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Research Article

Using desktop GIS for the investigation of accessibility by public transport: an isochrone approach

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Abstract. The application of existing desktop geographical information systems (GIS) to the assessment of accessibility by public transport has been investigated. Two approaches to the measurement of accessibility—aggregate accessibility measures and the space-time geography framework—are described. It is suggested that isochrones (lines of equal travel time) are a natural way to combine these approaches in a GIS setting. A desktop GIS application has been developed which can automatically generate isochrones for travel by public transport. The application successfully copes with the complexity of the public transport of a large city (Glasgow), comprising bus, rail, and underground services. Journeys may include an initial walk to a public transport stop, several interchanges between services of the same or different modes, and a final walk. Options provide for plotting isochrones for journeys by bus only or train only; and for exact or approximate isochrones, the latter generated more quickly. The application is described in some detail, and assessed. Sample outputs are presented, including an example involving further processing of isochrones to produce a constrained accessibility map, which demonstrates the generality of this approach.

1. Introduction

Current desktop GIS is well-provided with standard tools for investigating transport problems which might be broadly termed 'network analysis'. Shortest path, travelling salesman and locational problems sensitive to the catchment area of planned facilities all fall under this general heading, but often assume travel by private transport over the road network. The work described in this paper extends the application of GIS in transport to accessibility via scheduled public transport.

The purpose of this work was threefold: first, to establish the capability of typical current desktop GIS in dealing with the public transport system of a large city; second, to examine the feasibility of producing isochrone maps for such a transport system using GIS; and third, to show that isochrone-based analysis has the potential

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to become a flexible and powerful tool in transport analysis more generally, and in particular, that it offers a simple way of combining different approaches to accessibility analysis. Glasgow in Scotland was chosen for the study because of the availability of digital data, and because the complexity of the transport network presented a realistic problem.

Some of the previous work on accessibility is briefly reviewed in the next section. We conclude that isochrone-based analysis may be a particularly useful approach in the GIS context, and the remainder of this paper describes a simple system which has been implemented to allow a user to generate isochrone outlines. This work was undertaken in a period of around three months, and in §3 the implications of this time restriction for data collection, data representation and overall design of the system are described. A detailed description of system implementation follows in §4, and in §5 some of the limitations of the system are considered along with suggestions for improvements or extensions. Sample output from the system is presented in §6. In that section we also revisit the contention that isochrones are a useful general tool in accessibility analysis, especially in their applicability to approaches based on space-time geography. The paper concludes with a discussion of the merits of the current approach and some comments on the usefulness of desktop GIS in this type of application.

2. Theoretical background

2.1. *Accessibility measures*

Accessibility is generally agreed to be hard to define but critical to any serious understanding of transport issues (Hanson 1986). A related concept is *mobility* which describes the ability of people to travel over distances. A simple approach to measuring mobility is to count numbers and lengths of journeys, and express results as an average distance per person per unit time. Mobility on this measure has increased consistently over time as technology has produced faster forms of transport (see for example table 1-1 in Hanson 1986, p. 8). However, it is clear that much of this increase in mobility arises from necessity—homes, places of employment, retail outlets and leisure facilities are more geographically dispersed. There is a suggestion in the literature that as mobility has increased travel times have remained more or less constant, and may even have risen somewhat (Tolley and Turton 1995).

The goal of any transport system is not mobility *per se*, but access to facilities. The demand for transport is a derived demand, arising out of travellers' needs for products and services. So, to evaluate a transport system we need some measure of its effectiveness in delivering people to the facilities they wish to use—an accessibility measure. Koenig (1980) refers to a definition proposed by Dalvi (1978), where accessibility 'denotes the ease with which any land-use activity can be reached from a particular location, using a particular transport system'. This definition makes it clear that accessibility refers to a given origin, a given transport system, and a given land-use activity. For example, the accessibility via public transport of employment opportunities to residents of a particular housing estate might be of interest. Koenig goes on to present the most general formulation for the accessibility A_i of a location i in the form:

$$A_i = \sum_j O_j f(C_{ij}) \tag{1}$$

where O_j is the set of opportunities (or facilities) available at location j, C_{ij} is the distance or time or cost of the journey from i to j, and $f(C_{ij})$ is some function of the cost. Usually f has the characteristic that as the cost increases, the value of $f(C_{ij})$ falls. This represents a weighting of the sum so that more distant opportunities rate lower in the accessibility measure. There is an extensive literature exploring the merits of variants of the function f. Exponential, Gaussian, and various other forms have been investigated (see for example Hansen 1959, Wachs and Kumagai 1973, Weibull 1976, Doling 1979, Frost and Spence 1995; Pirie 1979 reviews many of these). It is clear that different approaches will give different results. For example, Guy (1983) illustrates how the precise method used can lead to different conclusions and Al-Sahili and Aboul-Ella (1992) show how much simpler approaches can still be useful.

2.2. *Constrained accessibility: space-time geography*

Another approach to accessibility contends that any realistic assessment of the situation should take account of typical subjects' time-budgets. A location may afford access within one hour to a range of facilities, but if typical residents do not have schedules or *time-budgets* which give them two or more hours to spare to make the return journey to use those facilities then they have no effective access. This *space-time* approach to accessibility was pioneered by Hägerstrand and others at the University of Lund. Robertson (1981) and Forer and Kivell (1981) are good examples (see also Parkes and Thrift 1980 for an overview, and Huisman and Forer 1998 for a more recent perspective). The idea is illustrated in figure 1. The diagrams are two-dimensional with space represented as a single dimension only. For an individual resident at location A, leaving home at (say) 8.00am, the shaded area in figure 1 (*a*) indicates the range of accessible locations, when there is no constraint on the individual's movements other than the transport system. The slope of the lines diverging from A will vary with the speed at which the transport system allows movement through space. Now, if this individual must be at work at location B by 9.00am, then this constrains movement and effectively limits accessibility to the shaded area in figure 1 (*b*). The parallelogram is the intersection of all the points which can be reached from A starting at 8.00am, and all the points from which B can be reached by 9.00am. This shaded area is often referred to as a *space-time prism* since it actually exists in three dimensions—two of space and one of time. Figure 1 (*c*) shows the effect of a faster transport system, whereas 1 (*d*) shows the advantage of flexi-time arrangements. The space-time approach to accessibility is more satisfying intellectually than the earlier overall accessibility indices, although it does suffer from problems of application—specific individual cases must be considered, and it is difficult to summarise results. In practice both approaches are useful and complementary.

2.3. *Isochrones and accessibility analysis*

Isochrone accessibility analysis is based on a special case of equation (1) above, where f is a step function, with value 1 where the cost (here expressed in units of time) is less than or equal to some specified limit, t, and value 0 where the cost exceeds t. In other words only those opportunities reachable from i within time t are included in the accessibility calculation. In principle the set of all locations reachable from a given point p in the specified time t can be identified; if they are joined together on a map, the resulting line is an isochrone from p. There is a strong case to be made that an isochrone map can provide 'a more realistic measure of the

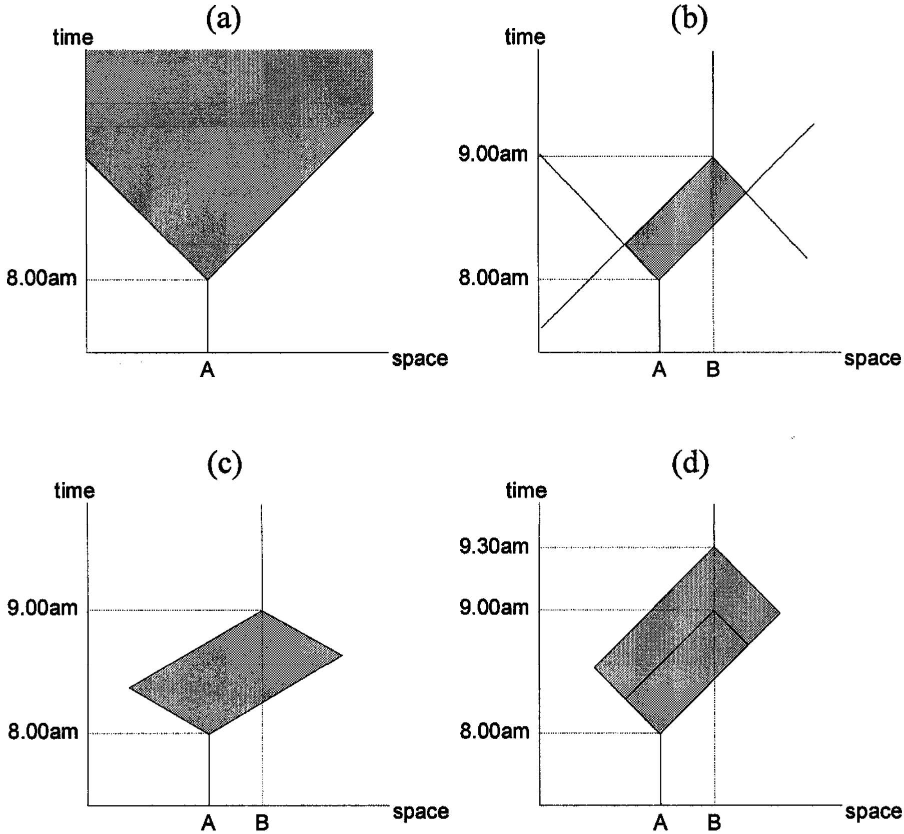

Figure 1. Space-time prisms showing travel with constraints.

way people perceive their opportunities: so many within such and such a journey time' (Doling 1979). The readiness with which an isochrone analysis of accessibility can be understood certainly ought to make it a useful method for public consideration of transport options. In the remainder of this paper, *isochrone* is used to refer to a line joining a set of points at equal travel time from a specified location, whereas *isochrone area* refers to the set of all points contained within an isochrone which are reachable in the specified time *or less*.

It is difficult to determine when the isochrone map originated, but it was certainly before any of the authors of this article were born, since Monkhouse and Wilkinson (1971) quote examples drawn in 1932, 1938 and 1939. Isochrone maps, showing travel times by public transport from the city centre, were used to assist urban transport planning in the 1950s (Kok 1951, Rowe 1953). Although isochrone maps do appear in a few of the major works of the quantitative revolution in geography in the early 1960s (see, for example, Bunge 1962), they are, surprisingly, completely absent from several well-known studies on highway development, quantitative geography, and network analysis. Instead, isoline maps appear which show more elaborate variables such as population potential, commuting percentages, market potential, or rankings of accessibility by interstate highway.

Forer and Kivell's (1981) use of the space-time approach to deduce 'sensible' isochrones to plot for New Zealand housewives casts isochrones in an interesting light: if the diagrams of figure 1 are redrawn in three dimensions so that space has two dimensions, then an isochrone area is a horizontal slice through the unconstrained space-time prism or 'cone'. Figure 2 (*a*) illustrates this idea. Constrained accessibility can be deduced for the start and end destinations A and B, by intersecting various of the isochrone areas for A and B, depending on how much time is available for the journey (figure 2 (*b*) gives an idea of what is involved). Points on the surface of the shaded volume can *just* be reached with no time to spare; points inside the volume leave time free for other activities. A more detailed description of this process is provided in §6.2 where the feasibility of carrying out this process in a GIS is examined.

The generality of isochrones to both the approaches to accessibility discussed above is the major motive for their use in this study. The generation of isochrone areas in a GIS environment yields the immediate benefit that they may be re-used in various analyses. For example, facilities recorded in other data layers, lying within particular isochrone areas can be selected to provide the basis for weighted sum accessibility measures. On the other hand, simple geometric manipulation of isochrones can facilitate space-time geographical approaches.

3. Design fundamentals

This section outlines the more fundamental design decisions and assumptions underlying this work, before the fuller description of the following sections.

3.1. *Data requirements and representation*

A primary objective of the system design was to minimise the data requirements. This was achieved first by limiting the scope of the system to off-peak weekday public transport in the study area. Such a limitation is obviously significant, but does not in principle prevent the system being extended to include more detailed information about transport service timetables. With regard to train services this restriction was particularly effective, since all services in the region offer a regular service ('and at the same minutes past each hour') in the off-peak period. Thus each train service is stored as a list of records, each of the form:

[Route number] [Station stop number] [Station ID] [Time]

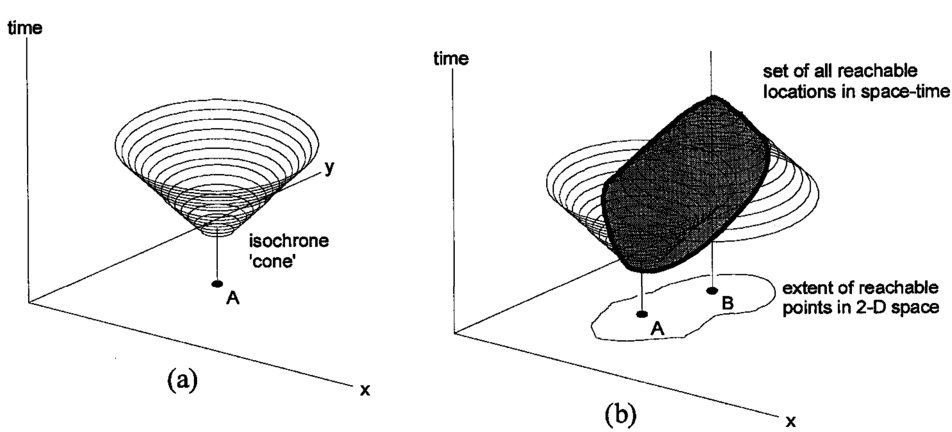

Figure 2. Three dimensional space-time prisms.

The route number is a unique identifier, the station stop number indicates the sequence of stations on a particular route, the station ID is a unique identifier for each station, and the time field is an integer value in the range 0 to 59 indicating the minutes past the hour at which the service runs. There is also a station table containing station names and geo-locations referenced by the station ID. This representation only works well when the space-time location of each route stop (station) is known, and so it presents problems for the compact storage and rapid acquisition of bus route data, where bus stop locations and arrival times are not known with any precision, and are also so numerous as to present problems of data acquisition. To minimise the data requirement for bus routes, each route is represented by a single record of the form:

[Service number] [Poly-line] [Interval] [Duration]

The poly-line here represents the route taken by the bus service through the street network. The interval is the time in minutes between timetabled services, and the duration is the timetabled duration in minutes of the service from the start to end of the route. This represents a significant simplification of the bus timetable data, but is adequate for the initial feasibility work described here. A more complete representation would clearly require that either full data for bus stop locations be captured (in which case a representation like that adopted for rail services could be used), or that selected points along the route be stored with associated timings. The latter representation would at least allow account to be taken of the variation in bus service speeds in the city centre and outside. However, either approach would require a great deal more data, and in any case does not affect the underlying aim of examining the feasibility of constructing isochrones in a GIS.

For that much neglected mode of transport 'on-foot' UK Ordnance Survey street centre-line data was used to build a standard GIS network data layer. No significant further processing of this data was carried out except to assume a nominal pedestrian speed of 100 m per minute so that network distances could be converted to times. This speed is perhaps rather fast, but could be readily adjusted.

3.2. *Basic algorithm*

Production of an isochrone data layer, from which a map might be partially constructed, proceeds in two basic steps:

(*i*) Use of timetable and street network data to determine the elapsed times by which a traveller setting out from a specified point and at a specified time might arrive at railway stations and bus routes in the study area.
(*ii*) Use of basic GIS spatial processing (building shapes by intersection and merging of simpler shapes) to convert the set of elapsed times from (*i*) into the complex isochrone required, for a specified elapsed time limit.

Step (*i*) results in a set of time-labelled points (in effect a 'punctiform' isochrone as discussed by Miller 1991). These points are the starting location, railway stations, and 'bus boarding points' identified by the system as locations at which a particular bus service might be boarded. Each point is also labelled as to whether the traveller arrives there on foot or not. Step (*ii*) originates walked journey segments from each of the points which were *not* reached on foot, in order to build the isochrone. Additional points along bus routes are temporarily created during this step—bus alighting points—and each of these is also used as a starting point for the final walked segment of traveller journeys.

Thus, the core of the design is the creation of a set of time-labelled point locations. The time-label indicates the elapsed time by which a traveller can reach that point. This set of points is referred to in the remainder of this paper as the set of *space-time locations.* Where the meaning is clear, *location* is used for brevity.

4. Implementation details

4.1. *Using GIS tools to determine optimal travel routes*

This section outlines the procedures involved in 'simulating' a traveller setting off from a specific location and determining where she can reach at what times. In this context, three modes of travel are available: walking, trains and buses (the Glasgow underground has been treated as a railway system). Clearly, route choice in a public transport system is influenced by many factors other than travel time. Minimising the fare, the number of interchanges, walking distances, or waiting times are all plausible traveller strategies. A classical economic approach to this complexity might involve creating a more complex cost function based on all these factors (and others). However, this would surrender one of the principal advantages of the time-as-cost isochrone approach adopted here, in that the resulting isolines would be hard to interpret, and further manipulation of such lines (by intersection and merging, for example) would be a questionable procedure. These considerations eliminate the need for sophisticated simulation of traveller behaviour, and reduce the problem to shortest path (minimum time) determination for the Glasgow public transport system.

Initially, only a user-specified starting location is stored, together with all the stations. If the user indicates an interest in 'bus-only' travel then only the starting location is stored. The starting location elapsed time is '0', and none of the stored station locations (if any) have an associated time. The first operation is for the traveller to walk to nearby bus routes and stations. Stations are then tagged with the time taken to reach them, and bus route boarding points are added to the set of space-time locations with associated times. The system then repeatedly works through the sequence of operations shown in figure 3. The current space-time location with the earliest arrival time is examined to see if connections from it afford earlier access to other locations. Hence at a station location, the railway timetable is examined to see if it is possible to reach other stations by train, sooner than the currently stored time. If the station has *not* been reached on foot, then the walk time to nearby stations and bus routes is determined and corresponding new records are added to the set of space-time locations if there is an improvement in journey time. At a bus boarding point location, connections to other bus routes and connections to railway stations are examined, and new records are added to the space-time location set if any improvements in journey time are found. The details of these mechanisms are discussed in the sections which follow. Having determined if any other space-time locations can be reached sooner than any previously stored result, the current location is tagged as having had its arrival time finally determined, and the space-time location with the next earliest arrival time is selected for consideration. This process repeats until all space-time locations have had their arrival times determined. The astute reader will recognise this as a straightforward adaptation of Dijkstra's (1959) shortest path algorithm to a multi-modal environment, where the existence of particular connections is affected by the current time, as expressed in timetable information represented as described in the previous section.

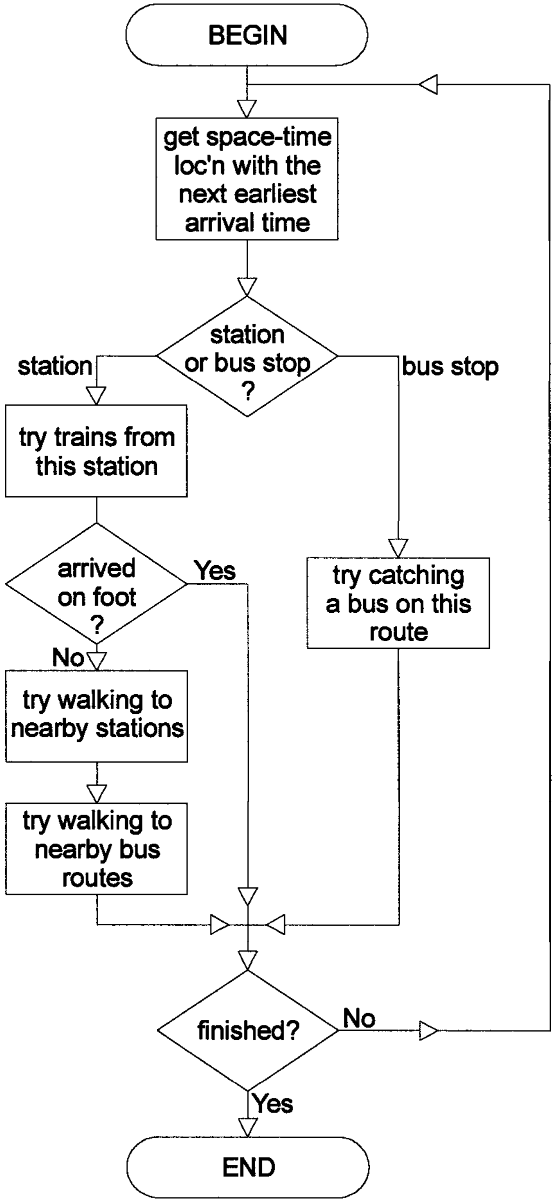

Figure 3. Core loop of minimum travel time algorithm.

4.2. *Walking*

Walking is the only mode of travel which makes use of the GIS network analysis tools. This use is restricted to solving simple, fully defined shortest path problems, that is the walk to nearby railway stations or bus routes. The main concern in this section is how best to determine *which* shortest path problem to solve.

Different approaches have been used to search for nearby railway stations, and nearby bus routes. For the railway stations, a set of Voronoi proximity polygons based on the railway stations in the Glasgow region was produced and manually edited: parts of polygons on the opposite side of the River Clyde from their station were merged into neighbouring polygons on their own side of the river, except where bridges enable the river to be crossed on foot. The resulting polygons provide a way of predicting sensible stations for a traveller to use from her current location. A traveller considers using any station in 'her own' polygon, and also any station in neighbouring polygons. This results in reasonably sensible choices without too much effort. Figure 4 (*i*) demonstrates this, and also the way in which some proximity polygons have been altered.

A better approach might involve creating the proximity polygons using the traveller's current location and the stations. Then nearby stations are found by selecting those in neighbouring proximity polygons to that of the traveller's location. The search area by this method is shown in figure 4 (*ii*). This approach is likely to lead to fewer anomalies than the current one, but would involve altering the Voronoi polygons during execution, which is likely to be slow. It would also require an automated replacement for the manual editing process described above, which would be complex. Another alternative would be to use network proximity polygons as described by Okabe *et al.* (1994).

A simpler technique is used to determine nearby bus routes because the 'neighbourhood' approach is not applicable without storing the position of all bus stops. Instead, every bus route within a specified distance of the current location is considered. For each route the boarding point for the traveller is then taken to be the point on the bus route at which the closest (Euclidean distance) approach occurs. Usually, this will yield a sensible solution, although in special cases it may not. For example, in figure 5, for traveller 1, this approach is sensible because the bus route locally is fairly direct. For traveller 2 the boarding point chosen by this method is poor: either of the unfilled 'flags' might be a better point to board the route, depending on the direction of travel.

4.3. *Train travel*

When the current location is a railway station it is a relatively simple matter to consult the stored timetable data to determine which other stations can be reached by direct connection from this station, and whether the proposed journey yields an earlier arrival time than currently stored. However, as only the minutes part of any train service departure time is known this must be adjusted to reflect both the time

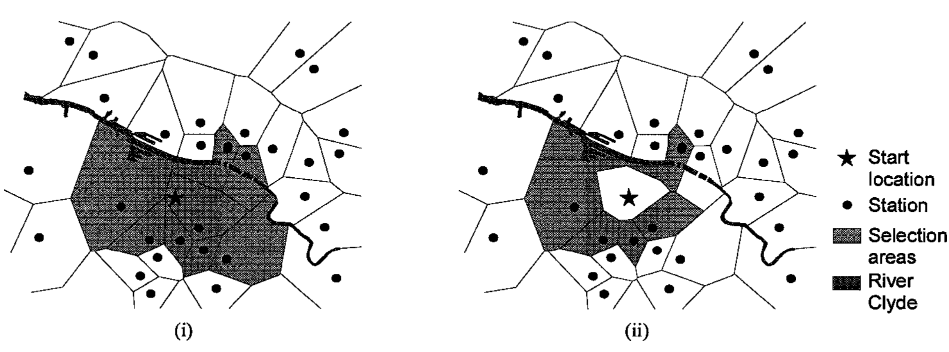

Figure 4. Searching for nearby stations by two possible methods. Based upon the Ordnance Survey mapping with the permission of The Controller of Her Majesty's Stationery Office, (© Crown copyright ED 0236/99.

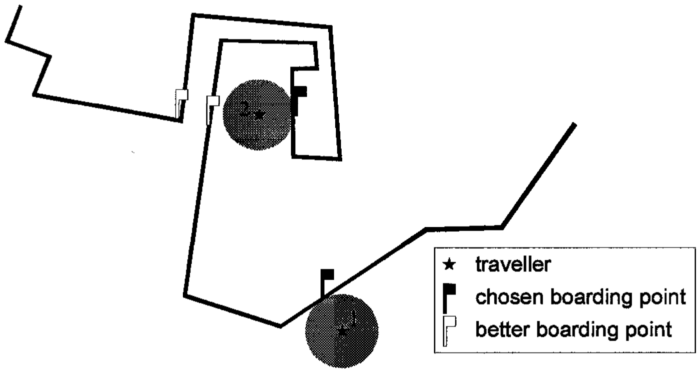

Figure 5. Selection of initial bus boarding points.

at which the traveller has arrived at the current station and whether the sequence of stations under consideration 'straddles the hour'—a sequence like 53, 57, 59, 02, for example. Apart from this wrinkle, determination of train journey times is simple.

4.4. *Bus travel*

Initially, no points on bus routes are stored. Instead, as the traveller progresses from the starting location, 'bus boarding points' are determined and included in the set of space-time locations. These are then treated as starting points for bus journeys, which may yield improved arrival times for railway stations, or connections to other bus routes. Alighting points are never stored: they are determined as required. This is true both during travel time determination, and during isochrone construction. In the latter case, sequences of alighting points at equally spaced two minute intervals from stored boarding points are generated, and used to construct each bus route's contribution to the isochrone.

Connections to either railway stations or bus routes from a current bus boarding point make use of a buffer zone constructed around the current bus route. The extent of the buffer is specified by the user. The size of the buffer may be different between stations and bus routes. This makes sense since it is likely that travellers will tolerate longer walks to connect with the rail network than they would to connect to other bus routes—given that they can expect to make faster progress via the rail network in return for the extra 'investment' of time in getting there. Recent work by Lee and Lee (1998) explores this phenomenon in measuring accessibility on a subway network.

Connection to railway stations is achieved simply by considering any stations which fall inside the buffer zone. The point on the bus route which is closest to the 'target' station is used as an alighting point and the walk from the alighting point over the street network to the station is determined using the GIS shortest path network analysis tools. The duration of the bus journey to the alighting point is determined by calculating what fraction of the whole bus route it represents, and assuming that the bus route is traversed at constant speed.

Connections between bus routes are handled in a similar way. That section of a 'target' bus route which is contained within the buffer zone around the current route is traversed until the closest point of approach is found. This is a candidate boarding point for the target route, and the journey time to this point is calculated in a similar way to the journey in the station connection case. The simplest case is shown in figure 6, where *target route 1* has only one simple intersection with the current route. Where a target route has two or more (disjoint) sections inside the buffer (*target route 2* in figure 6), two or more candidate boarding points will result. Where the current and target routes run along the same streets or approximately parallel over significant lengths (*target route 3* in figure 6) no attempt is made to determine which of the two end points A or B would be a better point at which the traveller should change buses.

Any candidate boarding points on a target route are retained if they improve on existing ones for that route. There are three possibilities when a second or subsequent boarding point on a given route and at a given time is under consideration (clearly if a candidate boarding point is the first on that route, it is always stored). Consider the diagram in figure 7. C is a previously determined boarding point, D is a potential new boarding point. Each has an associated time, t_C and t_D. The journey time from C to D, via the bus route, is T. Now, if

$$t_C + T < t_D, \tag{2}$$

then clearly boarding point D is redundant, and is discarded, since it provides no improvement in arrival time at points further along the route. The mirror-image case, where

$$t_D + T < t_C, \tag{3}$$

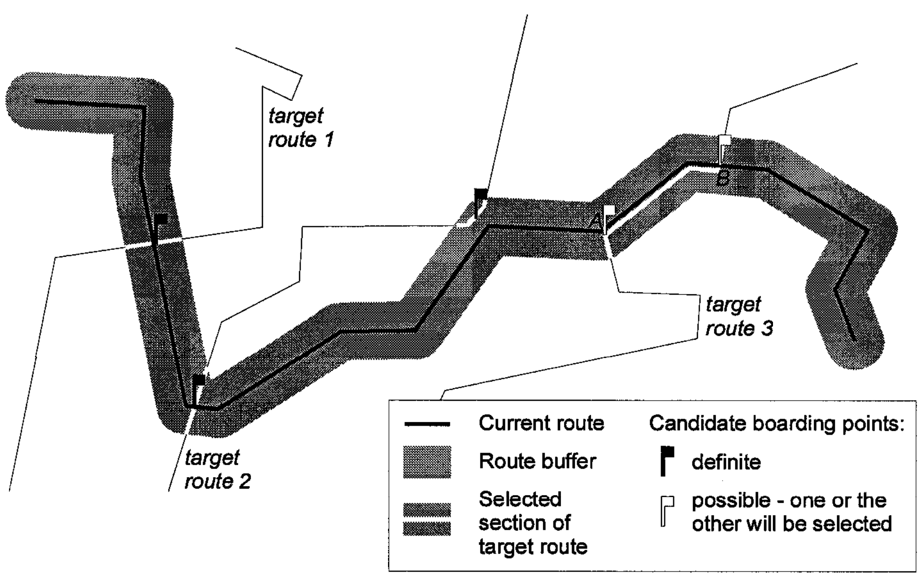

Figure 6. Bus route intersections.

Figure 7. Comparing bus boarding points.

means that D supersedes C, which is now redundant, and is discarded. The intermediate case where

$$T < |t_D - t_C|, \tag{4}$$

means that both boarding points should be retained, since one provides earlier access to its segment of the route, while the other provides better access to its segment.

4.5. *Creating isochrones*

Once a set of space-time locations (i.e. a set of arrival times at railway stations and the final set of bus boarding points) has been determined the construction of isochrones may be carried out. Two versions of isochrone construction are offered.

A 'quick' version simplifies matters by assuming that the final walked portion of journeys can be represented by 'steady progress in all directions'. In other words isochrones are constructed from circles of various radii. This assumption is not unreasonable in built up areas with a fine street grid. Clearly it falls down outside built up areas, and when dealing with major natural barriers such as the River Clyde. The Clyde is handled by creating shapes representing (overlapping) regions north and south of the river. The overlap is in areas where the Clyde does not represent a significant barrier to pedestrian movement, because there are bridges. Isochrone elements are modified by intersection with whichever of these regions applies, to remove inaccessible areas.

A slower approach uses the *ArcView*™ FindServiceArea request and arguably produces better results, because it is based on the street network. Much work could be done refining details of the street network, introducing different pedestrian speeds and time penalties at complex junctions. However, all these effects are second order, and improvements are likely to be marginal, considering how much detailed editing and refinement of the network would be required. Confirmation that the quicker circles method produces broadly acceptable results is provided by figure 8. In and around the built up urban area, the circle-based method produces isochrones which are a good approximation to the more 'accurate' service area method.

5. Some limitations

5.1. *Use of train timetable*

An interesting theoretical problem is raised by the use of the train timetable. The choice of starting time (entered by the user) is critical to the end result. Fair comparisons between locations can only be made by running the system a number of times using different starting times and somehow averaging the results. It can be argued that a better approach would be to use the average interval between trains as has been adopted for bus routes, and estimate a waiting time for trains in any particular direction. This does not seem entirely satisfactory, since it does not reflect differences in the way travellers use these two modes. It seems likely that train travellers will tend to know when the service they need runs, and to set off in time to catch it. Buses, on the other hand, unless they are express services, or very infrequent, may be perceived as unpredictable, essentially random in their running, and users tend to 'just turn up'.

5.2. *Simplification of bus travel*

The speed of bus travel has been simplified as noted in §3.1, so that buses are assumed to travel at a constant rate along the whole of their route. This is clearly a simplification likely to underestimate bus speeds in the suburbs and overestimate them in the city centre. The introduction of a representation of bus services similar to that adopted for train services would be required to minimise this inaccuracy. A further simplification occurs in the calculation of waiting times, where the first leg of a journey is by bus. It is assumed that travellers must wait half the time interval between services on arriving at a bus route. This may be fair for relatively frequent services, but is likely to overestimate the waiting time for services which run less frequently, when we might expect travellers to be more aware of the timetable and behave accordingly. In the current context, where the focus has been on feasibility and methodology, such inaccuracies are not important, but should be borne in mind.

The method of determining bus connections also has a number of limitations, which have been mentioned in §4.4. In fact, the general problem of determining minimum time paths through a network of public transport routes is difficult. Many strategies could be adopted. Constructing a network to represent all the possible interchanges, using timetable data, is one option, but was rejected from the outset as requiring too much data. An improvement over the current method would involve recording which connections had already been attempted using an 'interconnection matrix'. This would not be difficult to implement and would yield significant performance improvement by avoiding needless rechecking of connections. Other approaches would involve more complex 'spatial reasoning' tasks—the sort of decisions which come naturally to humans but which are difficult to program. An obvious example is where two services run along the same streets to approximately the same destination. No traveller would be likely to change from the number 6 bus to the number 6A, if they both go to the city centre. Building this sort of decision making into the system would be a complex task. The techniques required are still beyond the scope of GIS. In the longer term this is precisely the sort of problem which we might expect the large and growing literature on spatial reasoning to assist in tackling (see for example Frank and Campari 1992, 1993, Frank and Kuhn 1995, Hirtle and Frank 1997).

6. Sample outputs

6.1. *Easterhouse isochrone maps*

Complete maps for the whole study area have been produced but are difficult to present in the journal format. Instead, figure 9 shows a typical output from the system, derived for travel by all modes, from Easterhouse. Easterhouse is an outlying housing estate on the eastern edge of Glasgow which is generally regarded as deprived, because of its high unemployment, poor housing and low incomes. The start time for this map was deliberately chosen to favour trains *travelling away from the city centre*. Nevertheless it is clear that residents of Easterhouse are likely to experience difficulties travelling on public transport to any area other than the city centre. Even places served by the railway eastwards from Easterhouse are comparatively inaccessible. Figure 10 shows the situation for a traveller who does not use the rail system (perhaps because of the higher fares). The lack of access to peripheral areas is even more marked. This demonstrates effectively how difficult it could be for residents of Easterhouse with no access to a car to take jobs at the increasing number of peripheral industrial and retail locations. The contrast between figures 9 and 10 is stark, partly because figure 10 presumes no use of the train system at all. A useful enhancement to the system would allow more flexible specification of tolerable journey profiles so that these issues could be thoroughly explored.

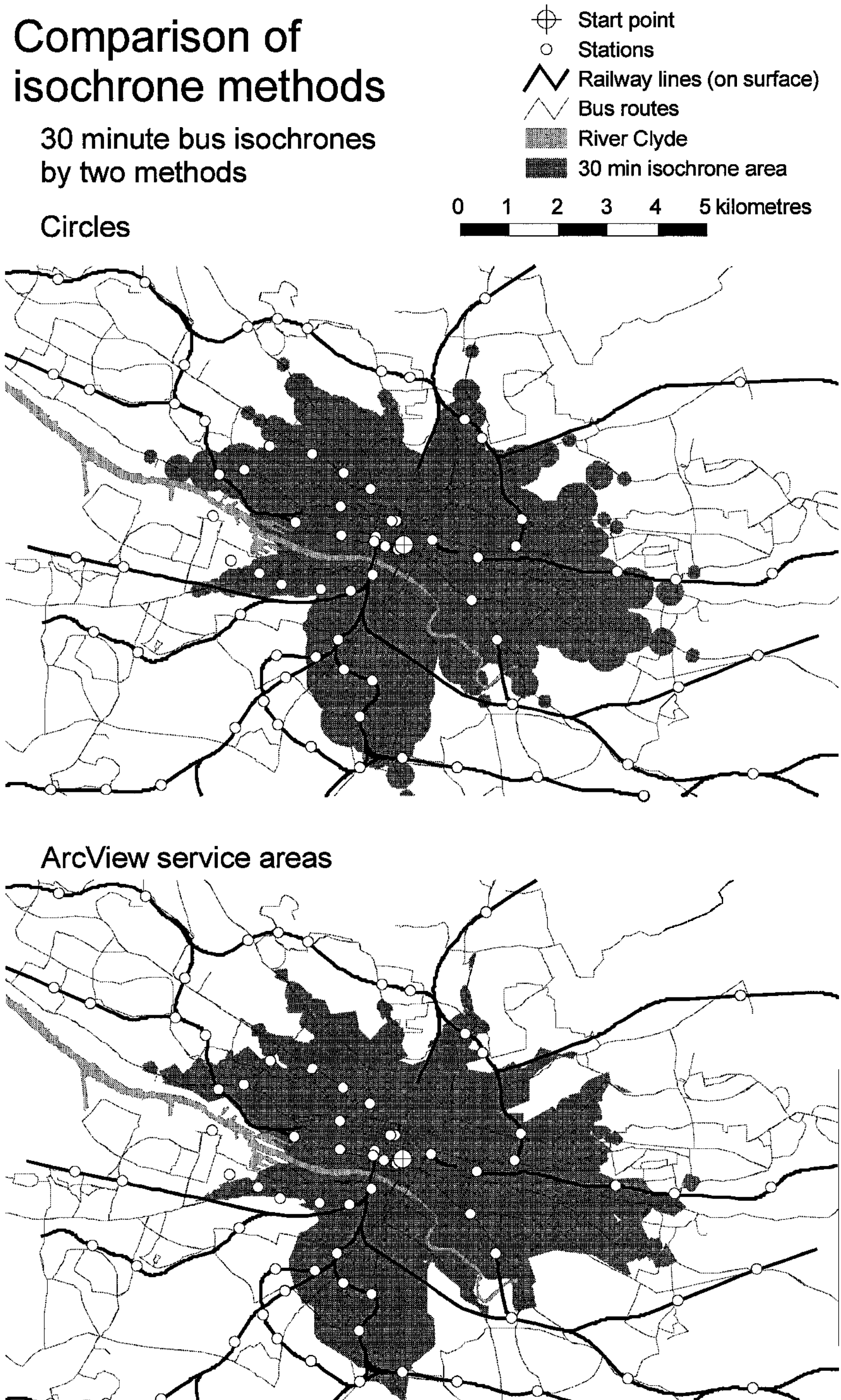

Figure 8. Comparison of two methods of isochrone generation. Based upon the Ordnance Survey mapping with the permission of The Controller of Her Majesty's Stationery Office, (© Crown copyright ED 0236/99.

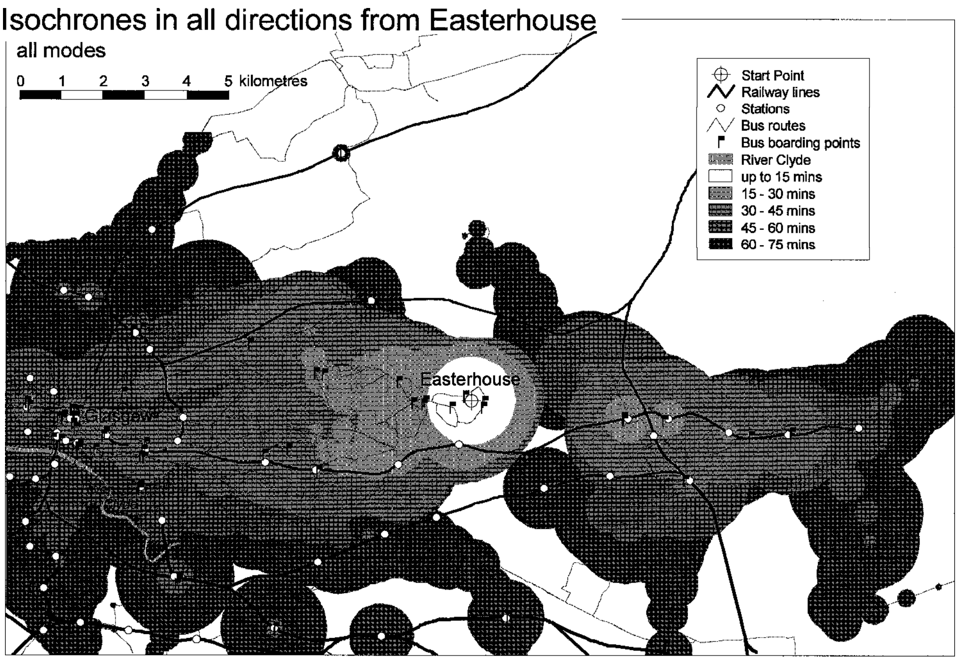

Figure 9. Isochrones for all modes of travel from Easterhouse. Based upon the Ordnance Survey mapping with the permission of The Controller of Her Majesty's Stationery Office, (© Crown copyright ED 0236/99.

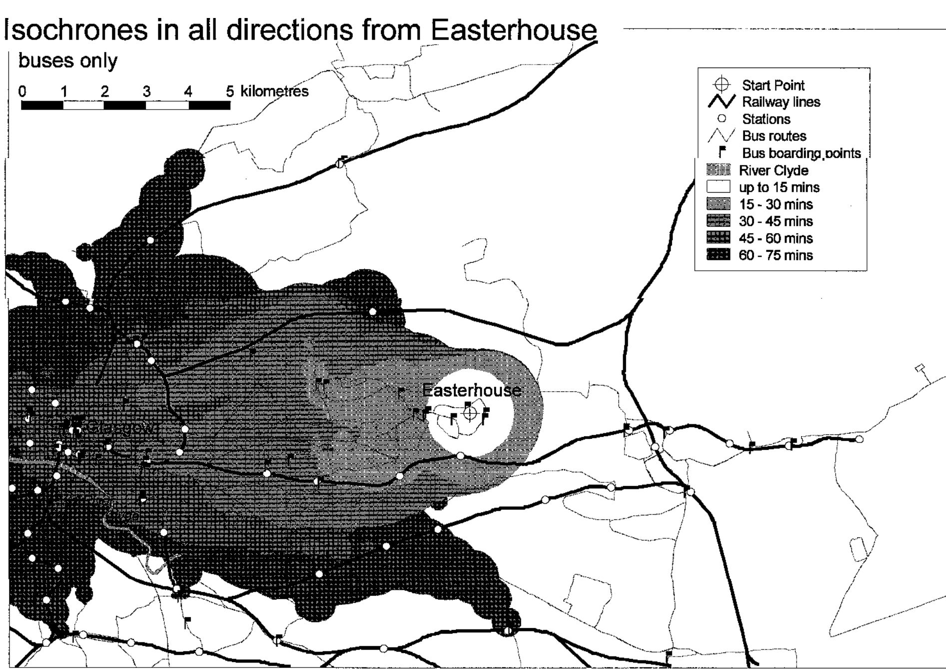

Figure 10. Isochrones for travel by bus from Easterhouse. Based upon the Ordnance Survey mapping with the permission of The Controller of Her Majesty's Stationery Office, (© Crown copyright ED 0236/99.

This graphic presentation of accessibility issues can be readily extended, and quantified, because the data is held in a GIS. It is a simple matter to relate the isochrone areas of figures 9 and 10 to facilities data, and furthermore to weight facilities according to the time limit of the isochrone area in which they fall. Thus, the accessibility measures of §2.1 can readily be constructed from the isochrone data layers.

6.2. *Constrained accessibility isochrone analysis*

The second output presented here shows how isochrones from two locations could be merged to produce accessibility maps for individual traveller's situations using the space-time concepts of §2.2. The example described here has been produced in a drawing package, using isochrones produced by the system, but the process could clearly be automated in the GIS. Two sets of isochrones were produced. Figure 11 (*i*) shows isochrones at 5 minute intervals from a work place *A*. Only buses have been used in the calculation. Figure 11 (*ii*) shows a similar set of isochrones from a school *B*, also at 5 minute intervals. Now, if we consider a situation where a parent working part time at *A* must pick up children from school at *B* one hour later, we can produce a set of shapes showing areas which can be visited *en route*, and the time available for doing other things (shopping, visiting the post office, and so on) at those locations. The result is shown in figure 11 (*iii*) together with the bus routes through this area. As we might expect, the areas where the parent has most

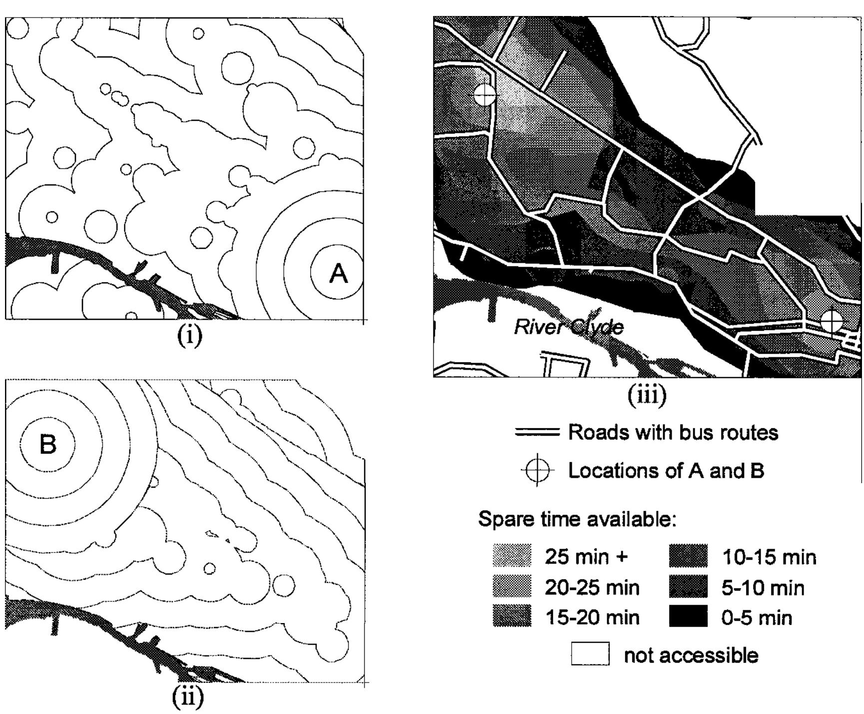

Figure 11. Constrained accessibility analysis using isochrones. Based upon the Ordnance Survey mapping with the permission of The Controller of Her Majesty's Stationery Office, (© Crown copyright ED 0236/99.

spare time for other activities lie close to the bus routes along which travel from the place of employment to the school takes place.

Refer back to figure 2 for a graphic representation of the processing involved. More formally, if the time available for the journey from A to B is T, then the set of points which yield 'free time' t is given by

$$\bigcup_{i,j} (A_i \cap B_j) \forall i, j — (i+j) = (T - t) \tag{5}$$

where A_i is the set of points reachable from A in time i, and B_j is the set of points from which B can be reached in time j. This formalisation of the processing is suitable for the vector representation adopted here. If instead travel times are represented as pixel values in raster format, then the available time t_p at any point p is given by

$$t_p = T - (t_{Ap} + t_{pB}) \tag{6}$$

where t_{Ap} is the travel time from A to p, and t_{pB} is the travel time from p to B. This second expression perhaps makes the processing more explicit, in that t_p can be seen to be the length of the intersection of the line through p parallel to the time axis, with the space-time prism, associated with the journey from A to B. Figure 12 demonstrates this calculation diagramatically, with space presented as a single dimen-

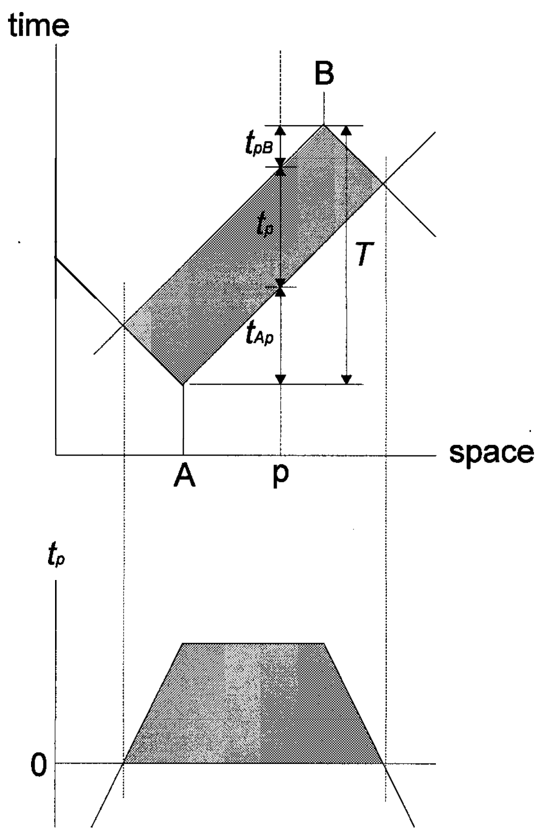

Figure 12. Determination of the volume of the space-time prism.

sion for clarity, and the space-time prism shaded as in figure 1. The volume between the surface formed by (6) and the plane representing $t_p = 0$ will equal the volume of the space-time prism for the journey from A to B of duration T.

It is worth noting that the destination requires a set of *travel-to* isochrones. Since bus waiting times have been simplified by ignoring the timetable, the *bus* travel-from isochrones used here are allowable. However, the way in which train waiting times are calculated could not be fitted into this approach easily, since it uses timetable data which is intrinsically unidirectional. However, producing travel-to isochrones would not be a complex modification.

7. Conclusions

This work demonstrates that an effective set of desktop GIS tools for automated production of isochrone maps can be produced. Furthermore this has been achieved in the context of a large city with a complex public transport network. This is a testament to the power and flexibility of current GIS.

Isochrones as presented and used here provide an easily understood method for examining accessibility by public transport. They can also be the basis of more sophisticated analysis techniques. Their clarity of meaning is also an advantage, and facilitates assessment of the transport options available to people. Given these advantages it is perhaps surprising that they are reported so infrequently in the literature. Presumably this is due to the laborious and intricate nature of construction by manual methods, and to past limitations in computing power. This work demonstrates that such limitations no longer apply.

Nevertheless, as is clear from the foregoing, simplifications have been necessary to make this work feasible. The resulting system remains slow, so that any kind of interactive investigation (of say proposed new bus routes) would still be a tedious and time-consuming task. Miller (1991) provides a useful discussion of some of the performance and programming issues in using generic GIS products in the transport accessibility context. It seems clear that dramatic performance improvements would require a different approach. This might involve 'intelligent spatial processing' akin to the methods by which humans navigate through a complex transport system, and involving techniques from artificial intelligence and expert systems. An alternative approach is that currently taken by suppliers to the transport analysis profession, who concentrate on specialist software based on extensions of basic network analysis, and apply them to sophisticated data-rich network models. Such systems are almost invariably based on much more extensive computing resources than those applied here.

Where GIS really comes into its own, is in immediately locating the resulting isochrones in relation to any other available data in the region of interest. This means that numerous accessibility problems are immediately capable of straightforward analysis using standard overlay techniques. More complex spatial manipulations can also be applied easily. The constrained accessibility analysis presented in §6.2 is a particularly interesting example, given recent renewed interest in space-time geographic approaches.

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