Geographic Information Systems for Transportation - Data Model for Road Infrastructure Maintenance in Uganda

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Abstract

A lot of data is involved in the planning and management of road maintenanceoperations. Sincemajority of these operations are based on location, a great deal ofthis data is spatial in nature.In Uganda, much of this data is stored as text document files, excel data sheets and video logs. Some organisations have nevertheless managed to store these data in Microsoft access databases linked to GIS systems. Even though the structuring of road maintenance data is not uniform, this data is shared by several organisations and often is required as archives for future use. Successful data sharing requires a common schema that is flexible to handle the needs of diverse participants. It is therefore apparentto have a data model that can boost data exchange between these organisations. Basing on document review and analysis of existing road datasets, this paper proposes a data model for road maintenance in Uganda. As foundation to a feasible data model recommendation, the road network numbering & referencing system in Uganda is discussed and a review of the nature of road maintenance data is made. In addition, areview of the fundamental GIS data models in transportation highlighting their major characteristics, strengths and weaknesses is made. Dynamic segmentation as an extension to the traditional arc-node data model is recommended for Uganda. As cited in the paper, several researchers have found this data model successful in dealing with transport planning analysis. Due to the multifaceted and varying aspects of road maintenance data, this modelallows for the analysis of precise and high value spatial resolution segments within the GIS. The location of multiple events can be stored with linearly referenced attributes without duplication with route geometry. More importantly, it allows for the sharing of network infrastructure with several applications for which transport data may be required.

Keywords: Data Model, Dynamic Segmentation, Geographical Information Systems for Transportation (GIS-T), Road Maintenance

1. Introduction

Transportation data is normally one of the core elements of base maps and in this context, it serves as essential reference data. According to (Filipov and Davidkov, 2006), it is also used for vital applications, such as routing, urban and regional planning, management and provision of public transport, emergency responses and general purpose mapping among others. Today, all these applications require Geographical Information Systems (GIS).Geographical Information Systems for Transportation (GIS-T) are interconnected hardware, software, data, people, organisations and institutional arrangementsfor collecting, storing, analyzing and communicating particular types of transport data about the earth (Fletcher, 2000).The mission of GIS-T is to develop spatial database management systems and computer graphics environment that can accomplish data integration at different levels of network representation (Sutton, 1997). Data representation is a fundamental focus of GIS (Shaw, 2010). This representation requires a model to facilitate the manipulation of datasets. For transportation planning, whichever the data model to be adopted, there should always be a common understanding of the transportation system in order to ensure effective data sharing (Dueker and Butler, 2000b). There is non-uniformity in the structuring of road maintenance data in Uganda. Using document review and analysis of existing roads datasets, this paper's intention is to define a data model to support data storage and exchange amongst a category of road maintenance participants, referred to as stakeholders by (Mazzi et al., 2010). This stakeholder group consists of organisations that have either ownership or maintenance responsibilities for transportation infrastructure. They include road contractors, road consultants, local governments, Uganda National Roads Authority (UNRA) and the Ministry of Works and Transport (MoWT). These organisations have different functionalities for the said data. These range from producers, integrators to users of the data. Data users may additionally include researchers (like the present author(s)), motorists, and the general public. There are also organisations using the transportation system in their businesses like the police, fire extinguishing departments, delivery firms, etc who often rely on data integrators to provide transportation data in the form of maps and networks for location, path finding and routing. It is therefore a requirement that application specific transportation databases be defined basing on a specific data model so that data sharing can be effective without costly redundant recollection of data from the field. Transportation data is extensive to collect; it is multidimensional with many attributes and is constantly changing. Because of this, the traditional arc-node data model is hard to deal with in efficiently expressing and analysing this kind of transportation data.

This paper discusses the road numbering and referencing system in Uganda as is being adopted by the Uganda National Roads Authority in the establishment of the national roads databank. Together with the nature of road maintenance data, the referencing system paves a background to the understanding of data modelling requirements for road maintenance. A review of GIS-T data models relevant to the Ugandan context is made, a basis on which dynamic segmentation for road maintenance in the country is proposed.

2. Road Network Numbering & Referencing System in Uganda

Road numbering and classification is a fundamental aspect of a road system. It takes into account andprovides for manageable codes to road datasets and their users. Until the conception of developing a national roads databank for Uganda, the road numbering and referencing systems have not been uniform for organisations that deal with roads data. The discussion below is adopted from the developments from the ongoing establishment of a Management Information System (MIS) for national roads and bridges in Uganda. Like in many countries, the road numbering and classification scheme is based on functional criteria. (Rodrigue, 2005, Dueker and Butler, 2000a, Dueker and Butler, 2000b, Dueker and Butler, 1999) affirm that most organizations that maintain databases of roads break them into logical segments to create discrete transportation features according to some business interests, such as a change of pavement type, jurisdiction, functional type, or at all intersections. In Uganda, this functional class is based on both present traffic volumes, and the function as an accessibility provider. The road classes therefore represent a guideline for road maintenance planning and design as well as orientation for road users. Each road class has been assigned a band of numbers as illustrated in table 1. The band assigned for each road class provides a large tolerance if roads are to be added in the future. Class A roads were numbered at a national level according to importance. Class B roads were also numbered at a national level, but clustered according to zones for better geographical orientation. Figure 1 demonstrates these zones. In order to avoid repetition, each zone was assigned a band of numbers as demonstrated in Table 2. Within these zones, nearby roads have successive numbers as much as possible. Class C roads were numbered similarly to Class B roads; however they are banded at a regional (station) level as shown in Figure 2. Table 3 shows the class C road number bands.

Table 1: Road Classes

Road Class	Description	Road Class Band
A – Primary Roads	National and international routes connecting major cities and towns, regional centres and neighbouring countries	001-100
B – Secondary Roads or District Roads	Collector roads connecting district centres with the primary roads. It can also connect other activity destinations like industrial centres or tourist areas	101-500
C – Tertiary or Local Roads	Serve the local traffic needs and are connecting the villages and local population to the general road network. It is characterized by short travel distances, low speed and traffic volumes and without access control.	001-999

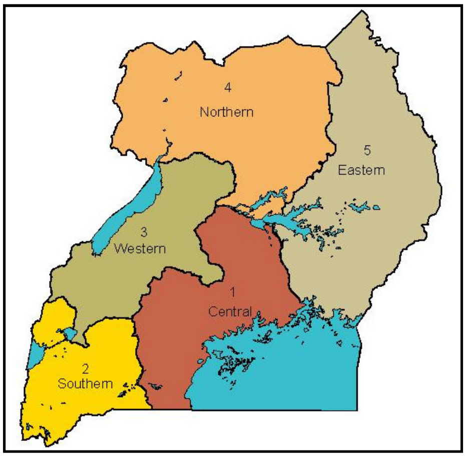

Figure 2. Uganda Zones

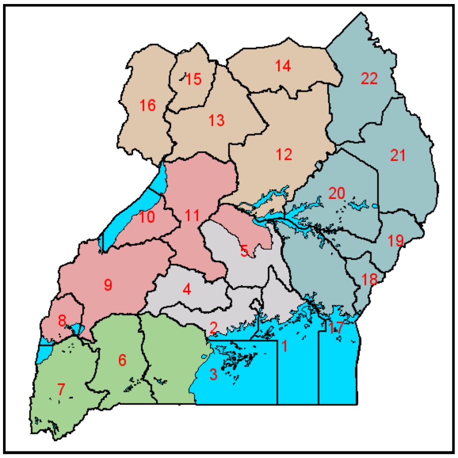

Figure 3. Uganda stations

Table 2: Class B Road Number Bands

Zone	Road Number Band
Central	B101 – B149
Southern	B150 – B199
Western	B200 – B249
Northern	B250 – B299
Eastern	B300 – B349

2.1 Road section and location referencing

Roads are broken into a number of sections based on roundabouts, major road junctions, region boundaries and station boundaries as nodes. All location reference points (LRPs) are assigned a unique 2-digit feature code for example Bridge (BR), Start of Road (ST) and Junction (JT). By combining this with the road number, section number, and the feature number, the feature reference number is formed. Reference to a bridge location for example would be BR[road user number][section number][Feature number]. The 15th bridge on a class C road (C213) along section 4 would be referenced as – BR [C213-04-15].

Table 3. Class C Road Number Bands

Station No.	Station Name	Road Number Band
01	Kampala	C001 – C149
02	Mpigi	C150 – C209
03	Masaka	C210 – C259
04	Mubende	C260 – C299
05	Luwero	C300 – C349
06	Mbarara	C350– C409
07	Kabale	C410 – C509
08	Kasese	C510 – C539
09	Fort Portal	C540 – C589
10	Hoima	C590 – C619
11	Masindi	C620 – C649
12	Lira	C650 – C679
13	Gulu	C680 – C699
14	Kitgum	C700 – C719
15	Moyo	C720 – C739
16	Arua	C740 – C779
17	Jinja	C780 – C829
18	Tororo	C830 – C859
19	Mbale	C860 – C919
20	Soroti	C920 – C959
21	Moroto	C960 – C979
22	Kotido	C980 – C999

2.2 Definitions of Some Important Terms

It is important to be conversant with these terms in the following discussion; *Transportation Feature/ entity* is some identifiable element of the transportation system which can be a point (bridge), line (road or rail road) or an area (airport). A linear transportation feature is often referred to as a route. *Jurisdiction* refers to the political or other context for designating transportation features and their names. In table 1, the numbers A, B and C signify the road jurisdiction. An *Event* is an attribute, occurrence, or physical component of a transportation feature. These are things that are not tangible and yet describe tangible element, for example speed limits and pavement types. These working definitions have been adopted from (Dueker and Butler, 2000b).

3. Nature of transport data

Transport data is both multidimensional and multifaceted. A transportation feature can be referenced as 1D – linear reference e.g. Kilo Metre distance, 2D- X, Y coordinates, 3D-X, Y, Z coordinates and 4D- X, Y, Z, Time dimensions. Transportation feature relationships can be defined both physically and logically. These defined features exist both in the real and virtual worlds. The virtual world in this case is the database where these data are stored.

Complexities in creating transportation databases (models) arise from the fact that there is often a one-to-many relationship between the real and the logical entities.Hunter and Shaw (2001) affirm the complex properties of transportation networks as being associated with their multimodal nature, having different logical views and "one-to-many" relationships amongst themselves. An illustration of these real, virtual, physical and logical realms is as follows. The real-physical entities refer to the transportation entities as constructed and used in the real world. Virtual-logical entities relate to data structures such as nodes, links and polygons. Virtual-physical entities relate to the geometric and attribute data corresponding to the transportation entity and displayed in the GIS database. These still maintain a one-to-many relationship as many links for example can be represented by a single cartographic line. No wonder (Dueker and Butler, 2000b) define transportation features as likening strings of pasta. For road maintenance, the data attributes include; the International Roughness Index (IRI), Surface Integrity Index (SII), skid resistance, and Pavement Condition Index (PCI), Average Daily Traffic (ADT), and gravel thickness to mention but a few. These modelling transformations are shown in table 4.

Table 4: GIS-T Modelling Transformations (adopted from Fletcher, 1987).

	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*

4. Data Models

A data model is a collection of conceptual tools for describing data, data relationships, data semantics, and data constraints. Data modelling requires a choice of a modelling language for example Unified Modelling Language (UML), Petri nets, Entity relationship diagrams, IDEF (Integrated DEFinition), ISDL (Interactive Systems Design Language) and workflow diagrams. There are 3 basic levels of data modelling; the conceptual, logical and physical data models. The conceptual data model portrays real world phenomena of interest at an abstract level with no implementation details. A logical data model translates the conceptual model into sets of constructs in a Database Management System (DBMS) in terms of entities and relationships. It describes the structure of a database which will be processed by the DBMS. The physical model then deals with the implementation of the logical model in the physical structure of the DBMS. GIS-T data models are in three broad categories namely, network, process, and object models. Network models are those concerned with the topology of connections and intersections of nodes and arcs of a transportation system. Process models are concerned with how transportation activities are conducted. By organising several transportation elements into a model, process models define processes by which some transportation planning or maintenance activity takes place. Object models identify many transportation objects and logically organize them in such a way that they can be used for any application.

There are a few GIS-T data models and standards on which these models are being developed. This is because GIS-T is still in development. Some of the existing data standards in the transportation field are Geographic Data files (GDF) (GDF, 1995, GDF, 1999) particular to object models, National Cooperative Highway Research Program (NCHRP) 20-27 particular to linear referencing (Vonderohe et al., 1998, NCHRP, 1997, Scarponcini, 2002) and the Topologically Integrated Geographic Encoding and Referencing (TIGER) that is particular to network models in the USA. The GDF standard was developed as a draft submitted to the European Committee for Standardization. It is a feature-based geographical data standard (Arctur et al., 1998) widely used in the Intelligent Transportation Systems (ITS) industry. A consortium of public and private entities developed GDF to improve the efficiency of the capture, the production and handling of road related geographic information (Curtin et al., 2003). The NCHRP in USA is designed to facilitate research to develop practical solutions to problems facing transportation agencies (Vonderohe et al., 1998, Adams et al., 2001) in establishing a datum for location referencing. The TIGER files are a network structure for applications of GIS in transportation. These files provide national coverage of the transportation network and other features for spatial data users in the USA. Table 5 gives a summary of GIS-T data models reviewed and of relevance to the Ugandan context.

5. Discussion

The relational data model is the most common logical data model that supports the node-arc representation. It is a user friendly data model in which a road section (arc) is believed to start and end at a node. These arc-node details are stored in relational tables (arc, node, event and turntables) hence the relational database. In this model, data is organised in a series of layers that are referenced to the geographic features. It is currently the most used data model for road maintenance in Uganda. Each table (relation) stores facts of a certain type. The rows are records of a transportation feature while the columns indicate various attributes of that feature. This model assumes that arc characteristics do not change between nodes which is not the case for many transportation applications. In addition, attributes in the relational model are linked to arcs with similar length and location without attention to the applications at hand (Mohammad et al., 2009b). The roughness of a pavement for example can vary substantially along sections of the road (arc). For road maintenance purposes, it is often a requirement to analyse road sections based on common attributes. With the arc-node data model, sections (arcs) are pre-determined by the way their geometry is stored in the database. The model in effect imposes a fixed level of spatial resolution limiting exploitation on road geometry which is useful for road maintenance and other such applications. In this model, it is difficult to support the one to many relationships between the real, physical, logical and virtual transportation feature attributes without redundant storage.

Several emerging GIS-T data models have greatly expounded on this traditional node-arc model (Miller and Shaw, 2000) because of these emerging challenges. Enterprise data models are intended to support not only one agency or application but the whole set of spatial data users within or across enterprises. These models have a common LRS and can support all the relevant applications including a wide variety of transportation domains, infrastructure management, public transit, freight, intelligent transportation systems, waterway navigation, hydrological analysis, utilities management and seismological sensing (Vonderohe et al 1995). The advantage of these models is the ability to facilitate data sharing and interoperability among GIS-T applications. This model type was boosted by the recognition of the need for many elements to be combined in order to provide an effective transportation system. This requires an integral of network and process models with cartographic entities.

Table 5: Summary of the Reviewed GIS-T Data Models

Data Model	Characteristics	Advantages / disadvantages
(Arc-node data structure) Relational database model	Consists of several relational databases connected to each other by a couple of primary and secondary keys	• It relaxes the enforcement of planar topological consistency (Goodchild, 1998, Spear and Laksmannan, 1998) • Assumes that arcs are homogeneous • difficulty in supporting one-to-many relationships among transportation entities
Enterprise	• Suitable for all organizations that make use of spatial data. • A data model with common features that support applications across an entire "enterprise" (e.g., agency, corporation) or across several enterprises.	• Late on the scene as there are a couple of discipline specific GIS units developed already in isolation • General difficulty to handle the big picture of a comprehensive data model and the myriad of database tables needed to implement it
Enterprise GIS-T data model (Duekler and Butler)	• Suitable for organizations responsible for any mode of transportation; e.g., aviation, highways, public transit, and railways • based on independence among geographic datum, events and geometry for cartographic display and link-node topology	• An extension (improvement) of the above enterprise data model. • Can accommodate areal transportation features • Is event data centric (Guo, 2001) as cited by (Zhu and Li, 2008), more inclusive and object oriented. • Consequently more complex

UNETRANS (Unified NEtwork-TRANSportation) Also referred to ArcGIS transportation data model	• Is a logical object oriented data model of GDF(Zhu and Li, 2008) • A generic and practical orientated data model, which is a representation of the essential elements for a broad range of transportation-related functions.(Curtin et al., 2003)	Is intended as a support tool for the range of users who participate in transportation science, planning, or management and provides a suggested base from which to build specific transportation oriented geodatabases. (Goodchild and Ott, 2000)
Geo TRANS Transportation data model	Is designed to satisfy the transportation information needs based on Intergraph products	• Limited to Linear referencing systems (LRS) • Supports multiple Linear Referencing Methods (LRM) (Hardy, 2005)

The Dueker/Butler data model is simply an extension of the enterprise data concept beyond LRS to include other transportation features. Its core is the transportation feature, jurisdiction and event points (Dueker and Butler, 1998). It is a more inclusive and complex model by supporting multiple networks, LRS events, cartographic representations and integrated spatial data particularly areal transportation facilities and events (e.g. airports, parking yards, etc.). Just like the basic enterprise data model, the GIS-T enterprise model is good at supporting data sharing among agencies as well as interoperability among GIS-T applications. However, a number of standalone GIS units have already evolved in Uganda. This can be both an advantage and a disadvantage. On the one hand, it may be viewed as an initiative that is too late on the scene and on the other hand, as providing a foundation for the adoption of the enterprise data model concept in the sector and country at large.

The UNETRANS data model works much like a document template in a word processor and not as a standard of sorts. It is a starting point, not an imposed standard model; and users can modify the template as needed to suit particular purposes. It is not a comprehensive model (Curtin, 2001), the reason for which Uganda can make use of it as a starting point in designing its own specific data models. Its primary focus is on the needs of organizations that manage road and rail transportation networks. The intent of its development was to provide a usable transportation GIS data model to; simplify implementation of enterprise projects, encourage consistency in data structures to facilitate data sharing and to provide a common starting point for application developers (Curtin et al., 2003). The GeoTRANS Transportation data model on the other hand is software limited to Intergraph's GeoMedia Transportation suite of products. It is also limited to LRS. In Uganda, ESRI products are most popular and in order to facilitate data exchange, it is the authors' recommendation that the data model to be adopted for Uganda should be compatible with ESRI software. However, GeoTrans's support for multiple LRMs is a prospect that Uganda could borrow from, considering that already at the moment; a couple of location referencing methods are in use.

The attempt to define a data model for road maintenance derives from ongoing research to develop a framework that can accentuate the use of Geospatial technologies (GITs) in road infrastructural maintenance. The research assessed gaps and limitations affecting GIT use in the sector. Relevant to the ongoing discussion was the absence of data standards in the form of structures and semantics, limited collaboration between participating organisations and policy limitations. With these challenges in place, a data model to address structures and semantics in turn is one of the strategies to facilitate GIT usage and data exchange in particular. An extension of the traditional arc-node model to facilitate dynamic segmentation is recommended. Dynamic segmentation is a technique that uses linear referencing to locate features along the network that are cross-referenced to the underlying arcs and nodes without modifying the underlying network topology (Nyerges, 1990, Huang, 2003, Goodchild, 2000, Weigang and Guiyan, 2009, Dueker and Vrana, 1992). The virtual network of routes and associated data is non-topological, and thus avoids many of the limitations of the arc-node network model discussed previously. Dynamic Segmentation is not an independent (standalone) model but a technique to structure data for improved analysis. This concept has been successful for a variety of road applications (Demirel, 2002, Huang, 2002, Huang, 2003, Dueker and Butler, 1998, Mohammad et al., 2009b, Mohammad et al., 2009a, Choi and Jang, 2000, Kennedy et al., 2000, Smith et al., 2001, Chou et al., 2000, Yuan, 2008, Huang and Yao, 2003, Guo and Kurt, 2004, Filipov and Davidkov, 2006, and Weigang and Guiyan, 2009). The most urgent need for the road maintenance sector is an initial structuring of road maintenance data after which the enterprise GIS-T data model concept may be relevant in facilitating collaboration and data exchange between the stakeholder organisations in road maintenance.

Dynamic Segmentation is the process of transforming linearly referenced data (also known as events) that have been stored in a table into features that can be displayed, queried and analyzed on the map (Mohammad et al., 2009a)(Mohammad et al., 2009b) through computations. It subdivides the road network into segments of variable length depending on the attribute values of those segments. This data structuring approach maintains a many to one relationship between segments and arcs of the network. It enables multiple attributes associated with pavement segments to be stored and displayed efficiently (Chou et al., 2000). The model maintains data referenced to the LRS and as recognised by Nyerges (1990) and Smith et al., (2001), location referencing and highway segmentation are fundamental design issues in a GIS-T.With the dynamic segmentation technique, once a route system is defined, it is used to associate the locations of event data with the base map layer in the GIS. Miller and Shaw (2000) define an event as an attribute that is associated with a portion of a route or a single location on a route. These events can be linear, point, and continuous. Continuous events are associated with the entire route and as such, they only need to be referenced at the locations where the event value changes. In a GIS, this event data is stored in separate data tables known as event tables. Each table can he linked to a route and queried. When a query involves more than one event, the tables have to be specialy joined, with each record in the joined table representing a new section (Huang, 2002, Huang, 2003). Illustrations of the types of events storage in a road maintenance dynamic segmentation data model are shown in table 7. a) b) and c)

Table 7a: Point events: Distress Type

Route ID	Section	Location		Chainage	Distress Type
		Latitude	Longitude		
C610	01	1.42164	31.36486	10	Pothole
C610	02	1.12699	31.59425	20	Corrugation
C610	02	1.11333	31.6765	25	Pothole
...	...	...	...	...	...

Table 7b: Linear Events: IRI values

Route ID	Section	From location		To location		Chainage		IRI value Attribute
				Latitude	Longitude	From	To	
B200	01	21.7388	32.48551	22.5704	32.49685	0	10	2.38
B200	02	29.0347	33.09672	29.1394	33.10143	10	20	2.42
B201	03	27.23	33.11316	27.4211	33.11117	20	40	2.68
...	...	...	...	...	...	...	...	...

Table 7c: Continuous events: posted speed limits

Route ID	Section	Location		Chainage	Posted speed limit
		Latitude	Longitude		
B200	01	21.7388	32.48551	10	30 Km/hr
B200	02	29.0347	33.09672	15	35 Km/hr
B201	03	27.23	33.11316	40	70 Km/hr
...	...	...	....		...

Given the network data attribution and representation problems associated with roads data, dynamic segmentation provides proven techniques to overcome the limitations of the simple GIS network data models that most GIS programs adopt.For roughness and rutting indices for example, dynamic segmentation places lengths of the road into categories of quality based on the roughness and rutting of both its own sequence and that of neighbouring segments (Kennedy et al., 2000).

5. Conclusion

The use of a data model for road maintenance organisations is advancement towards achieving standards for the related data. It more specifically allows for data sharing amongst the concerned organisations. For a data model to be developed, an understanding of the road numbering and referencing system of the jurisdiction is important. Equally important is the knowledge of the nature of the data to be structured. A review of these aspects has been provided in the body of the paper. Road maintenance data is more or less similar across countries. Some standards and GIS-T data models for transport data have been reviewed and characterised with advantages and disadvantages. Basing on this review and analysis of road maintenance data in Uganda, an extension of the arc-node data model with dynamic segmentation techniques is proposed for the road maintenance sector of Uganda. The traditional arc-node data model has several disadvantages that range from redundant data storage, which leads to space constraints, to ineffective analysis resulting in conclusions that are inconsistent with reality. On the other hand, dynamic segmentation has obvious advantages of; sustaining precise and high value spatial resolution segments, ability to locate multiple events, store linearly referenced attributes without any duplication with route geometry and supporting sharing of network infrastructure with different applications. A recommendation to include excerpts from some of the reviewed models has been made. In addition to the review, is a list of references for more background information and conceptual details relating to dynamic segmentation and data modelling.

6. Recommendation

Although specifically designed for spatial data exchange for ITS (Xiong and Lin, 2000), the GDF emphasize documentation of road and road-related information. Their design nature improves the efficiency of the capture, production and handling of road related geographic information, an aspect of which can boost the road maintenance data model definition for Uganda. And besides, these files form a main input for global standardization**.** Excerpts from this standard model are recommended for Uganda.Today, road maintenance organizations are collecting GPS data about incidents that were previously collected using LRMs. Also, in addition to roads inventory and condition assessment, the emerging data needs for road maintenance organizations are extending to include real-time data that will support intelligent transportation systems. Considering that to date, Uganda is using both linear and spatial location referencing for road maintenance events data, the data model to handle these diverse requirements should consider excerpts from both the NCHRP and Multi-dimensional Linear Referencing System (MDLRS) models. The NCHRP model is capable of handling increasing amounts of linearly referenced data and it provides an association between linear references and 2-D and 3-D references by associating the linear datum with the geometric objects that compose the cartographic representation (Koncz and Adams, 2002a). The MDLRS model on the other hand provides a comprehensive view of the temporal element of roads data. It was developed to be able to integrate and effectively use transport data across one, two, three and four dimensions and among linear and nonlinear referencing systems (Koncz and Adams, 2002b). This will address challenges of conflicting references to road maintenance locations and their subsequent repercussions.

In place of TIGER standards for USA, Uganda uses the concept of core datasets as framework data. These datasets are variously referred to as base, framework, core, fundamental, or reference datasets (Musinguzi, 2007). They include administrative units, digital imagery, cadastral layers, transportation, geodetic framework, hydrography and elevation. Harmonization of the roads maintenance data structure with that of these datasets is of fundamental importance. For purposes of spatial location referencing, development of a precise geodetic framework will further support for location referencing using GPS coordinates.

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