

Energy reliance, urban form and the associated risk to urban activities

Michael J Saunders, Susan Krumdieck and André Dantas

Abstract

Current transport energy supply is finite; it will peak and decline. Replacement renewable energy resources will not match current consumption levels. Transport systems will be subject to supply shortages and increasing constraints. Currently, transport planning does not consider energy supply disruptions or constraints. However, energy supply fluctuations and shortages severely affect transport systems. Spatial patterns and activity systems combine to produce the transport-energy requirements of a region. A newly derived method was created to assess transport-energy reliance for suburban/urban areas. The method differs from traditional transport modelling because it is concerned with energy capacity, not road capacity. Transport behaviour occurring within the built environment and activity system of a suburb are analysed. A case study was performed so that the derived method could be applied to a real situation. Simulations of behaviour modification produced a maximum of a 64% reduction in transport energy consumption for the study region. One hundred percent resilience/reduction (zero reliance on transport energy) was only achieved through modifying the spatial layout of the built environment. The method adds a new dimension to transport modelling: understanding the risk of reliance on transport-energy for suburban/urban areas.

Refereed Paper

This paper has been critically reviewed by at least two recognised experts in the field.

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INTRODUCTION

Transport planning needs to incorporate two new factors into transport system design and long range planning:

- a) temporary energy supply fluctuations/shortages
- b) systemic energy constraints.

Current transport energy supply is finite; it will peak and decline. Replacement renewable energy resources will not match current consumption levels. Therefore, transport systems will be subject to supply shortages and increasing constraints. Transport planning does not currently consider energy supply disruptions or constraints.

World energy resources become constrained when consumptive demand exceeds supply. Geophysicists estimated that world oil production would peak in 2005 (Deffeyes 2001). Renewable resources offer only a fraction of current energy supplied by finite sources. Extensive research has showed that renewable energy sources cannot replace finite sources at current consumption levels. Other researchers present similar findings: Taub (2003) believes that renewable energy capacity could, at most, be increased in the USA to 50GW by 2010, but this would only reduce gasoline consumption by 1%.

Transport-energy planning is not a part of transport planning. The most commonly used modelling tools make no provision for energy constraints, even though we know that energy supply fluctuations and shortages severely affect transport demand. The 2000 fuel protest in the UK illustrated the affect of energy constraints/shortages on transport systems. These effects included dramatically reduced car use and inability to access activities (Polak et al. 2001).

The transport system is a function of land-use planning and activity systems (Ortuzar and Willumsen 1994). Spatial patterns and activity systems combine to produce the transport-energy requirements of a region. Suburban development has created further spatial separation of activities (Silva et al. 2001). The increased travel distance required to access activities entails an increase in energy consumption. Land-use planning has to date not addressed the issue of reducing the separation of activities or modifying travel behaviour to meet an energy requirement.

We believe that energy can be included in transport and land-use planning. The transport-energy system of a region, which is related to the region's land-use, needs to first be modelled and analysed. A case study was performed for one activity of a suburb that demonstrated how energy can be included in transport and land-use planning. Ultimately, the method could be used to develop strategies for urban/suburban areas that would allow residents to access activities without reliance on transport energy.

This paper is divided into five sections. The next section presents the background theory used to develop the method to assess the reliance on transport-energy. The transport-energy method is then presented in the following section. Application of the method to the case study is described in the fourth section. The final section comprises the conclusions and introduces recommendations for future studies.

BACKGROUND THEORY

Two different levels of analysis were used in the method: strategic analysis and component analysis. Strategic analysis defines the holistic system goals and then identifies the critical system components. Spatial patterns and travel behaviour were identified as the critical components of the transport-energy system. New transport models were then created utilising Monte Carlo methods to analyse these components.

Traditional transport engineering and modelling involves the assessment of current demand for transport and estimation of future transport demand requirements. The newly derived transport-energy models differ from traditional transport modelling because they are concerned with energy capacity, not road capacity. In traditional transport modelling, travel cost is represented as an impedance to travelling. Generalised travel cost is a function of distance, time, travel taxes and fuel costs. As cost increases, trip lengths decrease, altering the trip length distribution. Our transport-energy models are independent of an impedance function because it is assumed that all residents will continue to perform trips from their house to required activities (e.g. shopping for food; work; recreation) regardless of cost or system failure

Variables of the transport-energy models include only:

- trip length distribution
- vehicle energy consumption

- trip frequency
- mode choice.

Trip length distribution for required activities is assumed to be dependent only upon the spatial pattern of residences and activities of the study region. Trip assignment is not a vital part of the derived method. It is assumed that all residents have no choice in their access to activities and will access the closest available activity. In a fuel crisis, with reduced ability to travel, this situation is more likely to occur. Trip distances from residences to activities are calculated using geographic information system (GIS) transport modelling software.

Behaviour variables (trip frequency and mode share) are only affected by an energy constraint and are independent of any other variables. A reduction in trip frequency or mode shift to non-vehicle modes will correspond to a reduction in energy consumption, as all non-vehicle modes (e.g. walking, cycling, horseback etc.) are assumed to require zero transport energy. Transport energy is considered as liquid fuel such as petroleum or electric energy.

The described variables are a function of transport-energy reliance and are used in the models to calculate transport-energy consumption. Each variable is represented as a probability distribution. Numerical methods used for the models comprise of simplistic mathematics and Monte Carlo methods.

Monte Carlo sampling refers to the traditional technique for using random numbers to sample from a probability distribution. Monte Carlo sampling techniques are entirely random. Any given sample will fall somewhere within the range of an input distribution. Samples have a higher probability of falling in the area of the distribution that has a higher probability of occurrence. Each Monte Carlo sample uses a new random number with weighted probability. With enough iterations, Monte Carlo sampling will recreate the input distribution. This sampling makes multiplication or addition of probability distributions a simple process. Individual samples from one distribution can be multiplied by samples from another distribution. Both distributions can be multiplied to produce a new distribution (as shown in *Figure 1*).

The distributions used in the models are density functions, so that the area underneath the distribution is equal to one. The average value of the probability distribution occurs where exactly half the distribution

density occurs above the x-axis value and half below. The y-axis values for density distributions do not have absolute probability values because of the requirement for unit area. The y-axis values are relativistic; a probability of 0.2 is two times more probable than 0.1. Distributions were manipulated for our models using a Microsoft Excel 'add-in' program, @Risk.

THE TRANSPORT-ENERGY METHOD

The method was created to assess the reliance of a suburban/urban area on transport energy in its current state and with modifications to its spatial layout. The method also assesses the ability of the study region to cope with temporary energy supply fluctuations and systemic energy constraints. The method analyses specific transport behaviour and built environment variables that determine how residents access required activities. Each activity is analysed separately.

The level of non-reliance on transport-energy determines the resilience of the suburban/urban area. The dictionary definition of resilience is: the ability to recover quickly from illness, change, or misfortune; buoyancy. The exact definition of the resilience of the built environment for the method is —

the percentage reduction from the current transport energy consumption of the built environment to the minimum feasible consumption possible. 100% resilience occurs when no transport energy consumption is required to access the required activity.

The minimum feasible consumption is a determinant of residents' ability to change their behaviour, (residents' flexibility). If all residents are able to continuously access the activity of interest using non-motorised modes, the built environment is defined to be 100% resilient regardless of the current level of energy consumption.

Figure 2 illustrates the steps of the derived method, which are summarised below.

Step One: Define the system for study which consists of the study region and behaviours of residents completing their required activity.

Step Two: Define the physical and behavioural variables of the study region and estimate the current energy consumption using the energy model.

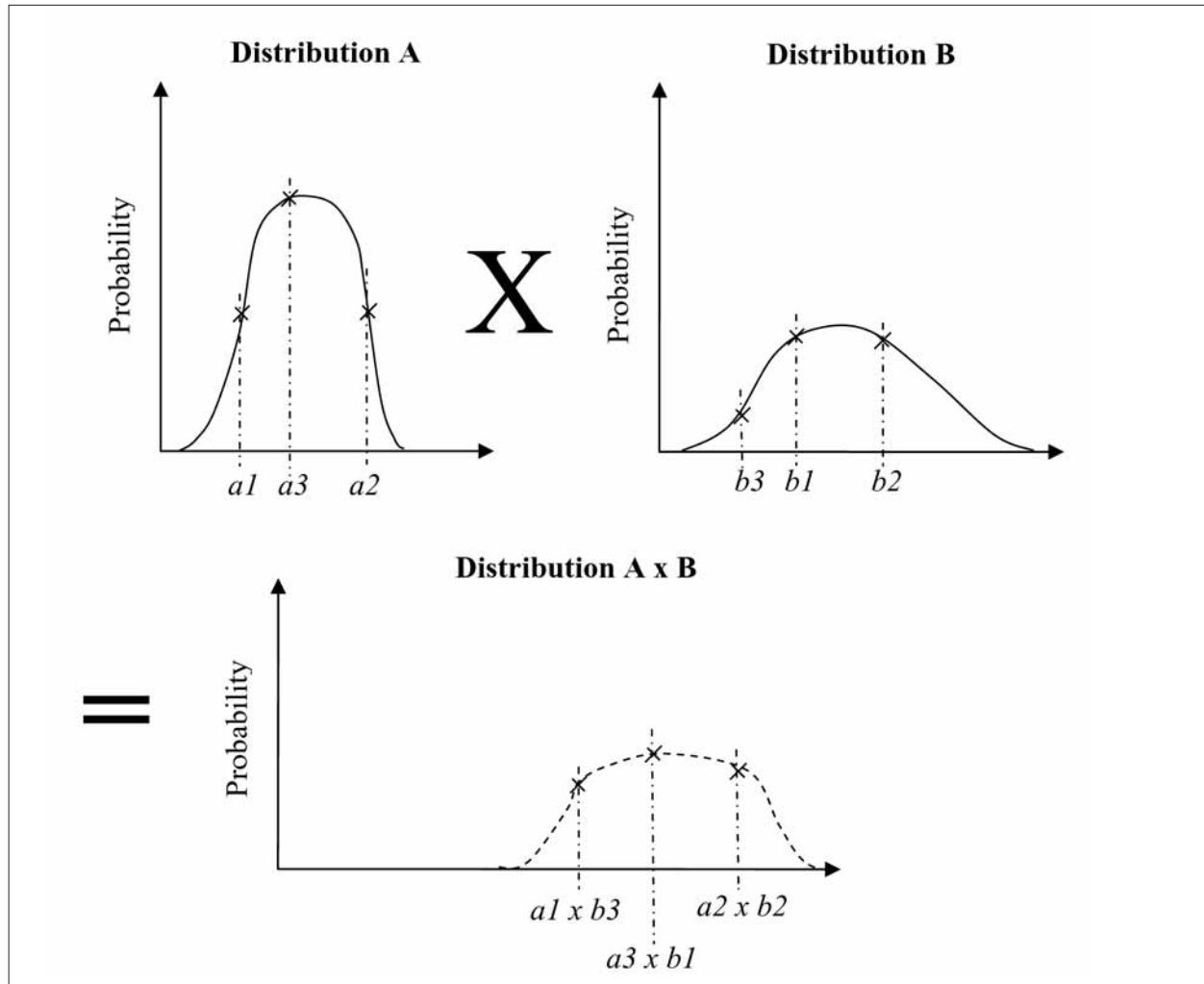


Figure 1
Illustration of multiplication of distributions using Monte Carlo methods

Step Three: Perform a risk analysis of the ability of the current built environment to provide accessibility to the required activity in response to a transport energy shortage. Define the limits for behavioural changes of the residents.

Step Four: Simulate transport-energy constraints by changing the model's behaviour variables to determine the resilience of the built environment.

Step Five: Modify the built environment of the model by changing the spatial layout of activities and vehicle type characteristics and determine the new resilience of the modified built environment. Continue to modify the built environment of the model until it is 100% resilient.

Step Six: Analyse the effectiveness of behavioural and physical changes to the study region.

The system for study comprises of an urban or suburban area with one activity isolated for study. The energy used by the residents in the study area to access the selected activity is assessed.

To create the model and perform the calculation (step 2), the variables first need to be defined. The built environment consists of two variables: trip length (TL_i) from the household to the required activity and energy consumption (EC_i) of the mode used to access the activity. Residents' behaviour also consists of two variables: trip frequency (F_i) and mode choice (M_j). Dimensional analysis shows that simple multiplication of the variables (TL_i) (e.g. km/trip) by (EC_i) (e.g. litres/km) by (F_i) (e.g. trips/week) produces a fuel consumption (e.g. litres/week) for each mode for the study region. The data for TL , EC , and F is converted to distributions that fit the real data as close as possible for multiplication by Monte Carlo methods. This involves creating probability distribution

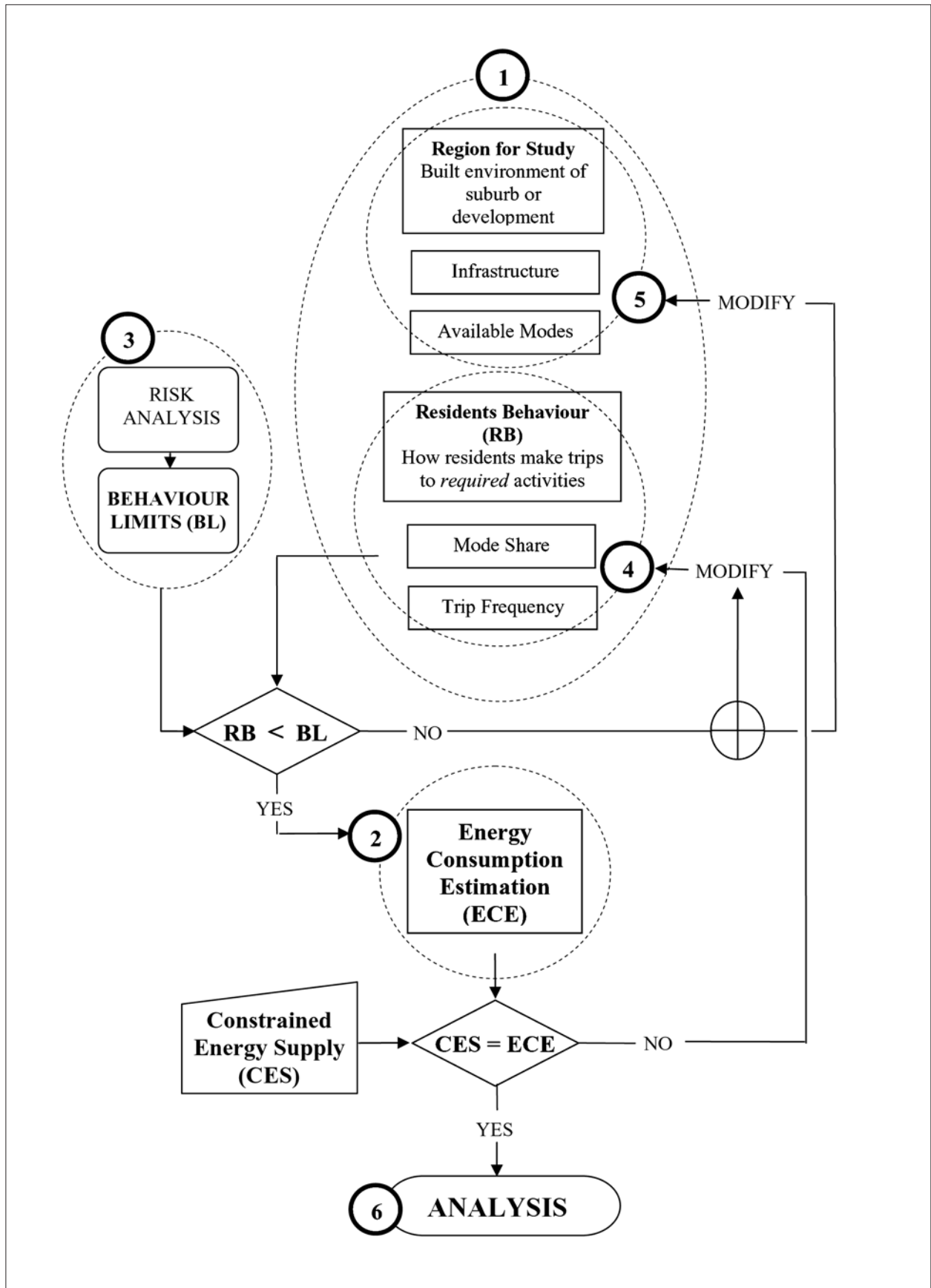


Figure 2
Overview of sequence of steps for the method

functions TL_{Dist} , EC_{Dist} , and F_{Dist} for each mode (M_j) that estimates the data for the combined individual TL_i , EC_i , F_i values. The @Risk program has a function that allows the data to be fitted to the best distribution, e.g. Weibull, Normal etc. These are used by the @Risk program for multiplication by Monte Carlo methods to obtain a complete resultant probability distribution of the energy consumption for the study region.

Separate energy consumption and trip length distributions are calculated for each mode, noting that some modes produce zero energy consumption (e.g. walking). The energy consumption for each mode is then summed to produce the total energy consumption (e.g. litres/week) for the entire region (for all modes from: $j=1$ to m) as shown in Equation 1.

$$E = \sum_{j=1}^m TL_{Dist} EC_{Dist} F_{Dist} M_j \quad (1)$$

The risk of loss of accessibility faced by residents (step 3) is dependent upon their reliance on transport fuel. High risk is therefore defined as a high level of reliance on transport fuel. This reliance is a function of the built environment and the individual characteristics of the residents. Most residents will be able to modify their behaviour to decrease reliance on transport fuel; however, there will be limits to the extent that they can modify their behaviour. Residents' flexibility is defined in a risk analysis (refer to Table 1). The behaviour variables are trip frequency and mode share. Realistic limits are defined or estimated for long-term behaviour changes that would be tolerable for residents. The extent that any resident is able to change their mode or frequency will depend on age, physical condition etc. Assessment of the potential for behaviour change to allow accessibility to the required activity during a fuel reduction or shortage is then evaluated.

Step 4 involves forcibly modifying behaviours to reduce energy consumption so that it equals an applied energy supply constraint. Given scenarios of energy constraints (e.g. oil shortage), this step focuses in estimating behaviour changes observed in the region's residents. Each transport energy constraint scenario first requires the level of constraint to be pre-determined as a per cent constraint (g) of the current consumption, which represents any value of oil constraint that is to be applied to the study region. After determining the constrained energy supply by applying Equation 2 (as shown in step A of Figure 3), the Constrained Energy Supply (CES) is compared with the Energy Consumption Estimation (ECE) in order to identify the need for behaviour changes (step B in Figure 3).

$$E_{[ct]} = g.E_{[cu]} \quad (2)$$

where:

- $E_{[ct]}$ = Constrained energy supply (CES)
- $E_{[cu]}$ = Current energy consumption
- g = applied energy constraint (%)

To determine the resilience of the built environment both behaviour variables (mode share and frequency) are adjusted to their maximum limits as determined in the risk analysis (refer to Table 1) to produce the minimum feasible energy consumption for the study region. Equation 1 is used for this calculation, with corresponding changes to the frequency distribution and mode share. The modes (m) (from $j=1$ to m) do not change, only the proportion of people using each mode changes. The mean value of the resulting probability distribution is compared with the original energy consumption estimation mean value. The percentage difference is, by definition, the resilience of the built environment.

Table 1
Risk analysis for behaviour change

	Level of Feasibility	Reasons
Maximum distance for non-motorised modes	Until residents are required to walk more than d_{max} (km)	Inconvenience, fatigue, physical inability.
Minimum trip frequency	Minimum trip frequency (F_{min}) trips per week	Requirement to access activity, part of daily / weekly routine

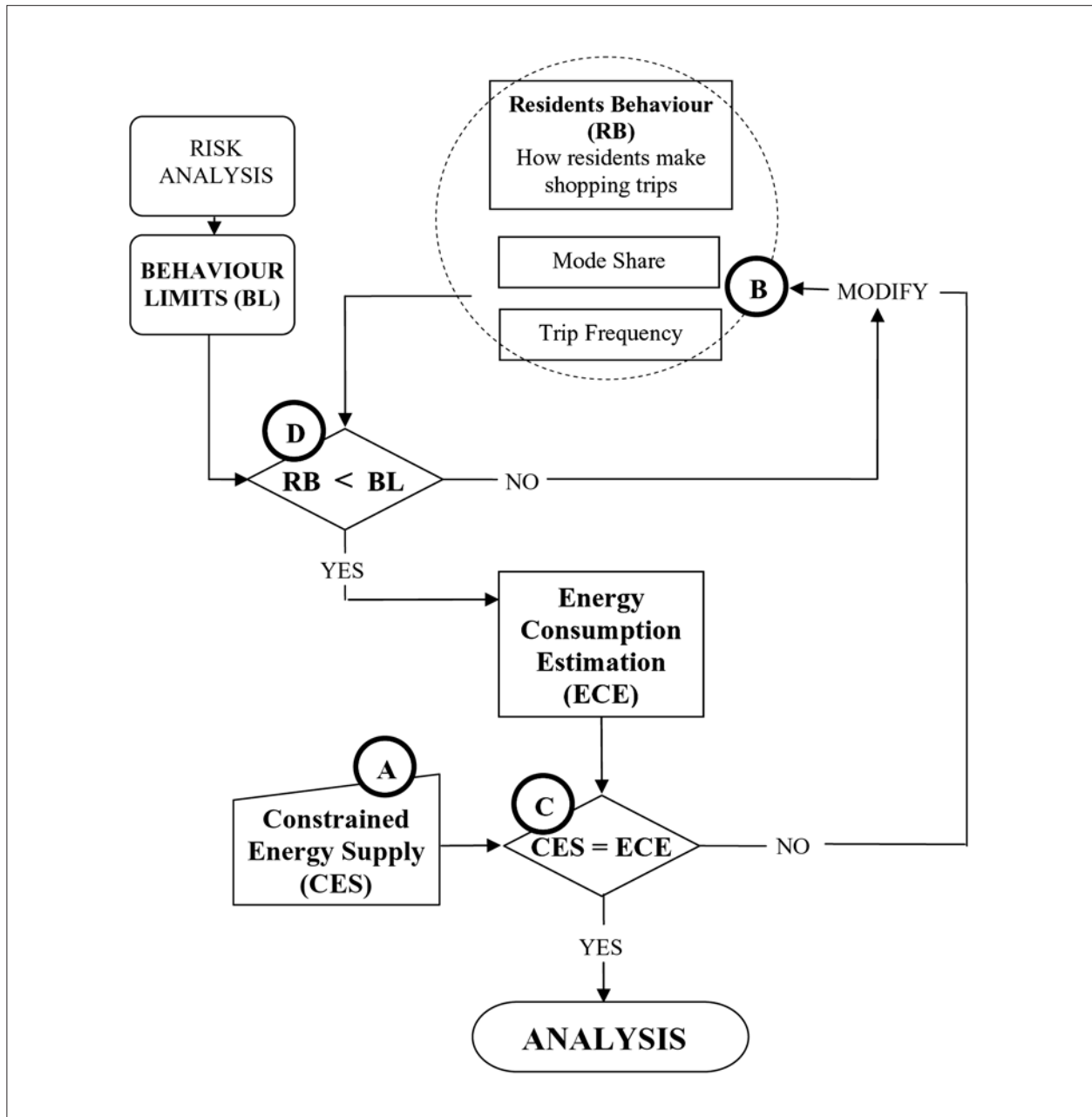


Figure 3
Schematic of behaviour change with energy constraints

Step 5 involves modifying the built environment. Modification of the built environment involves alterations to the transport technology and the suburban layout. The process and modifications can be seen in Figure 4. Each physical variable (transport technology and activity location layout) is individually modified. Maximum behaviour changes (refer to step 4) are then applied to the modified built environments to determine the new resilience. The built environment is continually modified until 100% resilience is achieved.

Modification of the transport technology will result in changes to the energy consumption distribution variable ($EC_{Dist.}$) in Equation 1. This change simulates a change in vehicle fleet, for example, introducing more fuel efficient vehicles to the study region. The other physical variable being modified is the spatial layout of the study region. Changing the location or increasing the number of locations of the specific activity being studied will alter the trip length distribution ($TL_{Dist.}$) of Equation 1. This change simulates land-use change or the introduction of one or more new locations for the activity of interest.

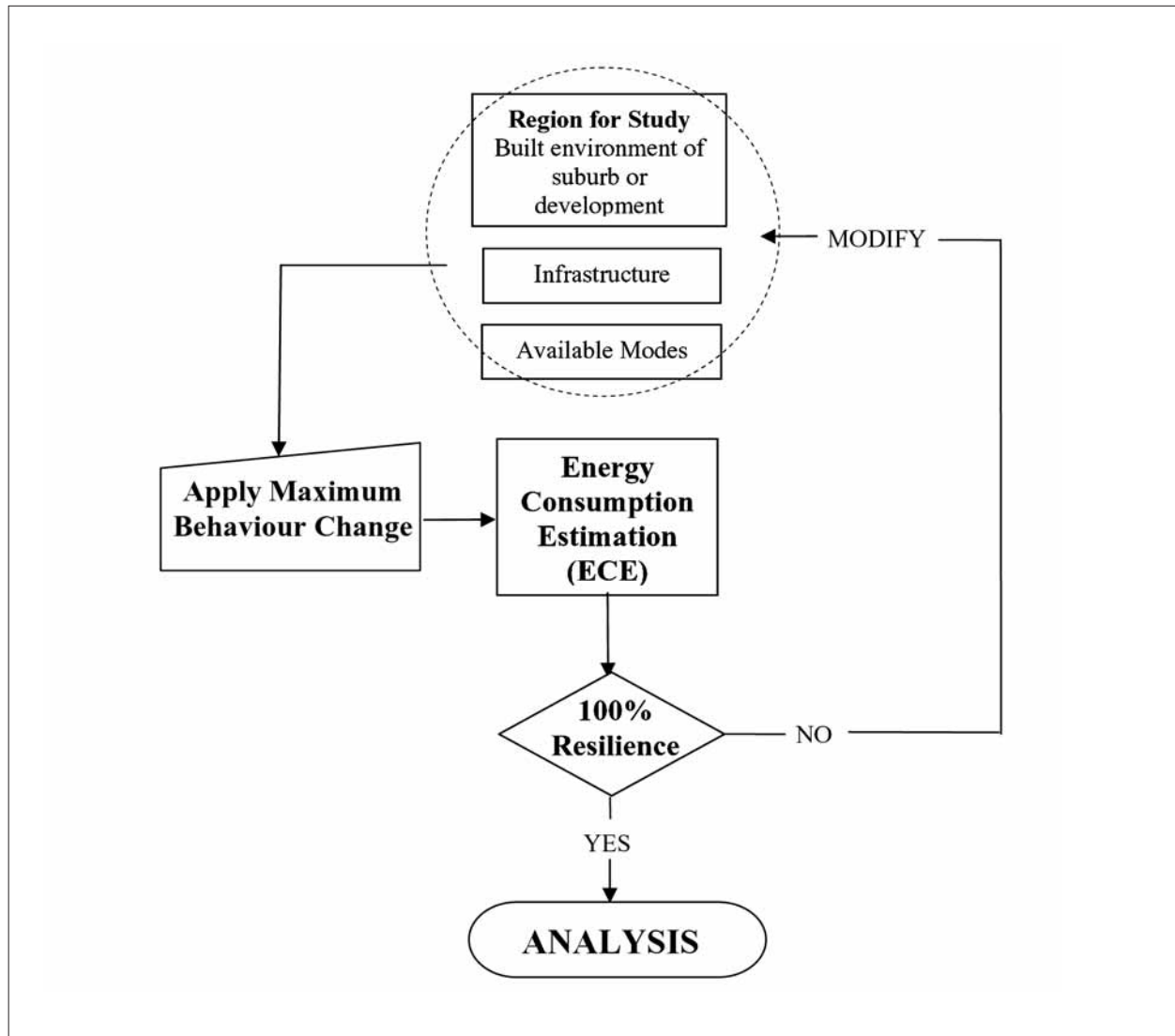


Figure 4
Schematic of modification of built environment

The final step of the method involves analysing the results from the previous steps and producing a summary of the situation. It is important to know if the study area is at risk in a fuel crisis (in relation to accessing the selected activity) and how much change would be required to minimise or eliminate the risk. This should be separated into behavioural and physical changes that would minimise the risk and the feasibility of these changes needs to be assessed.

CASE STUDY: SHOPPING FOR FOOD

A case study was completed for one required activity to demonstrate how the method is applied to a real situation (Saunders 2005). Northwood, a Christchurch suburb (located in New Zealand), was selected for study. The suburb lies on the fringe of Christchurch

and is a recent development contributing to Christchurch's increasing suburban expansion (Buchanan 2004).

Northwood was created to cater for recent urban expansion. The layout of the Northwood subdivision can be seen in Figure 5. The plan shows only one food retail outlet servicing the entire Northwood development. This food store is located at the entrance to Northwood. The development comprises of 695 houses and a network of roads allowing all residents to access their activities through use of (in most cases) private vehicles.

According to recent research conducted by Buchanan (2004), the current mode share of Northwood residents travelling to food stores is 94.6% vehicle and 5.4%

to the food store would be caused by physical incapability and would result in starvation or actions to regain access to the food store, including relocating closer to the food store or other actions to secure a constant food supply. *Table 3* displays the likelihood of the identified impacts occurring for two groups of residents: fit/healthy and elderly/mobility impaired. These groups are further divided into three subgroups classed by their distance from the food store. The group with less than 300 metres to the food store represents the current walking distance. The group greater than 750 metres represents those living further than the defined maximum distance of 750 metres. The group between 300 and 750 metres is the transitional group of residents.

The initial energy consumption calculation for Northwood was estimated in litres of petroleum consumed per week. The estimation comprises of the independent variables: trip distribution, energy consumption and frequency of trips (TL_i , EC_i and F_i) for each mode choice/use (m).

Mode choices are limited to two options: motorised vehicle modes ($m=1$); and all other modes ($m=2$). Only the motorised vehicle modes produce a value for energy consumption. Buchanan's (2004) transport survey estimated that only 5.4% of households do not use a motorised vehicle mode. The motorised modes consist of private vehicles and buses (0.9% use buses). Because the bus share is so low, this was included as part of the private vehicle calculations.

A GIS transport package was employed to estimate the on-network travelled distance from each household in Northwood to the food store. *Figure 6* represents the transport network in a geo-referenced data set according to New Zealand Map Grid, 2000. 695 residences were grouped into increasing 40 metre 'bands' of households. Each group of residences was then given an average distance from the food store, e.g. houses in the 0 to 40-metre 'band' from the food store were all reallocated to an average distance of 20 metres.

Households using non-motorised modes are assumed to be the closest households to the food store. With this assumption, households in the group 260 metres and less (accumulated percentage of 5.4%) from the food store will use a non-motorised vehicle mode. All other households are assumed to be using a motorised mode.

In order to estimate Northwood's private vehicle energy consumption distribution, motor vehicle registration data in New Zealand was used (Registrar of Motor Vehicles 1990-2003). Car registration data provided the motor size and type for each car. Using this data set and vehicle energy conversion rates (DOE 2004), the energy consumption was computed (assuming that Northwood residents have car types typical of the range found within New Zealand). When converted to an energy probability distribution ($EC_{Dist.}$), the fitted data was best approximated by a log-logistic function. The distribution gave values of 7.34 and 14.92 litres/100 km for 5% and 95% probability limits respectively. This means that there is a 90% probability that a household in Northwood will have a vehicle with an energy-consumption within these limits.

The trip frequency distribution ($TF_{Dist.}$) for Northwood has been estimated to best fit a Weibull distribution. Trip frequency data was not available for Northwood shopping trips and it was decided that this data was not needed for the level of accuracy required for this study. With a minimum feasible trip frequency of 1 trip per week it is estimated that more than 3 or 4 trips per week are unlikely. The trip frequency probability distribution places 90% of shopping trips occurring between 1.226 and 2.731 trips per week. A definite limit occurs at 1 trip per week, with no trips occurring at a less frequent rate.

Applying *Equation 1* for the motorised transport mode ($m=1$), the current energy consumption was estimated as shown in *Figure 7*. The energy consumption probability distribution estimates that for any given week there is 90% probability that fuel consumption will be between 140.23 and 316.25 litres/week; with a mean value of 217.08 litres/week for the entire suburb.

Maximum modification of the behaviour variables produced a 64% reduction in transport energy consumption from the current situation. By previous definition, Northwood has a resilience of 64%. Modifying the vehicle type characteristics (more fuel efficient vehicles) considerably reduced energy consumption to a maximum possible 30% improvement, however, 100% resilience (zero reliance on transport energy) was only achieved through modifying the spatial layout of the built environment. Two options were considered for the addition of new food stores. Option A (*Figure 8*) leaves the original food store in place and adds the required minimum

Table 3
Risk impacts table for Northwood

Impacts	Risk (Reliance on transport energy)					
	Fit/Healthy			Elderly/Mobility impaired		
	Distance from food store (metres)			Distance from food store (metres)		
	<300	300-750	>750	<300	300-750	>750
Loss of access to food store	Low	Low	Medium	Medium	Medium	High
Modified access: Behaviour change	Low	Medium	High	Medium	High	High

Probability of impact occurring: High, Medium, Low

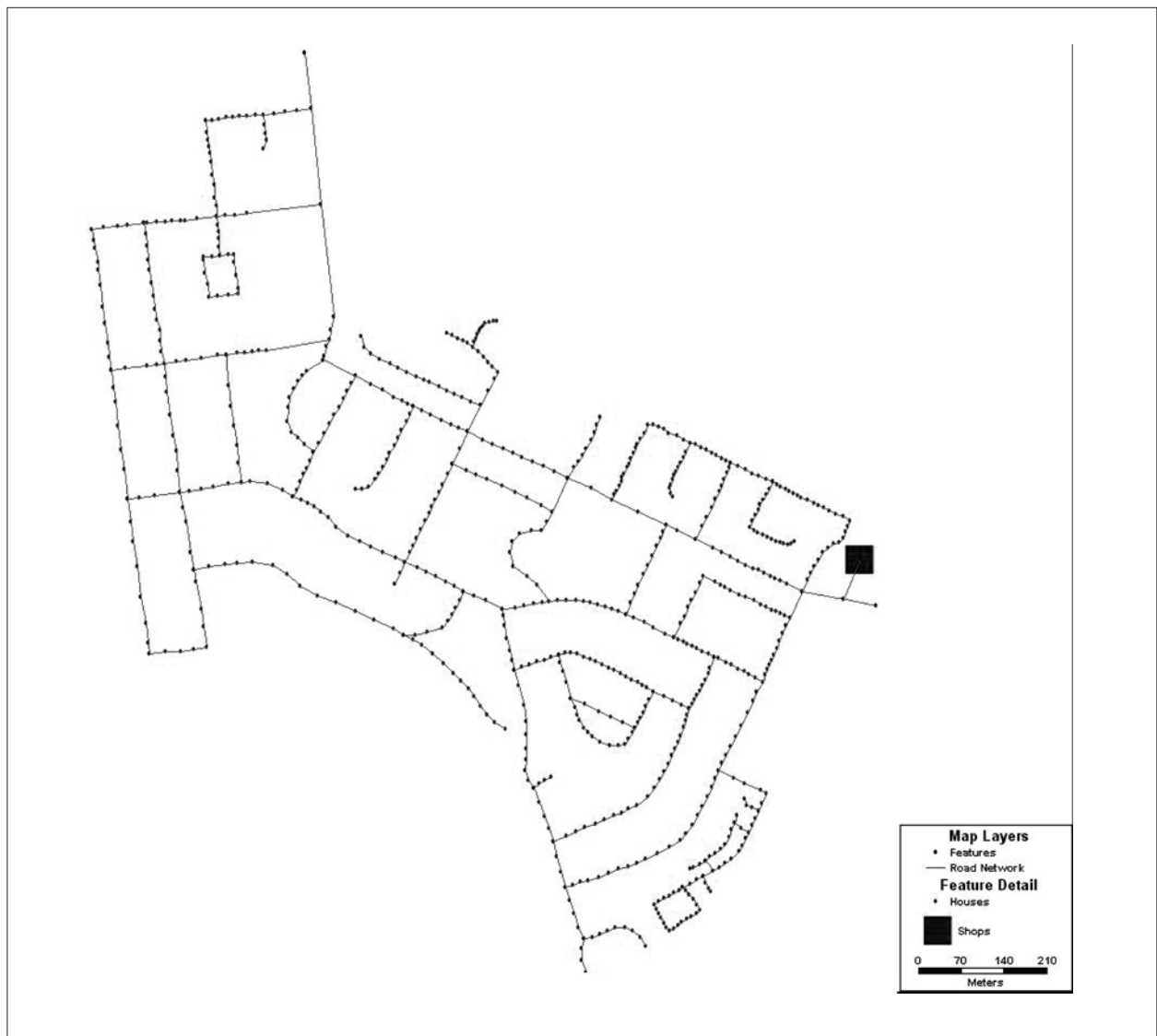


Figure 6
Northwood network map for calculation of trip distribution

Figure 7
Energy consumption distribution estimation for the entire Northwood region

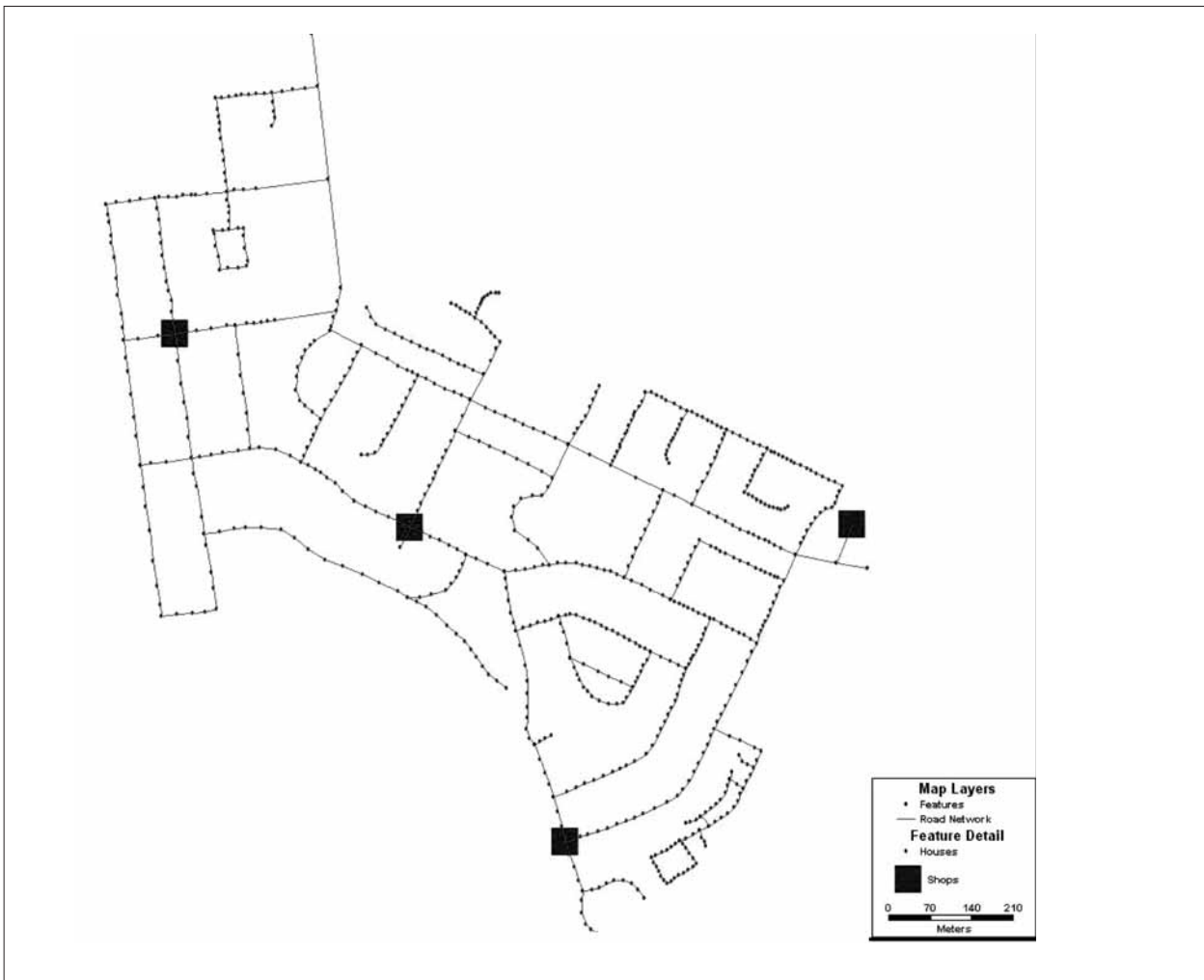
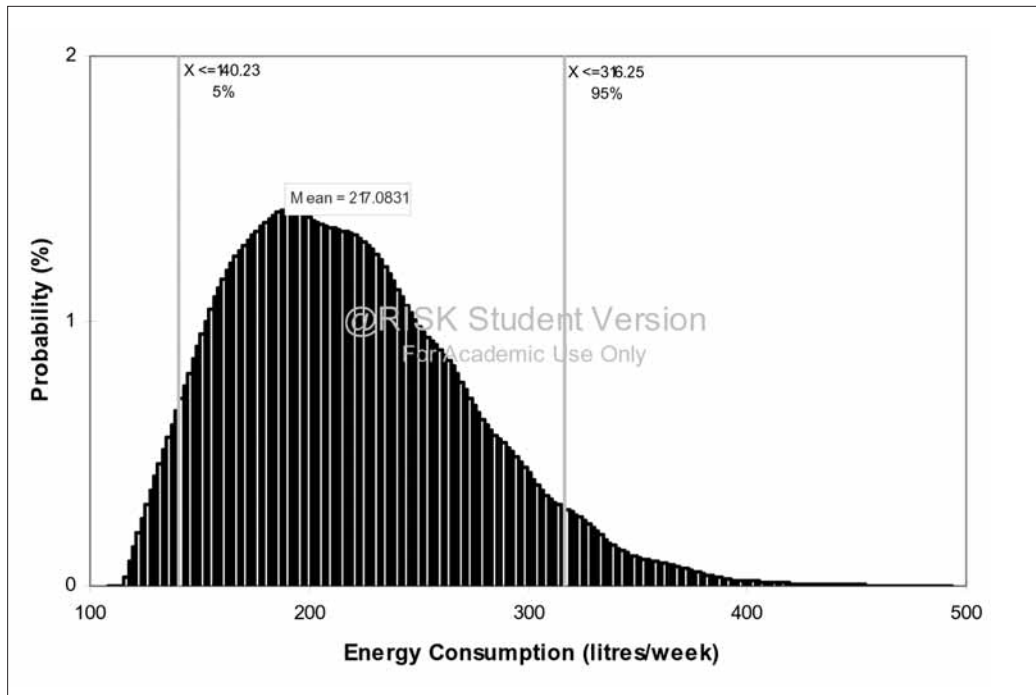


Figure 8
OPTION A: Northwood layout showing additional required food stores

additional food stores to achieve 100% resilience. Option B (Figure 9) removes the original food store and places new food stores in locations that satisfy the requirement for 100% resilience. These modified built environments achieved circa 60% reductions in transport energy consumption (with current assumed behaviours and current vehicle fleet) however, with behaviour change, 100% transport energy reduction was achieved without exceeding the previously defined behaviour limits.

It was concluded that behaviour change provided some flexibility to cope with systemic energy constraints but not complete supply shortages. Shortages would cause loss of accessibility to food stores for residents located further than the defined 750 metre limit. However, addition of new food stores removes all risk facing the residents. It was found that less overall food stores are required if the original food store is removed and planning begins from scratch

(Figures 8 and 9). This implies that land-use planning is a major contributor to the energy reliance of Northwood.

CONCLUSIONS AND FURTHER WORK

Application of the conceived method to transport-energy systems has successfully included transport energy into transport modelling. The derived method allows suburban/urban areas to be assessed as to their reliance on transport energy. Specifically, it analyses the affect of temporary energy supply shortages and systemic constraints on a transport system.

Energy consumption and suburb resilience were shown to be dependent upon both the behavioural and physical characteristics of a suburb. Energy reduction can be achieved through changes to either the behaviour or physical structure of a suburb.

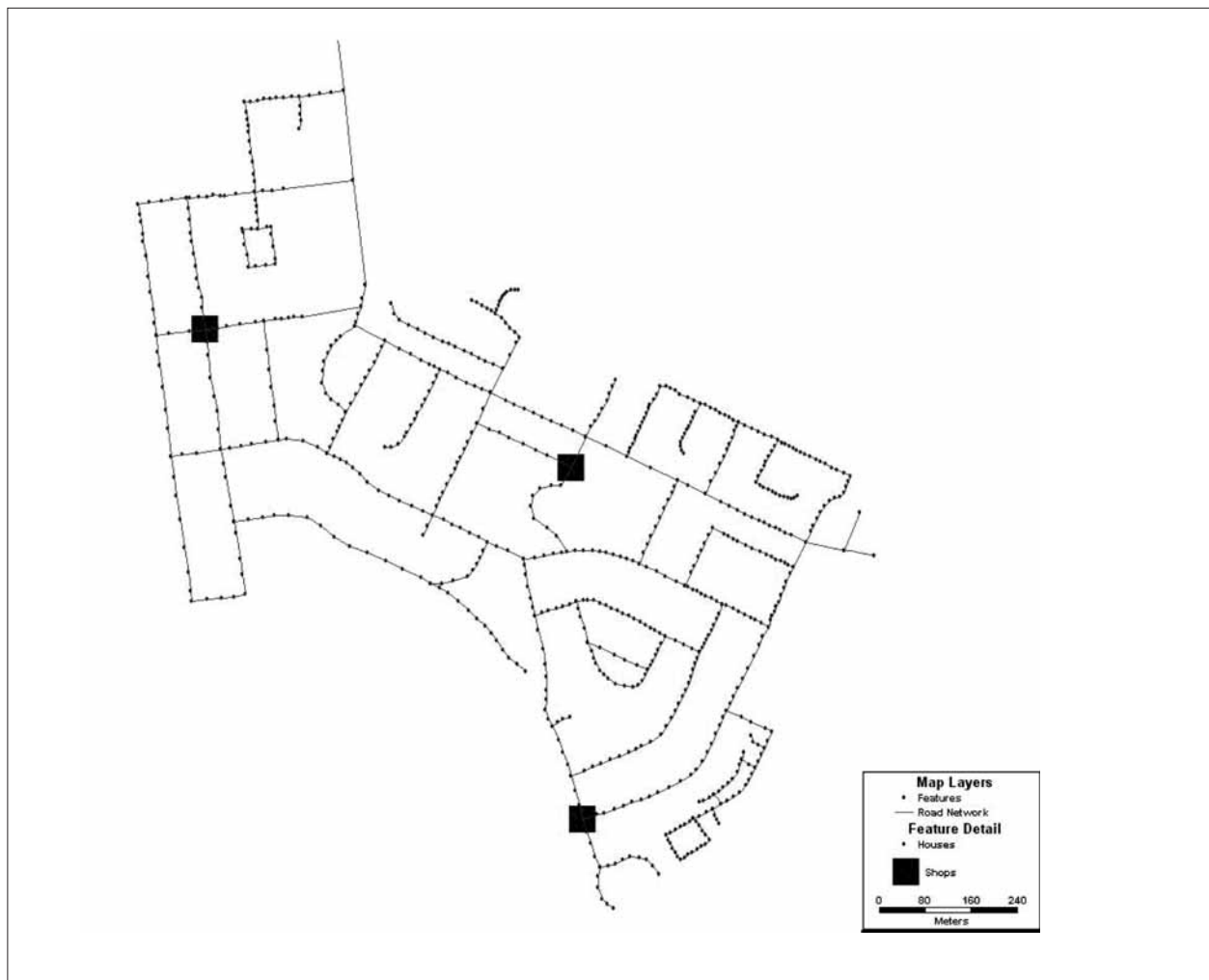


Figure 9
OPTION B: Northwood layout showing minimum food stores required

However, only physical changes can reduce energy consumption to zero. This is due to many suburbs' built environment not being initially designed to allow for access to activities without the use of transport energy.

Different suburbs will have differing levels of resilience to transport energy constraints. Suburbs facing the highest danger and likely to suffer more severe impacts will have a low resilience level and high current energy consumption. The case study produced a resilience level about 60% and energy consumption of approximately 217 litres per week with no modifications to its physical layout. This provides the suburb with flexibility to adapt to future oil constraints.

The method and models require further development before they can be used extensively by transportation engineers. An aspect that needs to be considered when analysing the results is the economic feasibility of implementing any strategies that involve changes to the spatial structure. In the example of the case study, it may not be economically feasible to simply open new food stores.

An oil crisis in the world would most likely lead to a transportation crisis in fuel-reliant countries. Energy constraints will be realised within the design life of suburban/urban areas. Until now, energy analysis tools and techniques have not been available to direct transport planning in the required direction. This newly derived method and approach provides a starting point for more in-depth and accurate models to be created in an attempt to represent the urban transport-energy situation and identify possible future strategies.

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Michael Saunders

Michael Saunders completed a Master of Engineering at the University of Canterbury in 2005. He is currently working on call for Opus International Consultants and completing a doctorate in Sustainable Transport Planning at the University of Sao Paulo, Brazil.

André Dantas

André Dantas is Lecturer in Transportation Engineering, University of Canterbury, New Zealand.

Susan Krumdieck

Susan Krumdieck is Senior Lecturer in Mechanical and Energy Engineering, University of Canterbury, New Zealand.

Contact

Michael Saunders
USP – Escola de Engenharia de Sao Carlos
Departamento de Transportes
Av. Trabalhador Sao-carlense, 400
Centro 13566-590
Brazil
Tel: +55 (16) 33739595
Email: michael@sc.usp.br or michael.saunders@opus.co.nz