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Object Based GIS-T Data Model for Road Infrastucture Maintenance in Uganda

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Abstract

There are several cases of poor transport services in Uganda that are caused by the bad state of roads. Road maintenance proved ad hoc until recently when the need for preventive maintenance was recognised and plans of making it a priority put in place. Since roads are geographically located, the use of Geographical Information Technologies (GITs) in collecting, managing and analysing road condition is paramount. And yet, these technologies are under utilized for road maintenance. This paper derives from research aimed at accentuating the use of GITs for Road Infrastructure Maintenance (RIM) in Uganda. The research addressed three objectives, (1) to assess the gaps and limitations in GIT use and access for RIM, (2) to develop a methodological framework for enhancing the use of GITs in RIM and (3) to develop a Geographical Information Systems for Transportation (GIS-T) data model for RIM in Uganda. In line with the 3rd objective, the paper specifically presents an object data model for RIM. This was accomplished through identification of road maintenance data requirements, review of: organisational reports, workshop proceedings, organisational terms of reference for various projects and existing data models & standards in transportation. An understanding and consideration of the Information Quality Levels (IQL) was paramount. This resulted into a conceptual and logical data model for RIM based on concepts of dynamic segmentation and linear referencing. The conceptual model depicted using entity relationship diagrams identifies with 3 entities - the road's network and the point and line events that exist on it. Besides logically documenting the various classes from the conceptual data model, the ESRI provided template for logical data modelling was used. The model separately emphasizes objects having spatial reference, objects without spatial reference and the relationships between them. The study concludes that a common definition and understanding of the country's transportation network is essential to adoption of the proposed model. The choice of GIS software with the full set of dynamic segmentation tools is fundamental for implementation of the physical model. This idea of modelling data is a contribution to standardisation of geographic data sets for the sector.

Keywords

Data model; Dynamic segmentation; Geographical Information Technologies (GITs); Road Infrastructure Maintenance (RIM); Linear referencing; Uganda

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Introduction

For sustainable development of a country, a well maintained road transport network infrastructure is fundamental in the promotion of socio-economic and industrial developments. Authentic information relating to the condition of the transport infrastructure is a fundamental requirement for road network management. This information that supports decision making is required to be up to date, reliable, relevant, easily accessible and affordable. The Transportation Research Board (TRB) [1] asserts that geospatial data are a foundation for relevant and critical information for planning, engineering, asset management and operations associated with every transportation mode. These are data referenced to the earth surface according to a coordinate system. Because the road network is geographically located, geographical reference to it gives additional clarity. The strategic plan of the National States Geographic Information Council of the United States of America dated January 1, 2009, highlights that 'Geospatial information is one of the nation's most important and under-utilized assets in the effort to achieve greater efficiency and effectiveness of government agencies and private industries'. Geographical Information Technologies (GITs) which are specialised Information and Communication Technologies (ICTs) that deal with the collection, management, storage and manipulation of geo referenced data are quite fundamental in dealing with this relevant data for decision making. More recently, it has become clear that GIS, together with GPS, aerial photography, RS techniques, and other spatially related tools for decision making, comprise a larger array of complementary tools that can be grouped together under the more comprehensive title of GIT [2].The use of these technologies is increasingly shifting from reference to dynamic decision making tools. And yet these technologies are under utilised for Road Infrastructure Maintenance (RIM) works in Uganda. A few stakeholder organisations in RIM are using GITs. Their use however is limited to preparation of map reports to higher level managerial offices. Data is haphazardly structured in their databases in addition to the absence of standards for the datasets used. The datasets are characterised by varied accuracies, differences & uncertainties in reference frames and varied location referencing approaches.

This paper derives from research aimed at accentuating the use of GITs for RIM in Uganda. The overall research addressed 3 objectives: (1) to assess the gaps and limitations in GIT use and access for RIM, (2) to develop a methodological framework for enhancing the use of GITs in RIM and (3) to develop a GIS-T data model for RIM in Uganda. In line with the 3rd objective, the paper specifically presents an object data model for RIM. The following sections discuss the methodology adopted, the nature of road maintenance data, the concepts of dynamic segmentation and linear referencing which are fundamental in effecting spatial data analysis of road maintenance data. The proposed conceptual and logical data models for RIM in Uganda are presented.

Methodology

Three procedures were involved: (1) Identification of road maintenance stakeholders, their roles and the road maintenance

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data requirements, (2) Understanding and consideration of the Information Quality Level (IQL) data categories, and (3) Review of existing data models and standards in transportation [3]. These were accomplished using a set of document & datasets review, interviews and focus group discussions. These were conducted in Kampala, Uganda with the road engineers, managers and GIS specialists in the identified organisations responsible for RIM. These organisations included Ministry of Works and Transport, Uganda National Roads Authority, Kampala Capital City Authority and private contractor and consultant companies.

Bennett et al. [4] define 5 levels of information quality (IQL) for general use (IQL-1 to IQL-5). These correlate to the degree of sophistication of the data combined with the required methods of collecting and processing it for decision making. The higher the decision level, the higher the IQL. For policy making at the highest decision making level, for example, IQL-5 data is recommended. Low-level data (IQL-1) for example can be condensed or aggregated into progressively simpler forms to become higher-level data (IQL-5). IQL-1 data is more sophisticated, much more detailed, and necessitates more processing and analysis techniques before use.

Besides adaptation from Jelokhani-Niaraki et al. [5], the model has been developed with reference to the enterprise GIS-T data model by Dueker and Butler [6,7], and the ArcGIS Transportation Data Model: UNETRANS – Unified Network for Transportation from ESRI [8,9]. The location and condition aspects of the data elements as presented by Paterson and Scullion [10] form the foundation of the proposed models.

Road maintenance data

Road maintenance data also referred as road condition data is both multidimensional and multifaceted. It is multidimensional in the sense that reference to a transportation feature can be made as either: One dimensional (1D) - linear reference, e.g. kilometer distance from a known point location, Two dimensional (2D) - X, Y planar coordinates, Three dimensional (3D) - X, Y, and Z height information, Four dimensional (4D) - X, Y, Z, and time in case of dynamic objects. The data is also multifaceted in that relationships between transportation features can be defined both physically and logically. Whether physically or logically defined, these features exist both in the real and virtual worlds. The real world is the real world as we speak of it while the virtual world is the database where these data are stored (Table 1). Complexities in creating transportation databases (models) arise from the fact that there is often a one-to-many relationship between the physical and the logical entities. This means that one physical transportation feature can be logically defined in many ways. These real, virtual, physical and logical realms can be exemplified in Table 1. The road condition attributes as the physical virtual parameters are just a broad example of data values. These road condition attributes as elaborated in the logical data model in Figure 2 are tremendous. They include the Internal Roughness Index (IRI), skid resistance, Pavement Condition Index (PCI), Annual Daily Traffic (ADT), gravel thickness, etc.

Linear referencing

Linear referencing is a method that is widely used by transportation agencies to record position information along linear features [11,12]. It locates information on a linear feature using a single relative position on the feature by giving an address consisting of a distance and direction from a known point location. The underlying datum for linear referencing is the network itself and not the cartographic coordinate system for spatial referencing. There are various methods of linear referencing, including: (1) Kilometre point method - kilometre distance measured from the start of the road, (2) Kilometre post method - measures from a physical km post, (3) Reference point method - distance from known physical reference object along the road, (4) Reference post method - distance from well-established reference posts, and (5) Link node method [4].

Table 1: GIS-T Modelling Transformations adopted from Fletcher (1987) as cited by Miller and Shaw (2000).

	Logical	Physical
Real	*Legal Definitions* • Route • National route • District route • Political boundary	*Actual Facilities* • Highways • Roads • Intersections
Virtual	*Data Structures* • Networks • Links • nodes	*Data Values* • Lines • Points • Polygons • *attributes*

The link node method is a special implementation of the generic referencing system. The nodes refer to specific locations on the roads and the links are sections between the nodes. It is a special application of the reference point method where permanent features e.g. bridges, intersections, road junctions, etc. are given node numbers. Roads are then collections of adjacent links. As asserted by Kennedy et al. [13], a method for linear referencing is the basic foundation for road applications especially if GIS integration is involved.

Dynamic segmentation

In order to make proper management decisions regarding road maintenance, the pavement condition data must be summarized into homogenous lengths to aid prioritisation of maintenance works. Kennedy et al. [13] assert that the usefulness of the road maintenance data can be greatly enhanced by applying a segmentation procedure to produce uniform and consistent sections. Dynamic segmentation is a way of referencing linear attribute data on demand, based on a variable segmentation of a single network. It is the process of computing (on the fly) the location of events along a road using linear references. The dynamic segmentation process imposes two requirements on the data: (1) a unique identifier and measurement system for each linear feature, the road in this case. (2) a unique identifier and position along a linear feature for each event in an event table. This allows for analysis of road network's condition attributes and the creation of analysis segments based on road condition data from the event tables. As the condition of the road is not uniform all through, these attributes are always changing and likewise the analysis segments hence the term dynamic segmentation.

Dynamic segmentation involves a combination of multiple sets of values to any portion of a linear feature based upon trends in the data [13]. It is a method for segmenting a road network into segments without physically breaking the links and adding nodes [14].

The linear referencing system of a road is the foundation to the location and analysis of events on the road network using dynamic segmentation. In this sense, linear referencing is an efficient way of managing road maintenance data in a GIS.

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Proposed data models

Conceptual data model: Figure 1 represents the proposed conceptual data model, which emphasises 3 entities: (1) the roads, (2) the point events, and (3) line events referenced on it. It is a non-link based model in the sense that data exchange between the stakeholders involved in road maintenance is dependent on the point and line event data other than the link node structure of the road network. In the Model,

- Links are defined by a beginning and ending node and a node may end or begin one or more links.
- Roads are made of one or more sections, and sections consist of one or more links.
- One or more linear events must be referenced on a road, and one or more point events may be referenced on a road.
- A node may be a point event.
- A black spot is a location inclined to accidents on the road.

Bridges, black spots and culverts for example can be either points or lines depending on the type of analyses to be performed on them and on how the data corresponding to their location has been collected.

As noted, the conceptual model was modified with simplifications taken from the enterprise GIS-T data model [6,7]. The Dueker and Butler's enterprise GIS-T model was intended as a starting point for application specific transportation databases. Their model is not specific for road transportation but all linear transportation networks including, rail and air networks. Dueker and Butler's model elaborates more on reference objects being located on the earth using geographic points which are then transformed into cartographic points. In the adapted model of Figure 1, reference, geographic and cartographic points are inferred issues intended for consideration at the implementation stage.

Logical data model: In addition to logically documenting the various classes from the conceptual data model, logical data modelling made use of the ESRI provided template for use, extension and adoption to various systems. The resulting UML model in Figure 2 is an object relational data model that identifies and codes the attribute types and relationship parameters of objects. It separately emphasises objects having spatial reference, objects without spatial reference and the relationships between them.

The model contains a total of 19 classes: 'Link', 'Node' and 'Road' as feature classes, 'Bridge', 'Culvert' 'Black Spot', 'Road Office', 'Road Sign', 'Photo Dataset', and 'Point Ongoing Activities', as point events, and 'Jurisdiction', 'Maintenance Record' 'Line Referencing Point Feature', 'Surface Type', 'Unpaved Road Condition', 'Paved Road Condition', 'Video Dataset', 'Traffic Volume', and 'Line Ongoing Activities' as linear events. The 'jurisdiction', 'Road Office' and 'Maintenance Record' are uniquely referenced directly to the road.

The cardinality in the model is as explained in Table 2.

The relationships in the model are defined basing on maintenance standards as follows:

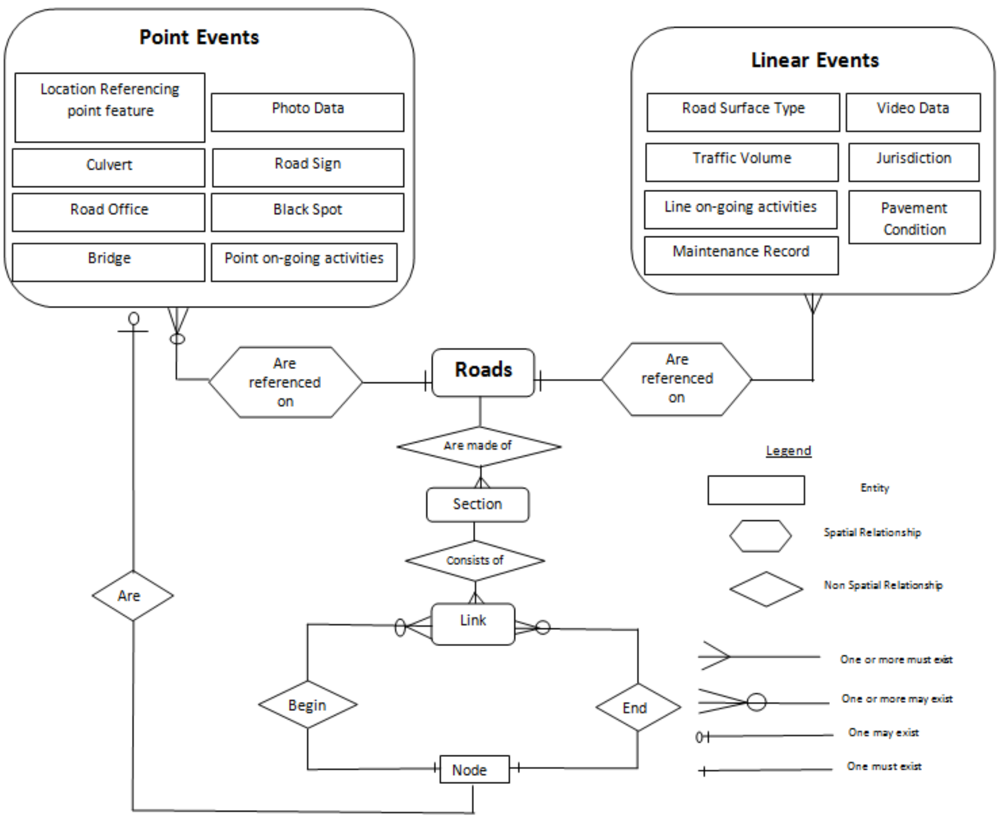

Figure 1: Conceptual Data Model - Adapted from Jelokhani-Niaraki et al. (2009).

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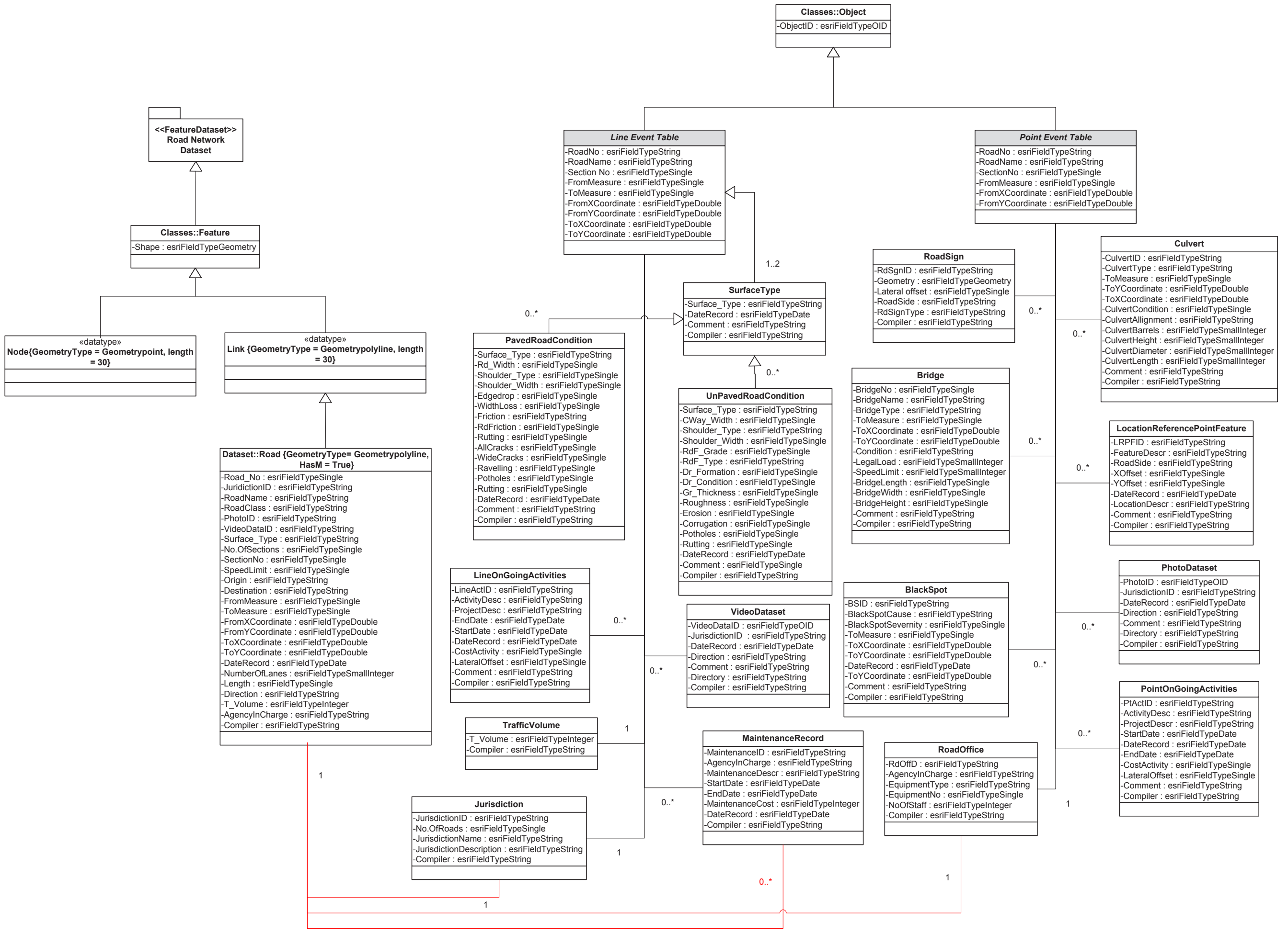

Figure 2: The Proposed Logical Data Model.

Table 2: Cardinality explained.

Indicator	Meaning
1	One only
1..2	One or two
0..*	Zero or many

- A linear event may have 1 or 2 'Surface Types'. 'Paved Road Condition' and 'Unpaved Road Condition' events that are sub classes of 'Surface Type'.
- Depending on the surface type of the road, a linear event may have zero (0) or many paved or unpaved road conditions.
- There may be none or many point and line on going activities on the road.
- A linear event should have only one value for traffic volume assigned.
- A linear or point event may have either none or many video and photo data sets archived.
- Zero (0) or many black spots, bridges, road signs and culverts may exist as events on a road.
- A road exists in only one jurisdiction. A road is assigned to only one road office and, Zero (0) or many maintenance records may exist on a road.

As bridges, culverts and black spots can be identified as point or linear events, the logical data model instances this by maintaining the attributes corresponding to the To Measure, To X Coordinate and To Y Coordinate to the proposed attribute list for cases of when identified as linear events.

Thoughts on implementation of the physical data model

The implementation and validation of the physical data model is an aspect that should be pursued further. This requires an analysis of the software, choice of the geodatabase type to be adopted, and accumulation of data to populate the database. A common understanding of the transportation system in Uganda is the backbone to using this proposed model. An explicit definition and documentation of the anchor points and sections that define the road network of the country is fundamental. These should be inclusive in the location referencing points feature dataset. This requires uniform and agreed mechanisms of defining road sections. Dueker and Butler [6] propose the use of pavement type, functional type, jurisdiction, and intersections to define logical sections so as to create discrete transportation features according to some business interest. Specific locations for the beginning and ending point measures for linear objects should be assigned and documented accordingly.

The ability to access and use tools that can manage and query linearly referenced data in GIS is quite critical especially now, as the use of GIS in transportation (GIS-T) agencies is being advocated for. A GIS platform that supports dynamic segmentation will be ideal. Not all GIS have the capability to perform analyses based on dynamic segmentation. The choice of the GIS platform should take this into consideration. Most users with ArcView, Geomedia and other desktop GIS software do not have access to the full set of dynamic segmentation tools [15]. However, ESRI's ArcGIS and Intergraph have dynseg data models in their software.

Conclusion

The continuous nature and changing analysis requirements of road condition for maintenance require that a provision for inclusion of more attributes in the model as may be required is established. The proposed model has taken this observation into consideration. Similarly, for a model intended for a number of organisations dealing with slightly different datasets, a provision for null values is paramount. This is considering that all sighted objects and condition attributes are not required for each of the participating organisations. Besides enabling spatial analysis for decision support in road maintenance operations, event data exchange amongst involved organisations within the sector is rendered by the model. Most importantly, modelling is contribution to standardisation of geographic datasets for the sector.

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