A GIS-BASED INTEGRATED INFRASTRUCTURE MANAGEMENT SYSTEM FOR LOCAL MUNICIPALITIES

Adelino Ferreira
Professor, Civil Engineering Department, Coimbra University, Polo II - Pinhal de Marrocos, 3030-290 Coimbra, Portugal, Tel.: +351.239797101; Fax: +351.239797146; E-mail: adelino@dec.uc.pt

ABSTRACT

The infrastructure departments of the Portuguese municipalities must make great efforts in beginning or continuing to use advanced information technology tools to increase institutional productivity and effectiveness in managing their municipal infrastructures. Nowadays, they use or are beginning to use independent management systems for each type of infrastructure, i.e., road pavements, bridges, signs, water pipelines, sewer pipelines, parks, and so forth. In the future, they need to begin the development of an Integrated Infrastructure Management System. This paper identifies the issues and needs that must be fully understood and considered in the development of an Integrated Infrastructure Management System. Doing so, involves determining and standardising an effective base linear referencing system, standardising data terminology, determining the shared data needs of the several divisions inside the department of infrastructures, and developing a comprehensive database design with special attention given to the types of data analysis functions performed by each municipal division. The paper also includes the application of the Integrated Infrastructure Management System in road maintenance management, road safety management and sewer network management using the same base linear referencing system. The final section of the paper comprises a synthesis of the conclusions reached so far.

1. INTRODUCTION

An Integrated Infrastructure Management System, considering all the components of the municipal infrastructures, allows defining integrated decisions of maintenance and rehabilitation. For instance, if a pavement condition is poor and the sewer pipeline has had more than two breaks in the previous year, then replacing the sewer pipeline and reconstructing the pavement is an appropriate integrated decision.

There are two ways to develop an integrated infrastructure management system. The first one is to maintain all the data in the current diverse format and to develop tools and methods that support data warehousing and access across multiple platforms and formats. Alternatively, one may redesign the entire data resource using a common format. The first alternative allows each municipal division to undertake the least changes. However, complex tools and methods are required to link data from different
divisions. The management of the linkages and the formats becomes problematic. But an even greater problem is that data may be spatially represented differently in each database. As a result, the actual spatial location of physical components cannot easily be determined. Thus, the data cannot effectively be used in combination with each other using a Geographic Information System (GIS). The second alternative provides an opportunity to design a common spatial framework that alleviates the majority of the problems noted above. However, this approach introduces organisational impacts and requires significant restructuring and rebuilding of existing databases.

With the proliferation and increased use of advanced information technologies such as GIS and database management systems (DBMS), the municipal infrastructure departments are beginning to recognise the need to promote the standardisation in the representation, management and use of data. The integrated system will allow combining efficiently tabular and spatial data that support queries, analysis and report generation. For the Portuguese municipalities the best choice is the second alternative, i.e., redesign its entire information resource. Doing so involved determining and standardising an effective base linear referencing system (LRS) to meet its needs, standardising data terminology, determining the shared data needs of the several divisions inside the department of infrastructures, and developing a comprehensive database design with focused attention given to the types of data analysis functions performed by each municipal division.

2. BASE LINEAR REFERENCING SYSTEM

The municipal infrastructure departments collect data about linear features, such as highways, city streets, rivers and pipelines, as well as water and sewer networks. In most GIS, these features are modelled in two dimensions using (x,y) coordinates. While these systems work well for maintaining features with static characteristics, these organisations have realised that their linear features often have characteristics that are more dynamic in nature. To handle this, these organisations have developed LRS to model their data. Linear referencing systems store spatial data with respect to a known location along the linear feature being modelled, such as an accident along a highway, a bridge along a city street, a flow gauge along a river, or a manhole along a sewer network.\textsuperscript{1,2,3}

Linear Referencing Systems are used to manage and promote the analysis of spatial data elements on transportation networks.\textsuperscript{4} An LRS includes techniques for storing, maintaining, and retrieving location information. An LRS may incorporate one or more linear referencing methods (LRM). A LRM is a way to identify a single location, that is, to reference a single position with respect to a known point. There are several types of LRM that can be employed in a GIS project. These include route measure, route marker-offset, link-node, x-y coordinate, address methods, etc. With some simplification one can say that location in all of these methods is described in terms of a linear feature and a position, or measure, along it. This measure can be the absolute distance from the beginning of the linear feature or can be the relative distance from a predefined point.
Along the linear feature. Consequently, two key linear referencing methods can be identified: route measure and route marker-offset. Most of the other LRM can be treated as hybrids of these two.

In GIS, every feature has a geometry associated to it. A feature can have one of these types of geometries: point, multipoint, polyline, or polygon. Each geometry is composed of two-dimensional (x,y) or three-dimensional (x,y,z) geographic coordinates. In order to handle dynamic segmentation, a feature’s geometry, instead of being composed of (x,y) coordinates, must be composed of (x,y,m) or (x,y,z,m) values. 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 and analysed on a map. For example, the Road Maintenance Division may segment road pavements dynamically according to the quality of the pavement surface (Figure 1). For the road Rua do Brasil (road_ID = 1002), the pavement is in good condition from the beginning to 700 meters, it is in fair condition from 700 to 1000 meters, and it is in poor condition from 1000 to 1400 meters. Attribute information describing quality characteristics specific to each road segment can then be maintained without splitting the road network.

The dynamic segmentation process imposes two requirements on the data: each event in an event table must include a unique identifier and position along a linear feature; and each linear feature must have a unique identifier and measurement system. When data is linearly referenced, multiple sets of attributes can be associated with any portion of an existing linear feature, independently of its beginning and ending. These attributes can be displayed, queried, edited and analysed without affecting the underlying linear feature’s geometry. In some GIS, the terms routes, route locations, and route events are used when one is talking about linearly referenced features. A route is any linear feature, such as a city street, highway, river, or pipe, that has a unique identifier and a measurement system defined (x,y,m). This measurement system defines discrete locations along the linear feature.

![Image of road network and attribute tables](image.png)

**Figure 1 - The dynamic segmentation process for a road pavement**
There are two types of route locations that can be modelled in a GIS: point and linear events. Point route locations describe discrete locations on a linear feature (such as an accident along a highway, a bridge along a road, a pedestrian crossing a city street, a flow gauge along a river, a manhole along a sewer network, or a pipeline leak) and require only one measure value. Linear route locations describe portions of a linear feature (such as a road segment with accumulation of severe accidents along a highway, a pavement segment with bad surface quality along a city street, or cracking along a sewer pipeline) and require two measure values, typically referred to as the *From* and *To* measures. Route locations and associated attributes stored in a thematic table are known as route events or simply events. A route location description requires a unique identifier for the linear feature and the measure value(s) appropriate to the event type. Dynamic segmentation supports event tables in a number of formats including INFO, Microsoft Access, dBase, Oracle, Microsoft SQL Server, delimited text files, and databases accessed via OLE DB providers.

The proposed base LRS uses a LRM designated by route measure and it is an attempt to provide a common referencing platform in which different data types can be represented spatially in a network structure in a standardised mode. The base LRS is intended to be the nucleus of the relational database and the GIS, i.e., it is the exclusive way to locate features that are a part of, or are located along, a particular road. The use of a base LRS also allows municipal divisions to incorporate additional databases into the Integrated Infrastructure Management System at some future time without changing their existing spatial referencing systems. It is, therefore, highly expandable.

The LRS makes possible to a GIS to be used to integrate decisions or interventions proposed by different Municipal Management Systems. The GIS have tools like overlaying, buffering, Structured Query Language (SQL) and others that can handle with this type of problem. Two or more decisions can be grouped if spatial proximity and temporal proximity are verified. Interventions are in the same road segment if the distance that separates them is below a threshold, which is verified using the (1) and (2) equations. One intervention is inside the work zone of another intervention if equations (3) and (4) are verified.

\[ |From\_M(X_{ist}) - From\_M(Y_{ist})| < \varepsilon_{From} \]  \hspace{1cm} (1)  
\[ |To\_M(X_{ist}) - To\_M(Y_{ist})| < \varepsilon_{To} \]  \hspace{1cm} (2)  
\[ From\_M(Y_{ist}) \geq From\_M(X_{ist}) \]  \hspace{1cm} (3)  
\[ To\_M(Y_{ist}) \leq To\_M(X_{ist}) \]  \hspace{1cm} (4)

where:
- \( From\_M \) = beginning of the road segment with intervention;
- \( To\_M \) = ending of the road segment with intervention;
- \( X_{ist} \) = intervention \( i \) defined by Management System X that will be applied to road segment \( s \) in year \( t \);
\[ Y_{ist} = \text{intervention} \ i \ \text{defined by Management System} \ Y \ \text{that will be applied to road segment} \ s \ \text{in year} \ t; \]
\[ \varepsilon_{From} = \text{distance value that depends on the type of intervention;} \]
\[ \varepsilon_{To} = \text{distance value that depends on the type of intervention.} \]

Decisions are time related if they are going to be implemented under the same time period:

\[ |T(Y_{sat}) - T(X_{sat})| < \varepsilon_T \]  

where:

\[ T = \text{year or day of the intervention;} \]
\[ \varepsilon_T = \text{number of years or days that depend on the type of intervention.} \]

Based on spatial and temporal proximities, the IMS can suggest that two or more interventions are related and should be implemented at the same time. The IMS is composed of a set of Municipal Management Systems and a GIS that works both as a graphical display of municipal infrastructures and their attributes and as a global planning and integration system using in-house available tools.

3. CASE STUDY

3.1 Introduction

The performance of the proposed base LRS was tested with the development of an IMS for the city of Coimbra (Figure 2), a Portuguese city with approximately 100,000 inhabitants. Initially, the system was developed using the MGE GIS from Intergraph.\textsuperscript{9,10} At this moment it is in process of transference for ArcGIS from ESRI.\textsuperscript{11,12,13}

The equipment used to collect data about the road network was the system VIZIROAD.\textsuperscript{14} Basically, this system is a data acquisition system, based on specific software, supported by a laptop (Figure 3). The system is composed of: two complementary keyboards, with 24 keys each one, that can be programmed with icons as required to collect data; one entry for distance pulses integrated in the left keyboard; and one supplementary input for pulses to be counted to use other equipments, as for example a Bump Integrator. The keyboards are connected to a laptop PC and to a pulse generator that is linked to the cable of the vehicle speedometer. Another equipment that can be used to collect road data is a GPS receiver (Figure 4). This type of equipment\textsuperscript{15,16} combines professional GIS data collection and navigation software in a compact handheld GPS receiver. The equipment's software provides clear and simple data display, editing and exporting capabilities. This type of equipment is an ideal solution for public safety personnel, utility workers, resource managers and anyone who manages positioning assets in the field. It is also valuable to create or update maps for analysis and storage in a GIS because data can be easily transferred between the GPS receiver and a personal computer.
Figure 2 - Coimbra’s main road network

Figure 3 - The data acquisition system VIZIROAD
3.2 Results

The Road Maintenance Division is responsible for implementing, maintaining and using a PMS to define maintenance and rehabilitation strategies for the pavements of the municipal’s road network. In this PMS, the quality of road pavements is evaluated through the index PSI (Present Serviceability Index) adopted by the American Association of State Highway and Transportation Officials,\(^\text{17}\) considering cracking area, rut depth, surface disintegration and longitudinal roughness. Figure 5 shows the PSI representation at 9 levels for Coimbra’s road network. Figure 6 displays the maintenance and rehabilitation interventions to be performed across Coimbra’s road network on the first year of the planning time-span. Both the quality of road pavements and the M&R interventions are represented spatially in a network structure using the same base LRS.

The Traffic Division includes the Road Safety Unit that is responsible for planning, designing, developing, implementing, and evaluating appropriate engineering response strategies that deal with road safety concerns throughout the municipality. One task that must be performed by the Road Safety Unit is the implementation and use of a Road Safety Management System (RSMS). Figure 7 displays the number of accidents in Coimbra’s road network. One can see that there is an intersection with more than twenty accidents during one year. For this site it must be done a particular road safety study to eliminate or reduce the number of accidents. Figure 8 shows the pedestrian crossings in Coimbra’s road network. One can make some spatial operations, for example, the intersection of the two layers (accidents and pedestrian crossings) and buffers, to see if there is any link between them. The last map (Figure 9) represents the quality of manhole covers that are a component of the sewer system. This map is also produced using the same base LRS.

\[\text{Figure 4 - A compact handheld GPS receiver}\]
Figure 5 - Road pavement quality

Figure 6 - Maintenance and rehabilitation interventions defined by the PMS
Figure 7 - Number of accidents in the road network

Figure 8 - Pedestrian crossings
4. CONCLUSIONS

The proposed IMS is composed of a set of Municipal Management Systems and a GIS that works both as a graphical display of municipal infrastructures and their attributes and as a global planning and integration system using in-house available tools. The base LRS is an attempt to provide a common referencing platform in which different data types can be represented spatially in a network structure in a standardised way. This LRS is intended to be the nucleus of the relational database and the GIS, i.e., it is the exclusive way to locate features that are a part of, or are located along, a particular road. The use of a base LRS also allows municipal divisions to incorporate additional databases into the IMS at some future time without changing their existing spatial referencing systems. It is, therefore, highly expandable. Data acquisition systems like the VIZIROAD and a GPS receiver that allows collecting data easily and quickly are ideal solutions for public safety personnel, utility workers, resource managers and anyone who manages positioning assets in the field. These equipments are fundamental to quickly load the database of the IMS. It is also important to include other infrastructure assets like the road drainage system, the road markings, etc., to completely integrate all the decisions. Finally, although to be necessary more developments, the IMS, taking into consideration all the components of the infrastructures, allows defining integrated decisions of maintenance and rehabilitation of all the municipal assets.
REFERENCES


