 4				
	C_ID	LS	O1	O2	O3	C_ID	LS	O1	O2	O3	C_ID	LS	O1	O2	O3	C_ID	LS	O1	O2	O3
001	200	1	2.5	1.825	0	200	2	2.5	1.825	0	200	2	6	1.825	0	200	1	6	1.825	0
002	200	3	2.5	3.75	0	200	3	2.5	0	0	200	3	6	0	0	200	1	6	3.75	0

Figure 14.   Lane-oriented 3D inventory management approaches.

volume events can simply be encoded by an elevation measure; it reduces the data-storage requirement as well. One disadvantage is that the actual position is implicitly calculated, indirectly derived from the rules and geometry of the lane ribbon. Approach 2 is more suitable for providing complex area features and 3D features; it is possible to generate 3D point, 3D line, 3D area, and 3D volume events with the choice of varying corner numbers.

3.4 *Semantic structure*

The relationship between the geometry layer and semantic layer, as well as the relationship among the objects, is given in the semantic structure, as shown in figure 15. Although the structure has mainly concentrated on the road network, the relation of the road network to other objects, such as district zones and 3D buildings, is also considered.

- The geometry layer consists of four basic entities: 3D point, 3D polyline, 3D face, and 3D body. The 3D point is the minimum feature that is a part of the 3D polyline, 3D face, and 3D body; linear objects refer to elongated regions that are specializations of a 3D face.
- The semantic layer includes lane centreline, carriageway centreline, and roadway centreline that are concrete 3D polyline objects, and area event, road zone, district zone, intersection zone, lane ribbon, carriageway zone that are concrete 3D factual objects, as well as traffic facilities, volume events, and buildings that are concrete 3D bodies.
- The lane-oriented 3D road network mainly comprises 3D polyline objects and 3D face objects. Traffic facilities, such as traffic lights and traffic signs, are also included in the lane-oriented 3D road network, represented as 3D bodies.
- As mentioned previously, area and volume events are managed on lane level, and so the relationship between an area event, volume event, and the lane
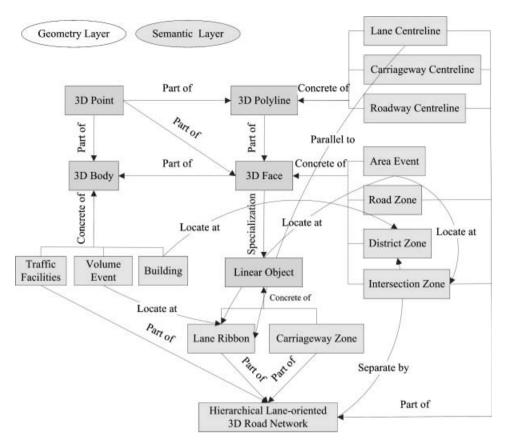
Figure 15.   Semantic structure of HL-3DNRM.

ribbon is 'locate at'. Buildings are often located at a district area; the relationship is defined as 'locate at'. Lane centreline is derived from the boundary of lane ribbon, and the relation between lane centreline and lane ribbon is 'parallel to'. The proposed lane-oriented 3D road network is in fact a 3D area-based visualization model as well as a lane-oriented non-planar analysis model. The relationship between the lane-oriented 3D network and the district zone is 'separate by'.

4.   Implementation issues

Based on the conceptual model and the topology, cartography and semantic structure of HL-3DRNM, the implementations were based on a 3D GIS software—VGEGIS5.0 developed by Wuhan University in China—in which 3D data management, visualization, and interoperability can be flexibly realized, and a more detailed microscopic environment can be well defined. The development and implementation environments are:

- Intel Pentium®4, CPU 2.00 GHz, 1.99 GHz, 512 MB RAM.
- Operation system: MS Windows XP; software: VGEGIS5.0.
- Programming tool: Visual C++6.0; graphical interfaces: OpenGL.

The experimental region is Wuhan city; the sample data are a series of main roads, including 3D road segments, 3D carriageways, 3D lane ribbons, and 3D intersection points. Given the number of lanes on a carriageway, lanes can be reproduced from the carriageway link, while the relationship between the lane link and carriageway link is simultaneously established with the custom computer program (Visual C + +). The lane-to-lane relationship should be maintained by gathering the turning information among lanes with the support of aerial images or on-site surveys. It is a time-consuming process; however, it is the basic foundation of most traffic applications, and, with the development of advanced image recognition, this process can probably be established in an automatic manner.

Database representation will now be introduced, followed by a discussion of the two applications: 3D dynamic segmentation and hierarchical routing.

4.1 *Database representation*

Figure 16 shows a real road-network system, which includes some important objects mentioned in this paper, namely, roadway centreline, carriageway, lane, intersection zone, intersection node, and lane ribbon, and also includes other related objects such as static objects, affiliated facilities, and moving objects. The segmentation rules are complicated in this sample case.

1. A road segment starts from an intersection and ends at another intersection, and the segment road node may be overlapped by an intersection node or paralleled with an intersection node.
2. Carriageway is the central line of a series of lane ribbons.
3. A lane is numbered in sequence from the left side to the right side of the traffic-flow direction.

For the database representation of HL-3DRNM, 12 tables are built in order to represent its hierarchical structures. The relationships within the table are illustrated in figure 17.

- Hierarchy 1 includes the link table, node table, and connectivity table of road segment; the connectivity table is built automatically via the geometric network of the road segment.
- Hierarchy 2 is made up of the link table, node table, connectivity table of carriageway and intersection node table. The connectivity table is built from
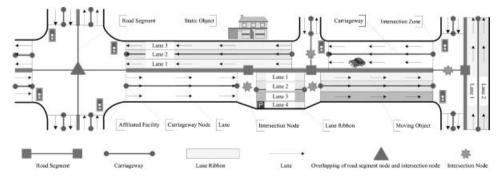

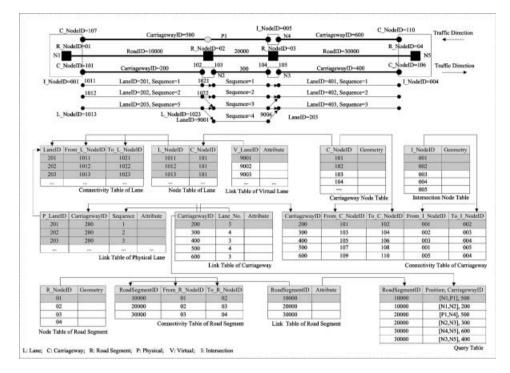Figure 16.   Example of real road-network system.

Figure 17. Database representation of HL-3DRNM.

the link table of the carriageway and the intersection node table by manual setting or is automatically derived via traffic rules.

- Hierarchy 3 includes the node table of lane, link table of physical lane, link table of virtual lane, connectivity table of lane. The connectivity table is also built manually or automatically derived via traffic rules.
- The query table connects the link table of carriageway and the link table of road segment, resolving the many-to-many relationships between carriageway and roadway centreline by introducing location point P.

4.2 *3D dynamic segmentation*

The purpose of implementing 3D dynamic segmentation is to investigate the validity of sequence-based and semantic-based 3D event positioning approaches on the lane level. The comparative analysis of 3D GIS-based dynamic segmentation (VGEGIS 5.0) and traditional 2D GIS-based dynamic segmentation (e.g. ARCGIS 8.3) is also discussed. The experimental results are shown in figure 18; furthermore:

- 3D features can be represented dynamically instead of just by encoding their geographic coordinates, thus improving the data operation efficiency and minimizing data storage, as well as maintaining the logical consistency of 3D features.
- Lane-oriented 3D dynamic segmentation outperforms traditional 2D dynamic segmentation in accuracy and flexibility. The use of a lane ribbon makes a real 3D inventory management possible, and events can now be located/visualized in area and volume formats.
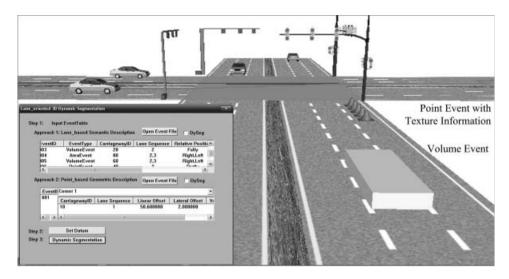
Figure 18.   Experimental results of 3D dynamic segmentation.

- The proposed sequence-based and semantic-based event description approaches provide flexible means for event locating. The semantic-based approach is better suited for 3D event visualization with regular shapes, and the sequence-based approach is better for 3D event visualization with complicated shapes and moving objects.

4.3   Hierarchical routing

In this section, a totally new routing strategy, namely hierarchical routing, is briefly introduced. As illustrated in figure 19, the strategy of hierarchical routing consists of three steps. The first is the calculation of the candidate routes based on the roadway centreline network. In this step, the k-shortest path algorithm is used, and the first three shortest paths are chosen as the candidate routes. Second, the related carriageway-based networks are loaded, and the optimal route is calculated. The third step is working on the lane-based network, and the lane-based navigable route is analysed. Route 1, Route 2, and Route 3 are populated from the roadway
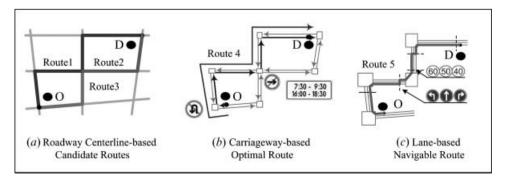

Figure 19.   Conceptual model of hierarchical routing.

centreline-based network, and are regarded as candidate routes; by taking the candidate routes as the available source of knowledge, Route 4 is then calculated on the level of carriageway, taking into account turning restrictions at interchanges. Route 5 is a lane-level navigable route, with more detailed traffic regulations being considered, such as lane sequence, and speed restriction of lanes.

To investigate the effectiveness of HL-3DRNM and the efficiency of the hierarchical routing strategy, three groups of comparative analyses were implemented:

- the comparative analysis of routing results between a roadway centreline-based network and a lane-based network;
- the comparative analysis of the number of virtual lanes at an interchange between a lane-based network and hierarchical networks;
- the comparative analysis of routing efficiency between a lane-based network and hierarchical networks under the same computational environment.

In figure 20, Route 1 is based on a roadway centreline network; however, it is obvious that this route is not reasonable under normal traffic conditions because

Figure 20. Experimental results and comparative analysis of lane-oriented routing.

there is a dividing trip that prohibits the turn moving from the right side of the street to the left side. Route 2 is a lane-based route under normal traffic conditions. The designed traffic rules at interchanges are described as [Virtual_Lane: LaneA-CarriagewayA-CarriagewayB-LaneB], Lane 1 is defined as a Left-turn lane and U-Turn lane, Lane 2 is defined as Go-through Lane, and Lane 3 is Right-turn lane. Route 3 is also a lane-based route but under emergency conditions, when special traffic controls are enabled to maximize the efficiency of emergency response. The designed traffic rule at interchanges is described as [Virtual_Lane: LaneA-Intersection-LaneB], by defining Lane 1 as an emergency lane with variable traffic direction.

Figure 21 compares the efficiencies of hierarchical routing and lane-based routing. For lane-based routing, the number of virtual lanes is very large. Taking an interchange as an example, if each carriageway is defined as containing three lanes (Left-turn/U-turn, Go-through, and Right-turn), the number of virtual lanes for a lane-based routing is 48. However, in hierarchical networks the number of virtual lanes is only 3. In table 2, the numbers of nodes and links and the computation time are further illustrated. For a small sample network with three interchanges, the numbers of nodes and links at carriageway level are 26 and 27, and the numbers of nodes and links dynamically created at lane-level are only 33 and 42. The computational times of both routing algorithms include the time for deriving the physical lane, building the virtual lane and discretizing lane among parallel lanes; for the hierarchical routing algorithm the total computational time is 11 ms.
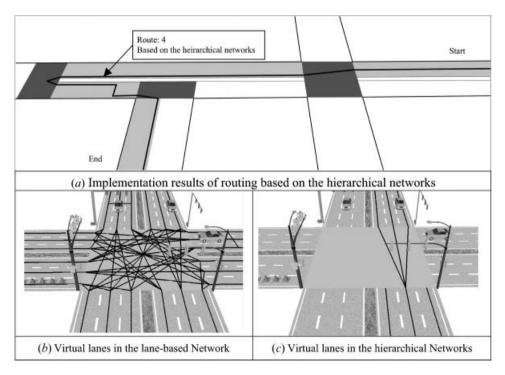

(a) Implementation results of routing based on the hierarchical networks

(b) Virtual lanes in the lane-based Network

(c) Virtual lanes in the hierarchical Networks

Figure 21.   Experimental results of hierarchical routing.

Table 2. Comparison of efficiencies of two routing approaches.

Efficiencies approaches	No. of nodes	No. of links	Time for topology building (ms)	Time for route computing (ms)	Total time (ms)
Lane-based	102	164	7.9	209	217
Hierarchical	26	27	0.3	3.3	11
	33	42	1.4	6	

5. Concluding remarks

Up until now, very little research has been carried out on lane-oriented 3D road-network models for two primary reasons: (1) only recently has low-cost sensor technology become available with higher positional accuracy (e.g. differential GPS (DGPS) receivers); and (2) today's commonly used digital road-network data do not have sufficient accuracy for lane-oriented micro-scale tasks, such as emergency response and automated navigation. However, with the rapid development of photogrammetric technologies, the capture of lane-oriented data will not remain a large problem, and research into lane-oriented 3D road networks will be more appealing.

HL-3DRNM provides a perfect solution for hierarchical lane-oriented routing and lane-oriented 3D inventory management, where rich 3D information and 3D dynamic segmentation can be manipulated with the support of lane topologic elements and lane ribbon polygon features. Compared with existing road-network models, LH-3DLNM is characterized by:

1. Representing availability of lanes, individual lane properties, connectivity among parallel lanes and at turns. The traditional single centreline network maintains roadways as linear and homogeneous features (Malaikrisanachalee and Adams 2005). In the context of evacuation routing, lane connectivity is very valuable, as abstracting an intersection into a single node conceals important traffic flow details that might cause delays (Ziliaskopoulous and Mahmassani 1996). The loss of information regarding lane connectivity (e.g. connectivity at interchanges, lateral connectivity between lanes, lane crossing and merging) and attributes (e.g. lane types, forecast traffic volume and lane closures) makes it impossible for city planners to implement the necessary control at lane level during emergency evacuation (Cova and Johnson 2003). Moreover, representing the availability of lanes will also facilitate dynamic segmentation for areal or even volume attribute representation at the lane level.
2. Supporting multiple topological and cartographic representation and various abstraction levels. Multiple topological and cartographic representations and various abstraction levels, such as street-level, synthesized lane level, carriageway-level, and actual lane level, have never been discussed in an integrated way in previous research. However, defining multiple abstraction levels and building their inner relationships are quite important for advanced network analyses, such as lane-based navigation and the Automated Highway Systems (AHS) of the future.
3. Referencing multi-dimensional road information in 3D space. Road information can be 1-D (linear referencing systems), 2-D (planar coordinates), 3D (planar coordinates and height information) and 4-D (time in the case of

dynamic objects) depending on the usage (Demirel 2004a). In addition, defining the geometry in 3D allows the implementation of a non-planar topological model that can naturally and effectively model the complex transportation systems, such as flyovers and tunnels. Modelling temporal issues is a long-term topic in GIS, and this problem is even more critical in dynamic transportation systems.

The experimental results show a multi-mode, multi-scale and multi-dimensional routing practice with the suggested implementation strategies, and the lane-based 3D inventory management is a novel approach and is flexible to the application environment. The research shows the possibility of integrating semantic information with the construction of a lane-oriented 3D road-network model, and of using more detailed information to describe transportation objects in a true 3D system.

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