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A Distinctive Conceptual Data Model for Spatial Highway Information Systems

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Summary: This paper presents a new approach to the conceptual data modeling of 3-D spatial highway information systems. It is shown; the revealed problems of current systems are mainly related with insufficient modeling possibilities of GIS. In order to establish a more generalized approach, highway administrations of various countries are analyzed namely; Turkey, Denmark, Germany and the U.S.A. In this context, after reporting the current status, the identified problems are going to be highlighted. Deficiencies are apparent; being information gaps at the technical and administrative flow and various non-integrated conceptual data models. In particular, the formal data model design methodologies and the multi-dimensional spatial character of road object are lacking. A special interest is going to be paid into topology related problems, which are also related with inadequate handling of multi-dimensionality. The approach presented here bases on the decomposition of geometry, topology and thematic data. The designed concepts are successfully implemented using the integrated approach in one object-relational system and results are evaluated on a pilot project.

Zusammenfassung: *Ein eindeutiges konzeptionelles Datenmodell für 3D-Straßen-Informationssysteme*. Diese Studie stellt einen neuen Ansatz für ein konzeptionelles Datenmodell von 3D-Straßen-Informationssystemen vor. Es wird gezeigt, dass unzureichende Modellierungsmöglichkeiten von GIS-Systemen viele Probleme aufwerfen. Um einen verallgemeinerten Ansatz zu begründen wurden die Straßendatenbestände aus vier Ländern analysiert: der Türkei, von Dänemark, Deutschland und den USA. Nach der Dokumentation des Ist-Zustandes und der Analyse wurden offen gebliebene gemeinsame Probleme herausgearbeitet. Einige Mängel betreffen Informationslücken im technischen und administrativen Ablauf, aufgrund der verwendeten nicht integrierten konzeptionellen Datenmodelle. Insbesondere fehlen formale Datenmodellierungs- und Design-Methoden, was zu Problemen beim Modellieren eines mehrdimensionalen räumlichen Straßenobjekts führt. Von speziellem Interesse sind die auf die Topologie bezogenen Probleme, die ebenfalls mit der unzulänglichen Behandlung der Mehrdimensionalität zusammenhängen. Daher wird bei der Datenmodellierung eine Trennung in geometrische, topologische und Sachdaten-Objekte vorgenommen und konsequent weiterbehandelt. Die entworfenen Konzepte werden erfolgreich auf ein Objekt-bezogenes Datenbanksystem abgebildet, installiert und an praktischen Daten analysiert.

1 Introduction

The Geographic Information System-Transportation (GIS-T) is identified having the highest information technology payoff potential by the highway administration, since this 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 in the world-wide 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

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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. 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.

In the frame of this paper the current problems of spatial highway information system is clearly outlined. Within these, problems related with topology and the inadequate handling of multi-dimensionality is going to be emphasized. In order to diminish the current problems, to provide the required 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. Furthermore, the multi-dimensional road information, using a non-planar approach, is successfully modeled. The designed concepts are implemented on a pilot project and results are discussed.

2 Current Status

Highway administrations, being one of the major governmental organizations, provide services and coordination at a national and international level to ensure the mobility of people and goods. This complex mission requires diverging tasks to be accomplished by means of various methods, depending upon required generalization level and quality of information. At the current status, responding various user requirements separately, such as pavement information system, tunnel information system or traffic safety information system, reveals the commonly used approach. However, several deficiencies are apparent; being information gaps at the technical and administrative flow, various non-integrated conceptual data models, lack of formal data model design methodologies and problems with modeling multi-dimensional spatial character of road object. Since the data used by the highway agency mainly have spatial character, several additional problems emerge. 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). 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. 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 illustrated in Fig. 1.

Excluding the planar coordinates, other dimensions, which have implicit references such as road identifier, name, stationing val-

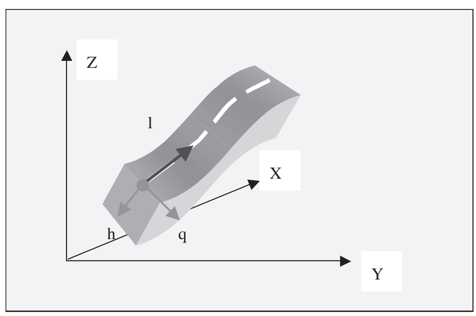

Fig. 1: Reference Systems.

Tab. 1: A Sample Text.

Road	Class	Nr. (LFD)	From Node (VNK)	To Node (NNK)	From Station	To Station	Length	Align-ment	Type	Radius	Clothoid Radius
B 2	B	46	3347012	3347010	0	84	3028		G	0	0
B 2	B	46	3347012	3347010	84	208	3028	R	R	600	0
B 2	B	46	3347012	3347010	208	455	3028		G	0	0
B 2	B	46	3347012	3347010	455	575	3028	R	R	350	0
B 2	B	46	3347012	3347010	575	597	3028	R	A	80	350
B 2	B	46	3347012	3347010	597	617	3028		G	0	0
...	...	...	...	...	...	...	...	...	...	...	...

ue, 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. Furthermore, although generally relational databases are in usage, fundamental principles of database design are lacking. A sample used in a spatial highway information system is presented in Tab. 1, which contradicts to the second normal form.

The current data modeling approaches are not sufficient to appropriately model the spatial information. Even though these approaches are highly expressive, they present limitations to the adequate modeling of spatial information, since they do not include geographic primitives that would allow for a satisfactory representation of spatial data (Borges 2001). Furthermore, these geometric primitives are not sufficient to realistically model the real-world road phenomena, such as clothoid. In case of dynamic transportation phenomena and facilities, the user requirements in 3-D and 4-D cannot be adequately responded. Although the basic philosophy of the most GIS approaches is discrete handling of geometric and thematic data, such decomposition has not been implemented satisfactorily. This is generally due to a lack of clarity in the separation of geometric and thematic data, unrecognizing multi-dimensionality, as well as the widespread practice of integrating geometry with topology. At the standard GIS conceptual data models, only one line or string is available representing both geometry and topology. In spite of some advantages, such as the reduction of total data storage requirements and increasing the spatial query processing performance, many disadvantages arise with data maintenance. Since in case of road object the geometry information in the system is frequently altered, displacements in geometry also affect topology. Therefore, data maintenance is required for both topology and geometry after every geometrical displacement. Additionally, since topology information is related to 1-D, 2-D and 3-D, multiple representations of topology are required in the applications.

Due the complexity embedded in GIS-T, according to (Goodchild 1998), (Thill 2000) extensions are needed to handle particular structures. One of them is planar versus non-planar model, wherein topological representation differs from cartographic representation by not forcing nodes at cartographic intersections. However, at the models evaluated all topologies are planar. The planar topology is based on the well-known graph theory, where links cannot cross each other without creating an intersection. The crossing links must therefore have to be splitted into several individual links. The planar networks have several advantages being; common and simple. Furthermore, the currently used programs for transportation applications employ algorithms based on the planar model. However, planar topology do not reflect the reality in case of road networks, where links can cross without creating intersection such as bridges, tunnels, overpasses, underpasses. In order to alleviate this problem, 'virtual nodes' have been introduced into the system, as in the Geographic Data Files (GDF) standard. The GDF, which is especially designed for vehicle navigation purposes, is mainly adapted from other GIS models; therefore 'virtual node' approach is widely used. A complete solution is not provided, since the planar model is inherently two-dimensional. Furthermore, due to the logical links produced for large number of road segments, which in reality represent a single continuous feature, high input and maintenance efforts are required. This intensive process of maintaining various features generally results introducing a significant amount of error into databases. Other complications arise in data update and maintenance when road is realigned. As a result, road information and many business functions, such as freight transportation management, real-time congestion management, traffic safety analyses cannot be efficiently utilized with the current systems. These problems mainly conclude insufficient user requirement responses, unpredicted data integration problems and finally lack of efficiency.

3 The Conceptual Data Model

In order to diminish the determined problems and cover the issues highlighted by the highway agencies, a conceptual data model is designed. During the constitution of external schema, a progressive approach appropriate to the conceptual data modeling requirements of an entire highway agency is reflected on. Furthermore, considering the peculiarity of spatial information, research on implemented systems and according to the previous studies conducted (Vonderohe 1997, VIS 1998, NWSIB 1998, NCHRP 1998, Gielsdorf 1998, BMVBW 1998, OKSTRA 2000, Dueker, 2000, Sutton 2000, Portele 2001), a criteria list is constituted. A model for this purpose should ensure 1.) conceptual decomposition of topological, geometric and thematic information 2.) support for multiple topological representation and various abstraction levels 3.) non-planar topological model 4.) integration of multi-dimensional road information in 3-D 5.) model for operational rules 6.) integration of existing databases 7.) incorporation of metadata 8.) interfaces to existing standards 9.) permanent non-spatial unique feature identifier

3.1 *Overview*

The main approach of the proposed data model is abstraction and decomposition of geometry, topology and non-spatial data. The data model is designed with four distinct components; being geometry, topology, road events and metadata. 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. 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.

Non-spatial information is introduced into the system as road event. The 'Road Event' object stores all non-spatial information including the attributes, occurrence and physical components of the road. 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 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. 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.

3.2 *The Topology Component*

Topology, being non-planar and having abstraction levels, is modeled as a logical abstraction of geometry. According to the user assessments, two abstraction levels are sufficient. The main elements of topology are

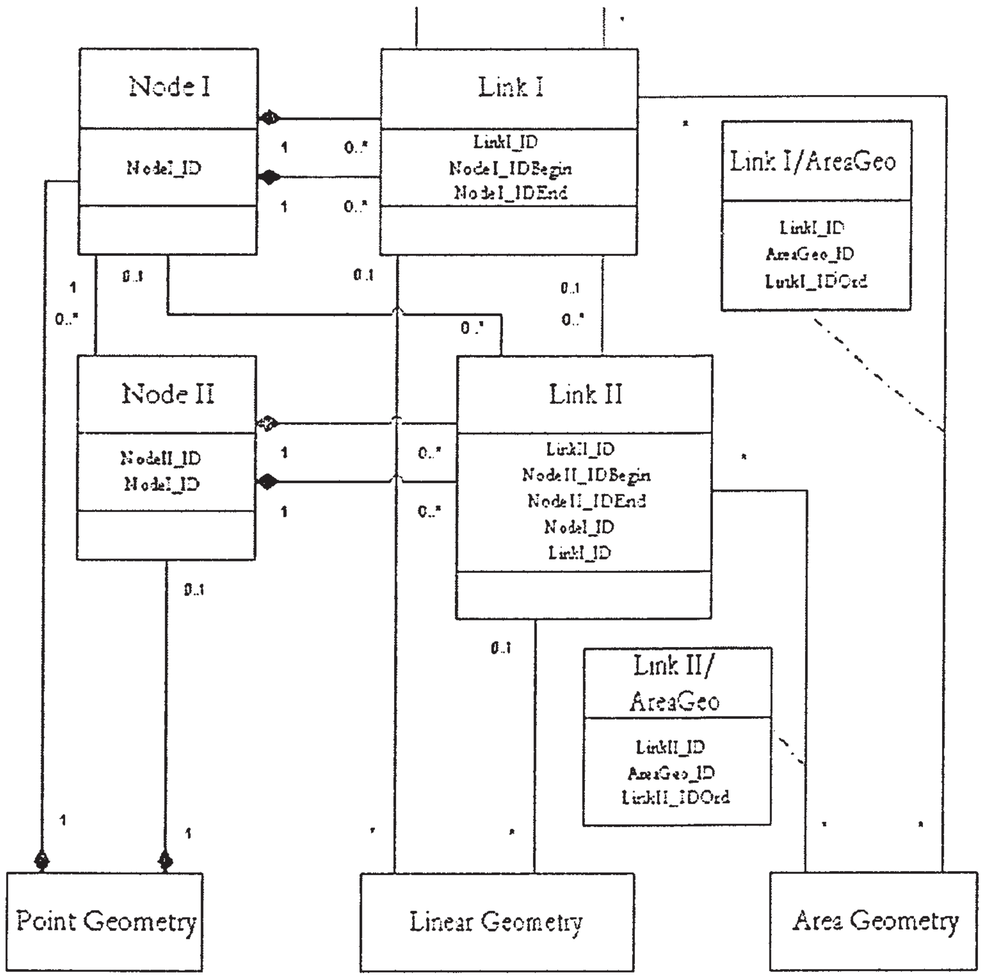

Fig. 2: The Topology Component.

Fig. 3a: An Air-photo, representing reality.

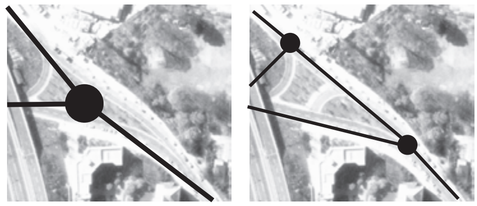

Fig. 3a: I-Level **Fig. 3b:** II-Level

Fig. 3: Topology Abstraction Levels.

node and link. These elements are adapted from traditional planar networks corresponding mathematical graphs. In order to define a link, beginning and ending nodes are required. A node can be assigned to many links. In the data model with two 1: 0..* aggregation associations are used for this relationships. Associations between node and link are applied to both abstraction levels, using the same aggregated associations. The modeled objects and their relationships can be examined in the Fig. 2 in detail.

Relationships between abstraction levels 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 second level topology element node ('Node II') a 1: 0..* relationship is assigned. This relationship maps reality adequately. 'Node I' may be composed of many nodes ('Node II') and every 'Node II' is assigned to 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 'Node I'. Road junctions are examples of such situations. 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'. The merging and subsequent separation of divided highways is an example of this, which is presented in Fig. 3.

Relationships between topological and geometrical components are described using the modeled associations. A node is represented at the geometrical level by a point. 'Node I' and 'Node II' have a 0..1: 1 relationship with respect to 'Point Geometry'. A node must be represented with a point, but a point need not be a node. This relationship is valid for both abstraction levels. 'Linear Geometry' has a relationship between the two abstraction levels; 'Link I' and 'Link II'. Between Link ('Link I' and 'Link II') and 'Linear Geometry' a 0..1: 1..* relationship is assigned. A link may be composed of many linear geometry elements and a linear geometry may be assigned to one link. The N:M association between topological element link and 'Area Geometry' is realized using association tables 'LinkI/AreaGeo' for the first level, and 'Link II/AreaGeo' for the second.

In order to obtain non-planar topology, vertical alignment elements of the entire network are required. With the designed objects at the conceptual data model geometry component 'Linear Element Vertical', 'Point Geometry' and 'Linear Geometry' object method *Detecting Alignment Elements*, vertical alignment elements are achieved. This method is based on the detection of alignment elements realized over significant parameters and elements, with the help of curvature diagram and applied for both vertical and horizontal alignment. If the beginning point and beginning tangent angle is known, with an approximation, alignment element parameters and their sequence can be uniquely defined (GRÜNDIG 1988). The curvature diagram is a graphical representation of the curvature (k), where (k) is defined with respect to stationing length (l) as;

$$k = \frac{d\tau}{dl}$$

Therefore, alignment elements can be identified with simpler functions being; straight lines parallel to axis, straight lines not parallel to axis and quadratic parabola. Since the geometrical element clothoid is not used for vertical alignment by the agency, two functions being; straight lines parallel to axis and straight lines not parallel to axis is relevant for the vertical alignment. For each point of the alignment, where the bearing angle is a function of stationing value, the cartesian coordinates (x, y, z) of points of the vertical (or horizontal) alignment results detecting the alignment elements with the use of simple functions integration. Adjacent elements have to fulfill conditions of transition in order to enforce the smoothness of the alignment and of its first derivative. In order to achieve the optimum result, additional constraints for geometrical and driving dynamics are considered in the adjustment model as observations. As result of these analysis, sequence of alignment elements, element type, radius, stationing values, coordinate list of alignment main points with approximation values are obtained.

3.3 *Implementation of Topology*

The proposed concepts are implemented on a pilot project using the data provided by the Brandenburg State Office for Traffic and Roads (BLVS), Germany. The sample data is located in an area to the northeast of Berlin around road B2. It is received in MapInfo (*.mif) and (*.dbf) format, in which the regulations of ASB (der Anweisung Straßen-Informationsbank) is used. The vertical and the horizontal alignment elements are present as non-spatial information. The available height information is the road gradient and road inclination values, which are linearly referenced (1-D) using the link-node method.

The proposed concepts are implemented after the constitution of physical data mod-

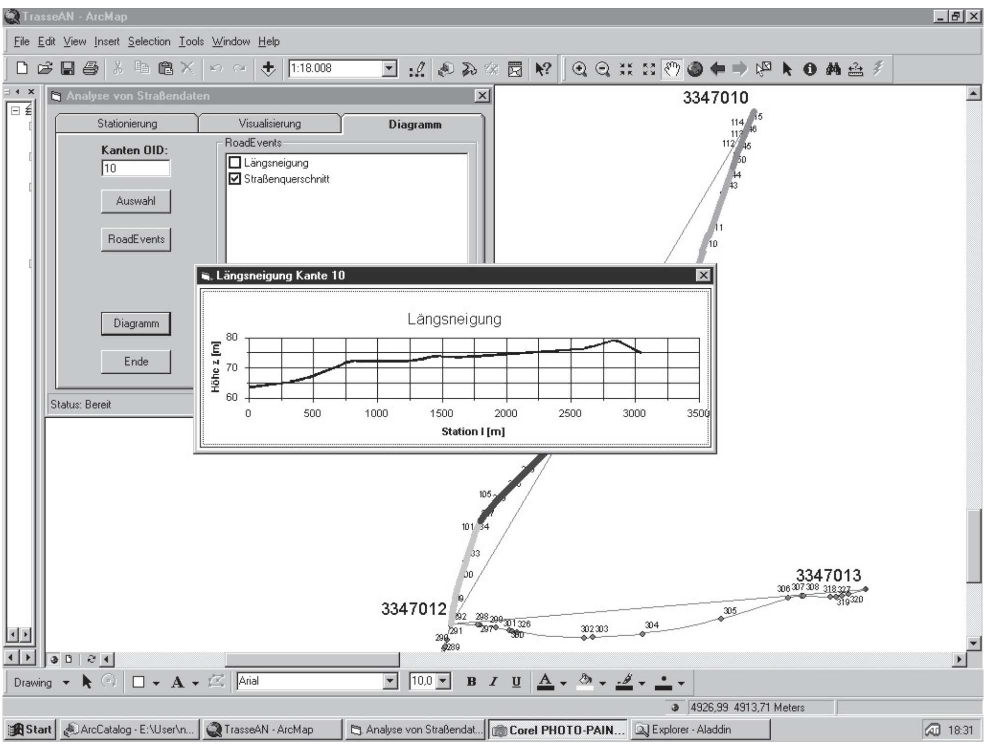

Fig. 4: The Vertical Linear Elements.

el. An object-relational database management system (DBMS), Oracle8i, with its Spatial Data Option extension and Microsoft Visio is used. The concepts are implemented on both ArcInfo8™ and Geomedia Professional 3.0, in order to compare the system feasibility and performance. Using the '*Detecting Alignment Method*' and available height information non-planar topology is achieved. Topology component is implemented as anticipated in the conceptual data model, shown in Fig. 4. An additional interface is designed in order to display non-planar topology. (PFANMÖLLER 2001)

In the pilot project the usage of vertical and horizontal geometric elements are practical and sufficient. However, in many cases, it is costly to employ such information. Although this information is widely used in daily operations, often it is not in digital form. In case of unavailability of vertical elements, non-planarity can be obtained using Digital Terrain Model (DTM) since the height information for the entire highway network can be achieved. However, several problems are apparent. Firstly, the accuracy required in applications, such as freight management and traffic safety, cannot be accomplished economically. As DTM accuracy is tightly correlated with the data collection method and the map scale, costs increase as the provided accuracy increases. Additionally, having high accuracy DTM data will not alone fulfill the requirements of applications. DTM does not match with road structures such as bridges, tunnels and overpasses in a one-to-one manner.

In order to solve this problem, other data sources, such as; geometrical design regulations, minimum overpass height, driving dynamics and traffic safety regulations, can be introduced to the system. However, in this case the solution is not unique, leading to redundancy. The control of redundancy can be achieved by means of adjustment techniques and also certificate the quality. This process is performed iteratively, until $\Sigma v_i^2 P_i$ is minimum and all conditions are fulfilled. Since an adjustment approach allows for a change of all parameters while simultaneously enforcing constraints together with the tolerance of the constraining points, the risk of introducing very "strong" constraints should be minimized. It can be done by loosening the "strong" constraints until the appropriate solution is achieved. Consequently, when the proposed method is applied to a system using DTM of lower accuracy, the non-planar topology can also be optimized for the entire highway network and expectations are fulfilled at low cost.

4 Conclusion

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 designed conceptual data model presents a considerable departure from traditional planar, centerline based, transportation network in order to comprehend the user assessments. In order to provide an efficient data management within highway administrations, the main approach of the proposed data model is abstraction and decomposition of components being geometry, topology and non-spatial data. The topology is independent of geometry, which in many other data models is ignored. A fully non-planar topology model is adopted here in order to resolve the current problems, supporting different abstraction levels. The conceptual data model designed fulfills the criteria list constituted in an optimized manner. Using this approach it is also possible to maintain other linear objects, which are topologically separated. Using this approach for rail network will be explicitly beneficiary for many applications at GIS-T, such as traffic safety and management of inter modular transportation.

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