Journal of Transport Geography 35 (2014) 1–11

Contents lists available at ScienceDirect

Journal of Transport Geography

journal homepage: www.elsevier.com/locate/jtrangeo

Accessibility modelling: predicting the impact of planned transport infrastructure on accessibility patterns in Edinburgh, UK

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ARTICLE INFO

Keywords:
Accessibility
Transport planning
Spatial equity
Edinburgh Tram
Geographic Information System (GIS)

ABSTRACT

The achievement of good spatial accessibility and equity in the distribution of urban services is one of the supreme goals for urban planners. With Scottish Government backing, the City of Edinburgh Council (CEC) has started to construct a tram network to cater for the future needs of Scotland's capital city by providing an integrated transport solution using trams and buses. Spatial Network Analysis of Public Transport Accessibility (SNAPTA) which is a GIS-based accessibility model has been developed to measure the accessibility by public transport to different urban services and activities. The model responds to several limitations in other existing accessibility models in planning practice. It offers an alternative and practical tool to help planners and decision makers in examining the strengths and weaknesses of land use – transport integration. SNAPTA has been applied to a pilot study in Edinburgh city to identify the contribution of the infrastructure improvements of the tram system and Edinburgh South Suburban Railway (ESSR) to improved accessibility by public transport to six types of activity opportunities. This paper outlines the concept and methodology of the SNAPTA model, and presents the findings related to this pilot study with a focus on changes in potential accessibility to jobs between four different public transport network scenarios. The accessibility values so obtained help to identify the gaps in the coverage of the public transport network and the efficiency in the spatial distribution of urban services and activities. The findings focus on whether the planned transport infrastructures for Edinburgh will lead to better accessibility and reduced inequity (in terms of accessibility) across the city.

1. Introduction

Being able to reach the spatial opportunities in the city-region where you live without too much hassle is considered as one of the dimensions of quality of life in empirical studies of life quality (Bowling and Windsor, 2001; Leitmann, 1999; Roseland, 1997). The ability to access necessary services is a function of the range of transportation choices available and their travel time, safety, cost, and convenience as well as the internal structure of settlements and the spatial distribution of opportunities (Banister and Hickman, 2007; Forward, 2003). The efficient connection of the distributed infrastructure of services and facilities with the infrastructure for movement across city regions is a pressing issue for urban managers. The changing intensity of development at locations in the city-region affects travel demand and the performance of the transport system whilst city scale transportation investment alters the accessibility of different parts of the city-region (Banister and Hickman, 2007; Chapin and Kaiser, 1979; Himanen et al., 2005; Holl, 2006; NICHES, 2007; O'Sullivan, 1980; Priemus et al., 2001; Sultana, 2006). The dialectical relationship between transport services and spatial opportunities affect both accessibility and spatial equity, another concept closely linked to quality of life.

The role that public transport plays in connecting communities and neighbourhoods and the impact of transport investment on those same communities is acknowledged in local transport policies that seek, for example, 'To improve the transport choices households have available to reach a range of services' or 'To promote accessibility to everyday facilities for all, especially for those without a car' (Hull and Karou, 2011). The spatial growth of urban areas and the decentralization of employment and facilities have made it harder for people without access to a car to make the daily commute and to take advantage of distributed retail and leisure opportunities.

In this respect, there has been a growth of interest in the concept of accessibility over the last decades, with many accessibility studies published in the academic press discussing how to measure accessibility and the contribution such decision support tools might have. Recently, the development of accessibility models has used a multitude of approaches to inform land use and transport decision-making (Karou and Hull, 2012). Therefore, translating the concept of accessibility into a practical planning tool

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0966-6923/$ - see front matter
http://dx.doi.org/10.1016/j.jtrangeo.2014.01.002

stems from the need for powerful techniques to help planners and decision makers deal with urban and transport management and provide better evaluation of the impacts of different schemes (or combinations of schemes) advanced by transport and land-use policies.

This paper focuses on accessibility addressing issues of spatial equity and transport disadvantage through two objectives. The first objective is to develop an accessibility model – the Spatial Network Analysis of Public Transport Accessibility (SNAPTA) – which has responded to the need for academic research models to be more practical and useful models for the world of planning practice. The second objective is to test the model through empirical study in the city of Edinburgh based on *ex ante* evaluation of the new tram system and Edinburgh South Suburban Railway (ESSR) to compare between the accessibility impacts of different scenarios of the completion of these infrastructures.

The paper is organised in six sections. The introduction has identified transport accessibility as a key dimension of quality of life and a priority for sustainable urban management. This acknowledges the interaction between land use and intensity, individual travel behaviour and transport provision. The next section introduces the case study of Edinburgh. Section 3 discusses the rationale for the construction of the tram system and re-opening of ESSR. In Section 4, the conceptual framework and theoretical underpinning of the SNAPA model is presented. Section 5 focuses on the methodology of SNAPTA application to Edinburgh's network while the last two sections outline the findings and further developments in SNAPTA.

2. Case study of Edinburgh

The city of Edinburgh is situated in the central urban belt of Scotland with an overall density of 37.65 persons per hectare (2001 census). The policies in the land use plan and Edinburgh's geographical location (bordered by the Firth of Forth on two sides) have contained urban sprawl, through the imposition of a green belt around the urban area and the encouragement of development on brownfield sites.

Edinburgh's population is projected to grow by over 59,000 between 2010 and 2030 (CEC, 2010). As Edinburgh's population grows, the demand for travel will increase. Population growth in the city region will also impact on levels of commuting into the city. Moreover, during the next 20 years, Edinburgh's economy is forecast to play a big part in Scottish economic growth (CEC, 2010). The city is currently commencing a huge phase of redevelopment. Edinburgh Waterfront is set to provide an additional 25,800 new residential units and nearly 350,000 m of new office, retail and other commercial developments between 2006 and 2020. Significant new development is also predicted to be progressively built by 2020 in West Edinburgh with some 250,000 m of new office space and over 200,000 m of other commercial space (TIE, 2006). Fig. 1 shows the location of housing and office developments programmed for completion between 2006 and 2015 based on outstanding consents and local plan allocations (CEC, 2008).

Continuing economic success has however created a number of challenges. With a substantial population increase expected and "The number of jobs……now expected to increase by 15% between 2000 and 2015" (CEC, 2007, p. 14) as well as the forecast rise in household car ownership by 30% from 2000 and 2016 causing twice as much time to be lost due to congestion over the same period (TIE, 2004, p. 2), the maintenance of connectivity and accessibility is one such challenge (Hull and Karou, 2011). The Transport 2030 Vision argues that, by 2030, without action, the demand for travel from/to the city by private car will far exceed the current capacity (CEC, 2010).

The City of Edinburgh Council has defined a series of actions including the implementation of new public transport infrastructures such as the tram system and ESSR to boost the transport system and improve accessibility in the Council's area. The expectation is to cut demand for road travel and to serve the new growth areas while they develop by delivering a reliable and safe public transport service and, consequently, by improving their accessibility. The Public and Accessible Transport Action Plan (PATAP) 2013–2020 suggests that the target is to increase public transport's share of all their journeys by 2015 by 1.3%, and by 2020 by 2.3%

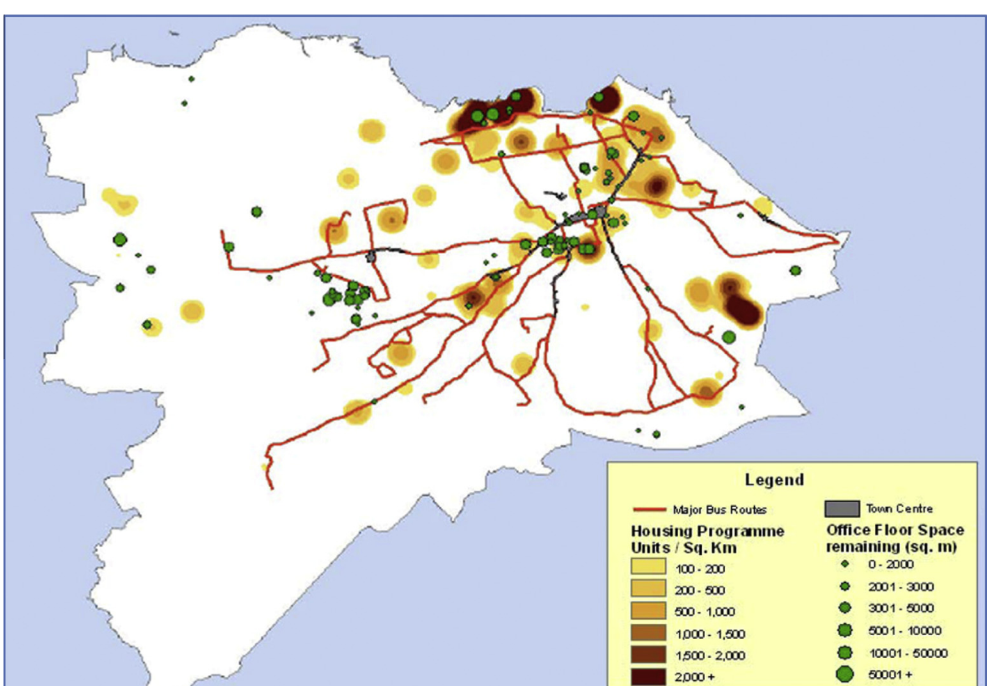

Fig. 1. Location of housing and office developments programmed for completion by 2015. *Source:* City of Edinburgh Council planning records (2008).

compared to the average attained between 2007–2008 and 2009–2010 (19.1%) (CEC, 2013a, p. 25).

The Scottish Government perceives high accessibility as essential to economic growth and competitiveness through "providing access to markets and enhancing the attractiveness of cities as focal business locations and tourism" (Scottish Executive, 2004, p. 18). In the National Transport Plan, accessibility is linked to improving journey times and connections and to the quality and affordability of public transport choices (Scottish Executive, 2006a, p. 2). Accessibility is translated into the Edinburgh Local Transport Strategy as "whether or not people can get to services and activities at a reasonable cost, in reasonable time and with reasonable ease" (CEC, 2007, p. 82).

A study carried out by MVA Consultancy (2008) in association with SEStran (South East Scotland's Regional Transport Partnership) used Accession model to look at accessibility to the key hospitals and employment sites in the region. The study focused on the calculation of travel times using walking, cycling, car and public transport before the construction of Edinburgh Tram. Two other previous studies of accessibility, before the development of the tram and ESSR, examined the transport and land use effects of major new land use developments in the Edinburgh city-region. Derek Halden Consultancy (2002) examined how accessibility to jobs would change if a proportion (20%) of future development (development not already committed) was allocated according to different spatial strategies (e.g. green belt development; development of new settlements, etc.). David Simmonds Consultancy used a bespoke version of TELMoS to predict the impact of two major new strategic headquarters developments to the west of Edinburgh beyond the city bypass close to the airport (Bramley et al., 2011). These two studies have identified two highly policy-relevant considerations for CEC. Firstly, the public transport underperformance in the north western zone of the city towards the city bypass which particularly affects zones of affordable housing (Halden, 2002). Secondly, that the development in one area outside the city bypass has an impact, in terms of congestion, pollution and traffic levels throughout a much wider geographical area.

3. The rationale for the Edinburgh Tram and South Suburban Railway

The Edinburgh Tram was first mooted in the 1990s and received parliamentary assent in March 2006. The Edinburgh Local Transport Strategy 2007–2012 defines the tram scheme as the key project coming to Edinburgh's transport network, emphasising that the Council is committed to implementing the project to strengthen the city public transport system. The Local Strategy argues that for the Edinburgh Tram to be successful and attract people, it will require full integration with existing bus services (i.e. through common ticketing, interchange points and timetabling), and with the fabric of the city (CEC, 2007). It is intended that Tram ticketing will be integrated with Lothian Buses covering day and season tickets. However, full ticket integration, e.g. where any bus service feeding into the tram provides a simple through ticket even for single journeys, cannot currently be delivered due to legislative restriction (CEC, 2013b).

The tram, which is being delivered by Transport Initiatives Edinburgh (TIE) – a company formed by CEC, is currently under construction with the completion date having been deferred on numerous occasions due to legal action concerning the financial costs, disturbance and upheaval costs.

The original 2001 proposal for Edinburgh Trams envisaged three lines across the city; the first being a circular route running around the northern suburbs, with the other two forming radial lines running out to Newbridge in the west and to Newcraighall in the south east respectively (CEC, 2006). All lines would run through the city centre. After Line Three was shelved, Lines One and Two were combined and split into three phases, with Phase 1 being further divided into Phase 1a and 1b (see Fig. 1), as follows:

- Phase 1a; Newhaven to Edinburgh Airport.
- Phase 1b; Haymarket to Granton Square.
- Phase 2; Newhaven to Granton.
- Phase 3; Edinburgh Airport to Newbridge.

As a result of the suspension of work on Line Three due to lack of Scottish Parliamentary approval and later on Phases 1b, 2 and 3 due to lack of funding (CEC, 2011), in September 2011 only the construction of part of Phase 1a from the Airport to central Edinburgh was started. However, the intention is to secure funding for the additional lines (CEC, 2013b).

West Edinburgh from the Gyle shopping centre to Newbridge has been identified by the Scottish Government as a national growth point. Tram Phase 1a at 18.5 km in length is, therefore, seen as vital to linking the 56 hectare development site at Leith through West Edinburgh growth point to the airport and "in responding to the expected growth in travel demand" (TIE, 2007, p. 41). The Business Case for the tram argues that the likely success of the development between Granton and Leith (Fig. 2), and therefore the CEC strategy, will be strongly affected by the provision of a reliable, sustainable public transport network, of which the tram plays an essential part (TIE, 2007, p. 41). The Business Case adds that in the absence of the tram Phase 1a and Phase 1b, the new proposed development in North Edinburgh may be diverted to less sustainable locations with less potential for successful transport integration (TIE, 2007, p. 41).

The Edinburgh South Suburban Railway (ESSR) is an existing double track railway line passing through the suburbs to the south of the city centre which is used by freight traffic crossing the city. The feasibility of reopening of the ESSR to passenger services, which were withdrawn in 1962, has been considered in a recent study for CEC by Atkins (2004).

Journey to work data shows that the corridor around south central Edinburgh in which the ESSR runs has high levels of public transport use, particularly to the city centre, but also for many peripheral journeys further afield (CEC, 2008). A number of objectives have been defined by CEC (2008) and Transform Scotland (2007) for the ESSR project to contribute to the wider strategy of the region and city. These include transforming cross-city links; improving accessibility to designated employment growth areas; provide an important feeder to Waverley Station and the programmed new bus/tram/train interchange at Haymarket; making a significant shift in peak period journey-to-work trips from the car to public transport; enhancing the connections between the areas served by ESSR and other public transport modes (i.e. Edinburgh Tram, the national rail network and bus services); ensuring access for all potential users to any new services or infrastructure; and minimising the environmental impacts of travel in the corridor of the railway (CEC, 2008; Transform Scotland, 2007).

The Atkins study in 2004 concluded that the most feasible option in the short- to medium-term would be to extend the existing North Berwick – Waverley/Haymarket services to Niddrie (see Fig. 3) (Atkins Transport Planning, 2004). However, the Atkins 2004 report argued that the construction of Line Three of Edinburgh's proposed tram system to the south east of the city would clearly reduce demand levels and significantly erode the case for the scheme since it would compete with the locations of planned stations on the ESSR (Atkins Transport Planning, 2004).

For CEC, however, the extent to which the tram and ESSR will attract current and future car drivers to public transport is critical. Also pertinent is how they will contribute to improved accessibility

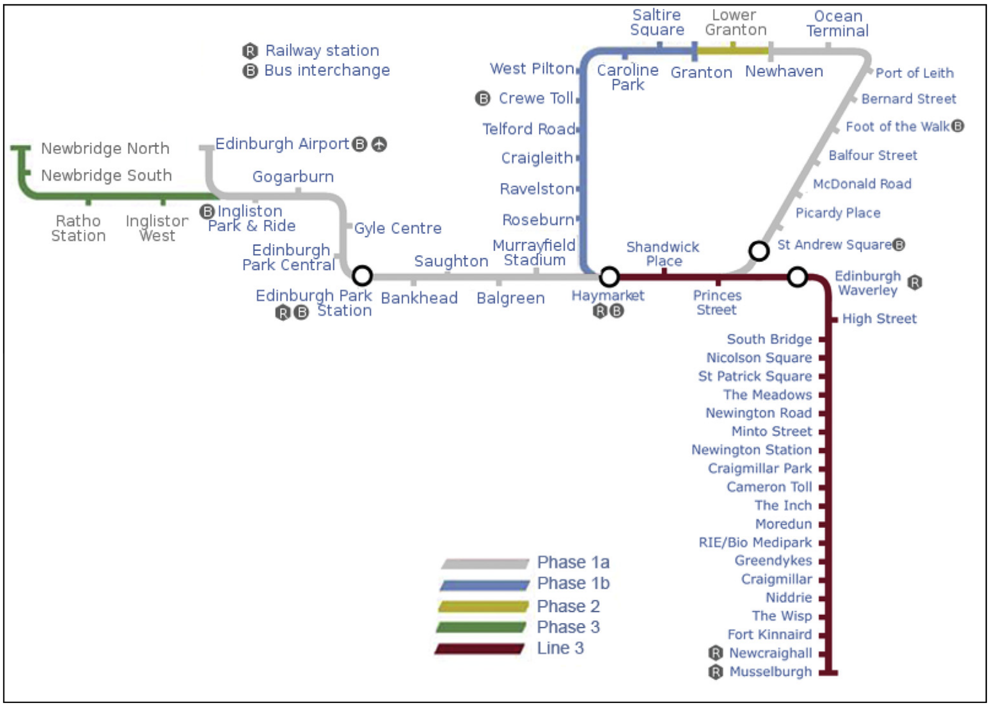

Fig. 2. Edinburgh Tram network. *Source:* http://www.edinburghtrams.com.

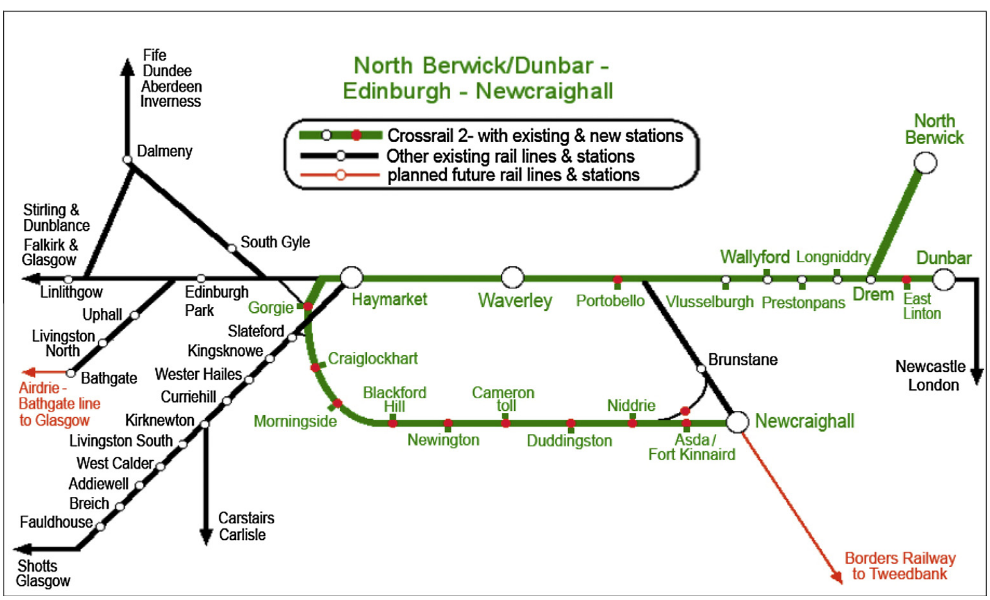

Fig. 3. Edinburgh South Suburban Railway (ESSR) re-opening proposal. *Source:* TRANS form Scotland (2007, p. 2).

and affect the relationships between local travel and activity choices. These latter issues are the subject of this research.

4. Conceptual framework and theoretical underpinning

Although many accessibility models have been recently developed and tested in scientific research (e.g. Gutiérrez and Gómez, 1999; Geurs and van Eck, 2001; Halden, 2002; Yigitcanlar et al., 2007; Curtis and Scheurer, 2010), the usability of accessibility models in planning practice is a much less-developed area of study. Many models are restricted to academic studies due to the complexity of their theoretical underpinnings which leads to a level of detail and complication that makes their output difficult for policy makers and practitioners to understand and interpret. Other models have been abandoned due to several failures or limitations related to operational and methodological issues. For example, some accessibility models are based on an inadequate theoretical basis or methodology by relying on very simple or inaccurate accessibility measures which either are not sensitive to changes in both the transport system and the land-use system, or fail to reflect actual travel behaviour.

Karou and Hull (2012) reviewed a number of current accessibility models, including: PTAL (London Borough of Hammersmith and Fulham), WALC (Transport Studies Group – University of Westminster), PTAM (West Yorkshire Passenger Transport Executive), CAPITAL (Transport for London), TRANSAM (Brown & Root), SONATA (SDG), Accession (MVA and Citilabs), SNAMUTS (Carey Curtis and Jan Scheurer), GenMod (Transportation Planning Department of Amsterdam), TMfS (MVA and David Simmonds Consultancy), ACCALC (Derek Halden Consultancy), LUPTAI (Tan Yigitcanlar and colleagues) and Space Syntax (University College London) and identified some limitations. Some of these models are inflexible and non user friendly in such a way which requires high modelling skills or a lot of time to operate and input or update the data. Other models require an external function to be integrated into the GIS environment which might be very expensive and needs a high level of expertise in operating the software. Being restricted to only one transport mode is another common limitation. In addition, most of the existing models have failed, somehow, to consider a number of issues in connection with how people perceive accessibility, including: measurement of the actual walk access time (or distance) when connecting with public transport or the private car; influence of physical features (e.g. slope); influence of traffic congestion; interchange option of public transport journeys between different modes or operators; influence of travel at specific times of day (i.e. peak time or off-peak time) and on specific days of the week (i.e. during weekday or the weekend); influence of the significance of urban activities; and the declining attractiveness of activities with increasing spatial separation (i.e. travel time or distance).

Several studies have investigated how to choose an appropriate accessibility measure or model and evaluate the usefulness of its application in planning practice (see Morris et al., 1979; Koenig, 1980; Cervero et al., 1995; Handy and Niemeier, 1997; Reneland, 1998; Halden et al., 2000; Ross, 2000; Geurs and van Eck, 2001; Geurs and van Wee, 2004; Keller et al., 2012). Although it is clear that there is no one best method for assessing accessibility, reviewing the literature revealed a number of issues that characterise the usefulness of an accessibility model for a particular situation in planning practice, as follows:

– Robustness of theoretical basis, providing an adequate representation of accessibility aspects, with a rational method of calculation.
– Sufficient level of data disaggregation.
– Not complex, simply operated, oriented towards clear objectives.
– Easily interpreted, understood and communicated with planners, researchers and policy makers.

SNAPTA is a GIS-based accessibility model which defines accessibility as "whether or not people can get to services and activities at a reasonable cost, in reasonable time and with reasonable ease". It offers better usability, covering aspects of accessibility adequately without making it very difficult to operate, interpret and, consequently, apply in practice. However, the model does not claim to provide the complete picture of actual travel behaviour and transport accessibility. It attempts to achieve a balance between the ease of interpretation and operationalisation and the complexity of the theoretical basis and data disaggregation. The performance of SNAPTA has been measured against the four above-stated criteria for creating a useful accessibility model in planning practice.

SNAPTA is intended to assist discussion and support decision-making within the fields of transport planning and land-use planning, particularly where government contexts call for more sustainable transport options to be developed. In this respect, the development of SNAPTA has been closely linked to the policy needs arising from the Edinburgh Local Transport Strategy (2007–2012) and subsequent reviews. Since such strategies present key sustainable transport ideas such as plans to boost transport and land-use integration and increase the reliance on public transport, SNAPTA provides an opportunity to deliver key elements of this strategy so that policy decisions are based on evidence of the impacts on accessibility. For example, using before-and-after analysis of network accessibility, SNAPTA helps to identify which centres need to be improved or where to promote the public transport network based on the criteria of accessibility measurement. The analysis output prompts practitioners and decision-makers to arrange the list of priorities and rethink the land-use patterns in locations with high public transport accessibility. The evaluation of spatial equity is another issue in which the application of SNAPTA can assist by highlighting the disadvantaged parts of Edinburgh where the residents do not enjoy equal access to opportunities (i.e. areas which require their residents to travel excessively to pursue the same amount and quality of a particular activity when compared with other areas around the city). Therefore, SNAPTA shows how transport and land-use integration can be clearly and visually communicated, and in so doing how the model's outputs can be used to influence CEC's transport and land-use decisions.

SNAPTA relies on a package of three accessibility measures with a different theoretical basis and criteria to quantify the spatial accessibility by different types of public transport modes to different types of activity opportunities, as follows:

(a) *Access time to city centre*. Calculating travel time or generalised cost between zones and the Central Business District (CBD) using public transport.
(b) *A contour measure*. The measure describes the total number or size of destinations that could be reached by public transport within a specific travel time. The outcomes can be expressed either by quantity or floor space area of opportunities or economic activities which makes the measure results simply interpreted. Different cut-off values for travel time have been used in the analysis according to the selected trip purpose.
(c) *A potential accessibility measure*. This measure is a gravity-based measure that includes a transport element, mainly the travel time between zones, and a land-use element determined by the quantity or size of opportunities per destination zone. A potential accessibility measure overcomes some of the methodological limitations of a contour measure. It uses an impedance function for travel distance, time or cost, reflecting the declining attractiveness of activities at a destination with increasing travel time (or distance) from the origin of the journey. However, the expression of the measure results in units that makes it less easy than the other two measures to communicate and interpret by non-modellers. The potential accessibility for the residents of each origin zone (A_i) can be defined by using Hansen's equation (1959), as follows:

$$A_i = \sum_J a_j.f(t_{ij})$$

where a_i is the attractiveness (i.e. quantity or size of opportunities) of destination zone j, t_{ij} is travel time, cost or distance from zone i to zone j, and $f(t_{ij})$ is an impedance function.

Several methods have been used to estimate impedance functions in accessibility studies (see Geurs and Ritsema van Eck (2001) for a discussion of these). This study uses a negative exponential function as the impedance function that can be expressed in the following equation:

$$f(t_{ij}) = e^{-\beta \cdot t_{ij}}$$

where β is a sensitivity parameter to travel time. With values ranging from 0 to 1, β reduces or increases the effect of travel time changes and determines the weighting of activity opportunities. Since this study measures accessibility at a local administrative level with a high spatial disaggregation (and relatively small zones), focusing only on use of public transport in which people are not very sensitive to a small variation of time (Boucq, 2007; Spiekermann and Wegener, 2007), a low value of 0.1 has been selected for β.

SNAPTA, therefore, takes into account the land use and transport characteristics of urban interactions and the availability of opportunities which can be accessed by public transport. It focuses on groups of people, and assumes that they have a set of social and economic activity needs to be met at different destinations, and that travel demand will be determined by the attractiveness of these locations and the quality of the transport infrastructure linking these places. Issues concerning the spatial equity of public facilities, the accessibility to workplaces and shops by public transport, and the changes to accessibility brought about by new transport infrastructure or the re-location of public facilities can all be interrogated through the model.

The use of the measures above for SNAPTA provides a package of accessibility measures that practitioners and decision makers can select. These measures have been widely used in the literature for diverse types of applications. They assess accessibility relying on different methodologies with different levels of complexity. Since each methodology is characterised by its own features to reflect various aspects of transport and land-use systems differently, the model users can set up the measurement framework in a way that serves the circumstances and objectives of different applications in planning practice and satisfies the priority of the aspects which must be covered. The fundamental difference between them is that the time access to city centre and contour measures focus on the separation between locations while the potential measure focuses on the interaction between locations (Gutiérrez et al., 1996). The theoretical underpinnings of the potential accessibility measure are that the interactions between an origin and destination will decline with increasing distance and time but that interactions are positively associated with the amount of activity at each location (Hansen, 1959).

5. Methodology of accessibility modelling

The modelling approach involves the development of the following scenarios that cover the key public transport projects programmed for Edinburgh's network (i.e. the tram system and re-opening ESSR) within different time frames:

(1) *Scenario A – the base year 2011,* reflecting the situation of Edinburgh's transport network in 2011.
(2) *Scenario B – the year 2014,* reflecting Edinburgh's transport network after the construction of part of Phase 1a (a single line running from the airport to the city centre).
(3) *Scenario C – long term development,* reflecting Edinburgh's transport network after the consideration of all tram lines including those envisaged or programmed for the long term, as follows:
  - Tram Phase 1a, the complete phase from and to Newhaven and Edinburgh Airport via Haymarket.
  - Tram Phases 1b, from and to Haymarket and Granton Square.
  - Tram Phase 2, from and to Granton Square and Newhaven.
  - Tram Phase 3, from and to Edinburgh Airport and Newbridge.
  - Tram Line Three to South East Edinburgh, from and to Haymarket and Newcraighall.
(4) *Scenario D – long term development,* reflecting Edinburgh's transport network after taking account of all the tram lines considered in Scenario C as well as re-opening ESSR (from and to Waverley and Niddrie via Haymarket including eight stations).

Six types of activity opportunities were selected to measure the accessibility to their locations by public transport within the Edinburgh Council's area. These are: (1) the central business district (CBD); (2) employment; (3) retail opportunities; (4) education opportunities; (5) health opportunities; and (6) leisure and recreation opportunities. SNAPTA uses the Scottish Census Data Zones (549 zones in Edinburgh Council's area) which are the key small-area statistical geography in Scotland based on 2001 Census with population between 500 and 1000 residents each (Scottish Executive, 2006b), so that contextual data on the population and socio-economic criteria can be used. The measurement assumes that all people living within a zone have the same level of accessibility regardless of their different travel demands.

The location and attributes of activity opportunities have been modelled in GIS (ARC/INFO). Land-use and socio-demographic data (at Data Zone level) including the total number of jobs, the floor space area of retail services and recreation facilities, and the number of patients in health care centres and hospitals, have been obtained under licence from the relevant government organisations. The data on the number of students in secondary schools and universities, and number of leisure and recreation facilities have been obtained from these organisations' websites. Once the required data are collected for each zone, they are linked to the associated centroids of zones within the GIS database. Since the model assumes that all individuals are gathered in the centroids where their journeys start and end, the determination of centroids are re-calculated on the basis of population density rather than geometric centres to avoid assigning population on non-residential areas such as parks and large unoccupied lands. However, in this study the accessibility impact of new transport interventions has been isolated from changes in the land-use system by fixing the data on activity opportunities in such a way that each zone holds the values of baseline year data on population, employment, retail, health, education, and recreation in all the scenarios.

A digital multimodal transport network of bus services, tramways and ESSR railways has been built in GIS. The network covers the whole area of study and consists of links and nodes. The nodes are chosen on the network to correspond to bus and tram stops and railway stations across the modelled area. For each transport link in the GIS data base, tabular attributes of its type, length and the time needed to pass that link have been built. SNAPTA takes into account walk access time from the origin, waiting time, in-vehicle time, interchange time and walk time to the destination.

Walk time is calculated as a constant multiplied by the straight-line distance from the origin (i.e. the centroid of origin zone) to the nearest public transport stop, from the disembark stop to the interchange stop, and from the final disembark stop to the destination (i.e. the centroid of destination zone). The calculation considers access to public transport services and interchange where the distance to a stop (or between stops) does not exceed 500 m, which is the maximum value of the range of 300–500 m walk defined by the Scottish Transport Appraisal Guidance (STAG) (Scottish Executive, 2003) as indicative criteria for an acceptable walking distance to bus stops in urban areas. SNAPTA uses the value of 1.2 as a constant multiplier for the straight-line distance in Edinburgh Council's area. This value is typically applied by the City of Edinburgh Council as a reasonable multiplier (personal communication with CEC). It is estimated based on the network patterns of

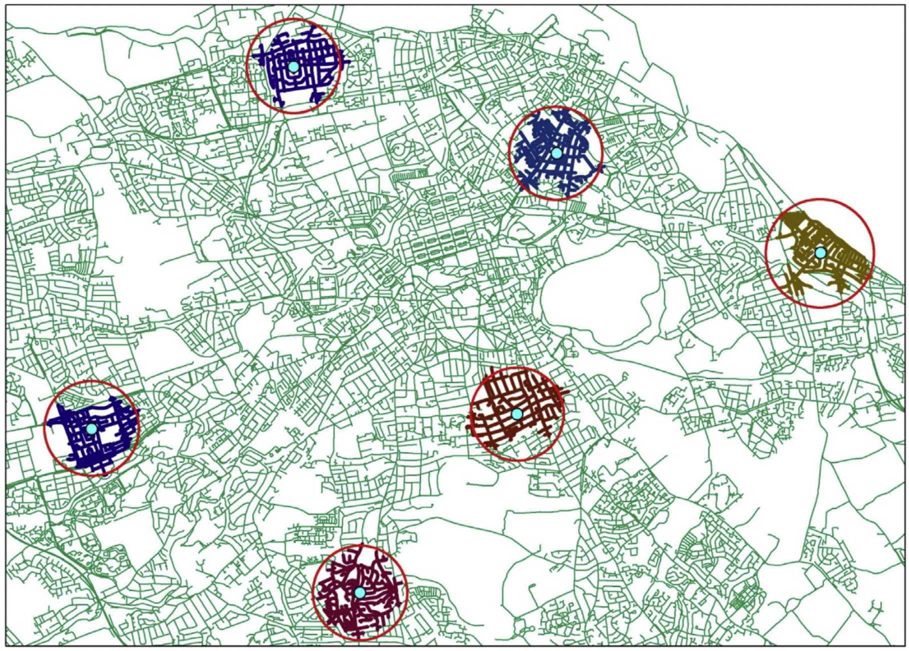

Fig. 4. Map showing how a multiplier of 1.2 is estimated based on a few example points around the city of Edinburgh with 800 m actual distance and 670 m radius circles. *Source:* City of Edinburgh Council, Services for Communities.

several example points around the study area with the 800 m actual distance and 670 m radius circles. Fig. 4 shows the location of six example points which have been selected randomly to estimate the multiplier value. Once walking distances are estimated, the model uses a walk speed value of 3 mph (or 4.83 kph) for average population to measure walking time (Jones et al., 2005 and Transport for London, 2010).

For the perceived walking time, the physical features that delay walk access from and to public transport facilities in the beginning and end of a journey are taken into account by estimating an extra walk time for each zone as a weighting value of walking time. This has been applied to slopes (e.g. for walking up a steep hill) and streets with heavy traffic volume which causes the delay before crossing. The total weighting value given to each zone is obtained by adding the slope weight up to 2 min to the traffic weight up to 2 min, meaning that the maximum extra walk time for each zone is 4 min.

Wait time at the stop of origin or interchange stop is calculated based on the minimum average of scheduled waiting time for the selected public transport service. For example, in the case of Edinburgh bus services, wait time is calculated using the scheduled waiting time for a service running every 10 min, since the most regular bus services in Edinburgh run with a frequency of 6 buses per hour during the morning peak time. This makes the minimum average of scheduled waiting time 5 min (0.5 * 60/frequency per hour) which is actually achieved by many services in the morning peak time. However, the trip calculations could also be performed with minimum wait time at the stop of origin (zero minutes), which occurs when an individual walks to the stop at precisely the time a bus/tram/train arrives.

The in-vehicle travel time of the currently running public transport services is calculated based on the timetables associated with the bus and tram stops or railway stations during the morning peak times, which already takes into account delay on the roads because of traffic congestion. The timetables of proposed services, particularly those for long-term development, are not all available at the time of analysis. In this case, travel time has been estimated based on the average time that a currently running service requires to pass through the same route or through another route which has the same speed limit and similar traffic volume.

Using the access time to city centre measure, accessibility is calculated based on the shortest journey time (or the fastest possible route) during the morning peak hours by public transport from the nearest node (bus stop, tram stop or railway station) in the network to the population-weighted centroid of each zone to the nearest node to the centroid of the CBD. The shortest possible journey time might be achieved by using one service only or though an interchange (one or more) between different services whether those services are provided by the same or different operators (i.e. Lothian Buses, FirstGroup Bus, E&M Horsburgh, Stagecoach Bus, Edinburgh Coach Lines) with the same or different transport mode (bus, tram or train).

The calculation of the potential accessibility measure is more complicated. It also involves the shortest possible journey times between any two zones using public transport. This generates a number of relationships for each type of opportunity which is equal to the number of origins multiplied by the number of destinations. Creating an origin–destination (OD) Cost Matrix is the technique that has been used in GIS to carry out the calculation of the shortest journey times on the network between zones. Once the travel time is computed for each relationship, the potential accessibility for the residents of each origin zone is obtained by applying Hansen's equation. A contour measure has been measured for each zone by calculating the size of the desired opportunity (land use attractiveness) that can be reached by using public transport from that node in the network nearest to the zone centroid within the specified cut-off travel time for the selected journey purpose. The study applied a cut-off value of 30 min for travelling to a large supermarket (for food shopping) and GP practice. A length of 40 min is applied to journeys for the purposes of work, shopping, secondary schools and leisure activities while 60 min is used for travelling to hospital and further and higher education institutions. These values have been identified by the Department for Transport (DfT) (2006) as the core accessibility indicators for the key public transport journey purposes. The

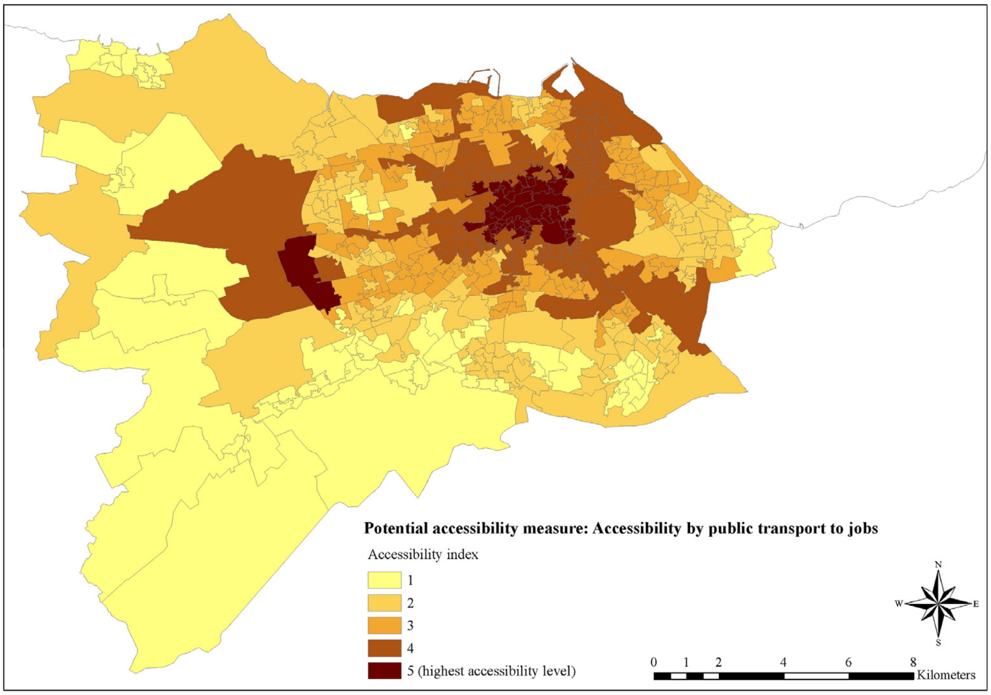

Fig. 5. Scenario A (baseline year 2011): accessibility to jobs (based on potential accessibility measure).

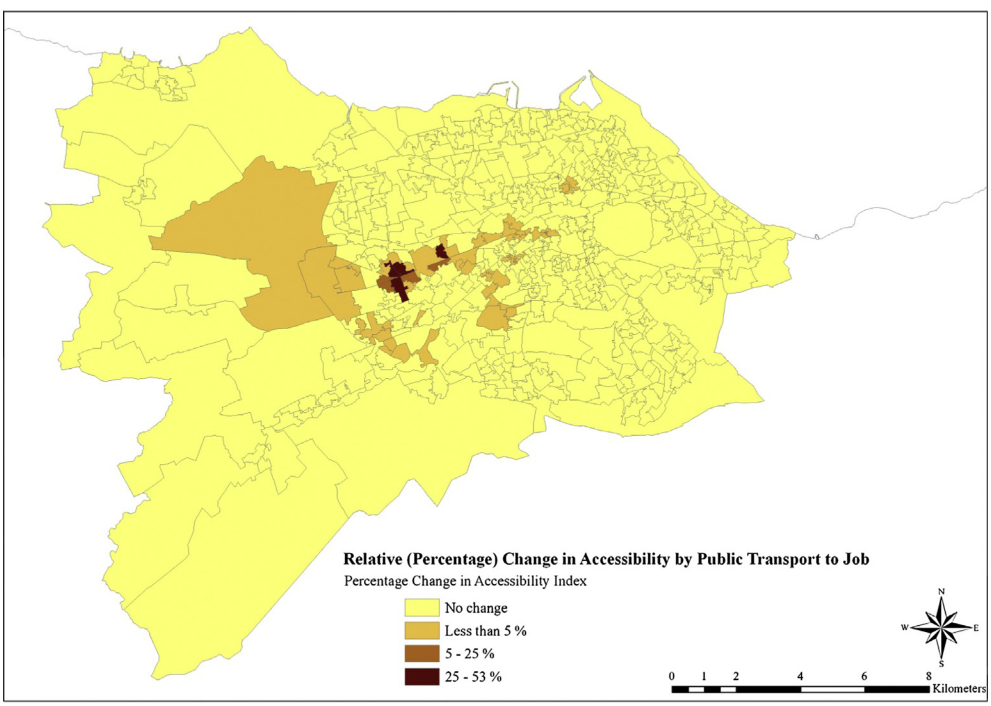

Fig. 6. Relative change (improvement) in potential accessibility to jobs between Scenario A and Scenario B.

variety in the cut-off values among different journey purposes can be explained by the fact that the choice of a supermarket and a GP practice is not as significant as the choice of leisure and education facilities. Closest Facility is the GIS technique implemented to execute this measure.

6. Findings

Once the calculations have been carried out, a simulation of the spatial distribution of accessibility is mapped in the GIS environment based on the sum of accessibility values that are generated for each zone acting as origin-location. Values of the absolute and relative (percentage) changes in accessibility between the baseline scenario and the development scenarios are computed to find out and demonstrate the contribution of the programmed transport infrastructure to the change in accessibility pattern to a particular activity across Edinburgh. Also, this allows a comparison of how the different measures incorporated in the model capture the accessibility changes.

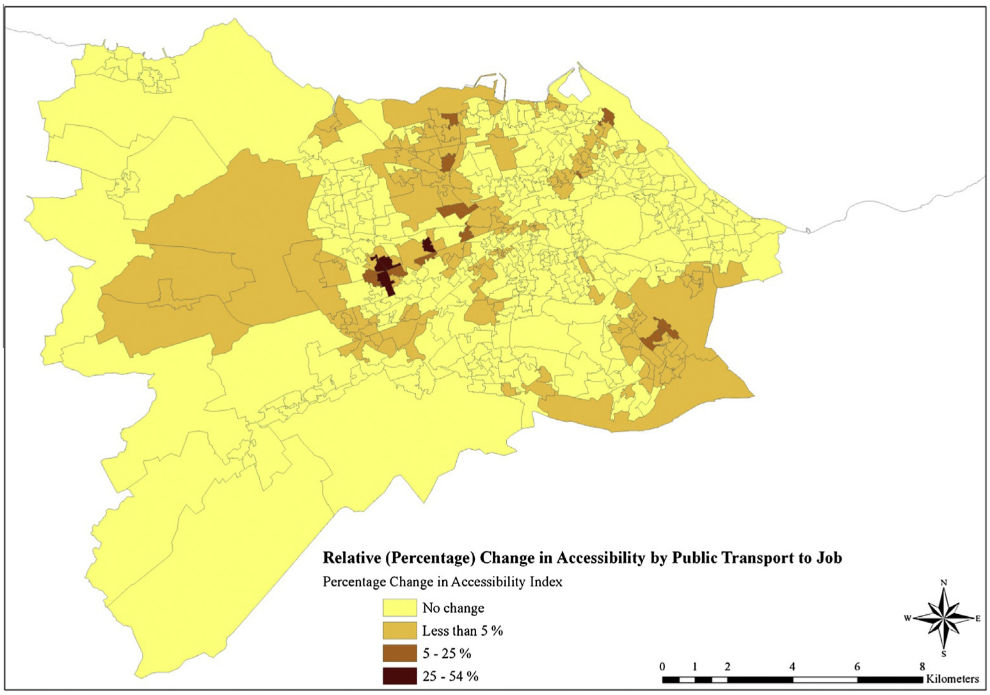

Fig. 7. Relative change (improvement) in potential accessibility to jobs between Scenario A and Scenario C.

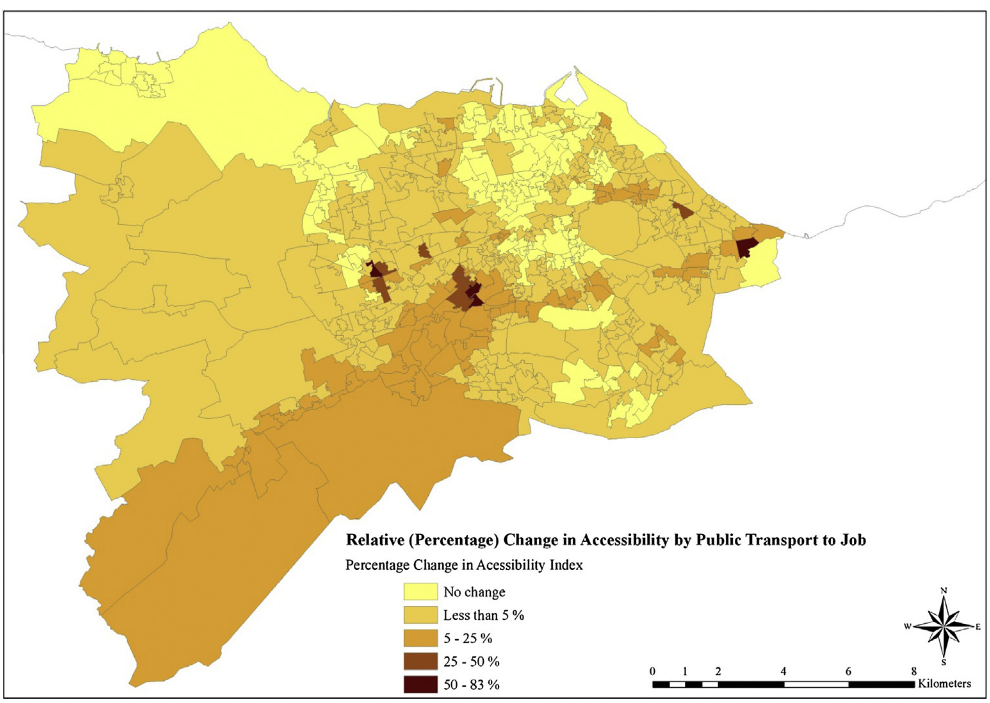

Fig. 8. Relative change (improvement) in potential accessibility to jobs between Scenario A and Scenario D.

The results of the accessibility analyses demonstrate interesting issues about the distribution of the impact of the tram and ESSR in Edinburgh. Due to space constraints, the results presented in this paper focus on the changes brought to accessibility to jobs only. The potential accessibility measure has been used taking into account the total number of jobs based in each zone as the attractiveness of destinations. It is not surprising that the analysis results of the current situation of the baseline scenario (see Fig. 5) and those of the development scenarios suggest that the zones with the best potential public transport accessibility to jobs during the morning peak time are located in the central area of the city followed by South Gyle Business Park in the west of Edinburgh. The map of relative change in accessibility to jobs between the baseline scenario and Scenario B after the completion of part of tram Phase 1a scheduled for 2014 shows that the spatial variation in accessibility is fairly small (Fig. 6). It indicates that the construction of the tram line from the Airport to the city centre has an insignificant impact on the potential interaction between most areas in the city for trips to the workplace, but has greatly improved the accessibility of some locations along the line by up to 53%.

According to Fig. 7, it is clear that the completion of all the tram lines considered in Scenario C has an impact on the accessibility of a larger area. The accessibility to jobs of the areas where the tram Phase 1b and the remaining part of Phase 1a are planned to run to in a loop around the northern suburbs, connecting the city centre with the Waterfront development site, has improved on average up to 5% with some locations having improvements of up to 25%. Similarly, in the south east of the city, Tram Line Three will improve the job accessibility of most residents by up to 5%.

A comparison between Scenario C and Scenario D identifies that overall, the predicted improvement on potential accessibility to jobs brought by the introduction of ESSR service to public transport network is significant. Fig. 8 shows that a considerable part of Edinburgh, particularly the south west of the city, would benefit by running ESSR with an accessibility increase of up to 25%. Moreover, the results highlight a substantial increase in the accessibility level of some zones around the city by up to 83% when all the tram lines and ESSR are implemented.

7. Conclusion

The model developed in this study is not intended to provide the complete picture of transport accessibility but it attempts to cover adequately the required aspects of accessibility measurement and respond to some common limitations in other models without making it very difficult to operate, interpret and, consequently, apply in practice. The challenge is not to argue that all the gaps addressed in SNAPTA are neglected in other existing models but it is more about building a practical accessibility model that could offer a balance between the ease of interpretation and operationalisation and the complexity of the theoretical basis and data disaggregation. The model has been tested and applied to the Edinburgh transport network, addressing the impact of the tram and ESSR on accessibility to different activities at a high level of spatial and data disaggregation of the land-use system.

The empirical conclusion obtained in this study has demonstrated the changes in potential public transport accessibility from the 2011 baseline case and through three different scenarios to the completion of the full infrastructure improvements identified in the Local Transport Strategy. GIS has been used to visualize the different types of data sets in map form portraying space–time accessibility to services and identifying the "hotspots" of unequal access. Whilst the current analysis provides information about the changes in accessibility between the 549 data zones, it cannot infer whether travellers' perceptions of the ease of reaching the facilities and services they require on a daily or weekly basis by public transport will also change.

The study has not looked into the factors central to understanding modal choice, which include cultural attitudes to specific transport modes and factors associated with gender, age, income and the number of hours spent working that influence travel behaviour (Weber, 2006). Although SNAPTA has been developed with a focus on public transport modes only which is considered as a serious limitation for some objectives, the model has the potential to include car-based modes as well. Therefore, further research will focus on enhancing SNAPTA by including accessibility by private car through building the road network taking into account the driving directions and the associated speed limits. In addition, the model will be expanded to cover a wider geographical area to assess accessibility and connections between the city of Edinburgh and the key destinations in the surrounding region such as major employment centres, universities and hospitals.

Acknowledgements

We are grateful to Damascus University, Syria which has financed this research and to participation in the COST TU1002 project. We also want to express our gratitude to the two reviewers for the comments and suggestions which have helped us to improve the paper.

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