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# Transportation GIS: GIS-T

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This chapter begins with a brief introduction to the main characteristics of the Geographical Information Systems in Transportation (GIS-T) field. The historical antecedents which led to the rise of GIS-T are described. This is followed by a description of the main components of a GIS-T, together with a discussion of the various types of operations and procedures which are commonly found in GIS-T packages. Generic and specialised GIS-T packages are described. This is followed by an overview of the use of GIS-T in government departments of transportation at the municipal, regional, and national levels. The latter part of the chapter includes a discussion of a number of specialised topics including Intelligent Vehicle/Highway Systems (IVHS), Automatic Vehicle Navigation Systems (AVNS), Automatic Vehicle Location Systems (AVLS), Automatic Vehicle Dispatch Systems (AVDS), and the use of surveillance systems. The conclusion provides suggestions concerning future developments in GIS-T.

## 1 INTRODUCTION

Transportation applications of GIS have become increasingly popular in recent years, so much so that they are now routinely referred to by the acronym GIS-T and this convention will be adhered to throughout this chapter. There are already whole conferences devoted to GIS-T (such as the GIS-T Symposium held each Spring in the USA) and many of the general GIS conferences have special sessions on GIS-T and closely related topics such as infrastructure management (see, for example, the proceedings from the annual conferences of the Urban and Regional Information Systems Association, URISA, and the annual US GIS/LIS conferences). Additionally, some organisations, including the Transportation Research Forum, have sponsored special panel discussions of GIS-T (Waters et al 1992).

GIS-T is well represented in GIS journals such as *Computers, Environment and Urban Systems,* the *International Journal of Geographical Information Science*, *Geographical Systems*, *Transactions in GIS*, and *Geographic Information Sciences*. There have been special issues of traditional transportation journals devoted to GIS-T (for example, the *Journal of Advanced Transportation* and the *Journal of Transportation Planning and Technology*) and special GIS-T journals such as the *IVHS Journal* (published since 1993). In addition, in the last decade there have been numerous government and research reports, books (e.g. Bonsall and Bell 1987), and other materials written about GIS-T and closely-related topics.

There are consultants and consulting companies who specialise in GIS-T and some of these, such as Simon Lewis of GIS/Trans Ltd, frequently offer URISA-sponsored workshops on GIS-T at the major GIS conferences. The GIS/LIS 96 Conference in Denver offered a new, advanced workshop on GIS-T for the first time. Finally, there are GIS packages which have been developed specifically for GIS-T, although much of the additional functionality required in GIS-T may also be found in the industry leading, generic GIS packages (see Church, Chapter 20; Elshaw Thrall and Thrall, Chapter 23; Maguire, Chapter 25). In short, it is possible to state unequivocally that GIS-T has 'arrived' and now represents one of the most important application areas of GIS technology (Maguire et al 1993).

This chapter considers the historical antecedents to GIS-T and shows how this branch of GIS has benefited from research in many areas including geography, computer science, and operations research.

## 2 ANTECEDENTS TO GIS-T

Many individual developments, both technological and conceptual, have contributed to the rise of GIS-T. Technologically, GIS-T, like GIS as a whole, benefited from developments in management information systems and database techniques in general, and relational databases in particular. The development of 'stand alone' packages for carrying out specific operations such as shortest path analysis and location–allocation modelling (Church, Chapter 20; Cova, Chapter 60; Rushton et al 1973) and more recently the McTrans programs (University of Florida, Transportation Research Center) all contributed to the development of GIS-T. The introduction of computer-assisted drafting programs into departments of transportation at various government levels (e.g. municipal, regional, and national) and computer graphics programs for displaying transportation systems (Schneider 1983) convinced many of the value of GIS in transportation. A detailed review of the adoption of all types of information systems in State Departments of Transportation (DOTs) in the USA is given by Lane and Hartgen (1989). On the hardware side, the development of powerful and low cost desktop computing hardware assisted the introduction of GIS-T into even the smallest government DOTs.

Many conceptual developments were also important in aiding the rise to prominence of GIS-T. These developments included work in operations research and programming, which led to new algorithms for shortest path analysis, routing procedures, solving the 'transportation problem' of linear programming, and the dynamic segmentation of links within the GIS-T (Church, Chapter 20). Frequently, these algorithms became embedded first in the stand alone packages such as Ostresh's (1973) shortest path analysis routines and then in the fully developed GIS and GIS-T packages such as ARC/INFO and TransCAD, respectively. Equally important was the development of a systems approach to transportation planning (Stopher and Meyburg 1975; Wilson 1974) and the so-called four-step model of trip generation, trip distribution, modal split, and network assignment (see Miller and Storm, 1996; Nyerges 1995, for later GIS implementations). These early contributions provided the conceptual structure for the efficient implementation and use of GIS-T in the transportation planning process leading to the development of the earliest, first generation GIS-T implementations in the USA.

One of the forerunners of the original GIS-T applications was the Geodata Analysis and Display System (GADS) which was developed by the IBM Research Division in the mid 1970s to help solve problems such as police beat and school boundary design (Keen and Morton 1978: 147–60). While GADS was not typical of the later generation GIS-T packages it did incorporate such datasets as traffic patterns and transportation infrastructure; it was essentially a rudimentary GIS. Shortly after this, and totally independent of the American work, research in Sweden led to the establishment of a road data bank which was used for transportation planning (Bydler and Nilsson 1977). In the Swedish system many of the fundamental problems and challenges in the development of GIS-T, such as the node and link referencing system and the data content of the system, were addressed and resolved for the first time.

The above represents a brief history of some of the more important milestones which led to the development of GIS-T in the 1980s and 1990s. A more detailed account may be found in Simkowitz (1988).

## 3 THE STRUCTURE OF A GIS-T

### 3.1 The Relational Database Management Model

Today most GIS-T use a relational database model for the storage of attributes. Grayson (1991) discusses the use of an external relational database management system (RDBMS) which uses Structured Query Language (SQL) in conjunction with the ARC/INFO GIS. This approach is becoming less necessary as many GIS and GIS-T packages incorporate their own RDBMS. Other database models such as flat files have been used but they became less popular in the 1980s because of the greater conceptual and operational elegance of the relational database (Worboys, Chapter 26; Healey 1991; Waters 1992a, 1995). Maguire et al (1993) describe the RoMIS system developed by Oracle Corporation (now Oracle Highways from

Exor Corporation) as part of their highways application package and also the HERMIS system developed for the Ingres RDBMS. While these systems allow for the efficient storage of transportation network and attribute data they do not provide any geographical analysis or mapping capabilities. Such capabilities are provided by ESRI's ARCHIS (ARC/INFO Highways Information System) which also includes an interface to Oracle's RoMIS. As Maguire et al (1993) note, this system is now used by Lancashire and a number of other English County Councils for GIS-T purposes – mainly inventory management and mapping and some limited forms of statistical analysis. The GIS-T developed by London Transport (UK) also uses the INGRES database which in this case is linked to the Genasys Genamap GIS package (Adams and Corbley 1996).

## 3.2 Spatial databases

### 3.2.1 Spatial database structures

Bydler and Nilsson (1977) were among the first to address the complexity of developing a location referencing system for a GIS-T. This topic has been the subject of numerous articles in successive GIS-T Conferences of recent years (Goodwin et al 1995; Hickman 1995; Loukes and Walsh 1996; Moyer and Danielsen 1996; Okunieff et al 1995; Rowell 1996; Scarponcini 1995; Vonderohe at al 1995). Goodwin et al (1995) provide a summary of the more common systems. These include: link IDs using either a planar or non-planar graph representation; linear referencing systems where location is specified as distance from an established node or even a non-topologically significant point along the road (Goodwin et al 1995 note that the USA is working towards a national standard for a linear referencing system); coordinate systems (Scarponcini 1995 describes seven different coordinate systems and two different datums in use at the Minnesota DOT); street addresses (which frequently suffer from the problem of ambiguity because similar names are located in close proximity to one another); and finally, cross street matching which defines points as offsets from a given node and segments as the difference between two offsets. Bédard (Chapter 29) provides an overview of GIS database design principles.

That the problem of linear referencing and related systems is complex, user specific, and not easily resolved is articulated by Scarponcini (1995) who determined 45 different ways of segmenting a road after interviewing just 30 Minnesota DOT employees. The relevant characteristics included physical features, planning related attributes, geometric characteristics, traffic and related attributes, maintenance information, amongst many other attributes. Five levels of abstraction were determined: simple, in which the transverse (across the road) characteristics are homogeneous; directed, where a given attribute may differ on either side of the road; detached, where such things as frontage roads, collector/distributor roads, and access ramps and loops are all considered; laned, in which each lane has its own associated attributes; and finally, the component level which considers the cross sectional detail of the road such as the cut/fill slope, the sidewalk, curb, shoulder, and pavement components.

How the information is stored within the database is a challenging problem. Maguire et al (1993) note three possible solutions. The first involves introducing a new node wherever there is a change in the associated attribute data. This produces redundancy in the database tables holding the attribute data. The second method is to produce multiple layers with nodes wherever the attribute changes in each distinct layer. This produces multiple copies of the same arc leading to redundancy in the geographical databases. The final solution is known as dynamic segmentation and was pioneered by Fletcher (1987). Here only a single copy of the arcs is stored but the various sets of attribute data are 'mapped' onto the arcs whenever the data are displayed or employed in analytical operations using any one of the linear referencing systems described above.

### 3.2.2 Sources of spatial data

For GIS-T in North America spatial information on network structures may be obtained from census files such as TIGER (American) provided by the US Bureau of the Census or the AMF files (Canadian) provided by Statistics Canada. In the UK digital street centreline maps (an essential requirement for GIS-T) may be purchased from the Ordnance Survey (there are separate agencies for Great Britain and Northern Ireland) (Adams and Corbley 1996). Smith and Rhind (Chapter 47) provide an overview of spatial 'framework' data sources and their characteristics.

Road databases and other network files may be purchased from third party vendors who specialise in value-added data products (see Elshaw Thrall and

Thrall, Chapter 23). These firms may be in the business of simply supplying data or may be selling the data as part of a GIS package along with their GIS software. For example, MapInfo supplies Statistics Canada data along with their GIS package (Waters 1992b). Other agencies provide files of transportation related data, for example in the USA digital line graph (DLG) files are provided by US Geological Survey and the Department of Natural Resources in Canada provide similar road network information from the National Topographic Service. Again in the USA the Oak Ridge National Laboratory (ORNL) provides a 1: 2 000 000 scale highway network.

Spatial information can be digitised or scanned into the system. For GIS-T the scanned data usually have to be vectorised and hence scanning tends to be used for generalised planning work as opposed to detailed engineering applications. The global positioning system (GPS), based on the US Department of Defense's NAVSTAR satellite network, is increasingly used for data capture in GIS-T (Loukes and Walsh 1996; see also Lange and Gilbert, Chapter 33). In addition, this system is now being used with the automatic vehicle navigation system (AVNS) and location systems (AVLS) discussed below. Manual digitising and photogrammetric data input are also widely used in GIS-T (see Dowman, Chapter 31) and some firms have specialised in supplying digital road databases (Batty, Chapter 21; Waters 1993) to companies developing such industrial products as in-vehicle navigation systems (White 1991). A detailed description of the construction of a GIS-T and the process of integrating a variety of spatial datasets into a railroad information system centred on the Chicago region is provided by Laffey (1996).

## 4 ESSENTIAL OPERATIONS AND CAPABILITIES FOR A GIS-T

This section briefly overviews the most important capabilities of a GIS-T. A complete and comprehensive survey may be found in the excellent paper by Nyerges (1989).

### 4.1 Examples of generic GIS operations applied to GIS-T

Many of the operations commonly found in commercial GIS-T packages or systems being run by municipal governments or private firms (e.g. trucking companies) would incorporate the standard capabilities to be found in any GIS. These operations include data editing, display, and spatial and conditional search functions.

One standard editing feature that is especially useful in GIS-T is the ability to manipulate existing link attributes to produce entirely new attributes which have applications in transportation planning. Thus it should be possible to divide the arc length by the speed limit in order to estimate travel time (Rowell 1996). The ability to edit data spatially is essential. For example, knowing the number of individuals with particular socioeconomic characteristics who live within walking distance of a light rail transit station would help the transportation planner to estimate potential ridership. Display capabilities should allow for the import of raster images as background information for the vector transportation database, thus allowing users to orientate themselves to the real world. In addition, display options normally allow for the plotting of a variety of layers such as: administrative boundaries; interchanges; highways; population centres; intersections; streets; census districts; community boundaries and the boundaries of other districts such as schools, police zones, fire response districts; and important public facilities such as hospitals, nursing homes, point locations for hazardous goods, police stations, and fire stations.

Buffering capabilities are also a commonplace feature in generic GIS but they are particularly important in GIS-T for determining the accessibility of population groups close to transportation routes and services and for determining the environmental and noise impacts of these facilities (Love 1984). It is also important to be able to combine spatial searches and conditional queries within a GIS-T. For example, all narrow roads within 20 miles of a chosen feature should be easily obtainable. GIS-T applications often require extensive statistical analyses and thus there should be an interface which allows for efficient information export/import operations (Densham 1996).

Address geocoding is another critical feature for many GIS-T applications (Arthur and Waters 1995). Finally, the GIS-T should have report generating capabilities. These are important for accident analysis and road maintenance and this type of information has been obtainable from GIS-T systems since the earliest days (Bydler and Nilsson 1977; see also Cova, Chapter 60).

## 4.2 Working with matrices in GIS-T

Generic GIS packages usually store attribute data in the tabular form associated with traditional spreadsheet and database technology (Waters 1995). In such tables the row is often a geographical place such as a city or county and the columns represent attributes of that place such as the population and various socioeconomic characteristics. This is commonly known as the data view.

In a GIS-T an equally useful form of storage is the matrix in which both rows and columns represent the same set of geographical features, either points such as cities or areas such as traffic analysis zones (TAZs; Nyerges 1995). The rows are usually regarded as the origins and the columns the destinations. Thus each element of the matrix can store such information as traffic or commodity flows, travel time or distance measures, and migration patterns. This is known as the matrix view.

Because such matrices are the basis of many forms of analysis in transportation research (see, for example, Taaffe et al 1996) the GIS-T should be able to create, modify, and edit such matrices. Traditionally, these matrices are square but some GIS-T packages such as TransCAD (see below) allow the user to select sets of columns which may not be identical to the rows, and thus rectangular matrices are also possible.

### 4.2.1 Matrix display, sorting, and editing procedures

Any powerful GIS-T package should be able to display the marginal totals of a given matrix. If we suppose that the matrix represented the shortest paths between a set of TAZs, then the marginals would indicate the sum of the shortest paths, and this is used as a measure of zonal or network accessibility. Other useful measures include the highest, lowest, and average values for each row and column. One form of display that is common in transportation research is a map of desire lines (also known as a 'spider diagram') portraying the flows from one zone to all others. This is also used in location–allocation modelling (see below) to show the allocation of users to a facility. The ability to create such maps directly from the matrix view is a useful feature in any GIS-T. It should also be possible to sort the matrix on the basis of these marginal values or on the basis of the row and column labels. The GIS-T user should be able to edit cells, rows, columns, ranges of cells, or indeed the entire matrix in a single operation. The user should be able to perform the full range of mathematical operations on one or more cells in the matrix or to apply a formula to the selected cells. It is helpful if the GIS-T package can switch automatically between the data view and the matrix view, importing and exporting the data in either form. Finally, matrix copying, transposing, merging, and combining procedures are all useful to transportation analysts.

## 4.3 Modelling procedures

### 4.3.1 Shortest path analysis (SPA)

SPA is an essential precursor to many GIS-T operations. It is critical for route location models for determining the minimum environmental cost route (MERC: Lee and Tomlin 1997; and see Eastman, Chapter 35), for determining allocations in a location–allocation model, for trip assignment in transportation planning models (Nyerges 1995), and for automatic vehicle dispatch systems (AVDS, as discussed in section 7 below). Densham (1996) discusses the importance of SPA routines within his visual interactive location system which is part of an interface with the TransCAD GIS-T. With the advent of massive municipal and regional road databases, a major concern in recent years has been the size of problems which can be handled by existing algorithms and the solution speed. Zhan's (1996) work on this topic, in which he explores the use of fast shortest path algorithms on extensive road networks, is thus a welcome addition to the literature.

Shortest path algorithms in a GIS-T should be highly flexible in order to handle the many subtleties of the real world. It should be possible to solve the problem for one origin and one destination or for many origins and many destinations. The GIS-T should be able to store a variety of cost and other variables for each link in the network. Shortest paths in terms of time, distance, and cost may all be relevant (for example, tolls are becoming an increasingly important consideration in an era of transportation privatisation and the so-called 'PPP approach' of public-private partnerships). The number of lanes, their height and width, and restrictions such as those on hazardous materials should all be incorporated into the calculations. The more sophisticated GIS packages (e.g. ARC/INFO and TransCAD) allow impedance functions to be specified for turns of various types, traffic lights, on-off ramps, and other traffic controls and management devices. Algorithms for handling some of these features of the real world were originally developed in the 1960s (Kirby and Potts 1969), although recently much more comprehensive procedures have been developed (Ziliaskopoulos and Mahmassani 1996) which are likely to be quickly incorporated into standard GIS-T packages. Behavioural work on specifying relevant attributes for route choice is reviewed by Bovy and Stern (1990).

#### 4.3.2 Vehicle routing (VRo)

Vehicle routing problems include the development of routes or tours for deliveries and/or pickups from one or more depots (warehouses) at one or more stops (delivery or pick-up points). Such problems become more complex when there are time constraints at either the depots or the stops or both and when service times are variable. In some problems vehicle capacity is a serious constraint (e.g. delivering gasoline/petrol to a filling station) whereas in other applications this is not usually the case (e.g. delivering a pizza).

Packages such as TransCAD can handle all of the above variations but few packages, TransCAD included, can handle all of the complexities that often occur in the real world – such as mixed fleets (Wirasinghe and Waters 1983), mixed products, and open ended tours. In these cases three solutions are available: users can interface their own customised software with the GIS-T; a third party may provide software which can be interfaced with the GIS-T; or users can contact the GIS-T vendor for a customised solution.

#### 4.3.3 Arc routing (AR)

In arc routing problems the GIS-T user is attempting to find routes which will allow for an optimal (or at least an efficient) transversal of a set of arcs in the transportation network. Applications include bus service and any residential delivery, pick-up, or monitoring systems such as mail delivery, solid waste collection, or meter reading, respectively. One of the aims of such algorithms is to minimise the amount of 'deadheading' (a term most commonly used by bus companies) which is the distance from the point at which service is completed back to the bus depot, mail sorting plant, or other base facility (Waters et al 1986). Real world variations which a GIS-T should be able to handle include situations: where certain links may require no service because they perhaps lack houses; where service is required on only one side of a street; and where multiple passes may be required by street cleaning or snow ploughing vehicles. As with VRo problems there may be peculiar constraints such as time of day restrictions which may require customised solutions.

#### 4.3.4 Network flow models (NFM)

Three types of NFM are commonly solved using GIS-T packages: the assignment problem which seeks an optimal matching, on a one-to-one basis, of demand and supply points within the network; the so-called 'transportation problem' (Church, Chapter 20) which also seeks to satisfy a set of demand points from a set of supply points, but in which one supply point can service many demand points or alternatively one demand point can receive from many supply points; and the minimum-cost flow problem where not only link costs are considered but also link capacities and constraints, such as tunnel heights and bridge widths.

#### 4.3.5 Partitioning, clustering, and regionalisation

A common GIS-T application is the need to create regions such as sales territories or political districts (Horn, Chapter 67) within a database. In such cases a regional partition of the areal database is required. In the former case it may then be necessary to solve network routing problems in order to provide the sales personnel with catchments or tours (see Birkin et al, Chapter 51). In public sector applications such algorithms may be used for the design of balanced police beats and workloads. Usually the objective is to design contiguous and compact regions with equal workloads.

Clustering procedures can be used to produce regions within point, line, or area layers and are especially useful in regionalising networks. Waters (1973) showed long ago that standard clustering algorithms could generate effective regionalisations in networks which were treated as planar graphs, but were less effective in the more realistic non-planar formulation now being touted as the paradigm of the future.

#### 4.3.6 Location–allocation modelling

Location–allocation models seek to determine optimal locations for private and public sector facilities such as warehouses, factories, retail stores, ambulance depots, police stations, and fire stations, as well as optimal allocations of 'customers' to these facilities. These models have been an important topic in geography and operations research since the seminal work of Cooper (1963) and Hakimi (1964) in the 1960s. Stand-alone computer programs for location–allocation have been widely available since the early 1970s (Rushton et al 1973). A recent survey is provided by Dresner (1995). At present these procedures are routinely incorporated into GIS-T. Church (Chapter 20), Church and Sorensen (1996), and Densham (1996) provide detailed and up-to-date discussions of location–allocation modelling within a GIS context. Many of the most important breakthroughs in the location–allocation literature have been presented at the so-called ISOLDE (International Symposium On Locational DEcisions) conferences which began in Banff, Alberta, Canada, in 1978 and have been held around the world since then. The proceedings for these conferences are somewhat 'fugitive', although the more significant papers are usually published in special issues of operations research journals (see, for example, the *European Journal of Operational Research*, 1983, Vol. 12(1)) and more recently in the journal *Location Science*.

Packages such as TransCAD allow for a variety of goals to be optimised in facility location problems including: minimising the average cost of service (often referred to as the *p*-median problem); minimising the maximum cost of service (the *p*-centre problem); maximising the lowest cost of service (for noxious facilities); and maximising profit (Caliper Corporation 1996a: 91). Most applications have involved situations where both customers and facilities are point entities within the GIS, but Miller (1996) has extended the model to include all nine point/line/area customer-facility combinations within a GIS framework.

### 4.3.7 Spatial interaction and gravity models

These have been a mainstay of transportation planning since the 1950s (Taylor 1975). The gravity model is still used despite the limitations noted by Wilson (1974), although newer forms of spatial interaction models such as the entropy maximising model popularised by Wilson have largely replaced the more simplistic gravity model. GIS-T packages are now incorporating these procedures as standard operations. Spatial interaction models are increasingly being used as the basis for non-emergency applications of location–allocation models (Birkin et al, Chapter 51; Oppong 1992).

## 4.4 The urban transportation model system (UTMS)

The four-step UTMS of trip generation and trip attraction (how many trips?), trip distribution (where do they go?), modal split (by what travel mode do they move?), and traffic or network assignment (which route do they take?) is almost universally used in transportation planning (Nyerges 1995; Pas 1995; Taaffe et al 1996) and a GIS-T package should include procedures for facilitating this process.

### 4.4.1 Trip generation–trip attraction

The aim of trip generation models is to predict the number of trips produced by each origin zone or region. This task can be handled in a variety of different ways. Some of the more important choices include: modelling methods; the unit of analysis; the trip purpose; and the choice of explanatory variables (Caliper Corporation 1996b). Modelling methods include: cross classification procedures where the population is separated into homogeneous groups and trip production rates are empirically estimated for each group; regression models where the dependent variable is the trip production rate and the independent variables are personal, household, and zonal characteristics; and discrete choice models, such as the binary logit, which are used to estimate the probability of making a trip.

The GIS-T analyst has to make choices concerning the units of analysis: specifically, whether vehicle or person trips are being modelled (the latter is usually favoured as being a more sensitive form of analysis) and whether to work at the household or individual level. Trip purpose choices concern the type of trip being modelled. Usually, in municipal applications, the principal focus is the journey-to-work trip since this places most demand and stress on the transportation system, although in regional applications it may well be recreational trips especially in areas of high tourist demand (e.g. the English Lake District and the Canadian Rockies). Independent variables influencing trip-making behaviour include: personal characteristics (gender, age, income, occupation), household characteristics (family size, car ownership, number and age of children, household income), zonal characteristics (land use, residential density, accessibility, location), and network characteristics (level of service) (Caliper Corporation 1996b; Wilson et al 1977).

Trip attraction procedures determine how many trips are 'generated' by each destination zone. The same procedures may be used to provide estimates for destination zones as are used for origin zones, but generally regression models are the preferred method in the former instance. The explanatory variables in such models usually include the amount of land given over to office and retail uses or the employment in each zone. The spatial and temporal transferability of such models is an important issue, particularly where GIS-T packages invoke assumptions about likely values of model parameters.

If trip generation and trip attraction procedures do not agree in their estimates then trip balancing equations can be used to force them into agreement either by holding one constant and adjusting the other or by making both conform to a user specified total.

#### 4.4.2 Trip distribution

Trip distribution models are used to predict the flow values in the transportation zone, origin–destination matrix. This can be achieved either by scaling a production–attraction matrix of existing flows using the forecast predictions for origin and destination zones (using the so-called 'growth factor method') or through the use of modern derivations of the gravity model which employ entropy maximising procedures (Wilson 1974). In both approaches the model may be either singly constrained at the origin or destination ends or doubly constrained at both ends, while the inclusion of growth factor procedures is known as fratar balancing (Caliper Corporation 1996b). The growth factor models, while being easier to estimate, cannot model impedance to travel using distance, cost, or time values and thus – unlike the entropy maximising models – they cannot take into account ongoing improvements to the transportation network.

#### 4.4.3 Modal split analysis

Modal choice can be determined either at the zonal (aggregate) level or at the individual (disaggregate) level. Estimation procedures may involve either revealed or stated preferences (Louviere 1988) and these can be modelled using any of the regression, cross-classification, or discrete choice procedures mentioned above. Regression procedures have proved less popular owing to the violation of a number of the assumptions of the regression model. The most popular choices have been multinomial, binary, and nested logit models. Ben Akiva and Lerman (1985) and Horowitz (1995) provide comprehensive accounts of these procedures. This is a rapidly changing field in which new, more efficient algorithms are being developed all the time. Initially these will probably be available as 'add-ons' to GIS-T packages but will eventually become incorporated into the standard packages.

#### 4.4.4 Traffic assignment

A sophisticated GIS-T should allow for a variety of traffic assignment strategies ranging from simple tractable techniques to the more complex which are computationally intensive, especially for large municipal networks. Ranging from the least to the most complex and realistic, TransCAD employs the following strategies (Caliper Corporation 1996b: 170–2): all-or-nothing assignment in which all traffic flow is assigned to the shortest path; incremental assignment in which travel times are recalculated after all-or-nothing incremental assignments; capacity constraint assignment, similar to the previous method except that travel times are a function of capacity; user equilibrium assignment which is optimal in the sense that no traveller can improve his or her travel time – this can be formulated as a mathematical programming exercise but assumes perfect information; stochastic user equilibrium which avoids the perfect information assumption of the previous approach; and, finally, a system optimum assignment which minimises total travel time on the network.

Although this discussion implies that the four-step model is strictly sequential, in practice the process is usually iterative: in particular, the output from the traffic assignment may be used as input to the earlier parts of the model (Nyerges 1995; see also Miller and Storm 1996 for a discussion of the limitations of such a sequential approach). In addition, the GIS-T should be used to evaluate the efficiency and effectiveness of the forecast in terms of system parameters such as performance, safety, level of service, environmental concerns, and financial considerations.

## 5 SOFTWARE FOR GIS-T

### 5.1 Generic GIS packages

There are many generic or multipurpose GIS packages which can be used for GIS-T. Generic GIS range in price from the extremely low cost (even free) packages to those costing tens of thousands of pounds. Idrisi (see Eastman, Chapter 35) is a low cost, raster-orientated package with some vector analysis capabilities suitable for GIS-T applications, including the ability to calculate minimum cost paths (Eastman 1995). ESRI has been gradually increasing the functionality of its low-end ArcView software as it has released newer versions (see Maguire, Chapter 25). ArcView Version 3.0 introduced an extension called Network Analyst which has a variety of automated routing functions (see Plate 49). In addition, the Avenue scripting language allows the creation of new, customised GIS-T functionality (ESRI 1996).

Among the high-end commercial packages are Intergraph's MicroStation (and related software) and ESRI's ARC/INFO system, both of which have full network analysis functionality (Rodcay 1995). ESRI's annual ARC/INFO Map Books contain numerous transportation related examples of the use of ARC/INFO for GIS-T applications – past editions have included maps of 'pavement distress' indices, rail catchment areas, traffic volumes, air quality, travel mode assignments, and traffic noise distributions (ESRI 1990: 25, 42, 69, 70, 76, and 77 respectively).

### 5.2 Specialised GIS-T packages

Probably the best known of the specialised GIS-T software packages is Caliper Corporation's TransCAD, a superset of their GISPlus system. Version 3.0 of this program was released in 1995 under the Microsoft Windows operating system (see Plate 50). It includes all the standard GIS-T operations discussed above. Caliper also produces the inexpensive Maptitude desktop GIS package which has extensive GIS-T functionality. A number of other companies throughout the world have also developed specialised transportation packages with mapping and GIS capabilities.

## 6 GIS-T IN GOVERNMENT TRANSPORT DEPARTMENTS

### 6.1 GIS-T for municipalities

Nyerges and Dueker (1988) have suggested that municipal transportation applications fall into three levels. The main applications for Level I (map scales around 1:100 000) are transportation and urban planning, marketing, and facility siting. At Level II (1:100 000–1:1 000) the applications include routing and dispatching operations, address matching, and neighbourhood planning among others and for Level III (1:1 000) the applications are mainly facilities management, tax mapping, and engineering design.

### 6.2 GIS-T for regional governments and their transport departments

Again, following Nyerges and Dueker (1988), a similar breakdown into three levels can be shown for GIS-T applications for regional governments. The Level I applications are region wide, Level II and III applications involve smaller portions of the region and require higher levels of accuracy, respectively. Again there is an increase of approximately an order of magnitude in the scale, data volumes, and cost when moving from Level I to Level III but now the scales of analysis are 1:1 000 000, 1:100 000, and 1:10 000, respectively. The main applications are: network analysis and regional maps for Level I; regional planning, pavement management systems, traffic safety, and highway inventory for Level II; and project planning and engineering design for Level III.

### 6.3 GIS-T for national governments and their transport departments

Simkowitz (1988) discusses various GIS-T demonstration projects sponsored by the US Federal Highway Administration's (FHWA) Office of Planning. The first of these projects used the TIGER/Line file for Boone County, Missouri, USA. Other data sources used in the project included: census data, accident records, sign inventory, traffic signal inventory, and traffic counts. The software package used was TransCAD. The second project involved the city of Johnson, Tennessee, USA and the University of Tennessee Department of Civil Engineering. It concerned an investigation of the integration of GIS and traffic demand models. The FHWA has supported the development of the Geographic Roadway Information Display System (GRIDS). This displays data about the US interstate highway system and uses the ORNL 1:2 000 000 scale National Highway Network. The FHWA has also developed a highway traffic forecasting system. For nodes the network uses ten geographical regions developed by the Bureau of Economic Analysis. It is designed as a decision support system for policy issues related to the highway network and can predict the changes in the distribution of traffic

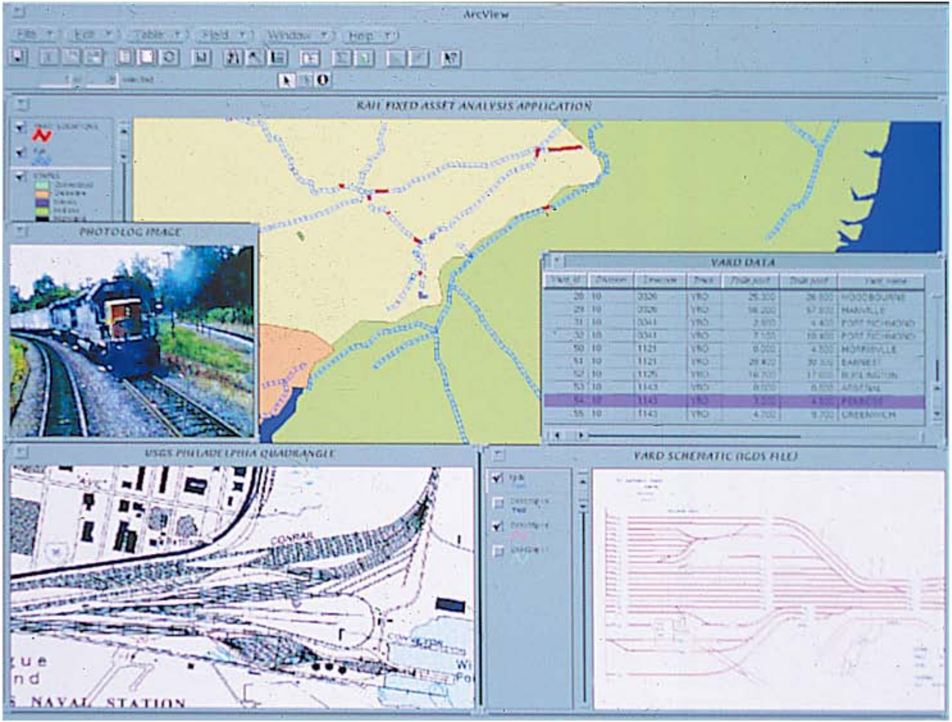
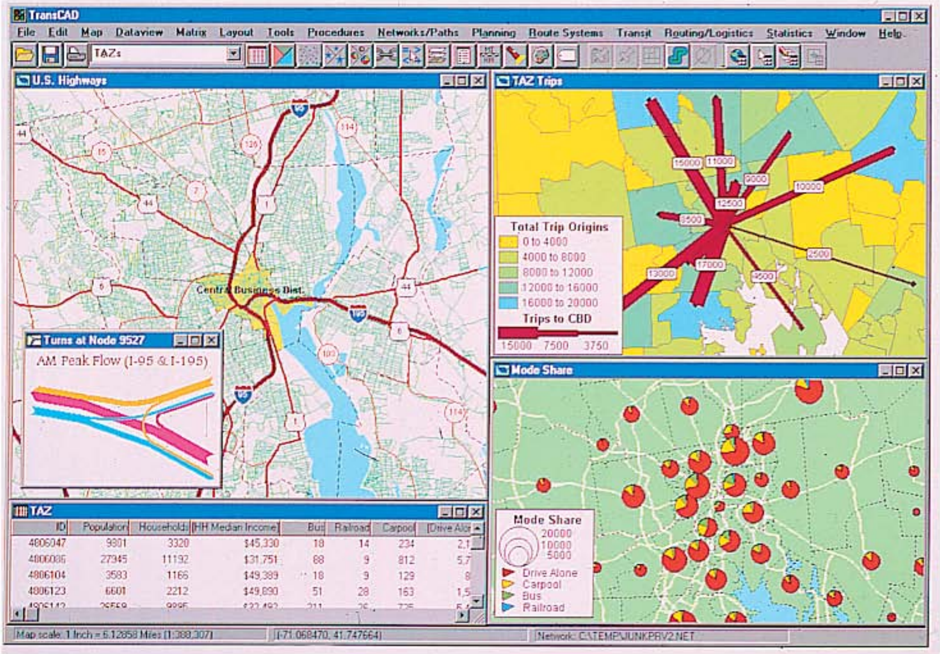


**Plate 49**
A screen shot from ArcView GIS 3.0 showing dynamic segmentation of railroads (reproduced by permission of ESRI).



| ID | Population | Households | [HH Median Income] | Bus | Railroad | Carpool | [Drive Alo |
|---|---|---|---|---|---|---|---|
| 4806047 | 9801 | 3320 | $45,330 | 18 | 14 | 234 | 2,1 |
| 4806085 | 27345 | 11192 | $31,751 | 88 | 9 | 812 | 5,7 |
| 4806104 | 3583 | 1166 | $49,389 | 18 | 9 | 129 | 8 |
| 4806123 | 6601 | 2212 | $49,890 | 51 | 28 | 163 | 1,5 |

Map scale: 1 Inch = 6.12858 Miles (1:388,307)

(-71.068470, 41.747664)

Network: C:\TEMP\JUNKPBV2.NET

**Plate 50**
A screen shot from Caliper Corporation's TransCAD package showing the rich functionality of a fully-fledged GIS-T program (reproduced by permission of Caliper Corporation).

among regions and vehicle types which would result, for example, from a change in regulations governing truck sizes and weights.

## 6.4 Level of adoption of GIS-T by government agencies

Lane and Hartgen (1989) have discussed the degree to which GIS has penetrated State transport departments in the USA. This work was based on a questionnaire sent to all State DOTs and discusses the adoption life-cycle process in the framework of a standard diffusion model. GIS and other similar software such as Capital Project, Road Management, and computer-aided design and drafting (CADD) systems were all surveyed. By 1989, 57 per cent of the State DOTs were using GIS and all of them were using CADD systems. Lane and Hartgen discuss the importance of different variables on the selection of an information system; their analysis demonstrates that increased productivity is the most important variable. On average, where GIS was adopted it was shown to be a recent phenomenon – less than three years old in 1989. Internal evaluation, information from other DOTs, and departmental ‘champions’ were shown to be the three critical variables influencing system choice. The slow diffusion of GIS-T might possibly be explained by the complexity of these systems and the misconstrued perception that they are not qualitatively different from the older CADD packages.

By 1992 Warnecke et al (1992) were able to conclude that GIS-T was one of the most common applications of GIS in US State government departments. They found that almost all state transportation and highway departments were using computer aided design and computer aided mapping and were quickly adding GIS analytical capabilities. Besides highway mapping, they found that at least seven other applications were being used in at least five states. These included: accident location information, bridge management, network management, pavement management, pipelines information, general planning, and traffic volume management. In addition, a few of the states were using GIS for applications such as nautical charts, school bus routing, hazardous materials routing, railroads, and highway landscaping. Although the list may appear impressive, given the fact that these and many, many more applications had appeared in the research literature years earlier it is surprising that the list was not still longer.

## 6.5 Case studies of GIS-T in government

Simkowitz (1988) provides a number of case studies of US State DOTs and how they have deployed GIS-T. Alaska, for example, has developed a Highway Analysis System (HAS). This is a mainframe database of highway related information and includes various programs for the analysis and processing of data and for report generation. Data stored in HAS include highway inventory, traffic, accidents, project history, a highway performance monitoring system, pavement conditions, bridges, signs, permit locations, rights-of-way, and railroad crossings. Idaho’s Statewide Geographic Information Advisory Committee includes representatives from the DOT and has decided to use the US Geological Survey’s digital line graph files. The Texas State Department of Highways and Public Transportation is using GPS technology to determine its primary geodetic control. Moyer and Danielson (1996) discuss similar work in the State of Wisconsin. GPS is also being used in the State DOTs of Virginia and Tennessee. The Wisconsin, Iowa, and Connecticut DOTs are using photolog technology to record images of their highway systems at approximately every 50 feet (15 m). In Wisconsin this information has been integrated into a GIS and can be readily retrieved by pointing at the appropriate location when displayed by the GIS. In Canada the province of Alberta’s Department of Transportation and Utilities has developed a GIS-T for network flow simulation, highway planning, and pavement management and evaluation. This has been developed from an earlier computerised highway network system which was used for travel demand forecasting. The Alberta GIS-T is now able to access the Alberta Government’s oil and gas well files, the Land Status Automated System, and other data banks.

For the UK, Lithgow (1995) provides a detailed review of the use of GIS by Lothian’s Transportation Department in Edinburgh, Scotland. Owing to the perceived high risk of implementing a fully-fledged GIS-T, Lithgow notes that two pilot projects were selected. One was the 1991 population census data for census analysis and the other was a road accident analysis system. Both pilots were highly successful and have continued as full working systems. They also led to the development of a comprehensive road management system for monitoring day-to-day operations which was developed around an Oracle database and the Smallworld GIS.

## 7 INTELLIGENT TRANSPORTATION SYSTEMS AND GIS-T

In this section a number of special topics in GIS-T will be considered, including intelligent vehicle highway systems (IVHS) and automatic vehicle location systems (AVLS), together with their more specialised sub-categories of AVNS and AVDS/AVMS. Increasingly, all these topics are being gathered together under the general rubric of intelligent transportation systems (ITS) (see the editorial in *GPS World* by Gibbons, 1996; also Blanchard 1996). A detailed discussion of the general topic may be found at NETrans Inc.'s web site which may be reached at the following URL: *http://www.its.netrans.net/index.html*.

### 7.1 IVHS

This is a generic term for a number of GIS-T related applications (Johns 1990) including: automatic vehicle identification and billing (AVI); weighing in motion; collision warning and guidance; driver information and route guidance through advanced travel orientation systems (ATOS); advanced trip planning systems (ATPS); advanced travel conditions systems (ATCS); advanced traffic signal control and operation; automatic incident detection; and automatic vehicle spacing among a number of others. Goodwin (1994) notes that ORNL in the USA is developing an information infrastructure to support data sharing across all IVHS applications and uses (a detailed discussion of such an infrastructure for ITS held at the John F Kennedy School of Government, Harvard, may be found at the following URL: *http://ksgwww.harvard.edu/iip/itstran.html)*.

### 7.2 AVLS

These systems are designed to locate vehicles at all times. Klesh (1989) noted that there are as many categories of AVLS as there are modes of travel. Concentrating on road vehicle applications AVLS were divided into two distinct categories: dispatch and stand-alone systems. The latter, often known as AVNS, are in-vehicle systems which are used to determine the shortest route between the vehicle's present location and an intended destination, and have been discussed in detail by Jeffrey (1987) and White (1991). Klesh notes that the dispatch category (usually given the acronym AVDS, but also known as automatic vehicle monitoring systems, AVMS) is broader in terms of the variety of users it supports and includes applications in the private sector (e.g. applications for taxi cab companies, delivery and collection, services, and security agencies) and in the public sector (e.g. police, fire department, ambulance, garbage collection, and transit services). AVDS may employ GPS, a beacon, or some other technology to fix the vehicle's position, but in addition this information is then relayed to a central site from which additional resources may be dispatched if and when necessary.

Holland (1990) provides a detailed review of the use of AVLS technology in many urban transit systems and notes how it can be integrated with scheduling programs developed for transit operations. Even by the start of the 1980s nearly 40 per cent of all US and Canadian transit operations used such computer aided scheduling packages (Schmidt and Knight 1981; Wren 1987). Holland determined that in Hull, Quebec, Canada, such an AVLS had resulted in a reduction of the number of active but unused buses from 22 to 2 out of a fleet of 190 producing approximately 10 per cent savings in the transit system's operating budget. AVLS also improves schedule adherence providing for more efficient service to the public which in turn translates into greater ridership through reduced waiting times.

### 7.3 Economic impact of ITS

In an overview of the economic impact of ITS on road transportation, Blanchard (1996) notes significant developments in Japan, Europe (Camus and Fortin 1995; European Conference of Ministers of Transport 1995), and the US (Catling 1994; Transportation Research Board 1995a). In the case of Canada, he estimates the costs and benefits of ITS to road transportation under three main categories and eight subsidiary systems (see Table 1): inter-urban freight (electronic clearance, roadside safety inspection); rural transportation (traveller information, electronic transactions, rural safety); and urban transportation (traffic management, information services, demand management). The most impressive gains come from improved urban traffic management which shows an almost 7:1 benefit–cost ratio with huge gains in time savings and substantial benefits in reduced emissions of volatile organic compounds and improved safety (see Obermeyer, Chapter 42, for an overview of benefit–cost analysis). It is also worth noting that Canada is generally considered to be behind Japan, Europe, and the USA in such economic impact analysis (Blanchard 1996).

**Table 1 Benefit–cost analysis – intelligent transportation systems annualised costs and annual benefits Canada-wide implementation, 2005 (in CAN$ millions of 1996).**

| | *Inter-urban freight* | | *Rural transportation* | | | *Urban transportation* | | |
|---|---|---|---|---|---|---|---|---|
| *Costs and benefits* | *Electronic clearance* | *Roadside safety inspection* | *Traveller information* | *Electronic transactions* | *Rural safety* | *Traffic management* | *Information services* | *Demand management* |
| *Infrastructure* | | | | | | | | |
| Capital | $3.3 | $1.6 | $22.3 | $7.7 | $45.5 | $212.2 | $51.6 | $38.4 |
| Operations and maintenance | $2.0 | $1.3 | $13.7 | $5.8 | $10.4 | $147.4 | $58.3 | $51.3 |
| Sub-total | $5.3 | $2.9 | $36.0 | $13.5 | $55.9 | $359.6 | $109.9 | $89.7 |
| *Vehicle* | | | | | | | | |
| Capital | N/A | $123.9 | N/A | $1.7 | N/A | N/A | $369.6 | $23.1 |
| Operations and maintenance | $4.3 | $7.6 | N/A | N/A | N/A | N/A | N/A | $0.0 |
| Sub-total | $4.3 | $131.5 | N/A | $1.7 | N/A | N/A | $369.6 | $23.1 |
| **Total costs** | $9.6 | $134.4 | $36.0 | $15.2 | $55.9 | $359.6 | $479.5 | $112.8 |
| *Benefits* | | | | | | | | |
| Time savings | $13.1 | $36.3 | $58.5 | $3.1 | $3.8 | $2050.0 | $630.0 | $39.6 |
| Volatile organic compounds | $0.1 | $5.7 | $5.8 | $0.6 | $0.8 | $63.0 | $13.0 | $13.8 |
| Safety | N/A | $53.0 | $1.0 | N/A | $58.3 | $81.0 | $54.0 | $14.4 |
| Other | N/A | $7.7 | $26.0 | $15.8 | $0.4 | $128.0 | $27.0 | $156.0 |
| **Total benefits** | $13.2 | $102.7 | $91.3 | $19.5 | $63.3 | $2322.0 | $724.0 | $223.8 |
| Benefit: cost ratio | 1.38 | 0.76 | 2.54 | 1.28 | 1.13 | 6.46 | 1.51 | 1.98 |

N/A = Not Available
*Source*: Transport Canada

# 8 FUTURE DEVELOPMENTS

## 8.1 Use of expert systems (ES)

In the near future GIS-T are likely to benefit from an infusion of techniques related to ES (Transportation Research Board 1995b). Heikkila et al (1990) suggest that ES can be used to determine which infrastructure improvements are appropriate in the light of changes (such as demographic changes) within the GIS-T. The GIS-T can then be used to evaluate the effects of the infrastructure change and this information can be entered into the ES. Taylor (1990) has developed design criteria for knowledge based route guidance advisors which take into account not only the characteristics of the system but also the characteristics of the users to whom the advice is targeted.

## 8.2 Integration with other GIS applications

A major development in the future for GIS-T will be their integration with other GIS applications. A common application of GIS in the past has been in the resource management and habitat analysis areas; however, wildlife habitat conservation is often in conflict with transportation infrastructure development. Alexander and Waters (1996) describe three complementary methodologies for resolving such conflicts, including traditional GIS analyses, knowledge elicitation from experts to develop expert systems to avoid conflicts between humans and animals, and preference analysis using paired comparison methodologies.

GIS-T will increasingly be used for analytical work within urban centres. Arthur and Waters

(1995, 1997) describe the analysis of traffic collision data in Calgary, Alberta, Canada (see Figure 1): having incorporated these data into a GIS-T they are able to show that speeding increases the likelihood of accidents, especially at intersections. This work supports the use of photo radar devices which are used by the police to reduce speeding at such locations, despite concerns over these surveillance technologies (Curry, Chapter 55; Lyon 1994; Lyon and Zureik 1996).

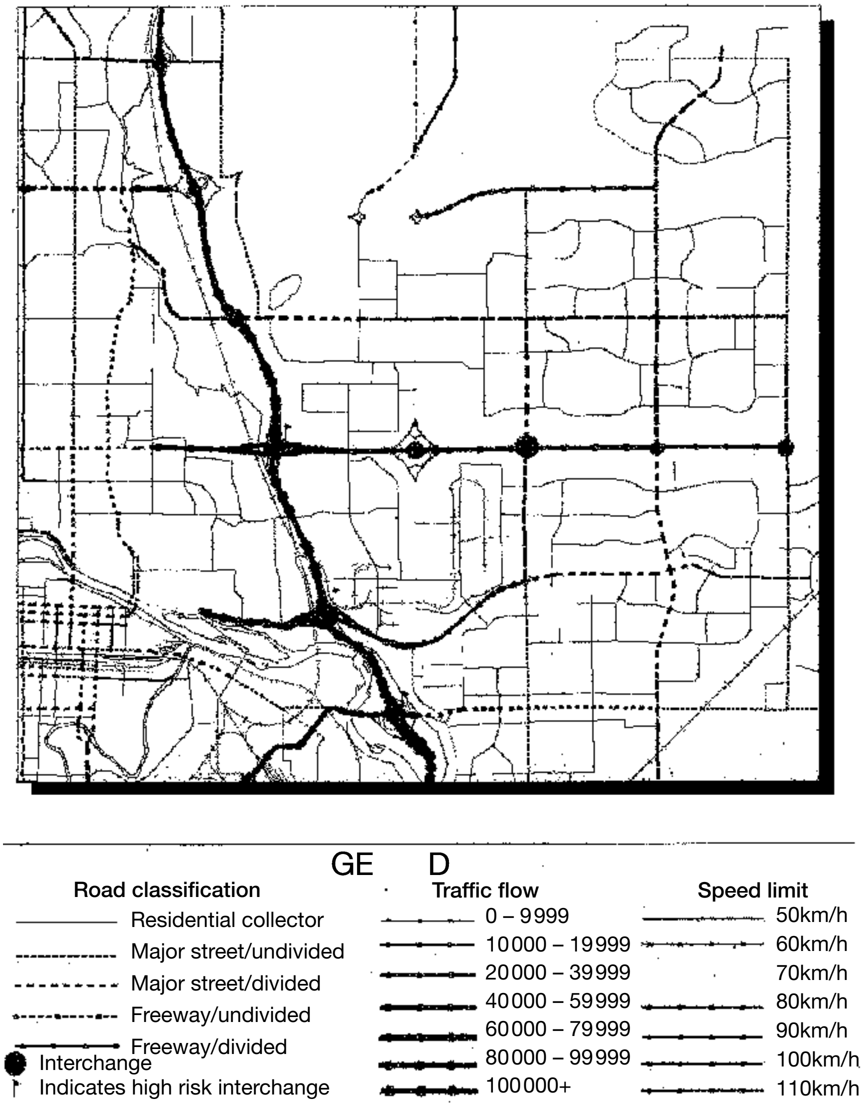


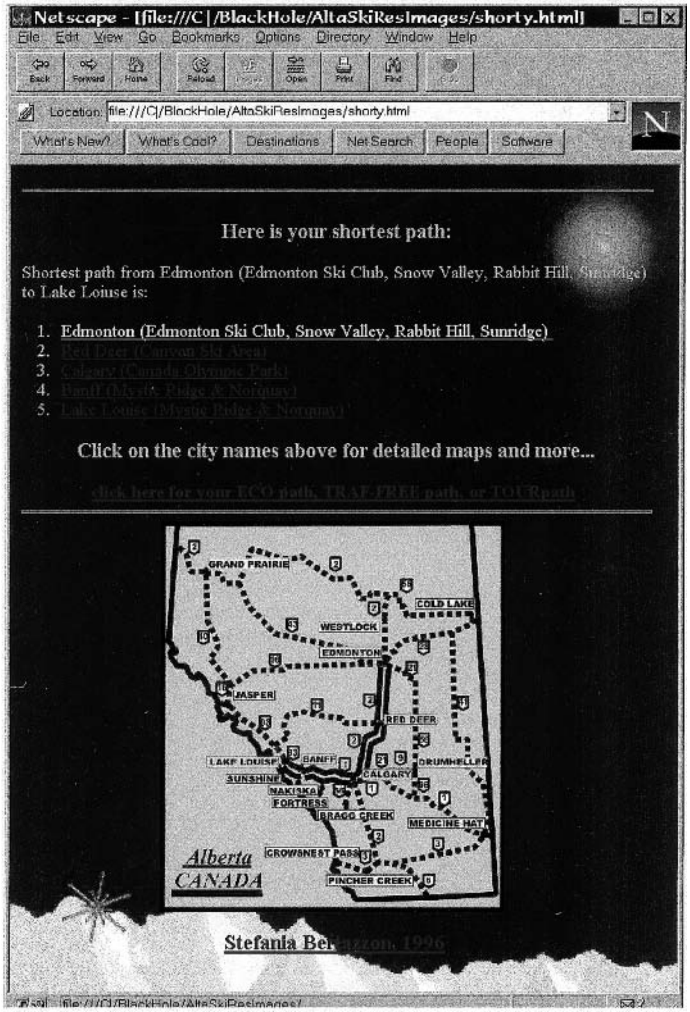
**Fig 1. The use of GIS-T to investigate the relationship between speeding and accidents in the City of Calgary, Alberta, Canada.**

*Source*: Arthur 1996.

## 8.3 The Internet and embeddable technology

In a recent cover story *Business Week* noted that for software 'the Web changes everything' (Cortese et al 1995: see also Batty, Chapter 21; Coleman, Chapter 22). Thus the future will be one in which data and maps and software are all available on the Internet for downloading or simply viewing (Elshaw Thrall and Thrall, Chapter 23; Maguire, Chapter 25). GIS will be redesigned into object-oriented applets (small applications) which will handle highly specific computing tasks but which can be combined to carry out more complex operations.

Many organisations are already making extensive use of the Internet and this is particularly true of municipal transportation departments which frequently make traffic service maps available over the Web. Good examples may be found at the CalTrans Web site (URL: *http://www.scubed.com/caltrans/*) with links to many other traffic maps. Bertazzon and Waters (1996) have described the use of a Web site for marketing ski resorts in southern Alberta. The Web site that they have built incorporates GIS functionality for determining shortest paths (see Figure 2) and provides route guidance and weather information on the Web in real time.



Here is your shortest path:

Shortest path from Edmonton (Edmonton Ski Club, Snow Valley, Rabbit Hill, Sunridge) to Lake Loiuse is:

1. Edmonton (Edmonton Ski Club, Snow Valley, Rabbit Hill, Sunridge)
2. Red Deer (Canyon Ski Area)
3. Calgary (Canada Olympic Park)
4. Banff (Mystic Ridge & Norquay)
5. Lake Louise (Mystic Ridge & Norquay)

Click on the city names above for detailed maps and more...

click here for your ECO path, TRAF-FREE path, or TOURpath

Stefania Bertazzon, 1996

**Fig 2. The Trip Planner: a new, Internet-based application for GIS-T.**
*Source*: Bertazzon and Waters 1996

### 8.4 Temporal GIS-T

The construction of temporal GIS databases is one of the ongoing challenges for the GIS community. Such formulations are particularly useful in the transportation sector. A series of recent papers (Clark et al 1996; Crawford-Tilley et al 1996; Masuoka et al 1996) discuss the design of a temporal GIS-T for the Baltimore–Washington region.

### 8.5 GIS-T and business geographics

Finally, there is likely to be a greater use of GIS-T within the business community for such applications as facility location and geodemographics and logistic applications. Reviews and case studies may be found in Birkin et al (Chapter 51), Bertazzon et al (1997); Birkin et al (1996); DeWitt and Ralston (1996); and Docherty et al (1997a, 1997b).

## 9 CONCLUSIONS

This chapter has provided a historical overview of the development of GIS-T together with a description of its main characteristics. Sources of data and software together with common applications of GIS-T in various levels of government have been described. A discussion of special topics within the broader field of GIS-T and a description of current and future research topics have concluded the account of this most exciting and useful field of GIS endeavour.

Although this chapter has shown that GIS-T has been part of the mainstream of GIS applications for a number of years it has yet to become part of the orthodoxy in transportation geography. Indeed, some of the most recent texts have completely ignored GIS-T (Hoyle and Knowles 1992; Simon 1996; Tolley and Turton 1995) while others, despite acknowledging the 'remarkable growth' and 'enormous promise' of GIS in transport geography, have made only token reference to this new technology (Taaffe et al 1996: 400). One exception has been the second edition of Hanson (1995) which devoted a whole new chapter to GIS-T (Nyerges 1995). In the future it is unlikely that any new transportation geography text will be able to ignore the overwhelming impact of GIS-T on the sub-discipline.

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