Estimating the Social Impact of Reduced CO_2 Emissions from Household Travel Using GIS Modelling

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1 Introduction

In New Zealand 25% of the total CO_2 emissions are from household transport, and emission levels are increasing at a greater rate than the population (Walton, n.d.). The *Reduced CO_2 from Sustainable Household Travel* research programme aims to assist in sustaining a reversal in this trend. The programme regards CO_2 emissions as “a direct outcome of fuel use” and investigates Transportation Demand Management (TDM), and Transportation Supply Management (TSM) strategies that will assist in reducing fuel use and consequent CO_2 emissions (Huisman, 2005; Walton, n.d.).

However, any transport management strategies designed to reduce CO_2 emissions are likely to have social impacts. Therefore, one of the objectives of this research programme is to assess the potential social impact of reduced fuel use from changes in household transport. The basic premise taken by this research is that the social impact of reduced CO_2 emissions from household travel can be assessed by measuring associated changes in access to the resources and facilities that form an integral part of the social environment, and then to assess how this access changes under different transport mode scenarios.

This paper reports on the development of a household-level GIS model that provides a measure of accessibility for different types of households under a given time budget and under different transport mode scenarios. First, different measures of accessibility are reviewed. Next, the operational definition of accessibility underlying the GIS model is described. Finally, the paper reports on the implementation of the model and discusses current progress.

2 Accessibility

Accessibility is a widely used concept with a variety of definitions and measures, many of which are application specific. However, there are three common components in most definitions of accessibility. In a recent review of the accessibility literature Halden *et al.* (2005) identify three primary components of accessibility: 1) individuals, 2) desired activities and/or destinations and 3) the link between the individual and the activity. Thus, accessibility relates to people, their activities, and how they accomplish these activities.

It is important to note that the first component (i.e. the individual) could be substituted with “groups of individuals.” We are often interested in the accessibility of certain groups of people as opposed to individuals. The UK’s recent accessibility planning initiatives are an example of this in that they are designed to target socially excluded groups such as the elderly, people on a low income, disabled, and the young (Solomon and Titheridge, 2006).

In addition to identifying the three primary components of accessibility, the review by Halden *et al*. (2005) also provides two frameworks for thinking about accessibility. The first framework incorporates two views of accessibility: 1) the people perspective (i.e. the individual’s view) and 2) the service provider perspective (i.e. the destination or opportunity). From a people perspective, accessibility is about how easily an individual (or group) can get to a destination. From the perspective of a service provider, accessibility is about how easily a given destination can be reached. In the current research we are interested in social impact, and so we are concerned with accessibility from the people perspective.

The second framework provided by Halden *et al.* (2005) is in the form of three questions which help clarify our understanding of accessibility and which loosely correspond to the three primary components discussed earlier. The three questions are:

1. Who/Where? – accessibility is an attribute of people and places
2. What? – what are the opportunities/activities/destinations being reached
3. How? – what separates people and places from the desired activities and/or destinations (e.g. distance, time, cost, information etc).

The "who/where" question is interesting because it focuses on the contrast between the people-based view and the place-based view of accessibility. Traditionally "place" has been the central concept within all geographic thought, including accessibility definitions and measures. For example, the distance or "reach" measures of accessibility and the gravity-based measures of accessibility reviewed in Huisman (2005) are place-based. In other words accessibility is an attribute of a place. This view of accessibility is limited because it does not take individual variation into account, that is, a solely place-based approach ignores the fact that different people will want to access different things. It ignores the individual.

Focusing more on the individual has been a trend in accessibility research and applications, in both transport and geographic information science. For example, from the transportation and accessibility planning perspective there has been a recent re-focusing of accessibility as an attribute of people (e.g. Halden *et al*., 2005; The Transport Studies Group – University of Westminster, 2005).

Miller (2007) also suggests that geographic information science needs to evolve beyond a place-based perspective and include a people-based perspective that focuses on the individual in space and time. Miller argues that the increasing mobility and connectivity of people is making the relationship between people and place more subtle and more complex. It follows that, if we think about the relationship between people and place in terms of accessibility, it is also making the concept of accessibility more complex. This does not mean replacing the place-based perspective. Rather it means extending the place-based perspective to include a people-based perspective. Miller's ideas and arguments make a great deal of sense when applied to the area of accessibility definition and measurement, indeed, Miller seems to be theoretically formalising the emerging trend.

Miller's (2007) idea's come from the space-time perspective that is based on an approach to human activity that has it roots in classical Time Geography (Hagerstrand, 1970) and which incorporates constraints imposed by individuals' activities in space and time. The space-time perspective offers a powerful concept for measuring accessibility at an individual level, although these approaches require detailed data on individual space-time activities, which is not always available at the level required (Community and Quality of Life, 2002). These ideas are consistent with Huisman's (2005) argument that accessibility has less to do with place and more to do with the limited time budgets available for travel and participation in activities for both individuals and households.

3 Operational definition of accessibility

As stated above, the aim of the research is to assess the social impacts of future travel under reduced fuel consumption scenarios. For the purpose of this research, we require a quantitative model that can assess the changes in accessibility induced by strategies used to reduce fuel consumption. It is important that this model can be implemented independent of these strategies.

Accessibility varies across, space, time, and different types of people. So for the purpose of this research accessibility is viewed as a space-time phenomenon that is an attribute of both different types of people, and of place. For reasons addressed in Huisman (2005), this model handles the issue of “different types of people” by implementing a household-level model and grouping households into different types.

There are many options for implementing a household-level model of accessibility. Huisman (2005) summarises the three categories of options in Figure 1. Level 1 consists of reach- (or distance) based accessibility measures, which are simple measures of spatial separation. These measures are highly generalised and exclude any people-based factors like mode, activities and time budget. Level 2 consists of opportunity measures of accessibility based on the space-time approach and can be modelled within GIS as action spaces (Huisman, 2005). Level 3 derives information from observed behaviour.

LEVEL 1	**“*Pure*” access model** (REACH) ▪ Fixed time budget ▪ Fixed mode ▪ Fixed activities
LEVEL 2	**“*Microsimulation*” model** (SPATIAL OPPORTUNITY AND CHOICE) ▪ Travel time based ▪ Fixed or calibrated mode availability ▪ Extensions: Calibrate with collected data - Frequency of use - Destination weightings - Household classification - Mode-dependent trips - Choice sets
LEVEL 3	**“*Behavioural*” model** (REVEALED ACCESS) ▪ Actual activities/trips ▪ Observed mode choice ▪ Observed time budgets ▪ Preference variables derived from actual trips

COMPLEXITY

Figure 1. Options for household-level operational model (Huisman, 2005)

The operational measure of accessibility is calculated from the cumulative opportunities available to a household within specified or derived time budgets, represented as a function of travel time and time available at a range of facilities and activity locations.

Facility domains include:

- Educational
- Shopping
- Recreational
- Health
- Social
- Cultural

This model uses proprietary GIS methods developed by Huisman and Forer (1998) and Huisman (2006) to calculate the remaining time at a range of activity locations for a given time budget.

It is possible to derive:

1) the total travel and activity cost for a given set of activities (simple measure).
2) which activities can be accessed for certain minimum amounts of time (more complex measure).
3) remaining time at a range of activity locations for a given time budget (still more complex measure).

A household-level access index is calculated from an iterative simulation model that explicitly models travel mode for each activity as given by:

$$A_{ih} = \sum_{a} \sum_{j} O_{ja} T_{ijm} \qquad \textbf{(1)}$$

Where:

A is the accessibility for a household at location *i*
h represents a household type
a represents a set of activities
T represents the travel time separating locations *i* and *j*
m represents the travel mode
O represents the opportunities (activities) available with mode

Source: Huisman (2005)

The access index shown in Equation 1 is a summary of the opportunities available to a household of a certain type given a set time budget and specific modes of transport. The access index is being calculated for a household of a certain type (people-based) and at a particular location (place-based). This acknowledges that accessibility is a function of both place and people and that different types of people at the same place may have different needs and potentially different accessibility measures. Conversely, the same types of people who will have similar needs, but who live in different places may also have different accessibility measures.

Once the access index is calculated for each household, it can then be aggregated from the household-level to the desired spatial unit. The access indices can also be grouped by a range of variables including transport mode, household type, and/or types of activities in order to examine relative accessibility (Huisman, 2005).

The outputs from the model are a set of indicators that will provide a measure of the impact of fuel reduction strategies for specific household groups. It is important to note that the model does not aim to simulate activity choice or travel behaviour. Rather, it allows us to look at the relative levels of accessibility for specific household groups by specific modes of transport for meaningful periods of time under different fuel consumption scenarios (Huisman, 2005).

The operational definition of accessibility described by Equation 1 and reported by Huisman (2005) was validated by a qualitative interview study (Rose *et al*., 2005). This qualitative study showed that many of the factors relevant to household travel decisions align with the assumptions underlying the operational definition of accessibility.

4 Implementing the GIS model of accessibility

The GIS model is an iterative simulation model that explicitly models travel mode for each activity to calculate an access index for households based on the conceptual and operational definition of accessibility described in Huisman (2005) and formalised in Equation 1. The model is implemented using data from a variety of sources. From Equation 1 we can see that in order to implement the model and calculate the access index (A), we need to obtain values for each of the variables in the equation. This section discusses the data required as model inputs and then outlines the model process.

4.1 Data requirements

The data required to implement the model are based on the variables in Equation 1 and are summarised in Table 2.

Table 2. Model variables and corresponding data requirements.

Equation Variable	**Description**	**Data Required**
ih	Location (*i*) of a **household** of type *h*	Household locations; Household types
a	A **set of activities**	Activities undertaken by a household. Different household types will have a different set of activities.
T	**Travel time**	Transport network information including public transport and travel time along the network
m	**Travel mode**	Model input; Information about what modes households of each type typically use for each activity
O	**Opportunities** (activities)	Facility and activity locations

4.1.1 Household

This model is a household-level model and therefore data on residential household locations is needed. Creating a residential household dataset is a relatively straight-forward process, but care needs to be taken to make sure that only residential households are included. It is also important to take addresses with multiple households (e.g. apartment buildings) into account. Consequently the creation of the residential household dataset requires manipulation of several existing datasets:

- Address data obtained from Land Information New Zealand's Core Record System (CRS), which is the New Zealand government's system for recording cadastral information.
- Zoning and land use data obtained from the local councils.
- Postal address data obtained from New Zealand Post's Geographic Postal Address File (GeoPAF), which is a dataset that defines and locates residential and business postal addresses (New Zealand Post, n.d.).

A key factor in this model is the fact that different types of people do different types of things and therefore different people living in the same area may have different accessibility measures. Therefore, we also need to know something about what type of household is at each location. For example, does the household consist of a single person living alone, or is it a family with children, or a group of unrelated adults? Due to privacy issues these data are not available at the household level, but the five-yearly New Zealand Census of Population and Dwellings (NZ census) provides information about household types at the meshblock level, where a meshblock is the smallest area used to collect statistical information and typically contains approximately 100 people and 40 households (Statistics New Zealand, 2002).

Data from the NZ census are used to establish the spatial distribution of household types. Table 3 shows the household type definitions chosen for this model. These definitions were chosen to fit both the census household types and the travel survey household types (discussed in section 4.1.2 below).

Table 3. Model household type definitions.

Household Type	Description
1	Single person
2	Couple without children
3	Couple with children
4	Single parent with children
5	Multiperson
6	Other

The census data on household types are disaggregated into a synthetic household population using spatial simulation and simulated annealing techniques. Given the data on residential household locations (obtained from manipulating the CRS, PAF, Zoning and landuse datasets) and on the percentage of each household type within each meshblock (obtained from the NZ census), we can use spatial simulation techniques to assign each household a household type.

"Simulated annealing" is a term used to describe techniques that create synthetic microdata for individuals or households that match the socio-demographic characteristics of the small geographic areas of interest (Ballas *et al.*, 2006; Melhuish *et al*., 2002). This approach addresses the problem of the lack of spatially disaggregate data at the individual or household level (often due to privacy issues) by creating individual or household microdata. Typically the microdata generated by these techniques are then used as an input into a spatial simulation model, an approach that is becoming more common in the spatial arena as there are increasing microdata needs for microsimulation models (e.g. Anderson, 2007; Birkin 2006; Huang and Ottens, 2007; Tiglao, 2004).

4.1.2 Set of Activities

For each household type we need to establish what types of activities they carry out, and the modes of transport used for these activities. To achieve this we use data from the 1997/1998 New Zealand Travel Survey (NZTS). The 1997/1998 New Zealand Travel Survey contains data from approximately 14,000 people in 7,000 randomly sampled households between June 1997 and July 1998 and between April and May 1999 (Land Transport Safety Authority, 2000). Data about households and the trips made (including activity and mode) were collected over two consecutive travel days for each individual in each household.

The NZTS household data includes data on household type that corresponds to the six household types defined for use in the model (Table 3). The activity data categories include: home, work, education, shopping, personal business, and social/recreation travel. Note that these activity categories relate to the facility domains that are of interest in this model.

4.1.3 Travel Time

Travel time relates to the multimodal transport network and the time of day. In other words, we need to be able to calculate how long it will take someone to get from point *i* to point *j* at a given time of day for a given mode of transport. The base data collected to enable these calculations with the GIS were: road network data, including data on road speeds and congestion related to the time of day, and public transport data, sourced from the Auckland Regional Council.

4.1.4 Travel Mode

Information about how households of different types are travelling to their various activities was collected from the NZTS (described in section 4.1.2). Travel mode is also the key variable in the model because it is the main item of interest in the research question. The model allows variations in travel mode and show how accessibility changes under different transport mode scenarios.

4.1.5 Opportunities (activities)

Opportunities are related to activities in that an activity is what a person wants to do and an opportunity is a place which provides a person with that service or facility. Consequently, there are likely to be many opportunities for each activity. For example, if a person wants to go to a doctor, then the opportunities would be represented by all the General Practitioners, Hospitals, and Medical Centres that are accessible within a certain time budget. For this model opportunities are the locations of facilities and services within the domains of interest. The opportunities are obtained from a facility database that has been geocoded for New Zealand (Pearce *et al.*, 2006).

4.2 Model implementation and progress

The model is currently being implemented in ArcGIS 9.x (ESRI, Redlands, CA). Several components have been developed and the basic process for calculating the access index for individual households has been tested manually. This section describes the progress towards model implementation as it relates to the main model processes shown in Figure 2.

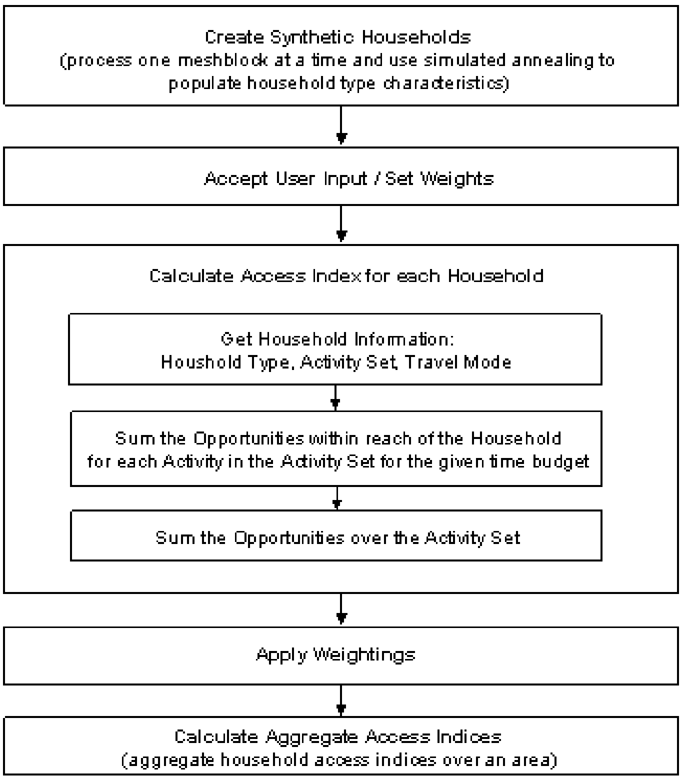

Figure 2. Model processes.

4.2.1 Create synthetic households

Synthetic households have been created by randomly assigning household type data to addresses within a meshblock. The percentage mix of household types within each meshblock was obtained from census data and used to randomly assign household types to each address. This random assignation of household type is a temporary process that will be replaced with simulated annealing at a later stage.

4.2.2 Accept user input / set weights

The main inputs into the model are the time budget in minutes, the number of trips per week, and a substitution percentage for each household type and activity set (e.g. shopping, recreation, education). The substitution percentage represents the number of trips that will be substituted by public transport and active transport. Figure 3 shows an example model input dialog.

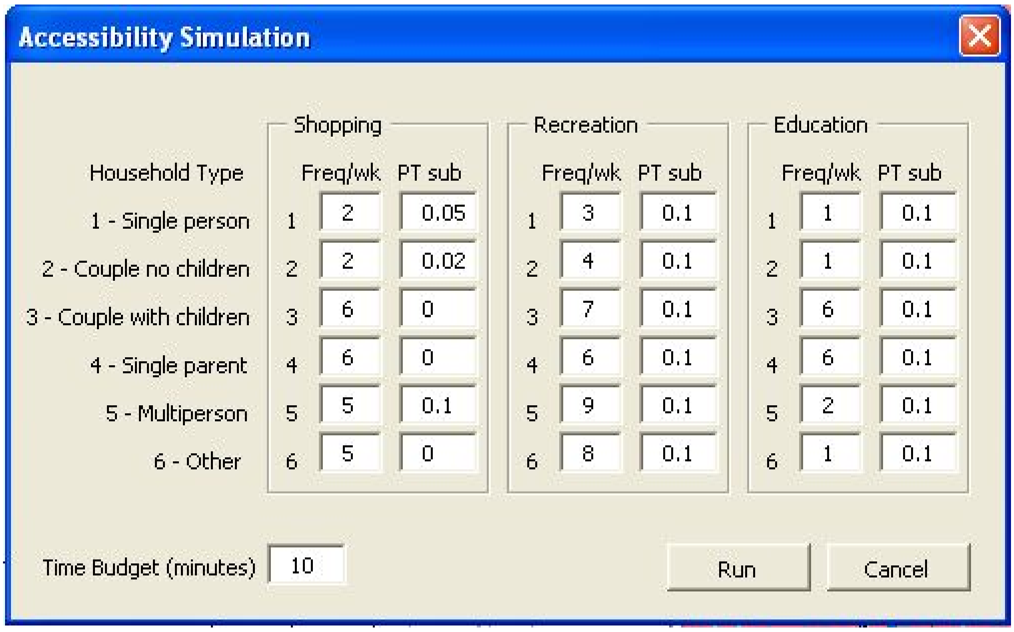

Figure 3. Example model input dialog.

4.2.3 Calculate the access index for each household

The manual process for calculating a basic access index for an individual household has been established. This manual process will be fine-tuned and then automated to form the core of the model.

In order to illustrate the concept of the model an example that calculates an access index for four households at two locations is outlined below.

Figure 4 shows the households that will be used in the example. Two different locations (Location 1 and Location 2) have been chosen in order to illustrate the place-based view of accessibility. At each location two neighbouring households (households A and B and households C and D respectively) of different household types have been chosen to illustrate the people-based view of accessibility, that is, how accessibility may differ for different types of people who live in the same location. For simplicity we will only use two modes of transport, driving and walking, in this example. The final model will include three modes of transport: driving, walking, and public transport. However, additional modes of transport (e.g. cycling) and differentiation between car drivers and car passengers could be included in later versions of the model if there are adequate data.

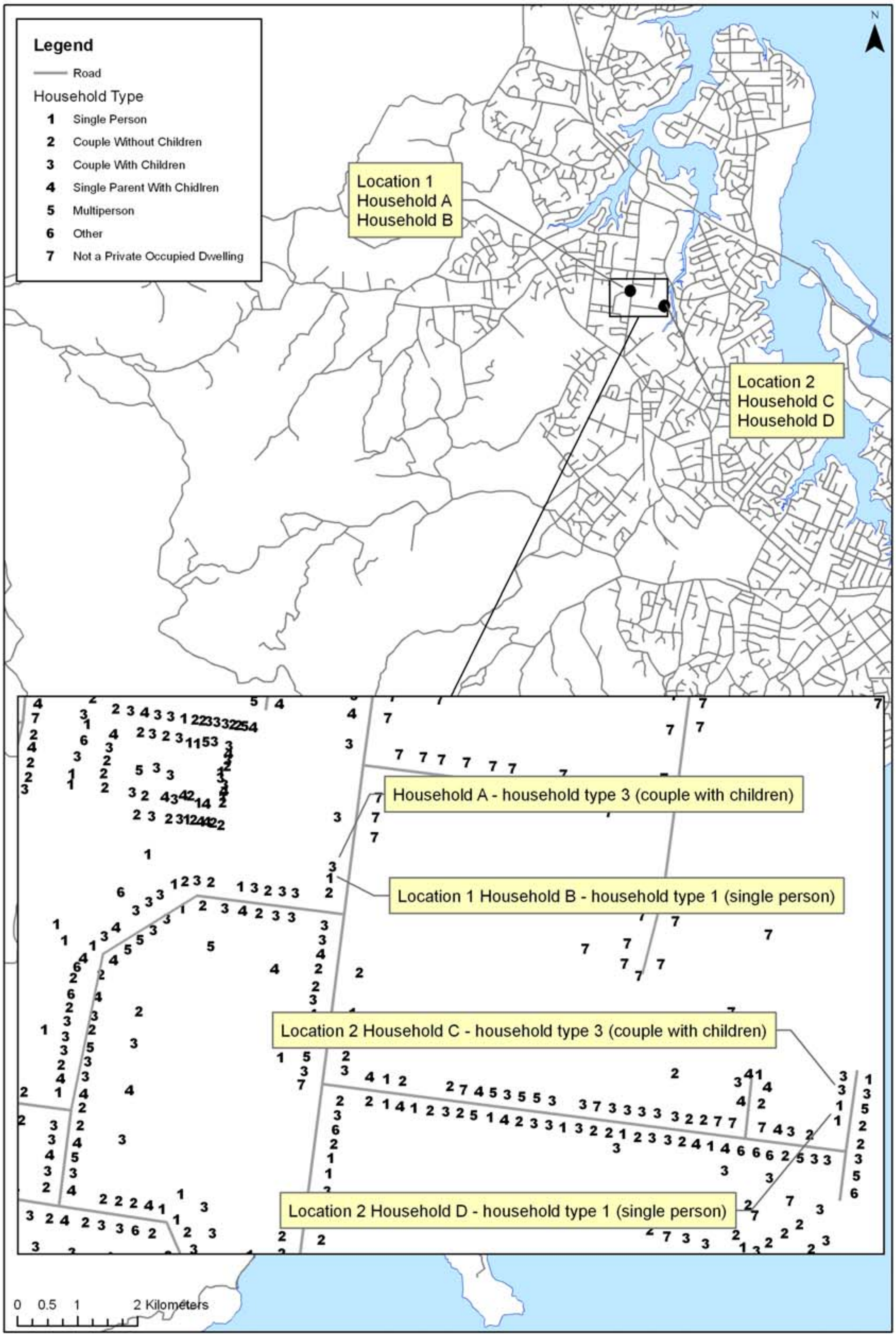

Figure 4. Location of example households.

The household information for the households is summarised in Table 4. For example, households of type 1 make on average 2.96 shopping trips per week, and of these 2.96 trips, 23% are via walking and 71% are via driving. The trip frequencies and mode percentages in Table 4 are loosely based on travel survey data but are not real data. When the model is operational these values will be input by the user in a similar manner to the example model input dialog in Figure 3. The time budget for the example is 10 minutes.

Table 4. Household information for the example household types.

	Household Type 1	**Household Type 3**
Shopping		
- trips / week	2.9	8.3
- % walk	0.23	0.18
- % drive	0.71	0.80
Recreation		
- trips / week	3.5	16.2
- % walk	0.31	0.18
- % drive	0.66	0.79
Education		
- trips / week	0.2	6.1
- % walk	0.33	0.33
- % drive	0.66	0.51

The next step is to calculate the number of opportunities for each activity set (shopping, recreation, education) that are within 10 minutes walk and 10 minutes drive of both locations. This is calculated using GIS functions. The walking and driving speeds are variables in these GIS functions and can potentially be included as model variables at a later stage.

Figure 5 shows the results of the GIS analysis, that is, the opportunities (e.g. schools, GP, dairy etc) that are within 10 minutes from each location for both modes of transport. For example, there are five educational opportunities within 10 minutes walk and 25 educational opportunities within 10 minutes drive of Location 1, respectively.

The location information (i.e. number of opportunities) is combined with the household information (Table 4) using Equation 1 to give an access index for each of the example households. The results are shown in the first column of Table 5. Change in accessibility under different transport mode scenarios is calculated using the same formula and modifying the values for the mode percentages. For example, given the same four example households and the same time budget of 10 minutes and a walking substitution percentage of 10% (i.e. 10% of driving trips are substituted by walking) we get results for a second scenario (Table 5).

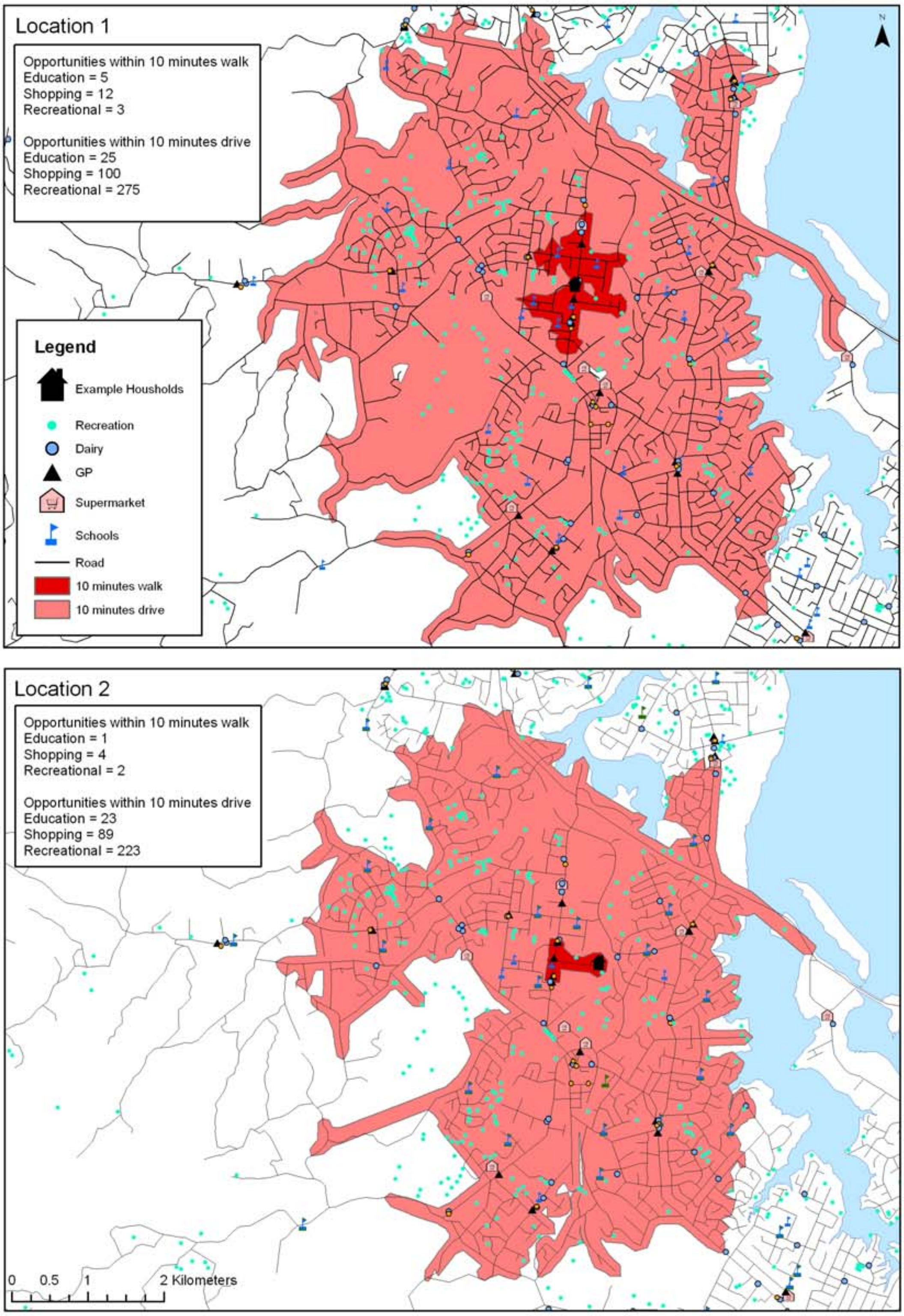

Figure 5. Opportunities accessible within 10 minutes walk and 10 minutes drive from the example locations.

Table 5. Example access indices for the four households under two 10 minute scenarios.

	Scenario 1 (no substitution)	Scenario 2 (10% substitution by walking)	Change in Access Index
Household A	4312	3786	526
Household B	886	762	124
Household C	3542	3100	442
Household D	731	626	105

The access indices represent the number of opportunities available to each household each week under a given scenario. For example, Household A is household type 3 in Location 1 and it has 4312 opportunities for shopping, recreation and education within a 10 minute time budget. Household B is also in Location 1, however, because it is household type 1 it has a different set of typical activities and therefore a different access index, that is, 886 opportunities for shopping, recreation and education within a 10 minute time budget. The different indices for different types of households at the same location illustrates the people-based view of accessibility.

Similarly, the place-based view of accessibility is illustrated by comparing households of the same household type at different locations. For example Household A and Household C are both household type 3, yet they have different access indices because they are in different locations.

We can estimate the change in access by calculating the difference between the access indices under the two scenarios. In our example the differences in the change in the access index could indicate that both location and household differences will lead to varied impacts to accessibility from a change in transport mode. However, it is important to note that the example and the results shown above are only given to illustrate the process and detailed interpretation of these example results is inappropriate. Further work is needed to ensure that the access indices calculated in the final model are meaningful.

4.2.4 Apply weightings

Once the basic model has been implemented the access index may be extended to incorporate weightings. These weightings would accommodate preferences for closer opportunities and for certain types of activities.

4.2.5 Calculate aggregate access indices

The model will calculate access indices for individual households. This will enable the access indices to be aggregated at a variety of spatial levels.

5 Conclusion

This paper describes progress in the development of a spatio-temporal household-level GIS model of accessibility to quantify the social impact of reduced CO_2 emissions from household travel. The model incorporates both people- and place-based views of accessibility as well as incorporating a temporal component through the use of time budgets. This is a more complex way of measuring accessibility and has greater data requirements. However, it is important to include people, place and temporal components because it acknowledges individual/group differences in required access to opportunities and available time budgets. The data requirements of an individual/group level accessibility model are a challenge. For this research, the data are not available at the required household level. This problem is addressed using spatial simulation and simulated annealing methods to disaggregate existing datasets.

The model is still being implemented and section 4.2 has outlined progress to date. Specifically, synthetic households have been created and a process for manual calculation of the access index for individual households has been established. The next steps are to: 1) ensure that the access index calculation is meaningful, 2) automate the access index calculation, 3) implement synthetic household creation using simulated annealing techniques, 4) test the model, and 5) implement a basic user interface.

Given the preliminary results from manual calculations of a) different types of households at the same location, and b) the same types of households at different locations, it seems that this approach may provide a useful method of estimating the social impact of reduced CO_2 emissions that takes into account both people- and place-based differences in accessibility.

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