A Generic Data Model Proposal For Multi-Dimensional Road Object

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WG IV/I – Spatial and Temporal Data Modelling and Analysis

Keywords: GIS, Databases, Modelling, Three-dimensional, Networks, Facilities, Status

Abstract:

A new, generic approach to the conceptual data modeling of multi-dimensional highway information system is presented in this study. The current status, which is analyzed in various countries namely; Turkey, Denmark, Germany and the U.S.A, reveals many problems and the success of the implemented systems are not clear. The multi-dimensionality of road object is generally ignored, where it can be static or dynamic, referenced to one, two, three or four-dimension. Furthermore, the restriction of current data models limits the ability of GIS to effectively model the real world. These problems mainly conclude insufficient user requirement responses, unpredicted data integration problems and finally lack of efficiency. This generic approach diverges from the current conceptual data models, since it bases on the decomposition of geometry, topology and thematic data. It presents a considerable departure from traditional planar, centerline based, transportation network in order to comprehend the user assessments. The data model is designed with four distinct components; being geometry, topology, road events and metadata. The first priority is given into geometry, where current models mainly emphasize on the thematic data component. The basic component geometry is defined in third dimension. Topology, being non-planar and having abstraction levels, is modeled as a logical abstraction of geometry. By means of the newly developed methodologies, one-dimensional road information is transformed into third dimension and integration is achieved. The designed concepts are successfully implemented using the integrated approach in one object-relational system on a pilot project. During the implementation of the concepts two different GIS software are utilized and results are evaluated.

1. Introduction

Due to the complex management tasks, the demand for dynamic and multi-dimensional GIS is increasing rapidly, especially in application areas of cadastre, transportation, urban planning and environmental systems. Among these applications, the transportation sector has different demands for dynamic and multi-dimensional GIS, since these two challenging topics promote the required data integration. In transportation applications, data integration not only enhances the efficiency of conducted applications, but also makes possible the necessary dataflow within the agency. Spatial information technology can be used as a logical and physical data and method integrator necessary to the highway sector. Due to such benefits, this technology is highly appreciated and widely implemented. Conversely, the wide spread usage accelerate the identification of problems, limitations and inadequacies of the current systems. In order to achieve a wider perspective and highlight the current situation within highway agencies, the study is conducted at four countries namely; Turkey, Denmark, Germany and the U.S.A. (Demirel,2002) Concentration is mainly given to the following topics; organization structure, user requirements, spatial data acquisition techniques, system architecture, existing information systems and the conceptual data models.

In the frame of this paper the current problems of spatial highway information system is clearly outlined. Within these, problems related with inadequate handling of multi-dimensionality is going to be emphasized. In order to diminish the problems, to provide the integrity and the efficiency, a new conceptual data model is going to be introduced, which ensures integration of all relevant data and business operations for the entire agency. The designed concepts are implemented on a pilot project and results are discussed.

2. Current Status

The complex mission of highway agencies requires diverging tasks to be accomplished by means of various methods, depending upon required generalization level and quality of information. In order to perform complete analysis, data exchange between divisions is necessary and analysis involving several divisions are common (Demirel, 2002). Existing data are usually managed with databases and technologies that cannot be integrated due in part to the lack of a comprehensive model for location referencing data (Koncz and Adams, 2002). During the study, it is examined that, many benefits of GIS technology are not recognized, demands of the organization cannot be fulfilled and the efficiency of spatial technology is mainly under estimated. Even in some situations existing systems have not been updated since the system implementation.

Since the data used by the highway agency mainly have spatial character, several additional problems emerge. The parallel usage and maintenance of several systems, requires collection, modeling and maintenance of spatial information redundantly, increasing the costs of the implemented systems and reducing the efficiency. The spatial data acquisition requires the highest efforts and costs, due to the high level necessity of completeness, actuality, correctness and well-defined data structure (BILL,1999).Although, the well-defined data structure is obligatory, conceptual data models of the implemented systems are not formally designed and documented. Software vendors' proprietary databases are used for storing spatial information. Other information sources, such as existing databases, are then linked to the system as non-spatial information. However, due to the nature of road object, these sources include multi-dimensional spatial information.

Road information can be 1-D (linear referencing systems), 2-D (planar coordinates), 3-D (planar coordinates and height information) and 4-D (time in case of dynamic objects) depending on the usage. The road object is associated with three different referencing systems being (X, Y, Z), (l,q), which describes linear referencing system and (h,q), defining cross-sectional road data, illustrated in Figure 1.

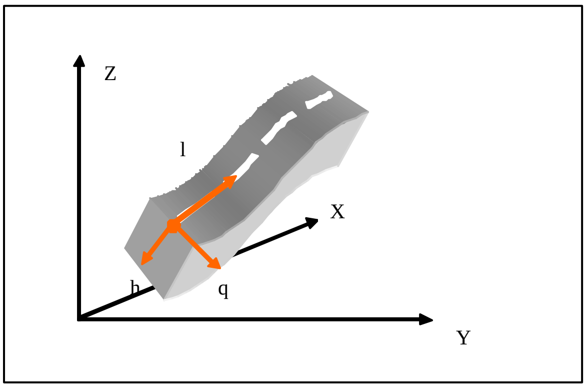

Figure 1: Reference Systems

Excluding the planar coordinates, other dimensions, which have implicit references such as road identifier, name, stationing value, gradient value, are considered as non-spatial information. This approach concludes several problems during the system maintenance, since road object is subject to change. Redundant information storage and mismatch of information is common.

Since road objects can be static or dynamic, referenced to one, two, and three or four dimensions, the traditional road data models are insufficient to support data integration. In the transportation context, three classes of GIS models are relevant, being: i) field models, ii) discrete models, and iii) network models (Goodchild, 1998). The network model is the commonly used one among these, since many applications only require a network model to represent data (Thill, 2000). The network data models represent topologically connected linear entities that are fixed in the continuous reference surface, inherently 2-D. In the model, arcs and nodes themselves are primitives of the discrete entity model, stored as geometric structures. Associating 1-D data with the 2-D planar model is a well-known problem, since an attribute was described as a spatial (1-D) event occurring on the network, however in many cases 1-D data requires to be associated with 3-D data.

In order to comprehend the user requirements and to diminish the determined problems, a generic conceptual data model needs to be designed after constitution of a criteria list. Considering the peculiarity of spatial information, several systems were analyzed (Vonderohe et al., 1997; Walter, 1997; Vejdirektoratet, 1998; NWSIB, 1998, NCHRP, 1998; Gielsdorf, 1998; BMVBW, 1998; OKSTRA, 2000; Dueker and Butler, 2000; Sutton and Wymann, 2000; Adams et al., 2000; Portele, 2001; Koncz and Adams, 2002). According to these studies, a model for this purpose should ensure: i) conceptual decomposition of topological, geometric and thematic information, ii) referencing multi-dimensional road information in 3-D and time, iii) transformation of datasets, iv) support for multiple topological representation and various abstraction levels, v) non-planar topological model, vi) history information, and vii) incorporation of metadata, involving accuracy and integrity constraints.

3. The Conceptual Data Model

The designed conceptual data model is constituted upon the criteria list. During the establishment of external schema, a progressive approach appropriate to the conceptual data modeling requirements of an entire road administration was reflected on. The data model was designed with four distinct components: geometry, topology, road events and metadata.

The main approach of the proposed data model is abstraction and decomposition of geometry, topology and non-spatial data. The basic component of the proposed data model is geometry, which the model is diverging from standard GIS models. In most GIS, geometry plays a secondary role compared to thematic data and conventionally used for graphical visualization. Consequently, it is redundantly implemented. The geometry component here is subdivided into three categories; point geometry, linear geometry and area geometry. According to the proposed conceptual data model, a complex object is an aggregation of several simple objects. The point geometry is defined in terms of a three-dimensional coordinate system, including height information. In order to achieve data integration, control of redundancy and optimization of data maintenance, linear elements were mapped by means of datum invariant parameters, which are either horizontal or vertical planes. The planar linear elements have three parameter types; line, arc and clothoid. Area geometry may be either planar or non-planar. By considering geometry to be the basic component, many of the problems noted are avoided.

Topology, being non-planar and having two abstraction levels, was modeled as a logical abstraction of geometry. Two abstraction levels are required for the multi-scale representations. The multi-scale representations result from seeing the world from different abstraction levels, as well as different points of view (Bedard et al., 2002). By possessing topological information implicitly, temporal management becomes easy. The main elements of topology were node and link. According to the conceptual data model, Link is a logical connection defined by two nodes. Topology elements are adapted from traditional planar networks. Associations between nodes and links were applied to both abstraction levels. Additional associations were defined for mapping the associations between two abstraction levels. Relationships between abstractions are modeled as follows: ‘Node I’, being a higher abstraction level may be composed of ‘Link II’ and ‘Node II’. Between the first level topology element node (‘Node I’) and the second level topology element node (‘Node II’) a 1: 0..* relationship is assigned, where ‘Node I’ may be composed of many nodes (‘Node II’) and every ‘Node II’ is assigned to only one object ‘Node I’. The relationship between ‘Node I’ and ‘Link II’ is modeled as 0..1: 0..*, where ‘Node I’ may be composed of second level links (‘Link II’) and a second level link (‘Link II’) may be assigned to none or only one ‘Node I’. Road junctions can be modeled using these associations. The relationship between ‘Link I’ and ‘Link II’ is modeled as 0..1: 0..*, where ‘Link I’ may be composed of second level link’s (‘Link II’) and a second level link (‘Link II’) may be assigned to ‘Link I’. By means of defined abstraction levels, support for multiple topological representation and various abstraction levels were incorporated into the system. Additionally, defining the geometry components in 3-D allows implementing a non-planar topological model. Implementation results can be found in Demirel (2002).

Non-spatial information is introduced into the system as road event. The road event includes all non-spatial information including attributes, time of occurrence, state and physical components of the road. Examples of typical road events are: traffic accident, construction project, road facility, video image, pavement type and road type. Road Events are assigned to geometry. The thematic road data has no spatial character including the third-dimension. The geometrical properties of the road data is provided by referencing the geometry component of the model fully in third dimension. The 'Road Event' object stores all non-spatial information according to the provided road event identifiers in the event catalogue. Having agreed on the standards for identification, associations between road events and geometrical elements were made. There was a 0..1: 0..* relationship between the Geometry ('Point Geometry', 'Linear Geometry' and 'Area Geometry') and Road Event objects. Every 'Road Event' should be assigned to one of the geometry types and many road events may be assigned to one geometrical object. All non-spatial properties of Road Event were stored in the object 'Road Event Properties'. This object has a tree structure with which it is possible to expand properties of road events to any desired level. Every road event may have many road event properties and every road event property must be assigned to only one road event, where 1:0..1 association was used for describing this. With the objects introduced above, the requirements of road administrations were fulfilled in multi-dimensional space, including planar and vertical sections.

In order to integrate 1-D, 2-D and 3-D coordinates, the member method *Dynamic Reference Transformation* of the 'Road Event' object was introduced. As all linear reference systems are based on the specification of the direction and distance from a known point to an unknown point, every linear reference system can be defined using the (l, q) system, where (l) is the distance along the road between the origin and the start point of the road event, and (q) the distance normal to the linear element at the start point of the road event, called linear element system. The linear element system is a planar system (2-D), where (l) coordinates are identical with the projection of road alignment in (x, y) plane. Since road administrations consider the use of linearly referenced methods to be inevitable, the transformation from (x, y, z) to (l, q) systems was modeled. During this transformation, linearly referenced data was not stored in 1-D, but rather in 3-D. The transformation needs to be realized dynamically, in order to prevent data inconsistencies and redundancy. The geometrical properties of a road axis in the (x, y) plane are described using the linear elements in 3-D and the usage of a three-step transformation (Gielsdorf, 1998) was adapted for the requirements of road administrations (Demirel, 2002).

The metadata component includes integrity constraints, history and quality. In GIS, due to redundancy, integrity constraints are required wherever geometry interacts. Several additional integrity constraints are defined externally in order to validate geometry and topology. The history for all objects and relationships is stored in the 'History' object, adopting the transaction log approach. One event type can have many history objects, for instance an operator can update many objects at one time (before the transaction), and every history object is associated with only one event type. All these processes are controlled by transaction rules. By using the history object, it is possible to report or re-create a required transaction and to model the current, past and future situations. Using the defined history objects, the time component is covered by the designed conceptual data model (Demirel, 2004). The quality aspect is implemented using member methods of the individual objects. The history approach is not followed, since it is very unlikely that errors or poor quality data needs to be regenerated. Using this approach the quality of the current data is reproducible at any time in the form of documents or tables. During the proposed data model, the quality control, error trapping, data consistency checks and acceptance tests are designed which will definitely increase acceptance and the success level of the system. The generic data model was described using the Unified Modelling Language (UML), where relationships are classified as dependency, association, generalization and realization (Booch et al., 1999) and illustrated in Figure 2.

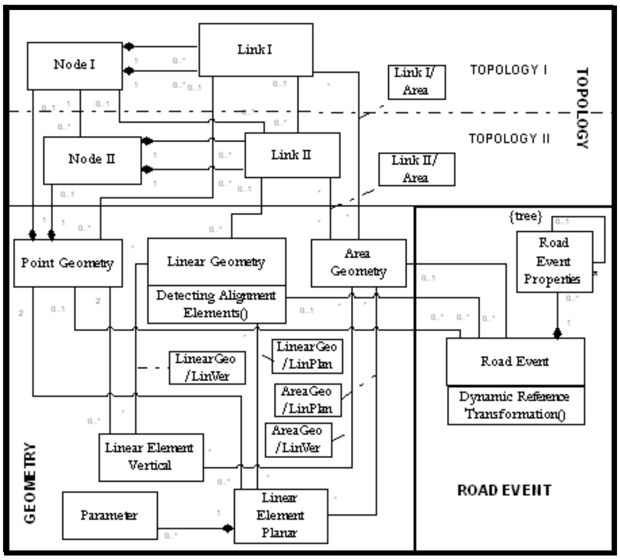

Figure 2: The Simplified Generic Model

In order to increase the efficiency and highlight the benefits of GIS-T, this study considered a progressive approach appropriate to the conceptual data modeling requirements of an entire highway agency. The main features of the proposed conceptual data model can be summarized as follows:

- Topology, geometry and thematic information is conceptually independent
- Multiple topologic representations, supporting different abstraction levels, are realized with two abstraction levels of topology, in order support diverse applications in highway agencies.
- With the incorporation of height information and the designed objects in the conceptual data model, non-planar topological model is achieved. In order to achieve non-planar topology, other techniques were also proposed including, introducing constraints by means of adjustment techniques.
- Road information, such as data collected through linear referencing systems or cross-sectional design information, is modeled with decomposition of spatial and non-spatial characteristics.
- Highway business-rules are modeled using integrity constraints, user defined methods and triggers.
- Existing road information was be integrated into the system without redundancy through defined methods and adjustment techniques.
- Metadata, including history information was modeled. Quality specifications, including accuracy certification, were defined in the conceptual data model for objects and introduced methods.

4. Implementation of the Generic Data Model

In order to test the developed concepts, two different datasets were used, being the 1:10.000 scaled data set of Brandenburg State Office for Traffic and Roads (BLVS), Germany and 1:25.000 scaled data set from western Turkey. Within pilot projects, the first abstraction level topology, geometry and thematic components were implemented. The developed approaches were successfully implemented using SQL scripts directly into Oracle8i, after the physical design of the conceptual data model. First, abstraction level topology, geometry and thematic components were implemented. Two different GIS software were used, GeoMedia Professional 3.0 and ArcInfo8™.

In GeoMedia Professional 3.0, the conceptual data model's thematic and geometry components were implemented. Two methods, the *Detecting Alignment Elements* and *Dynamic Reference Transformation,* were successfully implemented. Within the proposed conceptual data model, it was assumed that linear elements are defined by means of their parameters and then generated without storage of any other geometrical information. However, although it was possible to parameterize defined geometric elements and introduce them to the system;

- It was not possible to generate these geometrical elements automatically using their parameters, without the storage of any other geometrical information. Because, geometrical features must be identified by their planar coordinates.
- It was not possible to visualize the clothoid.

The first mentioned problem was solved by implementing the geometrical elements redundantly and controlling the redundancy with the developed methods. The second problem, the visualization of clothoid, was solved with the help of other geometrical elements, since it was not possible to define geometrical objects in the system.

The topology component can not be implemented in the manner proposed in the conceptual data model. The main problem encountered was the lack of user-defined types, meaning implementation opportunities were limited due to software vendor defined features, specifically spatial features. Topology information is considered differently in GeoMedia. Only in the "Maintain Coincidence Mode" ("On-the-Fly" topology instruction), displacement of one point has the consequence that, points which are situated within a determined distance will follow this movement. Additionally, it is not considered whether these points are assigned to topological nodes or not. There are some additional reasons, which affect the implementation of topology. The available mechanisms were insufficient in controlling the redundancies. The versioning concept is unavailable. A transaction is always automatically terminated in the system after a new object is created. This requires consistency checks to be realized immediately. However, in the conceptual data model consistency checks are pre-required for some entries, such as 'Link' and 'Node'. There are also situations where this is reversed, such as determining 'Point Geometry' and 'Node' relations. In this case control mechanisms did not provide expected results. Additionally, it is not certain whether the quantity of the consistency conditions required is realizable using triggers. A further problem results from the fact that the user does not have influence on the end of a transaction

Using the second selected software ArcInfo8™, users can define feature types and are not limited to the software vendor's concepts and definitions due to provided ArcObject concept. With the "geometry network" possibility, topological elements can be implemented according to the descriptions in the conceptual data model. In ArcInfo8™ integrity constraints called "validation rules" can be defined by the user. Additionally, the versioning concept is available. The conceptual data model was successfully implemented through ArcInfo8™, although during the implementation some problems needed to be solved. These are as follows;

1. *Geometrical elements can not be generated using their parameters.*
   The main concept is similar to that used by GeoMedia Professional, where geometrical features are assigned to their planar coordinates for visualization purposes. In order to solve this issue, geometrical features and parameters were stored by using the user-defined objects and methods. The occurred redundancies were controlled using user-defined methods and validation rules.
2. *Features having geometrical characteristics must be assigned to a pre-defined geometrical feature of ArcInfo8™.*
   Regardless whether an object is defined as a geometrical component or not, every object which should be visualized in GIS must have planar coordinates assigned to it, including the topological elements: node and link. During the implementation, an additional column was added to the physical data model table in order to define the geometry of feature. Consequently, objects such as linear elements were stored redundantly in the shape column with their geometrical information, in this case the coordinates of the polygon's points. These redundancies were controlled by consistency rules.
3. *The linear element clothoid is not supported in ArcInfo8™*
   Although clothoids were stored with their parameters in the database, automatic generation of parameterized elements was not possible. During visualization clothoids were simplified as line and arc objects.
4. *By using the "geometric network" of ArcInfo8™, topological relations can only be modeled between geometrical objects.*
   With the "geometric network" of ArcInfo8™, topological objects and relationships between each other could be established. However, due to non-separation between geometry and topology, this establishment can only be made between geometrical objects. Due to this limitation, implementation of a 0..1:1 relationship between 'Node' and 'Point' could not be realized.

In order to implement the proposed conceptual model, modifications were made with respect to fourth item. The geometric element point was subdivided into three parts being; node, element point and intermediate point. 'Node' was preserved as node. From the other new defined objects 'Element Point' defines the beginning or ending point of a linear element. The 'Intermediate Point' was introduced in order to indicate any location along a link, which is neither the beginning nor the ending point of the linear element. Additionally consistency conditions and checks were implemented in order to satisfy the required rules by the highway agency. The component 'Road Event' was also implemented subject to similar modifications. With the defined method *Detecting Alignment Elements* of 'Linear Geometry' geometrical component of the proposed conceptual data model was generated. Topology component was implemented as proposed in the conceptual data model, which is shown in Figure 3.

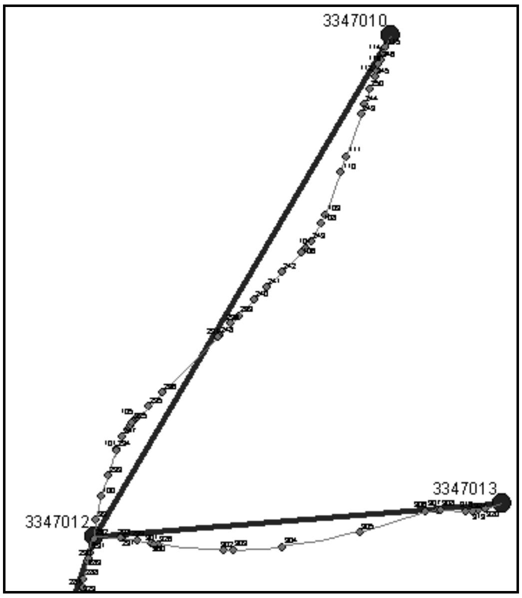

Figure 3: Implemented Geometry and Topology Components

The defined method *Dynamic Reference Transformation* of 'Road Event' was generated using ArcObjects. Through compatible programming languages such as Visual Basic, Visual C++ and Delphi, it is possible to create or add user-defined objects to a database, which operate directly with ArcObjects. As the sample data was dependent on the link-node linear referencing system, this methodology was used for re-transformation during designed interfaces. (Pfannmöller,2001*)* 'Road Event', described in the conceptual data model, was obtained using the program and existing interfaces. In addition, 'Road Event' object information identified at vertical sections were also realized using the methods *Detecting Alignment Element* and *Dynamic Reference Transformation*. The height information was already existed in the provided data set. The implementation results are illustrated in Figure 4.

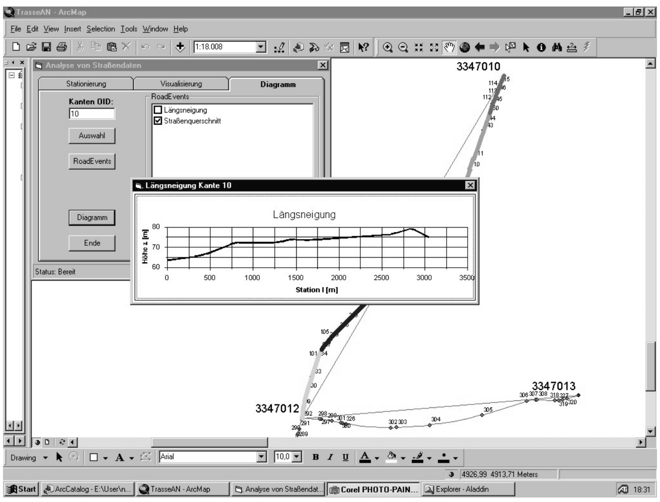

Figure 4: Implemented Geometry and Topology Components

The cross-sectional design information, which was predefined as the (q, h) reference system, was also implemented. Some of the defined integrity constraints in the proposed conceptual data model were performed using existing "validation rules" in "geometry network" of ArcInfo8^{TM}. Others were introduced into the system by means of triggers, which will be introduced below. An example of the validation rules used in the system

The maintenance of complex relationships and validation of complex rules are often needed to be defined externally, due to lack of realization of the encapsulation concept. In order to define these, triggers are in the Oracle database management system. A trigger is a method which is invoked whenever a specified object or attribute is inserted, updated or deleted. Ideally, it should be possible to invoke the full range of GIS methods within a trigger and it should be possible to cause the current transaction to be rolled back if an invalid condition is found within a trigger. Procedures are started explicitly by the user, by an application or also a trigger. These are procedures written in PL/SQL, Java, or C that execute ("fire") implicitly. With the releasing event it concerns one or more Data Manipulation Language (DML) operations (insert, update and delete). The connectivity rules, redundancy controls, integrity constraints were performed using this method.

5. Conclusion

In order to increase the efficiency and to provide data integration, this study considered a progressive approach appropriate to the conceptual data modelling requirements of an entire highway agency. The designed generic conceptual data model presents a considerable departure from traditional network-data models in order to comprehend the user assessments. With the *Dynamic Reference Transformation* method; i) decomposition of spatial and non-spatial information is realized. This increases the stability and simplifies the data maintenance, ii) thematic data is independent of geometrical displacements such as; realignment and error corrections, iii)multi-dimensional road information is mapped into the conceptual data model without redundancy, iv)no pre-defined methodology is required, users are free to apply the most appropriate methodology from their point of view. This is because every one-dimensional reference system is transformed dynamically and stored in a three-dimensional coordinate system, v) re-transformation into 1-D is modelled and supported by means of interfaces, vi)stochastic properties of linear elements and (l, q) parameters are available, vii)full integration is realized with other data acquisition techniques where information is referenced 3-D, viii)existing data with multiple referencing systems is fully integrated, ix)due to the minimal data acquisition requirements, a more economical solution is provided compared with other techniques, x)the proposed technique is independent of any software vendor or platform.

This generic approach ensured; i) the abstraction and decomposition of geometry, topology and non-spatial data, ii) the transformation and integration of multi-dimensional data in 3-D, iii) the support for multiple topological representation and various abstraction levels, iv) the non-planar topological model, v) the incorporation of metadata, involving integrity constraints, history and quality. The effectiveness of the developed concepts was tested on two different projects. According to the results of the conducted projects, this approach is explicitly beneficiary when compared with the traditional road data models.

Acknowledgements:

This study is a part of Demirel's Ph.D thesis at the Berlin Technical University supervised by Prof. Dr. Gründig, Prof. Dr. Altan and Dr. Gielsdorf. The author of this paper would like to express her sincere appreciation to Brandenburg State Office for Traffic and Roads, Danish Road Administration and General Highway Administration, Turkey for their collaboration and valuable contributions.

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