Transport Energy Footprinting

Author: **_Stacy Rendall – BEng(Hons)_**

Consultant Researcher – Abley Transportation Consultants

stacy@abley.com

ABSTRACT

Transport Accessibility Modelling is an analytical method for understanding the ability of people to access goods, services and destinations by various transport modes. It is increasingly being used by local government bodies, both nationally and internationally, to assess the effectiveness of transport systems. This paper presents an extension of the Transport Accessibility Modelling methodology developed by Abley Transportation Consultants for the NZ Transport Agency. The new method characterises energy consumption required by residents to meet a defined Minimal Energy Activity System.

A new measure of Active Mode Accessibility (AMA) is introduced, defined as the proportion of Minimal Energy Activity System trips the resident population can meet by active modes or public transport. The Transport Energy Footprint is calculated as sum of trips that cannot be met by active modes. A high AMA indicates the transport activity system can be serviced with a low energy input, resulting in a greater resilience to fuel price shocks and constraints, and greater possible transport system energy efficiency. A low AMA reflects the contrary. The methodology also highlights activities that cannot be accessed by the resident population without transport energy.

In contrast to Milne (2011), which assesses the strategic-level travel efficiency changes of development proposals, this paper focuses on the hypothetical best-case energy efficiency of the transport system as a measure of energy resilience. The paper introduces a spatial method for calculating the AMA of a selected study area using a GIS-based tool that has been developed by the University of Canterbury Advanced Energy and Material Systems Laboratory in collaboration with Abley Transportation Consultants Limited.

The paper presents a case study comparing two areas within the greater Christchurch region. The Central Christchurch area results in an AMA of 100%, and a minimum petrol requirement for private vehicles of 0L/person/year because there is a high density of destinations and a wide range of local facilities available for every activity. The satellite township of Rolleston results in a significantly lower AMA of 59% and a minimum petrol requirement for private vehicles of 911L/household/year that is principally due to a lack of local pre-school and high school facilities and an insufficient diversity of destinations.

INTRODUCTION

The transport energy consumption of households is strongly related to the design and layout of the urban form (Cao et al., 2009, Bento et al., 2003, Frank, 2004, Sharpe, 1978). However, contemporary urban forms have been designed under the assumption that transport energy is cheap and readily available. This disconnect between rising transport fuel prices and urban form will affect access to goods and services, and may generate significant flow-on social and economic costs (Auckland City Council, 2008, Harward and Mussen, 2008, Gusdorf and Hallegatte, 2007). Obviously residents will have to adapt their transport behaviour and reduce costs when faced with energy constraints, but there are limits to the extent of possible adaptation, defined by the urban form.

The hypothesis of this research is that the underlying geographic form of an urban area has some proportion of the resident activity transport system that can be met by ‘active modes’; walking, cycling or public transport. The measure of Active Mode Accessibility (AMA) is introduced and defined as the proportion of activities that can be reached by active modes, given the population demographics of the study area. A high AMA means the resident transport activity system can be serviced with minimal energy input. Consequently there is a greater resilience to fuel price shocks and constraints and therefore greater possible transport system energy efficiency. A low AMA reflects the contrary.

In contrast to Milne (2011), which assesses the strategic-level travel efficiency changes of development proposals, this paper focuses on the hypothetical best-case energy efficiency of the transport system as a measure of energy resilience. The AMA method is based upon accessibility analysis, extending the depth of the NZ Transport Agency (NZTA) methodology that was developed by Abley Transportation Consultants, with energy-based activity modelling and defining a measure of energy-accessibility. This paper introduces a spatial method for calculating the AMA within a selected study area using a GIS-based tool for applying the method and presents two case studies.

BACKGROUND

Transport Energy Consumption and the Urban Form

The transport energy consumption of an individual is a function of travel mode, distances to selected destinations and the frequency of travel. These are in turn dependent on individual behaviour and factors of the built environment. Although transport behaviour is complex and varied, certain links with urban form are apparent. For example, residents of highly walkable neighbourhoods (those that feature higher population density, higher network connectivity and varied land uses) tend to engage in a greater number of shorter trips, which are more easily made by active modes. As a result, they partake in approximately twice the number walking trips per week compared to residents of low walkable neighbourhoods (Cao et al., 2009, Sallis et al., 2004, Frank et al., 2005, Ewing and Cervero, 2010).

Figure 1 provides an example of the differences between a walkable and non-walkable urban form in Christchurch. The diagram was produced in ArcGIS by creating a 1.2 km network service layer around a point in two suburbs and highlighting parks and commercial destinations. The analysis does not account for the amenity or safety of the network and facilities but provides a coarse indication of walkability. The Central City (a) has a transport network with higher connectivity, indicated by a greater effective distance coverable for the same walking time, and a much greater range and number of available destinations compared to Northwood (b). Studies show that the most influential factors relating to fuel consumption are destination proximity and the availability and practicality of alternative (non-car) modes. Both of which are complex products of population density, network connectivity and land use mix (Bento et al., 2003, Sallis et al., 2004, Frank et al., 2005, Ewing and Cervero, 2010, Gordon, 2008, Kenworthy, 2003). Figure 1 qualifies energy consumption differences between two urban forms although it does not predict current travel behaviour or quantify energy resilience.

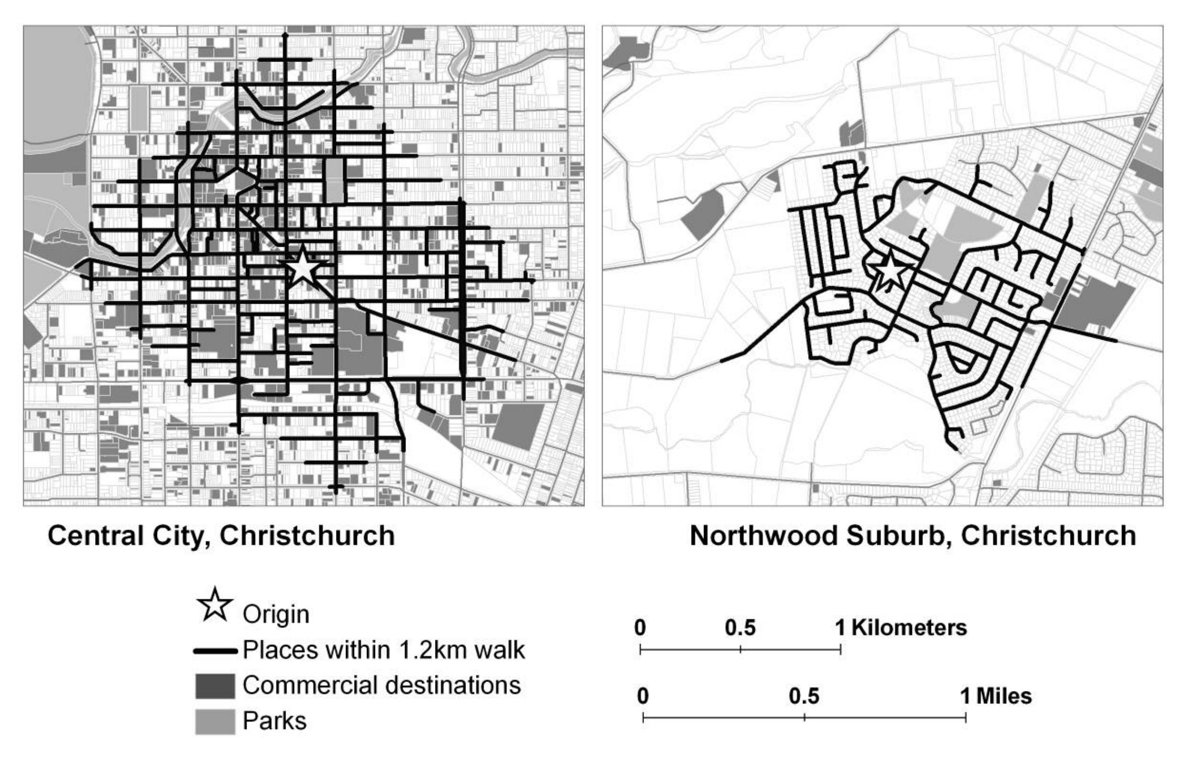

Figure 1: 15 minute (1.2km) walk along the road network in (a) the Christchurch central city and (b) Northwood suburb, Christchurch.

Energy Efficiency of the Transport System

In general, the concept of energy efficiency refers to "using less energy to produce the same amount of services or useful output" (Patterson, 1996). For a vehicle, energy efficiency is measured as the distance that can be travelled per unit of fuel input, for example litres of petrol. More broadly, energy efficiency is defined by the ratio:

$$\frac{\textit{Useful output of a process}}{\textit{Energy input into a process}}$$

The transport system is a complex product of residents, land uses and transport networks. The useful output provided by this system for its users is access to activities. The energy input to this system is the sum of fuel consumed in vehicles and human energy expended through physical activity. If a standardised definition of access to activities is utilised, the energy consumption required to meet this will constitute an efficiency measure.

Transport Adaptation and Resilience

To reduce the effects of both high fuel prices and potential fuel shortfalls, private transport users may have to modify their transport behaviour to reduce energy consumption (Krumdieck et al., 2010). There are five methods of transport adaptation: modifying travel time to avoid network peaks; chaining trips; changing fuel type; shifting to a more efficient mode; and changing destination, which includes participating in the activity without travelling (Krumdieck et al., 2010, Transportation Research Board, 1980, Chatterjee and Lyons, 2002).

If none of the adaptation methods is possible and the activity can no longer be accessed by car it must be forgone with consequent impact upon the individuals' wellbeing. The extent to which a user can adapt their transport energy consumption to reduce costs or meet constraints, without forgoing activities, is transport resilience. The extent of adaptation is limited by the nature and geography of the built environment and transport infrastructure (Chatterjee and Lyons, 2002, Transportation Research Board, 1980, Gusdorf and Hallegatte, 2007). A walkable form, such as that shown in Figure 1 (a), allows residents greater adaptability; alternative modes are more viable, due to shorter distances and higher density, and there are a large number and greater diversity of destinations available.

Short term fuel price increases tend to disproportionately disadvantage lower income households particularly where inexpensive housing is situated in low density suburbs near the urban fringe - both far from destinations and not adequately served by public transport (Transportation Research Board, 1980, Dodson and Sipe, 2005, Dodson and Sipe, 2006). However, supply disruptions which limit the availability of transport fuel, such as those experienced by western countries during the 1970's and in the United Kingdom in 2000, affect all residents. Higher income households still have a greater range of responses available such as purchasing a more efficient vehicle (Transportation Research Board, 1980, Chatterjee and Lyons, 2002, Peskin, 1980). During both historic fuel disruptions a large number of trips were forgone, including those for leisure, business and shopping activities. This indicates a lack of transport energy resilience that is partly a result of urban forms which did not allow residents to adapt, and resulted in further effects due to this lack of resilience on personal wellbeing, wider economic activity and retailers.

Accessibility Analysis

Accessibility is defined as the ability to access goods, services, activities and destinations; or "what, and how can it be reached, from a given point in space" (Bertolini et al., 2005, Yigitcanlar et al., 2007). Figure 1 highlights some of the precepts of accessibility; the central city is more accessible by all modes, including private vehicle because there is higher connectivity and a number of destinations are within easy reach, however, the walkability analysis neither includes public transport nor distinguishes destination types so the depth of the analysis is limited. A diverse range of metrics have previously been proposed to measure accessibility including methods for locational, individual and economic perspectives (Geurs and van Wee, 2004) and indeed further metrics continue to be developed (Abley 2010). Accessibility is often contrasted with the paradigm of transport mobility which is the ability to travel further, that then attempts to increase the throughput of the transport system (Miller, 1999). Planning for accessibility typically accounts for active mode and multi-modal options which are implicitly downplayed through the mobility analysis due to their lower distance coverage. Internationally, accessibility is increasingly becoming a policy goal; however, the criteria used in practice are often proxy measurements such as travel speed or time lost in congestion that are not particularly effective at evaluating the impacts of land-use and transport policy plans (Geurs and van Wee, 2004, Yigitcanlar et al., 2007, Straatmeier and Bertolini, 2008).

To better meet transport strategy goals, a number of GIS-based models have been developed in New Zealand and Australia that focus on measuring ‘person-based’ accessibility at the household level for a range of modes and destinations:

1. A model to quantify the social impact of policies to reduce household Carbon Dioxide emissions, embodied through changes in the level of accessibility (Mavoa, 2007).
2. The Land Use and Public Transport Accessibility Indexing (LUPTAI) model that seeks to measure how easy it is to access common destinations by walking and/or public transport (PT); it was the first model of its type to treat PT as a mode rather than a facility to be accessed (Yigitcanlar et al., 2007).
3. The comprehensive accessibility model developed by Abley Transportation Consultants Limited, a Christchurch-based company, which incorporates a flexible range of destination types and all modes including walking, cycling, PT and private vehicle modes and car parking (Abley, 2010).

However, accessibility analyses suffer from a lack of meaningful measures that are both theoretically sound and clear enough to be understandable for a variety of stakeholders and participants in the planning process (Bertolini et al., 2005, Geurs and van Wee, 2004). Additionally, the metrics often fail to distinguish the appropriate level of accessibility to be provided by the urban form. Geurs and Van Wee (Geurs and van Wee, 2004) identify the incorporation of activity-based modelling with accessibility indicators as one of their key paths for further research in the use of accessibility for the evaluation of land-use and transport strategies.

Activity Modelling

Application of activity based approaches in modelling urban travel demand is increasing within the field of transport research, and there is a growing body of literature detailing their use in practice (Algers et al., 2005, Iacono et al., 2008). Activity Models are definitions of personal- or household-level patterns of activity; periodic trips or tours are output for a given variable such as age, income, household composition or household status (Pas, 1988, Stopher et al., 1996, Wang and Cheng, 2001, Lee et al., 2009). The advantage of activity models over traditional approaches is their greater ability to account for behaviour changes, including responses to travel demand management (TDM) policies. The use of activity-based analysis is already widespread in time use studies and travel surveys; for example, the New Zealand Household Travel Survey collects trip data in terms of the activity purpose of the trip (Ministry of Transport, 2008). Some studies have utilised age cohorts to define ‘common activities’ that are performed at a homogeneous rate within the cohort; for example, pre-school through to secondary school education is an activity attended five times per week by children aged 3 to 17 (Saunders et al., 2008).

In this paper we propose an Active Mode Accessibility (AMA) characterization of the underlying geographic form and transport network for an urban area. AMA is defined as the proportion of activities that can be reached by active modes, including public transport, given the population demographics of the study area. A high AMA means the resident transport activity system can be serviced with minimal energy input; consequently there is a greater resilience to fuel price shocks and constraints, and greater possible transport system energy efficiency. A low AMA reflects the contrary. The AMA method is based upon accessibility analysis, extending the depth of the NZ Transport Agency (NZTA) methodology that was developed by Abley Transportation Consultants, with energy-based activity modelling and defining a measure of energy-accessibility.

METHOD

Theory

AMA is a behaviour-independent property of the built urban form. It is a function of population demography, distances to destinations and the viability of walking, cycling and public transport. AMA can be characterized as finely as at the single person or household level, but this study calculates it as an aggregate value at the census unit level within a defined study area. At this level AMA will: highlight activities that cannot be accessed by active modes; indicate how the transport network could be modified to increase active access; and produce a Minimum Energy Requirement for the study area by measuring the non-active travel required. The minimum energy requirement provides an energy footprint for the area, when compared to current vehicle travel.

The AMA analysis consists of three steps:

1. measuring both the travel time and distance along all networks from each residence to every activity (Accessibility Analysis using the NZTA methodology);
2. selecting, as a function of household demography and measured travel time, the mode for each destination; and
3. calculating the annual travel and fuel consumption, as a product of annual frequency, distance and mode.

AMA is the proportion of total activities that can be met by ‘active modes’: walking, cycling and public transport. Summing the number of trips and distances travelled by energy consuming modes, including public transport, produces a minimum energy requirement for the study area. Steps two and three of the method are based upon a *Minimum Energy Activity System*, constant over all study areas, defined by:

- Activity Model – yearly trips to activities, as defined in Table 1, by census age group.
- Mode Model – maximum travel time for each mode, by census age group.

Activity Model classifications were derived through an energy-based review of the relevant activity categories used in the New Zealand Household Travel Survey (NZHTS) and frequency sub-domains were applied to activities that possess a distinct frequency/facility split. Where relevant, facilities may occupy multiple domains. Annual trip to activity frequencies by age group are derived from the NZHTS responses for residents of urban areas.

Mode Model travel time limits for each mode and age bin are also derived from the NZHTS response data for residents of urban areas. The 90th percentile response within each age bin is utilised, after excluding responses for the trip purpose of recreational travel. Age, as opposed to income, has been selected as the defining variable for both models as maximum travel time and frequency by age reflect people’s ability and requirements. Income is a discretionary modifier of basic activity patterns, which goes beyond the scope of this research.

Both Mode and Activity Model values are generated from urban area responses within the entire NZHTS dataset. These are then weighted for the demography of each study area, to represent the varying ability and activity frequency of different age groups within the area.

Data required to implement the method for each study area includes:

- Census data of population age demography;
- spatial location of residences;
- spatial location of destinations, by activity classification; and
- transport networks for all modes (walking, cycling, Public Transport and private vehicle).

Model Structure

Assumptions:

1. Trends in basic activity patterns are determined by age group.
2. Residents are able to use the closest available facility for all destinations, except employment.
3. Employment is addressed separately by calculating the average travel time to reach a number of employment facilities. This value is currently hypothetical, but will be derived from the NZHTS and NZ Census data by measuring the number of employment opportunities, contained within Census units, that respondents travel past while accessing primary employment facilities.
4. Activity classifications contain multiple distinct destinations, this can be corrected for by assuming each destination attracts an equal share of trips to the activity.
5. All trips are assumed to be home based. However, annual travel, and hence fuel consumption, is weighted by a trip chaining factor derived from the NZHTS as the proportion of all non-home trips to the number of home trips.

Amenity and safety of routes and modes are not considered, neither is the ability to carry goods or passengers.

The model calculates then populates every household with the statistically average number of occupants of the statistically average age. The study area weighted activity model for households (*AMhh*) in the form of yearly household trips to activities, is calculated by summing the product of population count and personal activity frequency from the activity model (*AM*) per population age bin *(i)*, for each activity type *(j)*, and dividing by the number of households in the study area. Maximum travel times contained within the mode model (*MM*) are population weighted for each mode *(k)* by summing the product of population and age group travel time per population age bin to give a study area weighted mode model (*MMw*) that is also in time units. Network times for travel to each activity are calculated using a modified implementation of Dijkstra's algorithm (Wise, 2002, Eppstein, 2002). The output distance *(d)* is then tested against values within the population weighted mode model to determine the minimum energy mode for travel to the activity being considered. Household *(h)* distance to activity is then multiplied by the household activity weighting for each activity to give the total annual household travel to each activity. The net minimum travel demand to each activity in the study area can be determined by summing $AnnDist_{hj}$ within each activity for all households. Annual travel for each household is calculated by summing annual activity distances for all activities. Annual household travel is further summed for all households to give the net study area minimum travel demand. AMA is calculated in two ways:

1. *the AMA of four key destinations*; Primary School, High School, Grocery and Employment.

2. *the AMA of all trips*; the percentage of trips which can be made by active mode, which weights destinations of greater importance (higher trip frequency) within the study area.

A further summation of travel by energy consuming modes is also created, which, given an average fuel efficiency and study area population, can be used to determine the per capita minimum energy requirement of the study area. The Minimum Energy Activity System, which is constant over all study areas before population weighting, is a definition of energy transport level of service. Consequently, the minimum energy requirement is a measure of maximum transport system energy efficiency, weighted for the resident population. A lower per capita requirement means lower energy consumption is required to meet the same level of service, hence the transport system is more efficient. Energy footprint is calculated as minimum travel by private car compared to current travel for census units within the study area, which is derived from the national Warrant of Fitness database.

Application

Development has started on an implementation of the method as an extension to the Accessibility Methodology developed by Abley Transportation Consultants Limited for the NZTA. The existing accessibility model calculates travel times for walking, cycling, public transport and private vehicle modes to a flexible number of destinations. The extension of the NZTA methodology is fully described in the preceding sections and allows the model to be run at the City or Region level (depending on data availability). Further theoretical development of the project will increase the detail and sophistication of the model including the addition of a Monte Carlo simulation of population demography to enable a sensitivity analyses to be undertaken.

RESULTS

Two areas are compared; both from the greater urban region of Christchurch city. The results presented in this section are generated within an earlier version of the model than described in the Method section, the major differences are:

- the Mode Model is based upon travel distances, not travel time; hence, modes are selected based upon travel distance;
- Employment is not considered as a destination;
- Public Transport is not included; and
- distances to destinations within activity classifications are averaged.

Study Areas

The central city has a population of 5700, and is defined by an area within four main avenues covering nearly 7 km^2 over three Census Area Units as shown in Figure 2 *(a)*. The satellite town of Rolleston as shown in Figure 2 *(b)* lies approximately 20km from central Christchurch, has a population of 7000, and covers a land area of 11 km^2. It is comprised of one central Census Area Unit with populated areas overflowing into two neighbouring large rural Area Units; the study area includes only small sections of these adjacent units. The Rolleston road network is characterized by low connectivity cul-de-sacs while the central city is laid out in a grid pattern. Destinations were incorporated from both the study area and surroundings to avoid edge effects. For the central city a buffer radius of one census area unit, approximately 1km, was used for destination selection around populated areas to reduce edge effects. This buffer is shown in Figure 2 *(a)*, resulting in 1755 destinations in total, equating to 0.3 destinations per capita. A wider buffer of 5km was used for Rolleston, shown in Figure 2 *(b)*, and some destinations as far as 25km away were also included, to capture a suitable range of destinations. The Rolleston study included 103 destinations in total, equating to 0.03 destinations per capita.

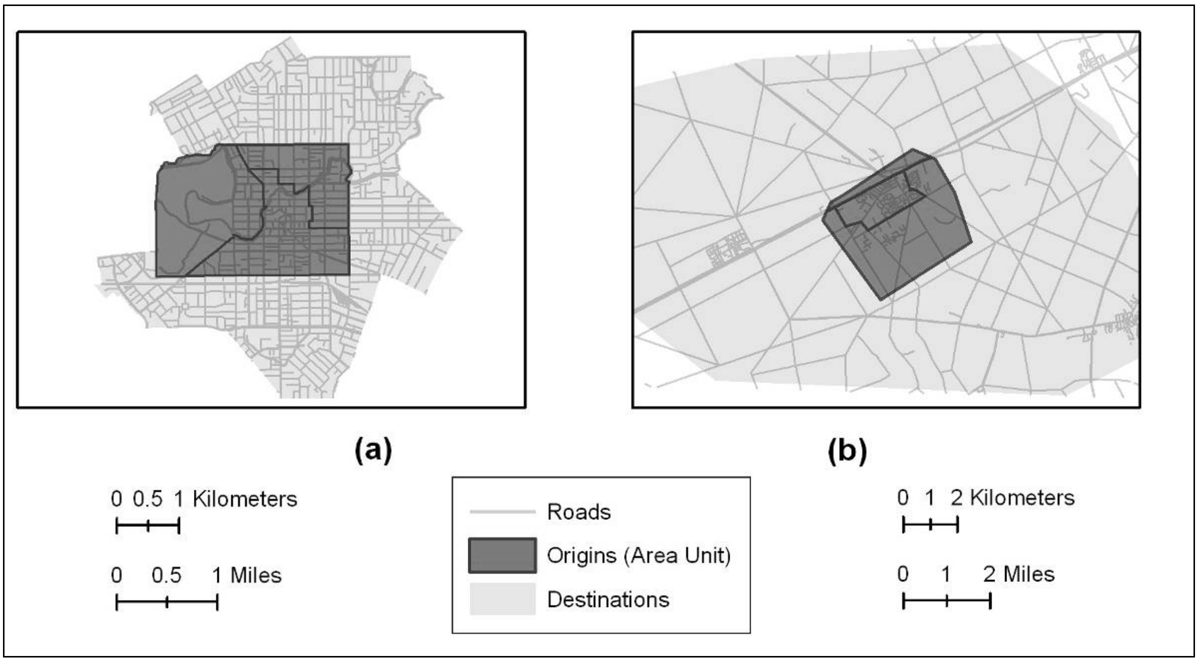

Figure 2: Study areas; central city (a) and Rolleston (b); size, layout and indication of destination selection buffers.

The population demography of each of the areas is shown in Figure 3. Rolleston has a much greater share of young families with children less than 15 years of age. The central city is largely dominated by young workers between 20 and 30 years of age, but interestingly has a slightly greater proportion of residents over 65 years than Rolleston.

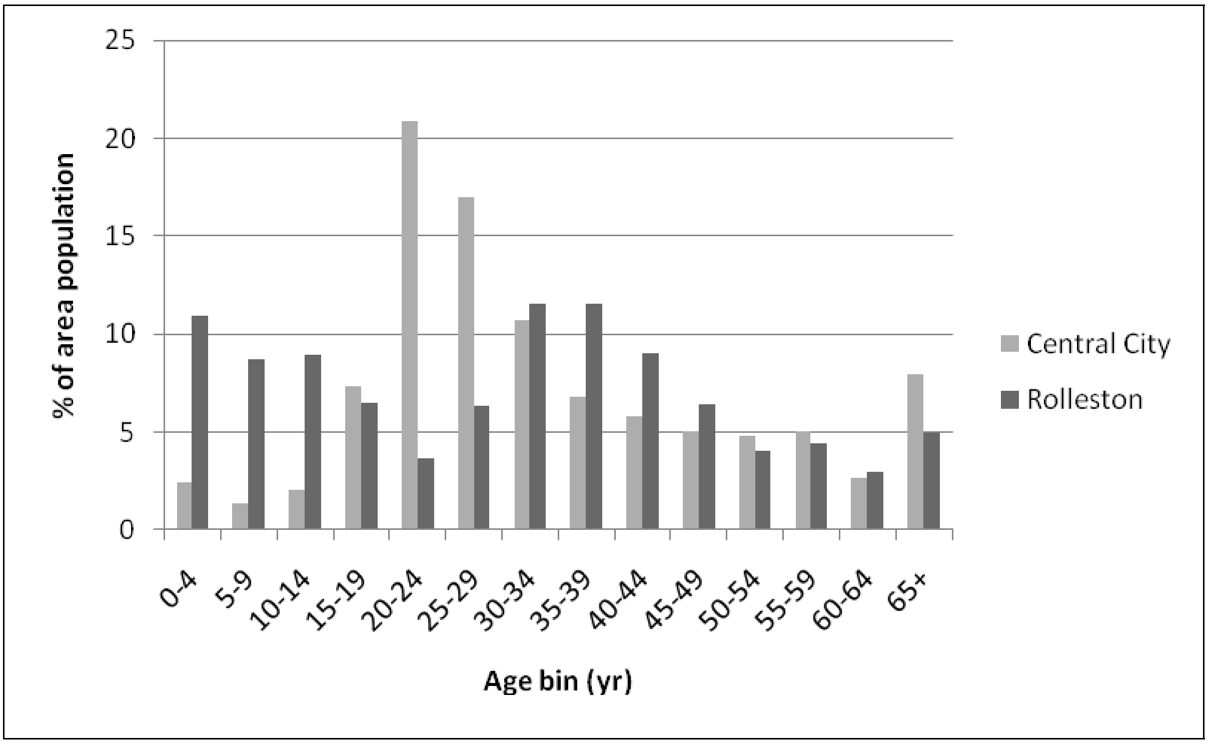

Figure 3: Relative population demography of the two study areas.

After weighting the age bin travel distances shown in Table 1 by the demography data in Figure 3, the average cycling ability for a resident in the central city is 6.7km and 5.8km in Rolleston. Walking abilities are 2.2km and 1.9km, respectively.

Table 1: Age bin travel distance by mode (before area demography weightng).

	0-4	5-9	10-14	15-19	20-24	25-29	30-34	35-39	40-44	45-49	50-54	55-59	60-64	65+
Walk	0	1.3	2.2	2.6	2.4	2.4	2.1	2.2	1.9	1.6	2.4	2.2	1.8	2.2
Bicycle	0	2.0	4.4	4.6	7.7	7.8	7.7	8.0	7.9	7.9	7.9	8.0	5.0	3.5

Model Results

Accessibility model results are displayed as the minimum energy mode required to access a number of activities; activities with frequency splits have been averaged. Almost all residents of the central city can access destinations via walking, as shown in Figure 4.

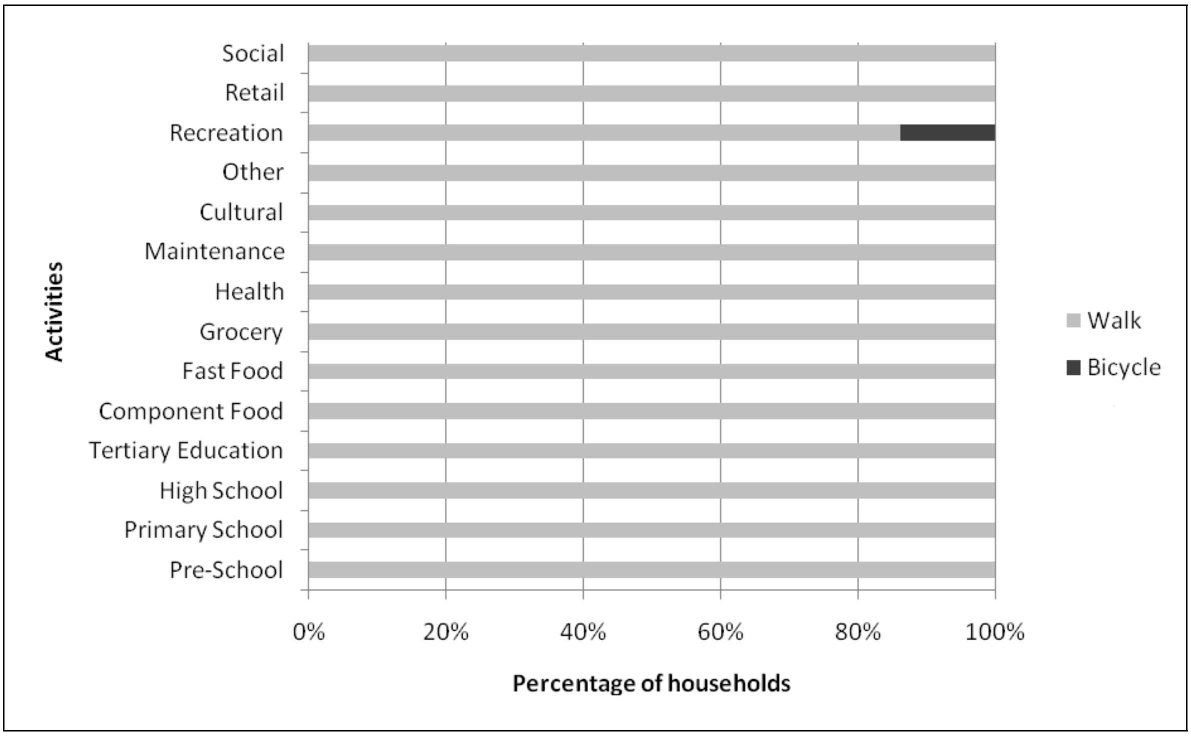

Figure 4: Minimum energy travel mode to capture activity for the central city.

Minimum energy travel mode is more varied in Rolleston, with a significant amount of car travel required as shown in Figure 5. Furthermore, the lack of diversity in local facilities within activity classifications, such as recreation, results in an average distance for many activities that is too great for active modes.

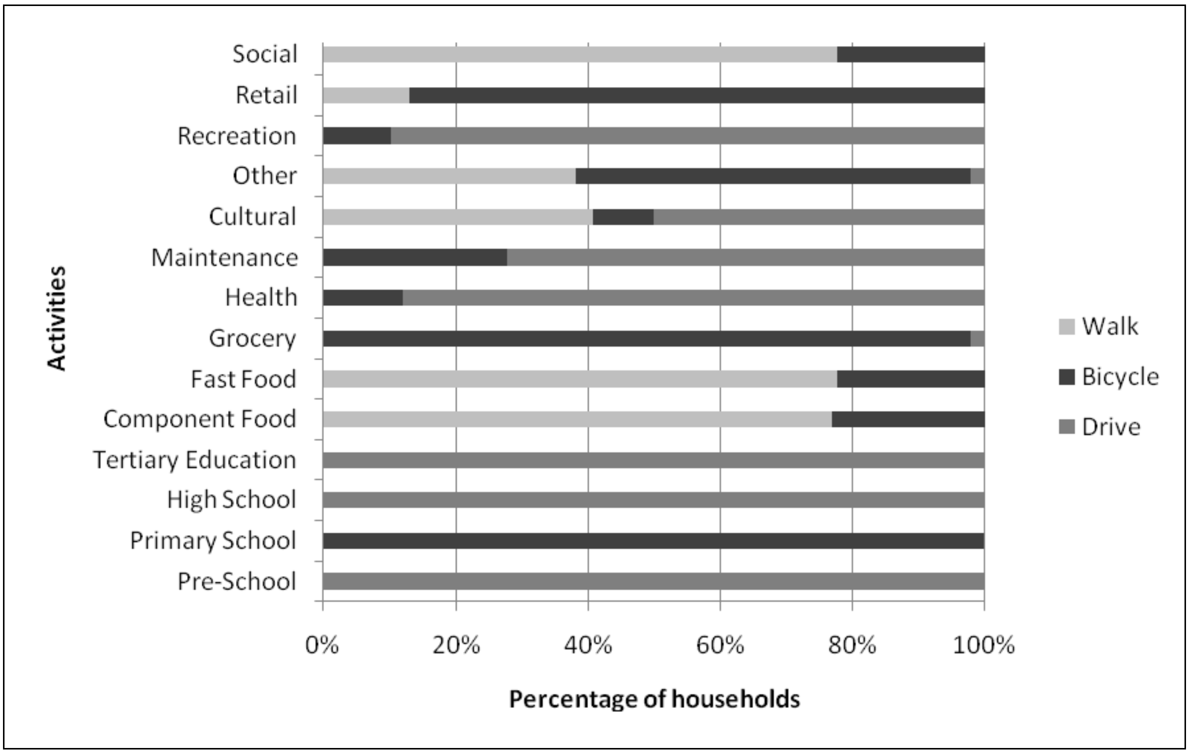

Figure 5: Minimum energy travel mode to capture activity for Rolleston.

Activity model results for each study area show that Rolleston residents are required to travel further than residents in the central city, the quantity of this additional travel is significant as shown in Figure 6. This figure shows $AnnDist_j$, the annual minimum household travel distance required for the activities. Given there are fewer destinations in Rolleston and road networks are not well connected, a greater amount of travel is required to reach activities. Furthermore, the greater number of children in Rolleston further increases the relative frequency with which education facilities are required to be accessed.

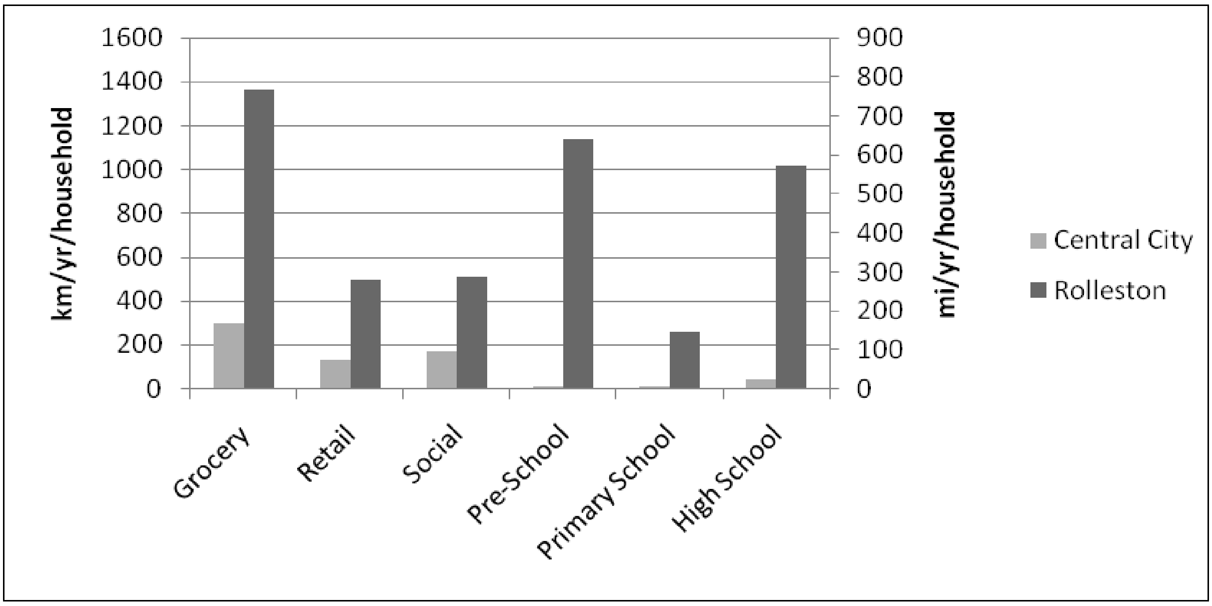

Figure 6: Annual minimum household travel demand for selected activities.

The range of net minimum household travel demand, $SumAnnDist_h$, for the central_city is 1,100 to 2,500 km/household/year, while the average is 1,700 km/household/yr. This corresponds to a fuel requirement of 170 L/household/yr, or a cost of 340 $/household/yr at current prices, if all made by private vehicle. Rolleston has a much higher range of minimum household travel demand; from 14,000 to 22,000 km/household/yr. This 8 to 12 fold increase is a result of the lack of proximate activity destinations, particularly pre-school and high school facilities, and the high proportion of school age children in Rolleston. The average minimum travel is 16,000 km/household/yr in Rolleston, corresponding to an average annual fuel requirement of 1,600 L/household/yr, a cost of 3,200 $/household/yr.

Within the central city both the AMA to key activities (Primary and High School, and Grocery shopping) and the AMA of trips are 100%, all activities can be reached by active modes alone. This indicates the resident activity system *could* function without any transport energy inputs; thus the minimum vehicle kilometres travelled (VKT) and fuel consumption are both zero and therefore zero cost. In Rolleston, the AMA to key activities is 66% and AMA of trips is 59%; fewer activities can be accessed by the resident population using active modes. There is a minimum VKT of 9,100 km/household/year and a minimum petrol requirement of 911 L/household/year that equates to about 1,800 $/household/year.

Discussion of results

The AMA method has revealed a significant quantitative difference in the resilience of the two urban forms. The results show that the satellite town of Rolleston has a much lower AMA than the Central City, having no pre-schools or high school, but a greater proportion of families with young children, and an insufficient diversity of other facilities. Consequently, Rolleston also has a higher minimum energy requirement. Notably, it is not the distribution of facilities within Rolleston that contribute to its low AMA, but the lack of local facilities for certain activities.

CONCLUSIONS

Urban form, transportation networks and travel behaviour are determinants of transport energy demand. The resiliency of transport activity systems to fuel price shocks and constraints has not been quantified before but it has historically been considered low for some contemporary urban forms.

This paper introduces Active Mode Accessibility (AMA) as a measure of the fuel resilience for a community with certain age, population and urban form characteristics. This novel method provides an understanding of, and empirically measures, transportation resilience and can be implemented using GIS and census data. The results represent a matching of the resident population demographics with the local accessibility of activity destinations. The AMA calculation introduced in this paper contributes both an important new understanding to future transport and land-use planning and quantifiable measures for maximum possible transport system energy efficiency and energy resilience.

The results of the two case studies investigated within this paper indicate some of the valuable outputs of this tool to better understand the factors that contribute to both transport resilience and vulnerability. The case study identified that access to education for children was particularly limited for the young families living in the satellite community of Rolleston. As both study areas are expected to significantly increase in population in the near future, these findings are valuable for future planning within the context of fuel constraints.

This new tool builds upon the work Abley Transportation Consultants has previously undertaken for the NZ Transport Agency. The further development of the AMA methodology and the ability to assess communities of different demographics yet similar urban forms provides practitioners with the ability to better understand planning applications and the effects of land use changes.

REFERENCES

ABLEY, S. 2010. Measuring Accessibility and Providing Transport Choice. *Australian Institute of Traffic Planning and Management National Conference.* Brisbane.

ALGERS, S., ELIASSON, J. & MATTSSON, L.-G. 2005. Is it time to use activity-based urban transport models? A discussion of planning needs and modelling possibilities. *Annals of Regional Science,* 39**,** 767-789.

AUCKLAND CITY COUNCIL. 2008. *Economic Analysis for Auckland, July 2008* [Online]. author. [Accessed 27 August 2008].

BENTO, A. M., CROPPER, M. L., MOBARAK, A. M. & VINHA, K. 2003. The Impact of Urban Spatial Structure on Travel Demand in the United States. Washington: The World Bank.

BERTOLINI, L., LE CLERCQ, F. & KAPOEN, L. 2005. Sustainable accessibility: a conceptual framework to integrate transport and land use plan-making. Two test-applications in the Netherlands and a reflection on the way forward. *Transport Policy,* 12**,** 207-220.

CAO, X., MOKHTARIAN, P. L. & HANDY, S. L. 2009. The relationship between the built environment and nonwork travel: A case study of Northern California. *Transportation Research Part A: Policy and Practice,* 43**,** 548-559.

CHATTERJEE, K. & LYONS, G. (eds.) 2002. *Transport lessons from the fuel tax protests of 2000,* Aldershot: Ashgate.

DODSON, J. & SIPE, N. 2005. Oil Vulnerability in the Australian City. Brisbane: Griffith University.

DODSON, J. & SIPE, N. 2006. Shocking the Suburbs: Urban Location, Housing Debt and Oil Vulnerability in the Australian City. Brisbane: Griffith University.

EPPSTEIN, D. 2002. Dijkstra's algorithm for shortest paths (Python). ActiveState.

EWING, R. & CERVERO, R. 2010. Travel and the Built Environment -- A Meta-Analysis. *Journal of the American Planning Association,* 76**,** 265 - 294.

FRANK, L. D. 2004. Economic determinants of urban form: Resulting trade-offs between active and sedentary forms of travel. *American Journal of Preventive Medicine,* 27**,** 146-153.

FRANK, L. D., CHAPMAN, J., BRADLEY, M. & LAWTON, K. 2005. Travel Behaviour, Emissions & Land Use Correlation Analysis in the Central Puget Sound. Seattle: Washington State Department of Transportation.

GEURS, K. T. & VAN WEE, B. 2004. Accessibility evaluation of land-use and transport strategies: review and research directions. *Journal of Transport Geography,* 12**,** 127-140.

GORDON, I. 2008. Density and the built environment. *Energy Policy,* 36**,** 4652-4656.

GUSDORF, F. & HALLEGATTE, S. 2007. Compact or spread-out cities: Urban planning, taxation, and the vulnerability to transportation shocks. *Energy Policy,* 35**,** 4826-4838.

HARWARD, E. & MUSSEN, D. 2008. *Fill up now before the fuel price shock hits* [Online]. Sunday Star Times. Available: http://www.stuff.co.nz/4576379a6442.html [Accessed 27 August 2008].

IACONO, M., LEVINSON, D. & EL-GENEIDY, A. 2008. Models of Transportation and Land Use Change: A Guide to the Territory. *Journal of Planning Literature,* 22**,** 323-340.

KENWORTHY, J. R. Year. Transport Energy Use and Greenhouse Gases in Urban Passenger Transport Systems: A Study of 84 Global Cities. *In:* The International Third Conference of the Regional Government Network for

Sustainable Development, 2003 Fremantle, Western Australia.

KRUMDIECK, S., PAGE, S. & DANTAS, A. 2010. Urban form and long-term fuel supply decline: A method to investigate the peak oil risks to essential activities. *Transportation Research Part A: Policy and Practice,* 44**,** 306-322.

LEE, Y., WASHINGTON, S. & FRANK, L. D. 2009. Examination of relationships between urban form, household activities, and time allocation in the Atlanta Metropolitan Region. *Transportation Research Part A: Policy and Practice,* 43**,** 360-373.

MAVOA, S. 2007. Estimating the Social Impact of Reduced CO_2 Emissions from Household Travel Using GIS Modelling. *30th Australasian Transport Research Forum* Melbourne.

MILLER, H. J. 1999. Measuring space-time accessibility benefits within transportation networks: Basic theory and computational procedures. *Geographical analysis,* 31**,** 187.

MILNE, A. 2011. Assessing Travel Efficiency at a Strategic Level. *IPENZ Transportation Group Conference.* Auckland: IPENZ.

MINISTRY OF TRANSPORT. 2008. *Detailed Travel Survey Information* [Online]. [Accessed 12th November 2010].

PAS, E. I. 1988. Weekly travel-activity behavior. *Transportation,* 15**,** 89-109.

PATTERSON, M. G. 1996. What is energy efficiency? : Concepts, indicators and methodological issues. *Energy Policy,* 24**,** 377-390.

PESKIN, R. L. 1980. Policy Implications of Urban Traveler Response to Recent Gasoline Shortages. *National Energy Users' Conference for Transportation.* San Antonio: National Academy of Sciences.

SALLIS, J. F., FRANK, L. D., SAELENS, B. E. & KRAFT, M. K. 2004. Active transportation and physical activity: opportunities for collaboration on transportation and public health research. *Transportation Research Part A: Policy and Practice,* 38**,** 249-268.

SAUNDERS, M. J., KUHNIMHOF, T., CHLOND, B. & DA SILVA, A. N. R. 2008. Incorporating transport energy into urban planning. *Transportation Research Part A: Policy and Practice,* 42**,** 874-882.

SHARPE, R. 1978. The Effect of Urban Form on Transport Energy Patterns. *Urban Ecology,* 3**,** 125-135.

STOPHER, P. R., HARTGEN, D. T. & LI, Y. 1996. SMART: simulation model for activities, resources and travel. *Transportation,* 23**,** 293-312.

STRAATMEIER, T. & BERTOLINI, L. 2008. Joint Accessibility Design: Framework Developed with Practitioners to Integrate Land Use and Transport Planning in the Netherlands. *Transportation Research Record: Journal of the Transportation Research Board*.

TRANSPORTATION RESEARCH BOARD 1980. Considerations in Transportation Energy Contingency Planning. Washington, D.C.: National Academy of Sciences.

WANG, D. & CHENG, T. 2001. A spatio-temporal data model for activity-based transport demand modelling. *International Journal of Geographical Information Science,* 15**,** 561 - 585.

WISE, S. 2002. *GIS basics,* London, Taylor & Francis.

YIGITCANLAR, T., SIPE, N. G., EVANS, R. & PITOT, M. 2007. A GIS-based land use and public transport accessibility indexing model. *Australian Planner,* 44.

ACKNOWLEDGEMENTS

The author would like to thank: Boffa Miskell environmental planning and design consultancy from whom the Central City origins data was acquired, on behalf of the Christchurch City Council; Steve Abley for reviewing and commenting on the paper; and Kit O'Halloran for his detailed review notes.