Geo-ICT in Transportation Science

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2008

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Abstract

Since the first appearances of Geographical Information Systems (GIS), transportation science has found in them its natural support, to represent, first, the spatial and, later on, the temporal aspects of transportation networks and infrastructures. As GIS developed so did their use in transportation science, and they became essential not only in visualization but also to facilitate and speed data management, algorithmic operations, and decision making. This paper analyses the contributions and influence of GIS in transport science on the basis of three frameworks: geodatabase, geomapping, and geomodelling, all of which highlight the importance of location.

1. Introduction

"The function of transportation is to move people or objects between spatial separated locations, with the purpose of meeting demand for goods, services and activities" (Hall, 1995). This broad definition highlights the linkage between transportation science and spatial approaches. Transportation science is devoted to explain the phenomena leading to the movement of people and objects from place to place, by both developing and exploiting theoretical and application tools (Hall, 2003).

Transportation systems, in order to improve their performances have always exploited the most recent advances in various fields of technology. Technological inventions have affected transport and progressively shortened distances, as we can see from Figure 1, which shows how distances on the planet have shrunk from the fourteenth century till the present time because of the increasing speed of vehicles, and, in the last few decades, of information as well.

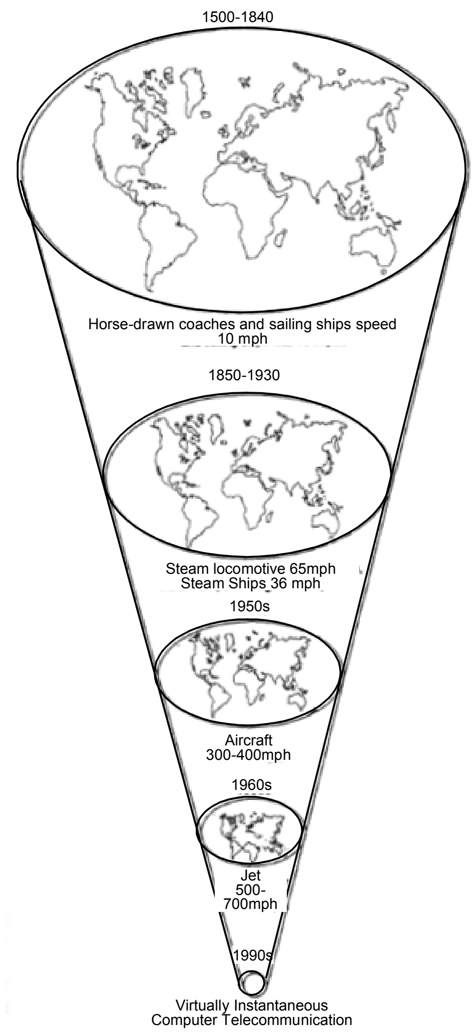

Figure 1 The role of technology in shrinking world distances (Golledge and Stimson, 1997)

At the same time, technological development has involved the enhancement of cartographic representation, right up to the development of Geographical Information Systems (GIS). Since GIS have a seamless relation with space and location, given that their main objective as a tool is to store, retrieve, and facilitate the analysis of spatial data (Goodchild and Janelle, 2004), they have become one of the most powerful tools to support transportation studies and applications. The liaison between GIS, or Geo-ICT, and transportation is indeed quite natural, given that transportation itself is linked to space organization and the development of networks in space and time, just like geography itself (Haggett, 1965). Capitalizing on this relationship both academics and practitioners have focused their attention on research/work that makes use of GIS in transportation applications.

“Geo-ICT and Transport” has been of importance in the academic world since the early 1990s (Miller, 1991; Kamal et al., 1994). However, besides some early contributions, which aimed at explaining the role of GIS in transportation planning (Sutton, 1996), no major efforts were made. A relevant attempt to collect and organize studies about GIS and Transport was made in 2000 by the academic journal *Transportation Research C* (reviewed by Fotheringham, 2002, Shaw, 2002). A special issue on “GIS in Transportation Research” was published in order to try to identify various perspectives on the use of such techniques in transport applications. Since 2000, many studies and applications have been published on the topic. While in the first research studies GIS were considered as a mere technique to support applications, in the course of time they were used to define the core methodology of the applications.

Today GIS are indispensable in transportation science applications (Spring, 2004). In several cases, it is sometimes formally required that public authorities with an interest in transportation build a GIS framework to handle and manage transportation data and projects. For example, the American Association of State Highways and Transportation Officials, together with the US Department of Transportation (DoT) have been organizing a GIS-T symposium for the past 22 years, in order to give practical support to government and private industry organizations interested in the use of GIS for transportation purposes. This shows that in transportation science the spatial approach is naturally integrated, contrary to other disciplines where there is a need to identify the particular role of “geographically oriented subdisciplines” in a distinct way. As an example, transportation scientists have been key players in the application of GIS (Goodchild, 2000; Thill, 2000).

GIS have influenced a variety of aspects of transportation science. Goodchild (1998), after recognizing in the discrete entity model and in the network model the GIS data models that are most interesting for transportation purposes, identifies the paradigms leading to their extensive use in transportation modelling. These are: digital map production, inventory and data management, integration of data, spatial analysis, and dynamic modelling. He continues (Goodchild, 2000) by differentiating three stages in the evolution of GIS-T: the map view (mainly concerning network visualization and interoperability issues); the navigational view (connected with network modelling and algorithm resolution); and the behavioural view (linked to the use of the network by people and vehicles, which implies the dynamic modelling of transportation phenomena).

More recently, Thill (2000) highlights the requirements of GIS in transportation applications and the core transportation research themes which employ GIS for "research, planning, and management" (referred to collectively as GIS-T). Like Goodchild, he provides a classification, but gives more attention to the use of GIS to handle large amounts of transport data rather than to the other aspects. According to Thill, GIS-T need:

- a data management system (whose aim is to facilitate the maintenance and the integration of the inventories of transportation infrastructures held by public authorities);
- data interoperability (in order to allow transportation data sharing among several agencies, each with its own data base);
- real-time GIS-T (for real time geo-referenced data storage, retrieval, processing, and analysis);
- large data sets (which involve the optimization of algorithms and analytical tools, and the discovery of innovative system designs);
- distributed computing (to allow the spread of GIS-T data over users and community, by means of web services).

Identifying the main fields of transport in which GIS could contribute and how, represented a serious challenge at the beginning of this decade. However, not only because of the rapid technology development and computing improvement but also thanks to the increasing interest from public academic authorities, GIS have undergone rapid enhancements in recent years, spreading and becoming systematic throughout the scientific world.

In 2006, Shaw and Rodrigue reviewed Goodchild and Thill's classifications. They considered that GIS-T studies can be classified into three groups: data representations, analysis and modelling, and applications. A review of the literature on Geo-ICT and transport leads directly to this classification, which is also very similar to the three frameworks suggested for this book. In our paper, we decided to adopt the geodatabase, geomapping, and geomodelling frameworks as a classification, with the goal of allowing for comparisons with other sciences. This classification will not lead us far from previous authoritative research and will make the discussion understandable to other disciplines.

Our paper is organized as follows: Section 2 deals with the specific significance and role of location in transportation science. Section 3 explains the use of Geo-ICT (GIS tools, spatial data and location-based services) within the three frameworks identified above, while in Section 4 the comprehensive phenomenon of the integration of Geo-ICT in transportation science and the obstacles encountered are analysed. In Section 5, a summary and future perspectives are discussed emphasizing the challenges faced by Geo_ICT.

2. Location in transportation research

Starting from the definition of Transportation Science in the previous section and considering all the newer studies carried out in this field, we can assume that the concept of “location” has a very wide meaning and at the same time is intrinsic to transportation itself. Each application in transportation science is carried out with reference to a particular spatial context, and therefore to a particular location (Taylor et al., 2000). For instance, the very reason why people travel is the presence of different kinds of activities in different places. Therefore, information about the location of activities and the location of people interested in them is essential in order to study travel demand and thus to optimally design transportation supply (Cascetta, 2001). Information about infrastructure locations is also important in order to design efficient freight and public transport services.

Recently, scientists have been putting great efforts into finding efficient ways of sending real time information to transportation systems users not only about the location of accidents, road congestion, various kind of emergencies (natural and human hazards such as fires, landslides, terrorist attacks, and so on) but also about transit position and vehicle tracking. Amongst possible examples, we can distinguish between static and dynamic location (Noronha and Goodchild, 2000). The first is related to the georeferencing of objects fixed in space, such as accidents, activities, infrastructures, while the second is related to objects changing their position in time, such as vehicles, passengers and goods. This dichotomy reflects the evolution of transportation science, which is increasingly adopting a dynamic problem-solving approach instead of the traditional static one.

It is important to note that in transportation science the term "location" not only refers to the position of passengers and goods, which is an input for transportation studies, but often is considered as a design output, when its meaning is related to the optimal localization of facilities (Chan, 2005). In order to deal with these location-based issues, transportation scientists first adopted Graph Theory. Graph theory can be used to explore the properties of sets of topological related lines and points characterized by specific weights, and thus to model and analyse transportation networks.

With the appearance of Geographical Information Systems (GIS), transportation scientists found attractive the possibility of giving a location meaning to network entities (nodes representing actual places or intersections and lines representing roads), an option which was limited in graph theory. For this reason, amongst the models provided within GIS, the network model is the one most used to represent topologically-connected linear entities (Thill, 2000). However, researchers have not limited GIS use to the traditional tools. Over time they have adapted and developed new tools for their own purposes, thus enabling: the representation of non-planar models and multiple lanes (Fall et al., 1996); the analysis of turns and intersections (Miller and Shaw, 2001); linkage between two or more transportation modes and hence networks (Southworth and Peterson, 2000); dynamic segmentation for the multiple representation of attributes of the same entity (Sutton and Wyman, 2000; Choi and Jang, 2000), and integration with transportation models (You and Kim, 2000; Berglund, 2001). Researchers, because of their needs to model reality more closely, have improved and enhanced the network model available in GIS. Technological advances in the field of computer science have also made this possible.

Since every element in the transportation system has its physical meaning and special characteristics if localized in a particular context or position, another important aspect of location approaches in science is the collection of data. The main transportation applications deal with the collection of several kinds of different location-based data, on aspects such as physical facilities characteristics, road traffic, activity localization, travel demand volume in a specific area, and vehicle tracking. The data collection method used depends on the particular nature of the collected data. For physical information, the most common methods are in situ surveys, cartographic analysis, and remotely sensed data; for travel demand, more or less complex sampling surveys (Cascetta, 2001) are used; for activity localization, it is possible to make use of national data sets (e.g. the Census in the UK, Istat in Italy, and so on), while for real-time traffic information, GPS and wireless tools are becoming indispensable.

The complexity of the transportation system, where modelling and analysis require connection with other fields such as land use, environment, and demography, leads to the unavoidable collection of large amounts of data. The data sets need to be stored, integrated, analysed, elaborated, and made available. Therefore, it comes as no surprise that transportation science is using the power of GIS to improve transportation data management and dissemination through the extensive use of a georeferenced database approach and web-based mapping. Even in this field, however, transportation scientists do not limit their efforts to the use and application of commonly provided GIS tools, but try to adjust the technology to their own needs, confirming again that GIS-T is not a particular GIS application, but rather a GIS development enriched by a Transportation Information System (Thill, 2000). In the next section, these aspects will be explored and analysed in detail using the following three frameworks.

3. Geo-ICT in transportation research

3.1. Geodatabase framework in transportation research

Transportation science has undoubtedly taken advantage of the possibilities to handle and manage large amount of data with Geo-ICT systems within their geodatabase framework. The most important sign of this is the widespread use of geodatabases in every transportation application. Transportation researchers use geodatabases for different purposes. These include: solving data interoperability issues; performing query optimization; resolving map matching issues; using these databases as a basis for transportation models and for creating data repository to build decision support systems; integrating GPS data; and sharing data by means of web tools. Because of the diversity in applications, scientists can exploit transportation data by storing such data in georeferenced databases. Applications of geodatabases in transport include: query definition for the optimal resolution of multiple path algorithms and other kinds of network problem, and the creation of efficient spatial query resolution engines, specifically designed for transportation models (Mainguenaud, 2000; Huang et al., 2000).

The first implementation of a network model was based on a relational database, which could easily be adapted to the abstraction of a network represented by a graph. This model, typically referred to as the “arc-node model”, besides modelling the network allowed topological relations to be created (Thill, 2000; Shaw and Rodrigue, 2006). This model was then expanded to handle linear referencing, thus facilitating the modelling of point events within the network. However, the arc-node model was still limited in its capabilities, restricting what transport researchers could do with it. With database developments and the need for network models to conform more closely to reality (i.e. multimodal networks), an object oriented model was proposed. This kind of model focuses on network features, which make interaction between the elements possible. This is a more intuitive model for transport scientists, since it is centred on objects and introduces a flexibility that the previous model did not offer.

The first attempts to create geodatabases for transport (Claramunt et al., 2000; Dueker and Butler, 2000) lacked common definitions of the transportation elements and of interoperability between traditional GIS and transportation-related models. But, as the models became more sophisticated and widely used, new integration frameworks were proposed. New frameworks considered geodatabases and their relational structure as suitable to store spatial data and maintain a shared digital world model. Examples can be found in the literature that exploit the acquired experience in the Geo-ICT field (several data models have been developed: see Jang and Kim, 2007 for an overview), the computing and software progress, the importance given to these issues by the appearance of international standards (ISO), and the newly created exchange languages (UML, XML, GML) and formats (shapefiles, coverages) (Darter et al., 2007; Jang and Kim, 2007; Scarponcini, 2007). These contributions have as their main purpose to propose new frameworks to overcome the problem of data sharing and interoperability.

Data sharing is one of the primary issues when using geodatabases for transport. For example, for transport planners, who need to integrate different data sources into one system for retrieval, processing, and forecasting, having a fully integrated GIS database is a must (for an example, see Thong and Wong, 1997). Interoperability means, as the EU INSPIRE directive also states, “the possibility for spatial data sets to be combined, and for services to interact, without repetitive manual intervention, in such a way that the result is coherent and the added value of the data sets and services is enhanced”.

One of the most common transportation applications using GIS, in which the interoperability issue is visible, is spatial matching between two or more different networks, coming from various data sources or from GPS surveys. While initially such a problem involved time and energy resources due to the necessity for manual manipulation (Xiong, 2000; White et al., 2000), several improvements have since been introduced by means of the capabilities of GIS and of ITS, as described by Quddus et al. (2007). The map matching issue is very important whenever the integration between GIS representation and GPS devices is considered (Taylor et al., 2000; Mintsis et al., 2004; Byon et al., 2007). In these cases, GIS often provides a database management platform for the integration, display and analysis of data collected from GPS.

Geodatabases have been used to integrate GIS and transportation modelling for particular purposes, such as travel time forecasting (You and Kim, 2000), congestion management (Quiroga, 2000), traffic entity estimating for different road categories (Blume et al., 2005), and to build spatial decision support systems (SDSS), mainly to help public agencies to make efficient transportation planning decisions. Frank et al. (2000) led an interesting application related to hazardous material truck routing. They compared studies which implemented a solution within a GIS and those using a GIS embedded in an SDSS. They identified the advantages of the latter which included support for the analysts. Adaptability to a wide range of problems, visualization and interaction, and plan-generation orientation are the special features of the SDSS developed by Arentze and Timmermans (2000). They present a review of SDSS approaches and a framework to support transportation planning and location decisions.

More recent experiences, mainly led by the US Department of Transportation (DoT), deal with the implementation of spatial information system infrastructures that provide planners with the right and most up-to-date information for efficient decision making (Hall et al., 2005; Bejleri et al., 2006). In this respect, GIS, and geodatabases in particular, are used to integrate data collected from diverse sources, to organize data in exchange and standard formats, to analyse data, and to create information which can be stored in the geodatabase itself and shared amongst public agencies and other stakeholders.

Similar efforts, even if as yet only at an early stage, are also being made by the European Community. The European Transport Information System (ETIS) aims to "identify and accommodate all required policy-driven information related to ETIS in a repository, to be kept up-to-date and controlled by experts and to be accessed through an Internet-based software tool" (Ballis, 2006). GIS technology is used in ETIS for its capability to store georeferenced information in georeferenced data banks and to visualize and represent geographical information, even by means of an Internet independent application. The ETIS framework is a starting point for other contributions (such as Tsamboulas and Mikroudis, 2006), whose aim is to build a comprehensive independent software (TRANS-POL) able to mediate between transportation planners' and transportation models' needs, in which Geo-ICT peculiarities of data integration, spatial query, representation and visualisation are essential.

As anticipated, one of the current research challenges regarding Geo-ICT and in particular the geodatabase framework is the data sharing issue, which can be implemented by means of interoperable data formats and languages, but is completely achieved when it is possible to share data across independent web-based applications. Several studies deal with this problem in particular and most of the contributions which make use of geodatabases consider the Internet as the final platform to distribute data across actors (see for example Peng and Huang, 2000; Ziliaskopoulos & Waller, 2000; Welch et al., 2007). Dissemination of web services of interactive location and path finding (such as Google Earth and Google Maps) is determinant for the development of such Internet-based system. A geodatabase can only be fully taken avantage off when paired with a visualization tool. In the next section the geomapping framework is discussed.

3.2. Geomapping framework in transportation research

Transportation applications themselves account for visualisation and mapping issues, in order not only to show results, but also to analyse and have an overview of the problems. From this point of view, transportation science has exploited the advances in geographical representation coming from Geo-ICT systems. Transportation applications have relied in GIS to explore new visualisation and mapping possibilities, raising questions regarding issues of map accuracy, map matching, location mapping, and advances in 2-D and 3-D visualisation.

Many attempts have been made to use digital maps to better represent transportation network features and the precise location of their attributes through dynamic segmentation, made possible from commercial GIS packages. Norohna and Goodchild (2000) for example, relate the location expression problem to the interoperability issue and develop methods to compare maps and overcome map accuracy problems when data comes from different sources. Sutton and Wyman (2000) compare dynamic segmentation based on the linear referencing approach, with dynamic location, which stores geometry as a single object in a database field.

A wide range of transportation applications and studies take advantage of the user-friendly environment provided by GIS software and of new possibilities from a visualisation point of view (Frank et al., 2000; Welch et al., 2007; Choi and Kim, 1996; Moudon et al. 2005). GIS allows the creation of flexible interfaces for visualisation of urban traffic data where map symbols and computer animations are distinguished as possible means to represent dynamic traffic phenomena (Claramunt et al., 2000). More recent advances advocate the use of GIS to handle representations of transport data in more than two dimensions, in particular when studying travel behaviour (Kwan 2000; Kwan and Lee, 2005; Pack et al. 2005, 2007). There is also considerable interest in mapping newer elements associated with networks such as risk and vulnerability (Church and Cova, 2000; Kwan and Lee, 2005). With the development of the Internet and web related services such as Mapquest or GoogleMaps for planning and route-finding, GIS has acquired a new role. Mapping services, some more sophisticated than others, are all over the Internet and are setting a standard for transport planners and agencies to follow (Tang and Waters, 2005).

3.3.Geomodelling framework in transportation research

If geomodelling is intended as the use of Geo-ICT in modelling the transportation system, from everything we said above it is clear that this kind of utilisation has been widespread in the field. The commercially available GIS systems which are geared towards transport (e.g. Transcad and the network extension of ArcGIS) allow different standard transport modelling processes out of the box. For example, ArcGIS has intrinsic functions for solving the travelling salesman problem (TSP), site selection, service areas, O-D matrix calculation and other spatial functions that can be linked with the network. On the other hand, Transcad besides the functions offered by

ArcGIS, has available transport planning functions such as user equilibrium and system optimal.

In the vast literature scanned, GIS has been used as a framework to support different modelling aspects in transport applications. Travel behaviour is one of the areas where GIS has been used for demand modelling of public (Choi and Jang, 2000) and private modes (Choi and Kim, 1996). GIS has been used to model travel choice (Byon et al., 2007; McGowen and McNally, 2007; Bricka and Bhat, 2006; Ogle et al., 2005; Tsui and Shalaby, 2006), destination choice (Chow et al., 2005), location choice (Nicholas et al., 2004; Shelton et al., 2004), mobility (Schlossberg, 2006), and accessibility (Hodge, 1997; Miller and Wu, 2000; Casas, 2003). It has been used for travel time forecasting (You and Kim, 2000), and risk and evacuation models (Church and Cova, 2000; Alexander and Waters, 2000; Horner and Downs, 2007). In terms of transport infrastructure, GIS has been used for road safety (Ozbay and Mukherjee, 2000; Wang et al., 2007; Li and Zhang, 2007), site selection (Nyerges et al., 1997), and investment and maintenance (Tsai et al., 2004; Ozbay et al., 2007). Intelligent transport systems have benefited from the use of GIS (Quiroga et al., 2006): for example, for data modelling and representation (Arampatzis et al., 2004), and traffic management (Ozbay and Mukherjee, 2000; Zhou et al., 2006). Transport services focusing on other than passenger transit, such as freight, have also made use of GIS (Southwork and Peterson, 2000; Frank et al., 2000). And, last but not least, research in transport policy has adopted GIS as a tool in areas dealing with pollution (Bachman et al, 2000; Armstrong and Khan, 2004; Brown and Affum, 2002), land use (Arentze and Timmermans, 2000; Vicente and Martìn, 2006), public participation (Prevost, 2006), and sustainable mobility (Celsor and Millard-Ball, 2007; Nijkamp et al., 2007; Cheng et al., 2007). Most of these examples use, as mentioned before, Geo-ICT to support transportation modelling and a wide range of transportation applications.

An original research direction, closely tied with the geodatabase framework discussed above, is the attempt to find the best data model to represent and model transportation elements. Dueker and Butler (2000), while proposing a custom enterprise GIS-T data model, also provide an assessment of the data models used in GIS-T, highlighting the advantages and limitations of each of them which includes the following standards: ISO 14825 Geographic Data Files (GDF, an international standard used to model road network data for navigation purposes) model (see ISO 14825, 2002), NCHRP 20-27 (Vonderhoe et al., 1998), and TIGER. Jang and Kim

(2007) outline the state of the art in transportation data models, including the Multi-Dimensional Location Referencing System (MDLRS) model (Adams et al., 2001); UNETRANS, the ESRI ArcGIS Transportation Data Model (Curtin et al., 2003) and TransXML (NHCRP, 2007). They explain that GIS-T and GDF data models employ a common relational model, while MDLRS and UNETRANS are object-oriented models. However, neither of them has a "semantically coherent framework" which would be useful in order to avoid dependence of transportation information on a specific platform. For this reason, they propose a different conceptual framework to develop a data model based on the ISO 19100 series of International Standards for geographic information. Therefore, we can argue that, if it is true that there are several efforts to develop and apply a proper data model "fitting" the transportation systems, this field is still being researched.

More consolidated is the research direction which leads to the development of commercial transportation modelling software based on GIS technologies. You and Kim (2000) provide a review of the integration of transportation (travel time forecasting) models with GIS, distinguishing the models including GIS, the ones connected with GIS, and the ones embedded in GIS software. Sutton (1996), as well, provides an early and interesting classification of the ways transportation models can be linked with GIS technology, and, in addition, gives pros and cons of each of them. The classification includes: "hard coding", which allows linking by means of a correspondence between tables of the GIS database and ones of the transport network; "warm linkage", when the choice is to build the transportation network within the GIS platform (examples are TransCAD, which despite what Sutton says in his review has been further developed and has a very wide diffusion); and, finally, "hot linkage" involves data sharing by means of standard formats between the transport model and the GIS platform.

After only one decade, substantial progress has been made, and what seemed 'off-putting' about GIS to some researchers (Sutton, 1996) has been rapidly overcome. Following one of the paradigms of Goodchild (1998), dynamic modelling is the future challenge of the use of GIS in transportation research. Since the work of Claramunt et al. (2000) who propose a "very dynamic" GIS that integrates static urban data with dynamic traffic flows to monitor urban traffic, other contributions have explored the potential of GIS in performing temporal-based analysis for studying land use and transportation interactions and other transportation applications (Shaw and Xin, 2003; Demirel, 2004; Yu, 2007; Ahmed and Miller, 2007).

3.4. Framework summary

From the previous sections it is possible to specify the main characteristics and obstacles identified by researchers in the three frameworks. The references cited are only a small portion of the vast existing literature about the use of Geo-ICT in transport. The reader can fruitfully start from them prior to deepening each particular field of study.

Briefly summarizing, for the geodatabase and geomodelling framework, interoperability and data model definition, beyond model integration, are necessary, while issues commonly raised within the geomapping framework are map accuracy, map matching, dynamic and multidimensional visualization.

The three key frameworks for the use of Geo-ICT in transportation science are mutually interrelated. This is evidenced by the growing development of Spatial Decision Support Systems (SDSS) for transportation planning purposes in the international literature and practice. Geodatabases are the core of SDSS, due to their capability to store, integrate, manipulate and retrieve large amounts of data coming from diverse sources and agencies. The geodatabase is commonly embedded in a comprehensive information framework which includes transportation modelling and macroscopic indicators as the outcome – typically represented in more or less advanced maps. Every step involves a logical procedure able to support transportation planning decisions.

This is an overall view which shows that each of the three frameworks has its own importance within transportation science. It is important to highlight that the main impulse for the use of Geo-ICT in the field has been its enormous power to organize and store data in a geodatabase framework. The relative popularity of this aspect of the Geo-ICT systems could be explained by the need to handle data coming from intensive data collection procedures and surveys, used as input for transportation models and analyses. Currently, the need to better represent and visualize and to enhance the already developed transportation models with special attention to location and geographic reference, contributes to the extended use of the other frameworks as well. This shows that Geo-ICT in transportation science has the ability to integrate the three frameworks into one tool, which is an advantage and an improvement on what was available in the past (when the three frameworks were separate and different tools were required for databases, mapping, and modelling).

Future research will most likely continue to exploit and encourage the integration of the three frameworks, in order to support transportation system analysis and modelling and to achieve an overall understanding of the dynamics that rule the system. Geo-ICT in Transportation Science *is* actually GIS-T, and, according to Fletcher (2000), GIS-T are "interconnected systems of hardware, software, data, people, organizations and institutional arrangements for collecting, storing, analyzing and disseminating information about areas of the earth that are used for, influenced by, or affected by transportation activity". This definition is supported by already-existing technologies, but calls for the cooperation of different actors: research institutes, public administrations, private agencies and the general public as well, in order to create proper infrastructures able to support not only land use and the transportation planning, but also people's everyday life (receiving and providing location-based real-time information on transportation networks and facilities). This is probably the main challenge (thus organizational more than technological) to be addressed in the future.

4. Integration and diffusion of Geo-ICT in transportation science

As explained in the introduction, Geo-ICT technologies are intimately connected with transportation science. The integration, or better the diffusion of Geo-ICT within transportation science, is a bottom-up rather than a top-down process. Initially Geo-ICT was used by researchers in their applications; with the development and continued use of the tools, awareness of their importance in the field gained recognition making Geo-ICT a required tool.

The field of transport saw an increase in the use of GIS tools in the 1990s. Actually, since the 1980s some GIS software (e.g. ESRI's ArcGIS) has had modules able to model networks, even if they were quite complicated to use. Thus, even if municipalities and utility companies were using it back then, it was in the mid 1990s that the first appraisals of the role of GIS in transportation planning and of the way to spread this technology amongst researchers and stakeholders took place (Sutton, 1996). Sutton argues that the introduction of Geo-ICT in Transportation was via its use in a wide range of applications. The aim was to use the “tremendous potential” of GIS in organizing and displaying but above all in managing transportation network data. This raised special issues such as dynamic segmentation. The study also recognizes that early practitioners started to investigate the use of GIS in Transportation and to form small research communities, which then led in the US to the organization of expert panels dedicated to explore GIS-T issues, and of special academic courses and Conferences about GIS-T.

Moreover, an identifiable driving force for the diffusion of Geo-ICT in transport can be linked to the recognition by public agencies, and therefore by national and international norms, of the importance and of the need to collect, integrate and update transportation data. This tendency, even if with some temporal gap, can be seen in Europe, where in the public sector the need for large-scale databases is stated (INSPIRE; Directive 2007/2/EC), and in the US, where by now the final stage of the integration model seems to have been achieved.

From an academic perspective, developments attained in the US (Sutton, 1996; Thill, 2000) were not followed in Europe, or at least have not been so widely documented. As far as the Italian case is concerned, the use of Geo-ICT in advanced transportation engineering education is not being exploited to its full potential. It is used as a side technology, which makes easier and faster a given process, which could be achieved anyway. But this trend is only apparent, because transportation engineers are well aware that without GIS software, modelling or simple visualization would be very hard and not competitive.

5. Summary and perspectives

The technology in the form of GIS, capable of implementing and manipulating networks, has been available for at least two decades. Initially, however, intensive training and knowledge of the software was required. GIS was an exclusive tool of geographers, while other disciplines were kept in the dark regarding what GIS could do for them. In terms of the software, the technology had not reached a level of maturity, and there were problems of storage and processing speeds, which for transport applications were very important. In spite of these shortcomings, as the technology evolved and GIS gained widespread recognition, the benefits of using it in the transport field became apparent. With its increased use, demand for more specific transport functions emerged, forcing GIS developers to improve their network models and incorporate transport-related functions into their systems. This is a trend that continues today. Users demand more functionality from the GIS, and the software companies are willing to comply. The existence of a tool that is so useful to model and implement transport applications has increased and attracted a number of users, who go beyond transport planners and researchers. GIS is now used by transport researchers across a number of different disciplines.

In this view, the main challenges recognizable from the literature reviewed are:

1. data-base information platforms;
2. real time GIS;
3. 3-D data management.

1. GIS has acquired an integrative role not only in transportation science but in other disciplines as well. It has become a development platform, which allows the different components of a project to be combined into one system. The three frameworks discussed in this paper – geodatabase, geovizualization, and geomodelling – can all be part of the same application, with a seamless and efficient interaction (see paragraph 3.4 above). This unique characteristic has made GIS a popular tool in the advancement of transportation science. As more organizations and researchers use GIS, the technology becomes a norm and its perceived usefulness and ease of use become apparent.
2. Real-time applications aim to know the (transportation) system conditions at every moment, in order to give as up-to-date as possible information to users (to influence their decisions) and to the system itself (to orientate its behaviour). Currently, the main problem of real time is not in the technological field, which experienced rapid growth, but rather in new modelling efforts, which are required to better understand how to use these advanced tools properly. Indeed the rapid growth in technology in recent years has opened the doors to applications not conceivable just few years ago, and, for this reason, not present in any modelling approach. In the transportation field, we are thinking of the applications on In-Vehicle Information Systems (IVIS) and the Advanced Driver Assistance System

(ADAS), which exploit all kind of devices useful for obtaining location-based information (already available), but whose impact on the transportation system is not yet clear and still under investigation.

3. In transportation science, during the last years, also very particular segments of research have appreciated the potential of Geo-ICT for data management. For example, specific applications, such as microscopic traffic simulation packages and driving simulation systems are now providing GIS importing and exporting tools, which in earlier versions (TSS, 2006; Oktal, 2006) were not considered at all. Moreover, the involvement of these new GIS users is driving the expansion of the capability of the information system to manage and use 3D data. In fact they require a more detailed representation of the transportation supply model for better evaluating single-vehicle behaviour. For this reason, the GIS capability to store, organize and retrieve the data concerning Z-values is becoming indispensable. At the same time, 3-D mapping will surely have an influence in enhancing navigation systems for ordinary drivers and give more accuracy to road databases (TeleAtlas, 2007).

Geo-ICT in transportation continues to grow in terms of the number of users and to promote the advancement of transportation science. The three frameworks discussed are evidence that transportation is an area where these technologies are readily applicable and can provide advantages in data storage, visualization, and processing/modelling.

GIS as a tool is flexible enough to allow researchers to propose improvements in these areas via programming (i.e. code development). However, this requires a level of expertise that is not easy to attain. Therefore, those who do have the knowledge and know-how to advance the field should share it with others. This can be achieved via the Internet creating a shareware site, following the example of other open source code projects that already exist in different areas. This will also allow a wider use of the tool thus increasing the number of users.

GIS as a science on the other hand, allows fundamental questions behind the technology to be raised. These questions relate to the three frameworks discussed in this paper and have as their objective to contribute to the advancement of science and technology. In particular, GIS technology has shown that it can be a flagship of transportation science and in time will transform and become one of the driving forces of the discipline.

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