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A new framework for the integration, analysis and visualisation of urban traffic data within geographic information systems

C. Claramunt [a,*], B. Jiang [b], A. Bargiela [a]

[a] *Department of Computing, The Nottingham Trent University, Nottingham NG1 4BU, UK*
[b] *Division of Geomatics, Institutionen för Teknik, University of Gävle, SE-801 76 Gävle, Sweden*

Abstract

Current geographical information systems (GIS) are not well adapted to the management of very dynamic geographical phenomena. This is due to the lack of conceptual and physical interoperability with real-time computing facilities. The research described in this paper is oriented towards the identification and experimentation of a new methodological and applied framework for the real-time integration, manipulation and visualisation of urban traffic data. It is based on proactive interaction between the spatio-temporal database and visualisation levels, and between the visualisation and end-user levels. The proposed framework integrates different spatial and temporal levels of granularity during the analysis of urban traffic data. Urban traffic behaviours are analysed either by observation of the movements of several vehicles in space, or by changes in urban network properties (i.e., micro- versus macro-modelling). Visualisation and interaction tools together constitute a flexible interface environment for the visualisation of urban traffic data within GIS. These concepts provide a relevant support for the visual analysis of urban traffic patterns in the thematic, spatial and temporal dimensions. This integrated framework is illustrated by an experimental prototype developed in a large town in the UK. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: GIS; Urban traffic; Real-time; Visualisation

1. Introduction

Recent developments in information technology are having a major effect on the way in which systems are designed and used in many application fields. Geographical information systems

* Corresponding author.
E-mail addresses: clac@doc.ntu.ac.uk (C. Claramunt), bin.jiang@hig.se (B. Jiang), andre@doc.ntu.ac.uk (A. Bargiela).

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(GIS) have been adopted as a successful solution by a wide range of disciplines such as environmental planning, business demographics, property management and urban studies to mention some examples. Currently, one of the most important challenges for GIS is to generate a corporate resource whose full potential will be achieved by making it accessible to a large set of end-users. In the urban domain, an important issue is the development of a co-operative traffic GIS that integrates static urban data with dynamic traffic flows (Pursula, 1998). Such a system will be of great interest for many applications related to the monitoring and analysis of urban traffic in which represented vehicles or network properties are changing in a fast and almost continuous mode. Recent advances in traffic systems include the development of graphical interfaces as a new functional level of monitoring tasks (Peytchev et al., 1996; Kosonen et al., 1998; Barcielo et al., 1999) and real-time traffic interfaces in the World Wide Web that display traffic conditions on a regular basis (Dayley and Mayers, 1999; Feng et al., 1999). Nevertheless, the functions provided by these solutions are quite limited in terms of the analysis and visualisation of urban traffic data. Furthermore, we believe that the full potential and benefit of traffic databases still need a closer integration with GIS that will facilitate the integration of traffic data as a component of urban and transport planning and environmental and health studies. However, current GIS software and interfaces do not provide the set of functions to make this technology compatible with traffic systems used for monitoring and simulation purposes. First, the integration of GIS and traffic systems is likely to be a challenging and worthwhile objective for user communities whose needs are not satisfied by a loosely connected set of existing systems. This poor level of integration is often the result of the different paradigm used within GIS and modelling systems and the fact that many integrated solutions often imply the re-design of existing solutions (Abel et al., 1992). Secondly, despite recent progress in the development of temporal GISs (e.g., Langran, 1992; Peuquet, 1994; Claramunt and Thériault, 1995), current GISs are still not adapted to the management of very dynamic geographical phenomena due to the lack of interoperability with real-time computing facilities. Moreover, the development of GIS applications, characterised by a high frequency of changes, implies a reconsideration of the modelling, manipulation, analysis and visualisation functions as GIS models and architectures have not been preliminarily designed to handle the properties of very dynamic phenomena.

The research described in this paper is oriented to the identification and experimentation of a new methodological framework for the real-time integration, manipulation, visualisation and animation of urban traffic data within GIS. We characterise a very dynamic GIS (VDGIS) as a GIS application which has a high frequency of change (e.g., real-time traffic databases, simulated traffic databases). Changes include modifications to located properties (e.g., traffic flows within an urban network) and moving properties of one to several geographical objects (e.g., vehicle positions within an urban network). A high frequency of change corresponds to a small temporal unit of change, which can be generally quantified in seconds or minutes. The scope of VDGIS is relatively large. It also includes, for example, real-time applications that monitor a large volume of urban or environmental data, and simulation systems that attempt to predict the future states of a real-world system. VDGIS objectives are multiple, from the control of the geographical locations of one to several moving objects, to the support of analysis tasks oriented to the identification of complex spatial behaviours. For example, traffic monitoring and simulation applications integrate real-time locations of vehicles on a second, or less, temporal granularity basis. The integration of GIS capabilities within these engineering systems is a promising challenge to explore as it could expand the current data management and visualisation functions of these systems, and further increase the potential benefits of the large information flows generated. Our research explores some experimental methods for the real-time integration (i.e., pre-processing), manipulation, visualisation and animation of dynamic phenomena within VDGIS. We analyse the representation of urban traffic data by either an observation of the movements of several vehicles in an urban network (microscopic level), or changes in the traffic properties of an urban network (macroscopic level). Moreover, due to the nature of VDGIS, urban traffic behaviours are represented at different levels of spatial and temporal granularities. We propose an integrated framework based on the interaction between spatio-temporal data and visualisation tasks on the one hand, and visualisation and end-users on the other. This two-step approach supports a flexible and interactive visualisation of urban network properties either for presentation, analysis or for exploration purposes. As such, this framework constitutes a proactive environment as defined in Buttenfield (1993). It supplies a dynamic component to GIS that allows the derivation of dynamic data from the successive states of a real or simulated urban traffic system. It also provides a multi-layered approach that combines thematic, spatial and temporal queries and visualisations that together constitute a flexible and powerful communication resource for the understanding and analysis of traffic events and patterns within an urban network.

The remainder of this paper is organised as follows. Section 2 introduces a brief review of the integration of the temporal dimension within GIS and cartography. Section 3 presents the methodological principles of a multi-layered approach that supports the visualisation of urban traffic properties. Section 4 introduces the roles of the pre-processing, visualisation and interaction tools in the development of our framework. Section 5 presents an application of these concepts in the context of a traffic GIS used in a large town in the UK. Finally, Section 6 draws some conclusions and outlines for further work.

2. GIS, cartography and time

A definition of temporal map has been suggested as a representation or abstraction of changes that support the understanding and analysis of dynamic phenomena (Kraak and MacEachren, 1994). Within GIS, a map can be considered as a visualisation and interactive tool generally oriented to the representation of a spatial configuration at a specific instant in time, or a spatial configuration valid for an interval of time. Cartography has a long tradition of representing spatial information in time. An early example is the Minard map realised in 1869 to illustrate Napoleon's march to Moscow (Tufte, 1983, p. 176). Nowadays, with the availability of a large volume of spatio-temporal data, both GIS and modern cartography face the challenge of exploring new methods and techniques to analyse patterns and structures in space and time (Buttenfield, 1993).

In conventional temporal maps, two approaches are often used in visualising dynamic phenomena (Szego, 1987; Campbell and Egbert, 1990). The first one, the map series approach, is composed of successive maps valid for an instant or a period of time (Fig. 1(a)). A map series along the time line provides a global view of change that is useful for the understanding of overall patterns. However, this approach is limited to studies oriented to the analysis of local changes and interactions in space and time. The second approach is more oriented to the representation and

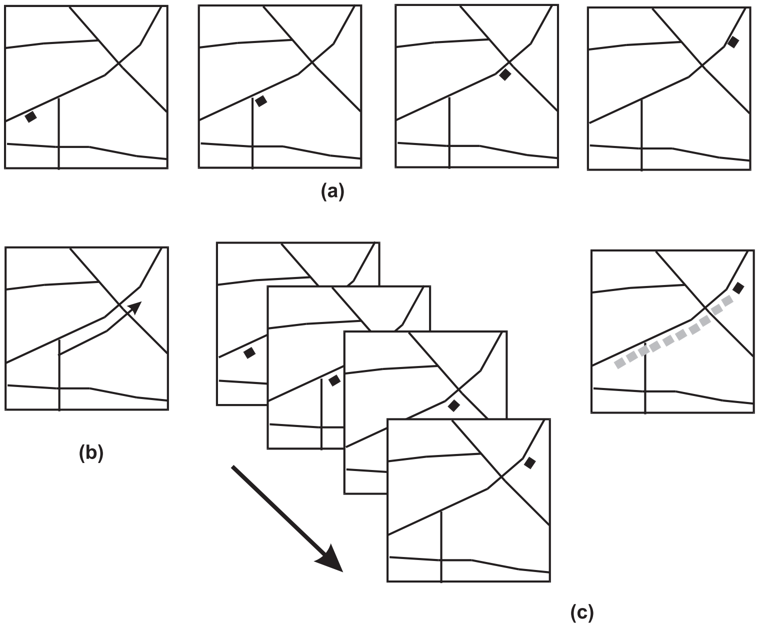

Fig. 1. Visualisation of changes with: (a) map series; (b) map symbol; (c) computer animation.

visualisation of local changes at the individual object level; cartographic symbols such as an arrow line, for example, are commonly used to indicate the trace of a dynamic object in space (Fig. 1(b)).

In order to facilitate the representation and analysis of dynamic phenomena and change patterns, cartographers have developed temporal aggregation mechanisms to reduce the number of snapshots of a map series, and to provide a level of temporal analysis adapted for the particular needs of an application domain. These concepts can be illustrated with the study of population migration in urban areas using temporal maps (Szego, 1987), or at the local level, by the map representation of daily individual activities (Parkes and Thrift, 1980). Animation techniques (Fig. 1(c)) also play an important role in the analysis of dynamic geographical data, as they provide a form of temporal continuity, thus facilitating an understanding of processes and changes. An animated map is a cartographic statement that occurs in time; its interpretation is based on the human sensitivity to detect movement or changes in a graphic display (Peterson, 1995). One of the first cartographic animations was in fact the urban growth simulation in the Detroit region developed by Tobler (1970). The combination of GIS and animations provide powerful platforms to simulate very dynamic phenomena. These can be used for the analysis of real-time systems (Valsecchi et al., 1999) or the simulation of human behaviours (Jiang, 1999).

The availability of a large volume of spatio-temporal data has stimulated research interest in visualisation and exploration of dynamic phenomena (Robertson, 1988; Campbell and Egbert, 1990; Kraak and MacEachren, 1994; MacEachren, 1994; Jiang, 1996). A map, or an interactive map, supports the visualisation of spatio-temporal objects, or properties in space, individually, but also more interestingly in a logic way, from which map users can perceive spatial relationships, density, arrangements, trends, connectivity relationships, hierarchies and spatial associations (Muehrcke, 1981). Efforts have been made on implementing strategies for the cartographical exploration of time-series data (Monmonier, 1990), proactive graphics (Buttenfield, 1993), and the identification of dynamic variables for the visualisation of changes (DiBiase et al., 1992; MacEachren, 1994). Recent advances have explored time-series animation of urban growth (Buziek, 1997), geological changes (Bishop et al., 1999), and socio-economical changes (Andrienko and Andrienko, 1998). MacEachren et al. (1999) have investigated the integration of geographic visualisation and data mining for knowledge discovery in the context of spatio-temporal environmental data. Various new terms have been used to reflect this evolution of cartography such as 'animated cartography' (Peterson, 1995), and 'exploratory cartography' (Kraak, 1998). Techniques for visualising time and change in cartography and GIS also benefit from related research areas such as information visualisation, human–computer interaction and data mining (McCormick et al., 1987; Schneiderman, 1994; Card et al., 1999; Chen, 1999). In particular, visualisation techniques used for the analysis of communication traffic in large computing networks are of interest as they are based on comparable network models. Let us mention among others the development of filtering, interactive manipulation of visualisation parameters, and the interactive use of temporal (e.g., selection of appropriate temporal periods) and spatial operations (e.g., zooming) for displaying telecommunication network traffic (Eick, 1996).

3. Visualisation of very dynamic phenomena: a multi-layered approach

Due to the limitations of current solutions, temporal GISs are often oriented to a cartographical visualisation and analysis of real-world phenomena that have a relatively low frequency of changes that cannot be considered as very dynamic according to our definition of VDGIS. Moreover, traditional maps show various limitations for the representation of very dynamic phenomena, due to the fact that traditional maps serve as both a visual representation and information repository of a real-world system. Nowadays, with the development of GIS and visualisation and animation techniques, maps are often considered as a proactive derivation of GIS data from the database level.

In the context of VDGIS, a visualisation can be considered as a result of several functional tasks, which depend on the database and cognitive levels. Firstly, from a technical point of view, visualisation functions are dependent on the database model and query processing characteristics, i.e., visualisation as an interface to a database. The expressive power and the flexibility of a visualisation are partly dependent on the database properties such as the expressiveness of the underlying database model and the data manipulation language. Secondly, a visualisation is subject to the end-users' perception, i.e., whether or not certain visualisation schemes are efficient in conveying relevant information. Therefore, an analysis of the principles that support the visualisation of geographical phenomena leads to our proposal of a multi-layered architecture that makes a distinction between: (1) the database and processing levels, (2) the visualisation interaction level, and (3) the end-user interaction level. These three components are characterised as follows.

Database level: The expressiveness of the database level is qualified by the database model used (e.g., relational, geo-relational, object-oriented), the query language implemented (e.g., SQL, geographical query languages), and additional analysis and statistical functions available. Very dynamic geographical data are characterised by an important volume of data generated (in the spatial, thematic and temporal dimensions) which constrains manipulation and visualisation operations.

Visualisation level: In the context of this research, the visualisation level represents derived and displayed geographical data presented through an interface that supports visual presentations of very dynamic phenomena. The visualisation level includes interaction tools, that is, the set of logical and physical computer facilities that allow users to act on the visualisation level (e.g., using menus, messages, keyboard and mouse actions).

End-user level: End-user backgrounds vary from novice, intermediate and expert users. They all intend to use a visualisation as a facility to enhance the understanding and perception of very dynamic phenomena.

These three component levels of a very dynamic system, oriented to the visualisation of real-world phenomena, provide a highly interactive environment. These three layers interact in successive order: the first interaction level represents the manipulation functions in which spatial, thematic and temporal operations apply on the database level; the second interaction level represents the control functions on the visualisation tasks operated by final users (Fig. 2). Due to huge information flows between these different levels, this framework also requires a flexible interface between the database and visualisation tasks in order to select appropriate database operations (e.g., spatio-temporal queries), and the visualisation tasks and the user level in order to achieve flexible and frequent user-interactions (e.g., visualisation and animation functions).

Current spatial database models do not consider the visualisation level as a proper part of the system but rather as an interaction level given to the final users. The main components considered in geographical database modelling and design are the integration, representation and querying of spatio-temporal data. However, recent research suggests that visualisation and user-interaction functions can be integrated as a proper component of the database modelling level. This includes the integration of graphic parameters within the query language and the modelling of query operations (Claramunt and Mainguenaud, 1996), description and manipulation of a visualisation as a set of derived objects (Voisard, 1991), and connections of different visualisations defined at complementary levels of granularity using semantic relationships (Stonebraker et al., 1993). We believe that these concepts are particularly relevant in the context of very dynamic visualisations

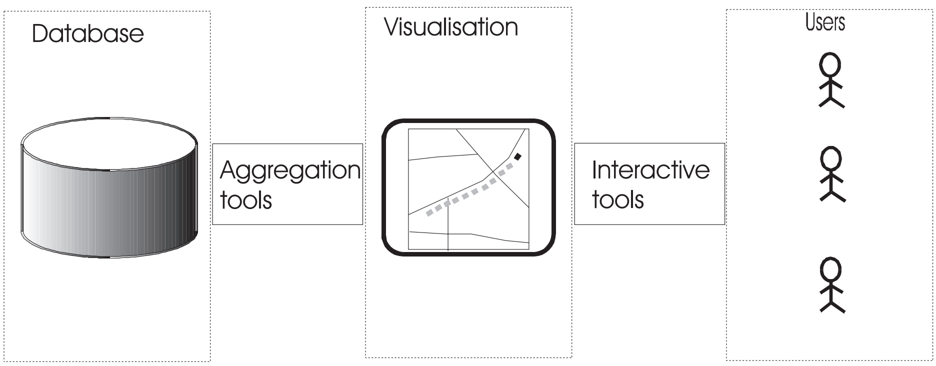

Fig. 2. A framework for visualising very dynamic phenomena.

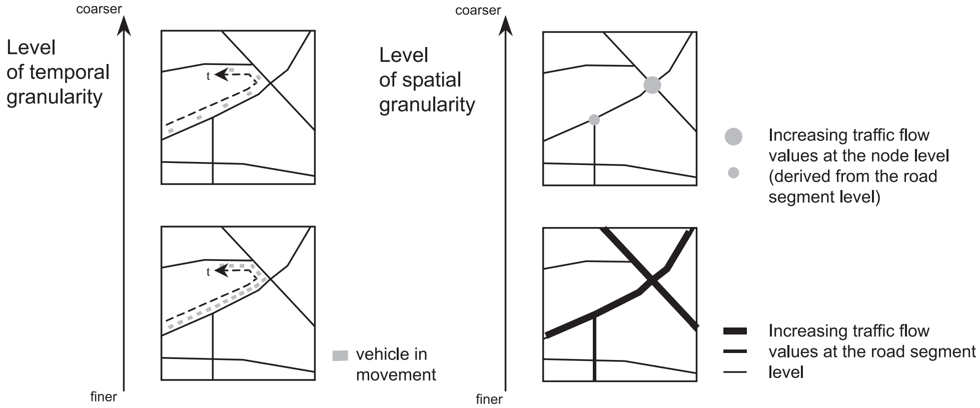

Fig. 3. Temporal versus spatial levels of granularity.

in which the information flows between the database, visualisation and user levels are particularly intensive. Such concepts provide a solution to the derivation of spatio-temporal data, as a query language that supports the expression of user-defined spatio-temporal queries on the one hand and as an interaction language between users and the visualisation level on the other.

We promote a flexible view of this multi-layered approach to the visualisation of very dynamic phenomena, which is independent of any data model or query language. The set of principles explored defines a user-defined level between a spatio-temporal database and the range of visualisation mechanisms required for the manipulation of very dynamic databases. Within the proposed framework, proactive aggregation tools are illustrated by the composition of derived views based on different levels of granularity in the temporal and spatial dimensions (Fig. 3). This interactive visualisation level allows for the manipulation of this user-defined level using different visualisation mechanisms (e.g., animated map, animated chart) depending on the objective of the end-user(s).

4. Pre-processing, visualisation and interaction

Within VDGIS, visualisations require a reconsideration of manipulation, animation and analysis functions. This is due to the very dynamic nature of the geographical phenomena represented. In the context of urban traffic data, a visualisation integrates the properties and behaviours of dynamic vehicles within their environment. It is widely recognised that the aim of visualisation is not only for visual representation but also for information exploration and discovery. Therefore, visualisation is supported by interactive and proactive functions such as basic display functions, navigation and browsing manipulations, query operations, integration of different granularities, re-classification of data, and combination of multiple views and animations (Kraak, 1998). Such a proactive environment facilitates the user's understanding and perception of dynamic phenomena.

A visualisation is different from the concept of traditional maps in various ways. Firstly, a visualisation can integrate multiple views; e.g., a geographical representation associated to a set of interconnected maps defined, for example, using different scales, and additional data media (e.g., photographs). Secondly, a visualisation goes further by integrating animated scenes that represent the temporal evolution of a region of interest and/or thematic property changes. A visualisation is then more than a static map as it also integrates a dynamic component, which can be user-controlled depending on the properties of the phenomenon represented. The structure of a visualisation is not a linear one but rather a complex one composed of different levels of granularity in both the spatial and temporal dimensions. Thirdly, a visualisation is completed by interactive tasks for the manipulation of its visual components (e.g., pan and zooming functions). As such, a visualisation is supported by a set of interactive facilities offered to end-users, which can then manipulate different visual components in order to develop a user-oriented perception of real-world phenomena.

In the context of VDGIS, visualisations combine geographical and thematic data along the temporal line from different media and sources using visual communication techniques. A visualisation integrates multiple components such as maps, charts and tables. Interactive functions, such as spatial operations or temporal brushes allow for the manipulation of visualisations, and in fact of the underlying GIS database. Several complementary aspects need to be analysed for the development of VDGIS visualisations:

- underlying properties of very dynamic geographical data;
- pre-processing functions for filtering large volumes of data;
- query and visualisation operations;
- interactive functions for animation and interface manipulation.

These considerations lead to the analysis of the nature of the dynamic data and changes to be displayed. Changes have been categorised by DiBiase et al. (1992) as changes in either: (a) spatial location; (b) spatial location and/or attributes; and (c) classification of objects within the attribute space (e.g., re-classification). Dynamic objects or spatial properties are difficult to evaluate on an individual basis. Therefore, the analysis and presentation of a set of dynamic objects often require the use of parsing, aggregation and/or statistical techniques (Kraak and MacEachren, 1994). This is illustrated, for example, by the pre-processing of the spatial, thematic and temporal properties of very dynamic objects. Often, passing from one spatial or temporal level of granularity to a coarser one provides a complementary insight for the analysis and understanding of spatial phenomena. Within the time dimension, temporal operators could be used for changing the temporal granularity of the phenomena represented. As such, these operations allow phenomena visualisation from a hierarchical point of view. Propagation of temporal constraints between spatio-temporal processes represented at complementary levels of granularity can be realised using constraint propagation algorithms (Claramunt and Bai, 1999). Reasoning and manipulation in temporal systems have been widely studied in temporal logic (Allen, 1984; Bestougeff and Ligozat, 1992; Badaloni and Benati, 1994). Formal temporal languages and operators are of particular interest for the temporal aggregation of very dynamic data. Generally, composition operations, based on the manipulation of temporal intervals, allow the representation of phenomena at a coarser level of granularity using temporal operators that aggregate temporal periods (e.g., from an hour to a day frequency of change). Within the spatial and thematic dimensions, aggregational, statistical and relational operations can also be applied. These operations constitute a set of pre-processing functions that cover the different dimensions of geographical phenomena.

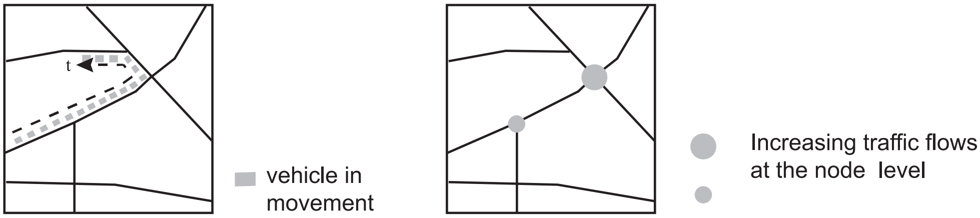

Fig. 4. Individual vehicle versus network property changes.

The information contained within a VDGIS visualisation includes dynamic objects and their changing properties on the one hand and the relatively static environment on the other. The latter acts as a visual background for presentation and animation purposes. For static data, a single visual representation is generally used, it is bounded in time by the temporal validity of the geographical data visualised which is either a time instant or interval. The static component of a visualisation provides support for the interactive exploration of changes as it gives a geographical reference to the dynamic phenomena analysed. The duration of a temporal visualisation scene (i.e., animation) can be proportional to the magnitude of the phenomenon represented. For example, the temporal progression of animation slows down as changes visualised are increasing in intensity. This type of animation technique is referred to as pacing (DiBiase et al., 1992). This also requires an analysis of the visual properties that support the presentation of dynamic objects

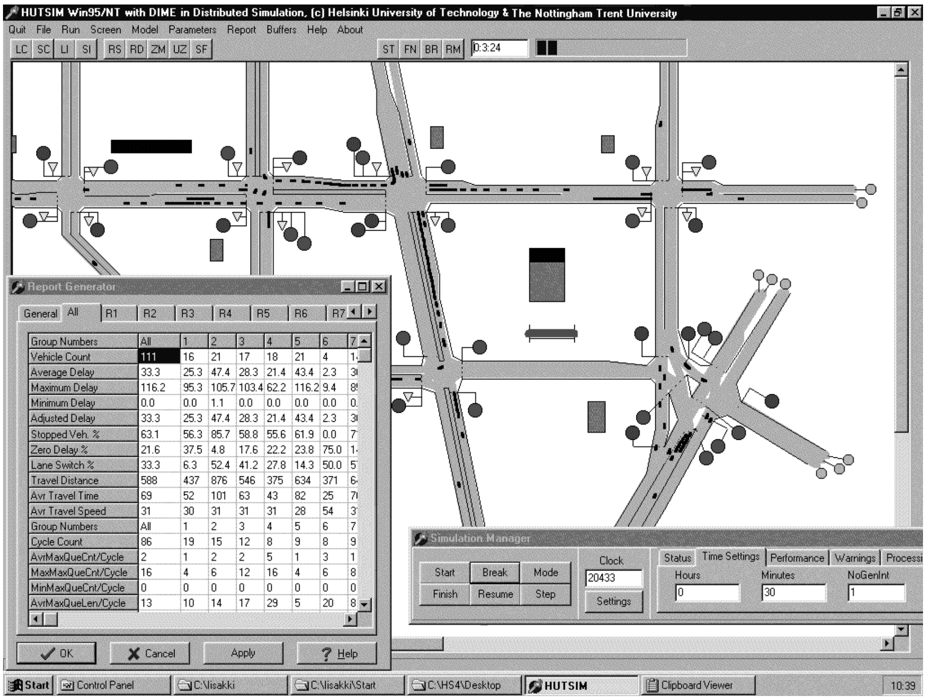

Fig. 5. Microscopic traffic simulation system.

within a visualisation. In particular, the design of a visualisation needs an integration of the visual constraints that affect the graphical layout. For example, the perception of the successive locations of individual objects is a difficult task in very dynamic visualisations (e.g., many vehicles moving several times per second as illustrated in Fig. 5). In very dynamic visualisations, moving vehicles are generally stable in the thematic dimension. In this case, the analysis of the thematic dimension is not of particular interest. This provides an interface environment for the development of actions at the interaction level (e.g., animating a visualisation using a temporal browser).

We make a distinction between the visualisation of moving vehicles and network properties considered at an individual level and the aggregation of moving objects and network properties used to represent the dynamism of an observed system at a coarser level of granularity. In other words, we may analyse changes in movements from place to place or differences in local phenomena from time to time (Vasiliev, 1996) (Fig. 4). Very dynamic individual objects are not active in terms of interface interaction. On the contrary, aggregated objects, temporarily and/or spatially, can be manipulated using interaction tools.

5. Visualisation of very dynamic GIS: application to urban traffic data

In the context of traffic applications, microscopic models represent a first modelling approach oriented to the monitoring and simulation of individual vehicle behaviours (i.e., vehicle displacements) (Kosonen et al., 1998) (Fig. 5). Approaches to microscopic models involve the representation and/or optimisation of complementary data such as driver behaviour, vehicle characteristics and performance, road components, lane structure and geometry, and their relationships. A simulation attempts to minimise the amount of data required to give reasonably accurate simulation results. For example, the HUTSIM micro-simulation system provides a flexible and detailed model potentially adapted to different traffic system configurations (Kosonen 1999).

Macroscopic models represent a second approach oriented to the measurement and estimation of traffic conditions at fixed points such as junctions, stop-lines or lanes (i.e., change of thematic properties at fixed network locations) (Peytchev et al., 1996). The main network entities used for the management of incoming traffic data are nodes that represent an intersection of roads within the network, road segments that describe a part of the road network between two nodes, and incoming lanes that represent an oriented lane which arrives at a node. This model makes a distinction between static entities that describe the geographical properties of the network (e.g., network, node, road segment) and dynamic properties that represent the behaviour of the traffic system (e.g., length of a traffic queue, number of cars per traffic light cycle). These entities and properties allow the representation of traffic flows at different levels of granularity (i.e., lane, road segment and node).

The framework of the VDGIS encompasses a full spectrum of current transport and traffic telematics (TTT) tasks ranging from the basic real-time information provision through optimising control and 'what-if' simulation modelling. The TTT (an amalgamation of two words telecommunications and informatics) is a collective name for a range of information and automation services that have been developed specifically on the basis of modern telecommunication technologies. Some of the most actively developed TTT services include traffic and travel information (urban, rural, motorway). The research prototype reported here relates to our work with the SCOOT traffic monitoring and control system which provides a basis for a whole range of telematics applications including microscopic and macroscopic traffic simulation and portable traffic information systems (Bargiela and Berry, 1999). The SCOOT traffic management system retained for the development of this project model a part of the city of Mansfield, a mid-sized city in the UK. The temporal granularity of incoming traffic data provided by the memory management system is given on a second basis. Such a frequency of communication flow leads to a huge volume of traffic data (about one million traffic data messages per day). In order to reduce such a huge volume of data, we decided to aggregate incoming traffic data to half an hour time interval samples. This resolution largely reduces the amount of traffic data generated, and is still relevant for the objectives of an analysis of traffic conditions. The applications have been interfaced using a generic inter-process communication facility developed at Nottingham Trent University, the distributed memory environment DIME (Argile et al., 1996). This communication environment is based on a TCP/IP protocol and a client-server architecture. This system has been developed and tested in conjunction with the SCOOT system. With the aid of DIME, the VDGIS can appear to SCOOT as another application that performs complex data aggregation and visualisation tasks while essentially maintaining its autonomy.

We illustrate these concepts in the context of the OSIRIS prototype oriented to the development of an inter-*O*perable *S*ystem for the *I*ntegration of *R*eal-time traff*I*c data within a GI*S* (Etches et al., 1999; Valsecchi et al., 1999; Grzywacz and Claramunt, 2000). The database method used to support the description of the traffic system is based on an object-relationship model (Etches et al., 1999). For the purposes of our prototype, the database design has been mapped to a geo-relational model. The resulting model supports both object and attribute versioning, thus allowing a flexible representation of temporal properties. The OSIRIS prototype extends the current capabilities of traffic monitoring systems in terms of database functions and develops a user-oriented interface based on the integration, aggregation, manipulation, visualisation and animation of traffic conditions within an urban network. Such a system complements the monitoring functions provided by real-time traffic systems. It is oriented towards urban studies that integrate traffic conditions as a parameter. Within OSIRIS, traffic data are imported from an urban traffic control system that optimises the split, cycle, and offset times of traffic signals. This traffic system is a macroscopic traffic system which is therefore not oriented towards the modelling of individual cars but rather traffic conditions within a road network (e.g., queue lengths). The OSIRIS implementation is realised on top of MapInfo GIS using C++, Delphi (a windows GUI editor and Pascal compiler), and MapBasic programming languages. The urban network component of the database is based on ordnance survey centre alignment of roads (OSCAR) data.

Changing the level of granularity in the representation of any real-world phenomenon has an impact on both the spatial and temporal dimensions. In the temporal dimension, the granularity of very dynamic data needs to be pre-defined according to user needs. Within a traffic system, incoming data based on a very dynamic frequency of change can be pre-processed according to the minimal time interval of interest (Valsecchi et al., 1999). In order to analyse traffic conditions at complementary levels of granularity, several spatial and temporal aggregation mechanisms have been developed. At the spatial level, the aggregation of traffic data is based on three complementary levels that provide different representations of traffic data flows, from the finest spatial level of granularity to the coarser spatial level of granularity, i.e., incoming lane, road segment and node, respectively (Fig. 6).

Additionally, a user-defined level allows the aggregation of traffic data on pre-selected routes (e.g., set of road segment ends). At the temporal level, the source temporal granularity provided by DIME (i.e., 1 s) is aggregated on a half an hour basis by the pre-processor (i.e., averages and maximum of traffic data values). A user-oriented temporal granularity is also selected during aggregation analysis according to application needs. The pre-processing functions of incoming traffic data have been implemented through a visual user interface. The pre-processing of a visualisation requires the definition of the temporal parameters (i.e., time interval, period of aggregation), the definition of incoming traffic attributes (either based on a maximum or average basis), and the levels of spatial and temporal granularity (Fig. 7). For example, pre-processing functions calculate averages and maximums (Fig. 7(a)) of queue lengths, traffic light periods, and node saturation. These functions are applied on either maximum or average incoming traffic data attributes (Fig. 7(b)). For the analysis of very dynamic phenomena such as traffic flows, spatial and/or temporal aggregations provide different levels of analysis. At a coarser level of granularity, aggregated behaviours are identified. Coarser temporal and/or granularity levels allow the identification of global changes. On the other hand, the analysis of local changes requires finer temporal and spatial granularity levels. Browsing throughout different spatial and temporal levels of granularity is an important functional requirement for the development of successful VDGIS in order to support a large range of user functions that cover both the study of local properties and the analysis of general trends within the urban traffic network.

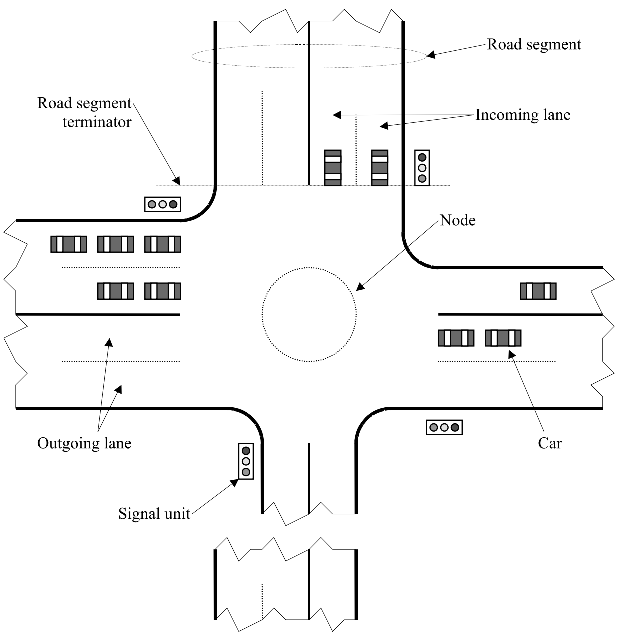

Fig. 6. Traffic network (sketch).

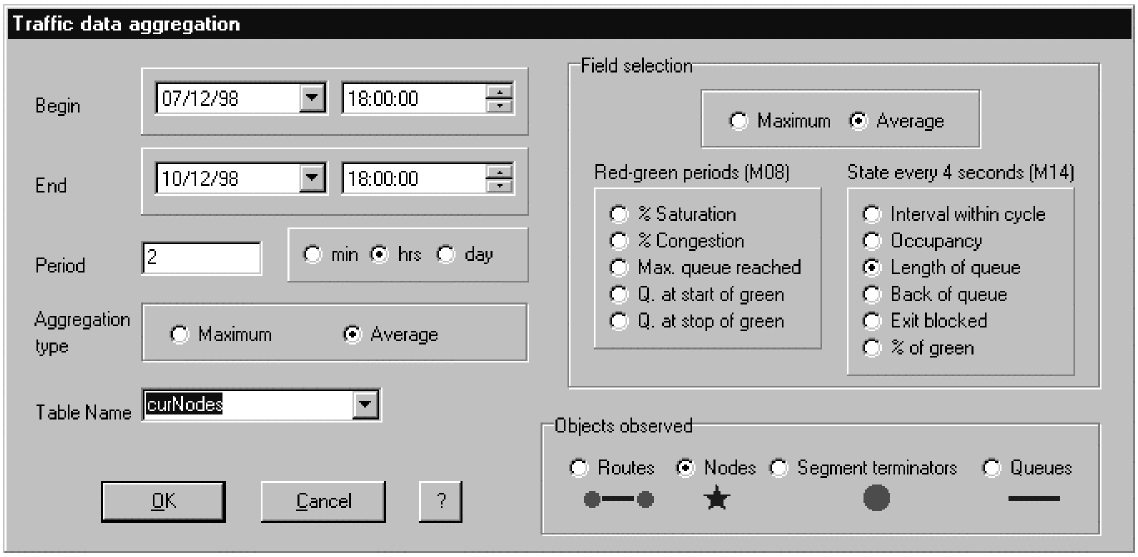

Fig. 7. Pre-processing: configuration parameters.

The query components of the OSIRIS prototype have been completed by the implementation of temporal operations that extend current relational and spatial operations provided by a GIS system (Grzywacz and Claramunt, 2000). Temporal operations are embedded within a query interface that integrates thematic, spatial and temporal operations. The temporal functions represent the extension developed. The graphic user interface (GUI) extends the current MapInfo query interface by integrating temporal predicates within the WHERE clause and temporal functions within the SELECT clause (e.g., Valid( ), Cast(Valid( ) as interval). A temporal operation wizard allows the user to create a temporal predicate (Fig. 8). Each temporal predicate consists of two operands and an operation in-between. The system controls the choices of

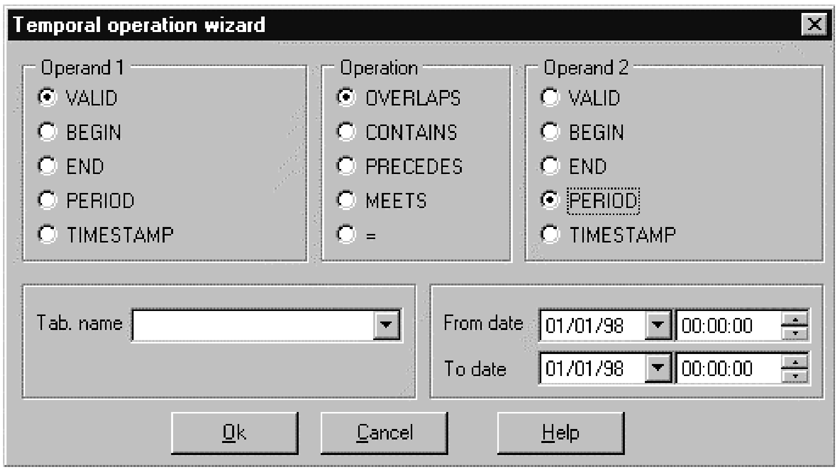

Fig. 8. Pre-processing: temporal operations.

operands according to the temporal operation selected by the user. This implementation is based on a dual approach that combines a first normal form (1NF) approach with TSQL2 temporal operations, which is the current database standard for temporal operations. Such a solution presents the advantage of being compatible with current geo-relational software architectures, which is a constraint of our prototype environment. Typical query examples are as follows: (1) display the spatial extents and deliver the identifiers, average number of passing cars, and valid times of the lanes that have an average number of passing cars greater than or equal to 25, during periods that end after 11:45 on 12 December 1998; (2) return the maximum value of average numbers of passing cars, for periods of time after 10:30 on 12 December 1998. This temporal manipulation interface implements the main operations defined in TSQL2, and extends the range of GIS querying capabilities towards the temporal dimension. These temporal operations complete the pre-processing and query capabilities of the OSIRIS prototype.

In order to provide complementary visualisation perspectives, multi-dimensional visualisation techniques reflect the dynamic properties of incoming traffic data (e.g., thematic chart, spatial chart, thematic animation, spatial animation). For example, an animation allows users to browse through the temporal traffic states of selected and aggregated traffic values within a considered period of time. Such functions enrich the user perception of traffic data through time and act as an exploratory tool that can be used to identify traffic patterns in space and time. These visualisations can be used to detect incidents in order to identify critical nodes, or for the analysis of traffic patterns within the traffic network. In the context of our project, the visualisation of very dynamic geographical data implies a high level of interaction that supports complementary user-defined tasks:

- definition of complementary temporal and spatial levels of granularity (Fig. 7);
- derivation of traffic data using query language capabilities (Fig. 8);
- combination of different dimensions in order to analyse patterns in the spatial, temporal and thematic dimensions (Fig. 9).

Within the scope of the OSIRIS prototype, different visualisation and animation techniques have been used:

- Map animations that present the variation of traffic properties located in the network, using different spatial (lane, road segment or node) and temporal aggregations (i.e., different temporal granules). Fig. 9(a) presents an example of spatial animation that can either simulate traffic behaviours at the queue, road segment or node levels. The animation can be controlled through the GUI with an interaction box that is user-controlled.
- Animated graphs that describe the variation of traffic properties, using different spatial (i.e., lane, road segment or node) and temporal aggregation levels (different temporal granules). Fig. 9(b) presents an example of thematic animation that simulates the variation of traffic queue values along the time line thanks to an interaction box that is user-controlled.
- Charts that present the temporal evolution of a traffic parameter for a user-defined route or set of road elements (i.e., lane, road segment or node). Fig. 9(c) presents an example of variation of traffic queue values along the time line for a set of traffic network nodes.
- Animations that present the evolution of the distribution of a traffic parameter for a user-defined set of temporal components (i.e., lane, road segment or node). Fig. 9(d) presents an animation that illustrates the distribution of traffic values for a set of traffic network nodes.

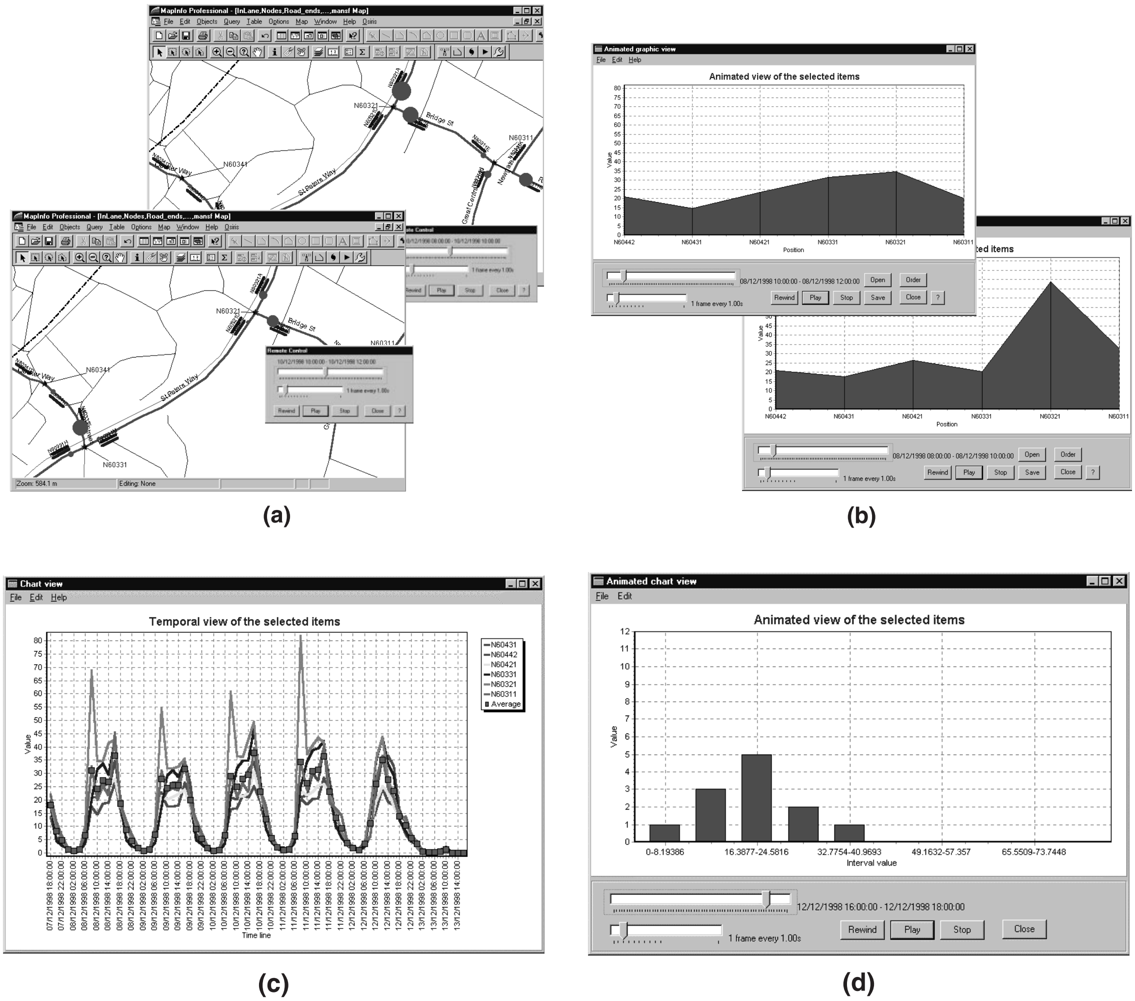

Fig. 9. (a) Spatially oriented animation. (b) Thematically oriented animation. (c) Thematically oriented chart. (d) Distribution-oriented animation.

The following screen snapshots – examples taken from the OSIRIS prototype – illustrate the concepts of visualisation and animation tools that integrate complementary graphical and cartographical techniques. The interaction level is given by a set of actions that support temporal browsing functions within the different visualisations. Different levels of granularity are user-defined during the aggregation of data selected for the visualisation process. All together, these visualisation and interaction tools provide a suitable platform that allows users to explore urban traffic data from various perspectives and to generate a set of dynamic visual representations that give an overview of traffic flows. Such functions enrich the user perception of traffic data through time and act as an exploration tool that can be used to identify traffic incidents and patterns in space and time. For example, OSIRIS visualisations can be used to detect the impact of an accident on the network, to identify critical nodes, or for the analysis of traffic patterns within a road network.

6. Conclusion

The experimental research presented in this paper develops a new framework for the integration, analysis and visualisation of urban traffic data within VDGIS. The integration of urban traffic data within VDGIS requires a sequence of manipulations that include pre-processing functions, selection and derivation of traffic data, and visualisation and animation tasks. In particular, the constraints of a VDGIS imply the development of pre-processing functions that aggregate incoming traffic data in both the spatial and temporal dimensions. These functions allow the analysis of spatio-temporal phenomena at complementary levels of granularity. The manipulation and analysis of urban traffic is based on several complementary levels: pre-processing, visualisation and interaction tools that allow users to analyse urban traffic data within GIS. The presented framework has been illustrated and validated in the context of a VDGIS for a real-time traffic system. The method proposed and the implementation realised with the prototype OSIRIS are original as the proposed architecture combines: (1) a dynamic integration of traffic data, (2) pre-processing of traffic data at complementary levels of granularity, (3) the integration of temporal operations within a GIS query language, and (4) an interface that supports visualisations and animations in the thematic, spatial and temporal dimensions. Further work includes the development and prototyping of a real-time traffic GIS for simulation purposes.

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