

Urban form and fuel shortage risk assessment: A method to investigate the impact of peak oil on travel demand

André Dantas^a, Susan Krumdieck^{b,*}, Shannon Page^b

^a *Department of Civil Engineering, University of Canterbury, Christchurch, 8140 New Zealand*

^b *Department of Mechanical Engineering, University of Canterbury, Christchurch 8140, New Zealand*

Abstract

There is growing concern about the risks to urban transportation with the advent of the peak in world oil production. Travel requires fuel energy, but current transportation planning does not deal with issues, policies or engineering designs for fuel constrained situations.

This research presents a method to assess the risk to activities due to future fuel shortages as a function of urban form. The method uses probability of fuel short fall and impact due to loss of trips, including the new metric of essential, necessary and optional trips in the travel demand patterns. A case study explored four future growth options from the urban development strategy of Christchurch, New Zealand. Various oil shortage scenarios are developed and imposed on each 2041 urban form. All urban forms would lose and/or change trips according to essentiality and available options, but the risk to activities would be very different for different future cities. The high urban density case would have the lowest risks to participation in activities, while sprawled urban forms would have the highest risks in all simulated scenarios. This risk assessment method is being considered for identifying unacceptable growth patterns and mitigation measure as part of the local long range planning efforts in Christchurch.

* Corresponding author, Tel: +64-3-364-2987; Fax: +64-3-364-2078

E-mail: andre.dantas@canterbury.ac.nz, susan.krumdieck@canterbury.ac.nz, shannon.page@canterbury.ac.nz

Key Words: Peak Oil, Energy Shortage, Risk Assessment, Essential Trips, Wellbeing

1. INTRODUCTION

There is growing public concern about the advent of a peak in the production rate of oil and the ensuing price escalation and fuel shortages. Over the past several years, discussion of peak oil has brought concerns about long-term fuel availability into the public debate (Deffeyes, 2001). Many people fear that the production rate of fossil fuel will soon decline, and at present, alternative (coal, solar, wind, biofuel, etc) energy sources can not substitute economically and environmentally (BTRE, 2005). Recent world wide disruptions to fuel supply due to Hurricane Katrina and labor unrest in the UK have demonstrated the vulnerability of existing transportation systems. The combination of declining energy supply, fossil fuel reliance and suburban growth represents an unsustainable trend in transport.

Despite rising alarm about future energy availability, major planning initiatives such as urban development strategies have not yet incorporated energy shortage risks. Strategic and long-term planning exercises have examined developmental matters such as urban form, community well-being, environmental sustainability and economic development, but they have almost ignored future prospects of energy availability.

Transport planners have historically assumed that fuel supply is unlimited. State-of-the-art transport models and methods rarely consider energy as an integral part of the transport and activity systems, (Greiving and Wegener, 2001; Ortuzar and Willumsen, 1994) let alone as a constraint on development. Existing models for transport energy demand focus on mode change and the effect on energy consumption. Some new work

relates energy to spatial patterns of urban settlement (Cooper *et al.*, 2002; Mindali *et al.*, 2004). In particular, energy is not currently considered in risk-analysis or reliability assessment of transport systems. Potential fuel shortage scenarios may be a source of debate, but should not be ignored in planning activities (Nicholson and Dantas, 2004).

Recently, energy consumption has become a concern in planning (Beca, 1981; Nix and Mayes, 1983; Wright, 1986, Waters, 1992), but very limited thought has been given to issues of fuel availability (Cervero, 1985; Bester, 2000). Planning authorities continue to develop transport policies that predict continuous growth of fuel supply (Lim, 1997; Chatterjee and Gordon, 2006). Despite many initiatives to encourage and enhance public transport, walking and cycling as alternative and sustainable transport modes, motorized travel is still dominant (De Silva *et al.* 2001). Growth tendencies and intensification of socio-economic activities altering urban forms and creating additional and complex travel patterns require substantial amounts of additional energy sources (Transport Canada, 1982, Danieri, 2000). Nevertheless, planning initiatives have focused on changing and managing transportation systems in order to cope with future travel demand patterns, assuming that energy supply will always be available to meet demand.

Understanding the relationship between urban form and the transport system may contribute in reducing exposure to the impacts of fuel shortage/crisis events. It has been argued that altering spatial distribution of urban activities (e.g. densification instead of sprawl), may produce changes in travel behavior. Travelers are likely to switch transport modes from private cars to walking or cycling within certain land use arrangements (Newman and Kenworthy, 1999). Urban form and transport system changes through planning actions may affect future travel behavior and create communities that are less

reliant on energy, because energy efficient mode choices as well as location/distribution of activities can be achieved throughout the urban area.

This investigation is motivated by the need to understand the new issue of peak oil in terms of transportation activities and urban form, and to develop a scientifically based approach to scenario building for long range transport and urban planning. At every level of government and business, there is awareness that the issue of peak oil represents an unknown yet relevant threat to business-as-usual (BAU). Current planning approaches which rely on BAU scenarios without consideration of constrained fuel availability are not accurate reflections of future conditions. While members of the public become increasingly concerned about the peak oil issue and the need to reduce fossil fuel use to reduce green house gas emissions, planners are reluctant to be seen a alarmist or “anti-growth” by bringing these issues into their economic scenarios. Introducing a risk analysis methodology into the land use and transport planning process may be a productive way to deal with the issue of peak oil and planning for constrained fuel consumption.

This research highlights the productive link between risk assessment and mitigation. In the area of natural hazards, identifying and analyzing risks provides a platform for public discourse of frightening and destructive possibilities, and acts as a driver for engineering and organizational research into technologies and practices that make communities more resilient. This paper presents a method to assess the risks posed by fuel shortages to urban activities. Particular attention is given to the relationships between urban form and risk.

In this paper we assess the risk due to declining supply of current petroleum-based products. We do not carry out any mitigation analysis with respect to alternative fossil-

based fuels (e.g. coal liquids or tar oils) or biofuels. While economists may debate the change in markets and the future availability of alternative fuels as petroleum fuel prices increase, it is not salient to the assessment of risk to reduction of oil energy supplies. This is because the current and BAU transportation systems rely entirely on oil products. If the supply of these products becomes constrained, then the situation will require change, and change has costs and impacts associated with it. It may be that the change involves investment in new supply systems, but that is a cost which would not have been incurred if the oil supply had continued to grow. Thus, the risk analysis presented in this paper deals with the probability and impact of reduced supplies of the current fuel; low-cost, high quality petroleum-derived petrol and diesel fuels for private motor vehicles.

The paper begins with the analysis of the oil supply situation and development of the probabilistic approach to peak oil. It then looks at the impact of fuel shortages on transport activities and explores the idea of essentiality of trips. The risk assessment method is then explained and the modeling approach is described. Finally the results are discussed through examination of case studies for urban planning options in Christchurch, New Zealand.

2. Analysis of peak oil and the probability of fuel shortage events

2.1 Oil supply

International discussion of the topic of peak oil has intensified in the past several years. There is some debate about the meaning of the term, “Peak Oil”. In this paper peak oil refers to a calendar year in which the global oil production reaches a historical high point. After this year, therefore, the world oil production rate will be less than the peak oil

year and will continue to decline continuously in some manner after the peak oil year. There is no question that the world oil production rate will peak and then will go into decline, as fossil oil deposits are a finite resource. What is not known is the year the peak will occur and what the rate of decline after the peak will be. The exact timing and ramifications of the peak and reduction in world oil supply is the subject of several government reports, documentaries and published books (Abdullah, 2005), but the scientific and engineering research literature is nearly devoid of analysis or modelling on the issue.

Petroleum geologists including C. Campbell, J. Laherrere, K. Deffeyes, and oil industry analysts, most prominently M. Simmons, have all published their arguments that the peak oil date will occur before 2020 (Campbell, 2003; Hirsch *et al.*, 2005). Even Shell Oil has acknowledged that a production peak will occur but argues that it will be around 2025 or later (Shell, 2005). In a now famous analysis, M. K. Hubbert carried out an analysis in 1956 that predicted a peak in USA oil production from existing fields by 1970. The details of his method were not published but have been reconstructed by Deffeyes. The analysis uses data about the production to date, history of discovery, size of the reserve and rate of current production. Although Hubbert's analysis was not taken seriously at the time, in retrospect, his method has been shown to be robust, as continental USA oil production did peak in 1970 (Deffeyes, 2001). Deffeyes asserts that Hubbert's analysis for known world oil reserves, production and discovery rates indicates that the peak oil year will be before 2009.

Most published reports on peak oil represent the global oil supply as a growth, peak and decline bell curve, with the decline rate mirroring the historical rate of production increase (Campbell and Laherrere, 1998). Hirsch *et al.* (2005) uses a linear decline after the peak with the rate of decline equalling the rate of increase up to the point of peak. The USA Energy Information Authority (EIA, 2000) have proposed a much steeper decline (around 8%) in global production, by assuming the reserves-to-production ratio remains constant after the peak in oil production. The EIA also present several delayed peak dates with higher peak production rates and with catastrophic decline rates following the peak, although they do not offer any analysis of the reasons why or likelihood that these incredible scenarios could occur. The historical global increase in world production over the past 20 years has been 1.6% *per annum* (BP, 2005). According to the Hubbert model with relatively symmetrical oil peak and decline, the world production would reduce by 1.6% *per annum* after world peaking.

2.2 Probability of peak oil occurrence

Current political and media speculation about peak oil seems to be focused on arguing about the date it will occur. However, risk analysis is not limited by specific information about timing of unknown events. For example, in the field of engineering dealing with natural hazards, the risks due to earthquakes and floods are analyzed, even though the exact event date and magnitude of the event cannot be known. We applied a similar approach to the issue of peak oil. We know with 100% certainty that a peak in oil production will occur. The majority of experts agree that by 2030 the peak will have occurred, so the 100% probability of occurrence is taken as 2030. A probability distribution of energy shortages was constructed from world oil resource, supply and

consumption data by making a histogram of the predicted peak dates. A negative exponential distribution fit to the published peak production predictions gives a distribution function the probability, $P(y)$, of the peak occurring in any year, y , between 2005 and 2030:

$$P(y) = \left(\frac{(r + y - 1 - 2005)!}{(y - 2005)!(r - 1)!} \right) \rho^r (1 - \rho)^{y-2005} \quad (1)$$

The cumulative probability that the peak will have occurred, $CP(y)$, by the year, y , between 2005 and 2030 is given by:

$$CP(y) = \sum_{y=2005}^y \left(\frac{(r + y - 1 - 2005)!}{(y - 2005)!(r - 1)!} \right) \rho^r (1 - \rho)^{y-2005} \quad (2)$$

Where the fit parameters are $\rho = 0.44$ and $r = 5$. The peak oil probability analysis developed in this research is the first reported in the literature.

2.3 Fuel supply shortage scenarios

In order to assess the risk to activities, the actual quantity of fuel being used is not as important as the impact due to shortages. For example, consider Newman and Kenworthy's (1999) data for the cities of Denver, USA and Brisbane, Australia. The citizens of Denver used roughly twice the gasoline per year that the residents of Brisbane used in 1980. The cities can be considered to have comparable standard of living, economic and social and activity level. In 1980 neither city experienced a fuel shortage, yet the Australians used half the fuel to carry out their transport activities. This difference in energy consumption can be attributed to differences in urban form which includes aggregate effects of urban density, public transport modes and usage, and destination distributions (e.g. locations of shops and work places relative to residences). If, in 1980,

the people of Denver suddenly had the same fuel available per capita that Brisbane used, then Denver would have experienced a fuel shortage of 50%, because they would have access to half the fuel they would use if the supply was unconstrained. This is the reasoning behind the future fuel supply shortage scenario model.

When looking at the future, the probabilistic difference between the hypothetical unconstrained demand level and the predicted supply level represents the shortage magnitude. The probability of a particular magnitude of shortage occurring in a given year can be determined from the peak oil probability, then using the continuous annual reduction rate after the peak of 1.6%. For example, the probability of a 7% shortfall, and any subsequent shortage events occurring is zero unless the peak has occurred. However, once the peak has occurred, the 1.6% supply decline model requires that the 7% reduction must occur 4.5 years after the peak. The subsequent reduction of 10% must follow the peak by 6.5 years. In the same way, the probability of different shortage magnitudes can be determined for a year of interest.

The probabilistic model in Eqn. 1 can be used for scenario development from two perspectives; analysis of the risk in a given year, or the risk of a given size shortage occurring. For example, in 2020, there is a 94.9% probability that peak oil will have occurred, and there is a 78% probability that fuel supplies will be 10% below 2005 levels. In 2020, the chance that fuel supply will be 20% below 2005 levels is a relatively low 7.3%. If we are interested in looking at the time horizon for a 20% shortage, we find that there is a very low probability due to reserve depletion through 2015. However, by 2030 there is a 90.7% probability that 20% less fuel will be available than in 2005. It should be

noted that this analysis does not include shortage probabilities due to natural disasters, war or political decisions.

3. Impact on travel demand

Risk is defined as a measure of the probability and severity of adverse impacts (Haimes, 1998). In the previous section, we dealt with the probability of fuel supply availability being less than the unconstrained demand. In this section, we turn to the characterization and measure of impact. The main idea for characterizing impact is that it results from involuntary change of travel demand. The basic measure of impact is proposed to be the degree of change imposed.

The condition where an urban area has less fuel available than the unconstrained consumption level is termed a “shortage event” and has a magnitude expressed as a percentage reduction from the unconstrained consumption level. In a shortage event, urban communities will undergo significant transformation in order to cope with fuel availability constraints. Activities and travel behaviour would consequently change in their priorities and characteristics. Depending on the level of fuel availability, people would adjust their travel patterns, giving priority to specific activities in order to minimize disruption and guarantee socio-economic, political and cultural continuity. This would be a very complex and dynamic process from the travel demand point of view.

In the following sub-section a definition of a new metric to assess impact of adjusting and/or losing trips due to fuel constraints is presented. The principles for assessing impacts of fuel shortages events are stated in the second sub-section. The third sub-section, describes how the principles are applied to determine impact in a risk

assessment framework. The basic hypothesis is that people will change their travel behaviour, or adapt, in order to preserve participation in activities, with preference to maintaining wellbeing. We propose the measure of *essentiality* as the parameter for this behaviour change dynamic.

3.1 *Concept of essentiality*

Surveys of travel behaviour under current unconstrained fuel availability conditions reveal that people rate as “un-necessary” or “discretionary” as many as 30% of their own trips (Gordon *et al* 1988; Cervero and Radisch, 1996; Banister *et al.*, 1997). We theorize that if a person is faced with a limited fuel supply, the relative importance of each trip would play a major role in deciding how to re-organize trips, which trips to take and which activities to participate in. For example, maintaining income and health are fundamental to people’s wellbeing. When forced to choose, work and food shopping trips would take priority over recreational travel.

We propose that trips can be categorized according to the degree of **Essentiality**:

Essentiality is an internal metric that people use to decide whether trips represent an essential, necessary, or optional contribution to their wellbeing, socio-economic connection and happiness.

In a fuel shortage event, people would use this metric to adjust their travel demand. In the spectrum of essentiality, travel of individuals and households would be categorized into three main types:

- Optional: trips which people would curtail without loss of wellbeing.

- Necessary: trips which people would not choose to eliminate, and when lost would cause some loss of social connection or opportunity or economic participation.
- Essential: trips which people would struggle not to eliminate, and when lost would cause harm to health, deprivation, loss of income, and limit the ability to meet basic needs.

This definition applies to household members as well as individuals. For example, a fuel shortage may mean that a sick member of a family could not be taken to a doctor, and this would affect the wellbeing of the whole family.

3.2 Impact principles

Based on the concept of essentiality and the trip categories, the main impact principle is introduced:

Fuel constraints cause changes to travel behavior including mode change, destination change, purpose change, efficiency change and elimination of trips.

Travel behaviour would change from normal (or current) travel demand for an unconstrained fuel supply. There would be two important types of changes in response to a fuel shortage/crisis:

- Changing trip characteristics, i.e. frequency, mode, distance, or destination are adjusted in order to preserve access to activities.
- Loss of accessibility to activities, i.e., not making a trip that would have been made with unconstrained fuel.

Both of these types of changes would be the result of fuel shortages, but losing accessibility would have a far higher impact. While changing behaviour may have

associated costs and other effects, it would not be on the same scale as the impact of losing participation in activities. There would be three different levels of impact when accessibility to activities is compromised:

- Low impact would occur if Optional trips were curtailed. It is assumed that elimination of these low essentiality trips would generate a low impact on wellbeing;
- Medium level impact would be felt if Necessary trips could not be made. If these trips could not be undertaken due to fuel constraints, then there would be a high impact on wellbeing of the household; and
- High level impact would occur if Essential trips were affected. The loss of these trips would cause extreme impact on the individual's wellbeing.

3.3 Urban forms and energy shortage adaptation

Future development scenarios of urban forms would be subject to potential impacts of fuel shortage. For a future urban form, the impact of a given energy shortage event is determined by the number of trips lost or adjusted and the essentiality level of those trips. The available energy in a shortage event is compared to the energy demand, and then travel behaviour is modified according to the user-defined rules and a new energy demand is calculated. The resulting travel patterns would be iteratively computed in order to meet the energy availability constraint.

The approach allows adaptation of the travel demand to be modeled via user-defined rules including preference for preserving Essential or Necessary trips, adjusting travel patterns (e.g. up-take of ride-sharing or shifting to public transport or walking). This process is iterated until the constrained travel demand profile meets the fuel constraint.

Mode change is the first change in travel demand. Each urban form has a maximum percentage of trips which can be accomplished by public transportation which could be determined by data for existing cities. Car trips in each distance bin are moved, with optional trips first priority, to the bus bin until the upper limit of public transport mode split is reached for that particular urban form. The next priority in the queue for trip changes is to move short distance trips from car to walking or biking, followed by moving of medium distance car trips to the bike mode up to a limit based on population health and other sociological factors. At the long travel distance, movement of car trips to walking is not possible, and only a small percentage movement to bike is expected.

Urban communities' resilience would be expressed in terms of minimization of changes in travel patterns due to fuel shortage. The lower the changes required to cope with energy constraints, the lower the impacts to the community. The dynamic adaptability would also be a function of information they receive, community relations, and the nature and efficacy of any existing fuel management systems.

4. Risk assessment method

The probability model for fuel availability from Eqn. (2) and the impact model laid out in the previous section can now be incorporated into an energy risk assessment method. This method estimates the risks to a particular urban form at a queried point in time. The risk assessment represents the divergence of activities participation from the business as usual (BAU) travel demand case due to energy restrictions. The risk assessment method quantifies how the reduction in trips from BAU is likely to impact the community.

The energy risk assessment method is applied to a particular urban area at a given point in time. The preliminary step is to specify the urban area, either in its present form or under a hypothetical development scenario at some point in the future. The target date for risk analysis is used to determine the fuel availability probability as outlined in Section 2. Given an urban form and a future fuel scenario, a 5-step analysis method as shown in Figure 1 is followed to quantify the risks.

1. The travel pattern without the fuel shortage event is determined via conventional transport modelling, using available data expressing unconstrained travel distances, mode choices and essentiality levels.
2. Energy consumption for the urban form is calculated using conventional methods for the BAU case.
3. A probability tolerance is set to determine the energy availability and this quantity (usually calculated in litres per capita per day) is compared to the BAU case.
4. If energy consumption is greater than the availability, then travel patterns are modified, and the new energy consumption is calculated from the new travel demand pattern using the same calculation method as in step 2.
5. Steps 3 and 4 are repeated, with the travel patterns modified at each step, until the energy consumption levels are commensurate with the available energy. The impact is then calculated, and the risk factor determined considering the difference between the original and modified travel patterns and the oil shortage probability.

The calculated risks can be compared and assessed for different urban form development plans or for current urban areas. The following sub-sections present the mathematical description of the impact analysis and risk assessment method.

4.1. BAU Travel pattern with no fuel energy constraint

The characteristics of a given urban form are routinely converted into a travel pattern indicator, T , that expresses the level of activity, considering the Travel Demand TD , for all modes and travel distance bins. We have added one further category for all trips, essentiality, ES . All trips for each distance and mode fall into one of the essentiality categories; optional, necessary and essential. The essentiality split is set out at the percentage of trips which fall into each essentiality category. Equations 3 and 4 represent TD and T , respectively, for a given urban form.

$$TD^{m,d} = MS^{m,d} * PO * \mu \quad (3)$$

$$T^{m,d,s} = TD^{m,d} * ES^s \quad (4)$$

where PO is the population in the study area, μ is the average trips per person per day, MS is a matrix of mode split per distance bin, ES is a vector of relative split of trips essentiality; and the subscripts, m,d,s refer to a particular mode, distance bin and essentiality level, respectively.

Figure 2 shows a schematic representation of the travel pattern indicator T , as a Trip Length Distribution (TLD).

4.2. Step 2 - Energy consumption for BAU trips

This step focuses in calculating the energy consumption using TD , population and energy efficiency data observed in the urban area under study. Equation 5 represents the energy consumption E calculation for a given urban form.

$$E = \sum_m \sum_d TD^{m,d} * EC^{m,d} DB^d \quad (5)$$

Where $EC^{m,d}$ is the matrix of energy consumption per mode and distance bin; and DB^d is a vector of distance bins (mid distance point).

Calculation of the cumulative energy consumption does not explicitly depend on essentiality, but the amount of energy used for optional trips can be separately calculated to give an indication of short-term energy reductions which could be affected without reduced wellbeing.

4.3. Step 3 – Comparison between BAU energy and shortage event

The energy consumption E , is compared against predicted available energy AE , considering future supply disruption scenarios. AE is calculated using Equation 6.

$$AE_e = (100\% - \Phi_e) * E \quad (6)$$

where AE_e represents the available energy in a supply shortage event e ; and Φ_e is the energy reduction level from probability distribution at the target date.

Using Equation 6, the need or not for changes in energy consumption, and thus change to travel demand, is verified.

$$ME_e = \begin{cases} 0; E \leq AE_e \\ 1; E > AE_e \end{cases}$$

where ME_e is an integer value indicating whether or not modification in travel demand pattern indicator T and consequently energy consumption is required in a supply shortage event E .

4.4. Step 4 – Modification of travel patterns to cope with energy availability

The travel demand pattern indicator T is modified in this step until energy consumption is below (or equal) to the available energy. There are a number of ways travel can be altered, resulting in a reduction of energy consumed. The following four steps are taken to modify the original travel pattern, T , into a modified travel pattern, Ψ .

1. Compute trip combining considering AE_e : Two trips are combined into one, effectively reducing the number of trips without losing any activity;
2. Compute mode changes considering AE_e : A single trip is shifted to lower energy consumption mode, keeping the purpose and distance bin the same;
3. Compute bin shift considering AE_e : A single trip is moved to a shorter distance bin than its original bin, whereas the mode and purpose are kept the same. This change represents that the trip is shifted to closer activity than originally observed; and
4. Compute trip deletion considering AE_e : A single trip in a given travel distance bin, travel purpose and mode choice is eliminated, considering that there is no energy available to perform it. Trip deletion can either be random, or prioritized, where the non-essential, long distance trips are removed first.

Ψ is subsequently used to estimate the modified energy consumption by using Equation 5 for the modified travel demand. The process is iterated and travel patterns are modified until energy consumption E converges to meet the energy availability criteria (i.e. $ME_e=0$).

4.5 Step 5 – Computing the risks of energy supply shortage

Using the results from previous steps, the risk R_e , to travel activities due to an energy supply shortage event e is calculated. Typically, the risk is of interest is for a given

urban form in a given year. As shown in Section 2, there are different probabilities for a range of shortages in a given future year. We suggest that the analyst would decide on an acceptance level for the possible shortage events, and use the probability of a fuel shortfall from BAU that meets their objectives. For example, in the year 2030, the forward probability model indicates that there is a 99% probability that the available fuel will be 10% below 2005 levels, but the world oil demand is projected to grow by 38% over that same time frame (IEA 2005). Urban planners who are looking at plans for growth out to 2030 may want to consider that there is a 99% probability that the fuel available to people living in that 2030 urban form will have nearly 50% less fuel available than the BAU scenario based on demand growth alone.

The impact weight vector, IW^s , according to the impact principles discussed in Section 3, can be assigned values which may vary depending on details which would be derived from behavioral studies and economics research. For illustration purposes, we have assigned the following impact weightings:

- Change of trip mode, destination or efficiency has $IW = 1$
- Loss of optional trips ($s = 1$ bin) has $IW = 2$
- Loss in necessary trips ($s = 2$ bin) has $IW = 3$
- Loss in essential trips ($s = 3$ bin) has $IW = 4$

Equation 8 presents the mathematical formulation to compute the risk, R_e . The probability for the chosen shortage event, e , is multiplied by an impact factor, which expresses the disparities between the participation based on the BAU travel pattern and the energy constrained travel demand.

$$R_e = P_e * \left(\frac{\sum_m \sum_d \sum_s T^{m,d,s} * IW^s}{\sum_m \sum_d \sum_s \Psi^{m,d,s} * IW^s} - 1 \right) \quad (8)$$

where P_e is the probability of occurrence of an energy event e ; and IW^s is a vector of Impact Weight for each change or loss in travel patterns at the essentiality level s . Equation 8 shows that if the same level of activity is carried out after the oil shortage, i.e. the weighted sum of T and Ψ are the same, the estimated risk is zero.

The repetition of these steps for a range of urban forms will produce risk indicators that should be comparatively assessed in order to identify the urban forms, transportation-activity system configurations and mitigation options that may minimize the impacts of potential fuel shortfall from the BAU scenario. At the two extremes, the highest risk would be posed if a very small number of trips could be performed under the constrained energy situation. On the other hand, the lowest risk would be occur if no changes in the travel pattern ($\Psi = T$) were observed even with the energy constraint. In practice, this risk assessment will represent a comparative measure which can be used to compare the viability of different existing and future urban forms.

5. Case study

This section focuses in analyzing how the method relates urban forms to risk levels through changes in travel patterns from the BAU case to comply with an energy shortfall event. The Urban Development Strategy Forum (UDSF) of the Greater Christchurch Urban Area, New Zealand, has been developed to examine growth options for the region. The UDSF produced four growth studies to 2041. The risk assessment method was applied to

the four urban form development patterns, using typical travel demand patterns for each form and using a shortage even probability for 20% shortfall from BAU of 100%.

The following sub-sections present the four UDSF urban form options, the characterization of the urban forms and travel demand patterns; energy supply scenarios; case study assumptions; and results.

5.1. Greater Christchurch Urban Development Strategy – urban development options

The Greater Christchurch urban area has experienced significant changes over recent years and predicted growth will require immediate planning interventions to cope with future community needs and expectations. For example, there has been considerable population growth due to natural increase and migration. According to census data, in the 10 year period 1991-2001, the population changed from 289,071 to 316,227 (CCC, 2003). Currently, over 400 people move to the area every month. The population in 2041 is estimated to reach 500,000 people (UDSF, 2004).

An urban development strategy forum (UDSF) has examined four options of urban forms and their related characteristics, needs and envisaged challenges to the year 2041 (UDSF, 2006). The urban forms are very distinct in the way future development is spatially distributed throughout the metropolitan area. The urban plans and their critical development characteristics are shown in Figure 3. The development options are designated according to the type of growth experienced over the next 35 years as BAU, Option A – Concentration, Option B – Consolidation, Option C – Dispersal.

5.2. Urban forms and travel demand characteristics

The travel patterns for each urban growth option were defined based upon UDSF documentation, international literature and travel demand modeling previously conducted by the Christchurch City Council (UDSF, 2004; UDSF, 2006). Travel distances were divided into three main distance bins based on a combined assessment of all transport modes and their respective travel distances. The short distance is up to 1.5 km, and the long distance is over 6 km. The average trip length for the short, medium and long distance bins are 0.75, 3.5, and 9.5 km respectively. The mode split (vector MS) was divided into 4 main transport modes, namely: car (MS 1), public transport (MS 2) and non-energy consuming modes walking (MS 3) and cycling (MS 4). Table 1 summarizes the mode split for each option, with the total per 100 trips (CCC, 2003).

Travel demand, TD , was calculated using Equation (3) for unconstrained energy demand with the mode split from Table 1 for 500,000 inhabitants in the study area taking 5 trips per person per day. These results were subsequently used to calculate the travel demand indicators, $T^{m, d, s}$, and Trip Length Distribution, TLD , according to Equations (3) and (4). Considering the travel demand patterns and an average petrol consumption rate in 2041 of 10 liters per 100 km, (MED, 2006) the energy consumption for each urban form for vehicle travel was calculated using Equation (5) The fuel consumption in million liters per day is 1.536 (BAU), 1.151 (Option A-Concentration), 1.483 (Option B-Consolidation), and 1.852 (Option C-Dispersion). The travel demand analysis is commensurate with other studies in New Zealand (Buchanan, 2004; Transfund, 2000; Denne *et al.* 2005).

For the purposes of this comparative study, each urban form was modeled with the same essentiality split; 20% Optional ($s = 1$); 30% Necessary ($s = 2$); and 50% Essential ($s = 3$). This essentiality split was applied to each distance bin and each mode.

5.3 Rules for energy shortage travel demand change and risk analysis calculation

The method laid out in Section 4 requires that the travel demand for the unconstrained energy demand case be modified to a lower energy configuration and compared to the constrained energy supply. There are some basic assumptions employed in the model:

- Relative split of trips essentiality is allowed to change (e.g. if an optional trip is eliminated, the proportionality is not adjusted to keep the essentiality split constant)
- Public transport availability is not reduced due to fuel shortage.
- Distance bins do not change
- Geographic location of activities do not change, i.e. homes, factories, shops do not move.
- No mitigation measures are applied after the fuel shortage event, i.e. no mode shifting, no destination changes and no efficiency adjustments.
- Vehicle efficiency and occupancy would not change after the fuel shortage/crisis event

The iteration of this method was implemented in MatLab® using the following rules for producing each new travel demand configuration:

- It will be necessary to reduce the number of trips in order to reduce the energy consumption. All eliminated trips are car trips. The priority for trip elimination is that long optional trips are eliminated first, then medium optional trips, and finally short optional trips. In a similar manner, necessary trips are the next to be reduced, and finally, essential trips; and
- It could be possible that people could shift destinations to a shorter bin in order to save fuel. It would also be likely that people would shift the efficiency of their trips to use

a better mileage car or to combine or share trips. However, for this case-study, the detailed information needed to determine the percentage of trips that could be shifted in this way was not available, so these types of changes were not allowed.

5.4 Results of case study risk analysis

The risk to transport activities due to reduced energy availability was calculated using the risk analysis method for each UDS growth option, and for four different levels of fuel shortage. Each energy shortage event was defined according to the probability distribution Equation (2). Table 2 and Figure 4 present the results of the simulations. A relatively low 7% energy reduction event has a 100% probability of occurrence by 2041. This is the level of shortage covered by the IEA member's agreement in the case of world oil shortage (IEA, 1974). The sprawling growth of Option C would pose the highest risk to urban activities, while the high density growth of Option A would have the lowest risk level for small fuel shortages. The urban sprawl pattern is consistently the riskiest growth pattern.

For each energy shortage scenario, significant changes in the travel demand patterns are observed in the modified Trip Length Distributions (*TLD*) as shown in Figure 4 for the 20% fuel reduction case. A significant portion of optional trips would be lost in all urban form options. Once again, Option C – Dispersal, would experience the highest number of lost optional trips at 90%. The availability of public transport options in the BAU and urban sprawl case, Option C, are noticeable in comparison to the more consolidated and concentrated growth patterns. It is well known that sprawled urban forms are difficult to effectively service with buses or trains. Thus, more trips are lost in the sprawled city, including some necessary and essential trips.

5.4. Discussion of case study results

The influence of urban form on the risks of energy constraint to the participation in activities is clearly observed in the simulations. In all four scenarios, the model indicates that different urban forms are exposed to different levels of energy risk. Depending on the future combination of transportation system and land use patterns in each urban form option, a wide variability in loss of trips due to energy constraints is demonstrated. Without any changes in the current development patterns or the implementation of mitigation options, daily activities in Christchurch would be destined to suffer major disruption and possible economic and social losses.

The shortage events modeled are relative to the unconstrained travel demand for each urban form. It should be noted that the Urban Development Strategy assumes that energy demand will grow from 2005 levels along with the urban population until 2041. But our world oil supply analysis shows that fuel supply will actually decrease by 2041. Thus, for the sprawled growth Option C, the 20% shortfall we used in the case study, would represent an actual fuel shortfall of 60% relative to the projected demand growth in 2041. The lower risk for concentrated development Option A is even more pronounced when we consider that the short fall exposure in 2041 is actually 45%. This result has profound implications if we consider construction and investment in urban forms in an unconstrained energy environment may mean that people living in those areas in the future could effectively be stranded and unable to participate in essential activities.

Option C - Dispersal has a 20% higher risk factor to 20% shortages than Option A - Concentration. This risk-gap (Option C-126 *versus* Option A-105) can be explained on the

basis of the usage of individual motor vehicles. A sprawled urban form's reliance on car travel would be extremely dependent on oil availability and any reduction would create significant disruptions. The disruptions to individual car travel could not be mitigated by mode changes to biking or public transport or closer destinations as these are not feasible in the low density development with large travel distances.

The percentage of optional trips is found to be a very important factor in the adaptability of urban transport to fuel constraints. Figure 5 is a plot of the risk factors for all of the growth options for each fuel shortage event level. Although there are risk differences between urban forms, the trend in risk is quite clearly increasing significantly as the fuel shortage approaches the limit of optional trip percentage. The 20% fuel shortage represents the elimination of nearly all optional car trips, and the beginning of elimination of necessary trips. In this case study, we rather arbitrarily selected 20% as the percentage of optional trips in the travel demand. However, there are no existing survey results or survey methods to gage the essentiality split. It appears that this measure of essentiality will be critical in developing management and response strategies for dealing with fuel shortages. Our research is continuing in the area of assessment of essentiality and the adaptability of different urban forms.

6. Conclusions

Urban transportation systems are well understood to have profound negative impacts on urban quality of life, including air quality, noise, and maintenance and operating costs. However, the urban transportation system is also vital to all urban activities. This research sets the framework for a new assessment of urban form; the risk posed by fuel shortage in the near term, and the Peak Oil fuel decline in the long term. Rather than the more common approach of seeking to affect energy consumption through urban development strategies, we assert that risk assessment will be a powerful tool in long term urban planning. There are some urban forms and some areas of cities which are at risk of becoming dysfunctional when oils supplies become constrained and decline. Planning development in these high-risk patterns is akin to allowing subdivisions to be placed in flood planes or on un-stable soils. The risk management perspective may contribute significantly to the public understanding of urban development decision making, and may provide a constructive means to integrate the issue of Peak Oil into long range planning.

The most important contribution of this research is the concept that energy shortage risks can be quantified, assessed and considered as part of urban and transportation planning decisions.

The present research has produced method to assess the risk due to constrained fuel availability to the wellbeing for a given urban form. First, a probabilistic assessment of future world oil supply was developed. Then the construction of travel demand patterns as a function of urban form was reviewed, along with the calculation of energy consumption associated with that travel demand. Next, we proposed that there is a spectrum of trip

purpose that relates to the wellbeing of the household. We theorize that individual and household trips can be characterized as either optional, necessary or essential to household wellbeing, and that the essentiality split would change in the event of fuel shortages. That is, a household trip to pick up a pizza may be classed as optional because there are activity alternatives such as walking to a cafe or cooking at home. During a time of fuel shortage, the household would choose to eliminate such an optional trip in order to save fuel for essential trips such as work or school or doctor's visits. The method assigns impact levels to the changes induced by fuel shortage, and determines the nature of the changes in the travel demand through an iterative method. The iterative method changes trip modes, distances, and eliminates trips according to adaptation rules until the modified travel demand energy consumption matches the constrained fuel supply. Finally, the risk to the transport activities is calculated by multiplication of the probability of the fuel shortage and the impacts of the travel demand changes.

A major contribution of this research is the investigation of adaptive change to fuel shortages. There is very little actual data for travel demand changes during fuel shortages for obvious reasons. This research proposed an adaptive activity model, based on preservation of wellbeing which we are continuing to refine and validate through experimentation. The adaptation model tracks travel behaviour change and takes account of the impact associated with these changes. When energy becomes constrained, people will act to preserve their participation in activities by changing mode, efficiency or destination. These changes represent an impact which may incur costs or disruption. If fuel shortages are large enough, people will preserve their necessary and essential trips at the expense of their optional trips. Eliminating these optional trips may not degrade the

household's wellbeing, but it will have some impact on general economic activities and on social connections. When the participation in necessary activities becomes curtailed, then the impact may include loss of community participation and may limit educational and economic opportunities. The highest impacts, including risks to health and inability to participate in work or shopping activities, are indicated for fuel shortages that require elimination of essential trips.

As a demonstration of the proposed risk analysis method, we applied it to a case study involving the long range growth planning for the Greater Christchurch Urban Area. Scenarios for four different growth patterns to 2041 have been modeled by the regional planners; a business as usual, concentrated CBD, consolidated centers, and dispersed urban sprawl. The travel demand patterns and mode adaptability models were developed for each growth pattern in 2041 assuming no fuel constraints. Then four different fuel shortage events, 7%, 10%, 15%, and 20% energy reductions, were imposed on the development patterns and the impacts calculated. The results of the case study were quite clear. The people living in low-density sprawled urban forms with very few work or resource destinations accessible by public transport, biking or walking, are at a higher risk than people living in concentrated activity areas with closer access to production and work activities.

Acknowledgements

This research project was supported by a research grant from Land Transport New Zealand. The authors wish to acknowledge the support and advice of the Christchurch City Council personnel and transport engineering practitioners at MWH.

Figure and Table Captions

Figure 1. Schematic representation of the risk analysis method steps. (1) model unconstrained travel activity for a given urban form, (2) calculate the unconstrained energy consumption, (3) compare the unconstrained energy consumption to the probable fuel shortage, (4) modify travel behaviour and calculate energy consumption, (5) iterate until the constrained travel demand has the constrained fuel consumption level.

Figure 2. Schematic representation of the travel pattern indicator T including distance, mode, and essentiality splits.

Figure 3. The four Greater Urban Christchurch development scenarios to 2041 with basic land use and transport characteristics.

Figure 4. Modified travel demand distributions for each growth option considering a 20% fuel shortage.

Figure 5: Results of risk analysis for different fuel reduction level for each case study development option showing a non-linear trend in risk with increasing fuel shortfall event.

Table 1. Mode and distance

Table 2. Risk assessment of alternative growth options for Christchurch in 2041.

References

Abdullah, B. (2005) *Peak Oil Paradigm Shift: The Urgent Need for a Sustainable Energy Model*, Medianet, Limited, St. James, Trinidad and Tobago

Banister, D. Watson, S., and Wood, C. (1997) Sustainable Cities: *Transport, Energy and Urban Form, Environmental and Planning B*, 24 (1), 125-43.

BP – British Petroleum (2005) *BP Statistical Review of World Energy*, 14 June 2005; available at <http://www.bp.com/genericsection.do?categoryId=92&contentId=7005893>

Beca (1981) *Energy in transport : personal transport energy use*; Beca Carter Holdings and Ferner Ltd, Kingston Reynolds Thom and Allardice Limited, New Zealand Energy Research and Development Committee, Auckland, New Zealand.

Bester, N. (2000) Incorporating energy criteria in intermodal transportation policy decisions; *Transportation Research Record*, No. 1522; pp. 83-86.

BTRE – Bureau of Transport and Regional Economics (2005) *Is the world running out of oil?*; Department of Transport and Regional Services; Australia Government; Canberra, Australia.

Buchanan, N. (2004) *The effect of urban growth on travel patterns in Christchurch*; Master of Arts (Geography) Thesis; University of Canterbury, New Zealand.

Campbell C J (2003) Industry urged to watch for regular oil production peaks, depletion signals *Oil & Gas Journal*, Tulsa: Jul 14, 2003. Vol. 101, Iss. 27; p. 38.

Campbell, C.J, Laherrere JH, (1998) *Preventing the next oil crunch - The end of cheap oil*, Scientific American Vol 278 (3): P. 77-83 MAR 1998

CCC – Christchurch City Council (2003) Christchurch City Social Trends Report; Christchurch, New Zealand.

Cervero, R. (1985) Short-run forecasting of highway gasoline consumption in the United States; *Transportation Research A*, Vol. 19a, No. 4, 305-313.

Cervero, R., and Radisch, C. (1996) Travel Choices in pedestrian versus automobile oriented neighborhoods, *Transport Policy* No. 3, 127-141.

Chatterjee, K and Gordon, A. (2006) *Planning for an unpredictable future: Transport in Great Britain*; Transport Policy; in press.

Cooper, J., Donegan, K., Ryley, T.; Smyth, A.; Granzow, E. (2002) *Densification and urban compaction: reinforcing the drive for sustainability*; Proceedings of the 83rd Annual Meeting of the Transportation Research Board, Washington, DC, USA.

Da Silva, A. N. R., Costa, G. C. F., Brondino, N. C. M., Avalos, M. S. (2001) *Urban Sprawl and Energy Use for Transportation in the Largest Brazilian Cities*, The 8th International Conference on Computers in Urban Planning and Urban Management; Sendai, Japan.

Daniere, A. (2000) Sustainable Urbanization in Megacities: Role of nonmotorized transportation; *Transportation Research Record*, No. 1685; pp. 26-33.

Deffeyes, K. S. (2001) *Hubbert's peak: the impending world oil shortage*. Princeton, N.J.: Princeton University Press, USA.

Denne T., Small J. Colegrave F., Hale R., Twomey I., and Smith B., (2005). *Oil Demand Restraint Options for New Zealand*, prepared for the Ministry of Economic Development, COVEC Ltd. and Hale & Twomey Limited

EIA - DOE, (2000) *Long Term World Oil Supply* available at www.eia.doe.gov/pub/oil_gas/petroleum/presentations/2000/long_term_supply/index.htm

Gordon, P; Kumar, A., Richardson, H. (1988) *Beyond the journey to work*; *Transportation Research A*, Vol. 22A, No. 6, pp. 419-426.

Greiving, S. and Wegener, M. (2001) *Integration of Transport and land-use planning: state of the art*, 8th World Conference in Transportation Research, Seoul, F1-6102.

Haimes, Y. (1998) *Risk modeling, assessment and management*; John Wiley & Sons; New York; USA.

Hirsch, R. L., Bezdek R., Wendling R., (2005) *Peaking of World Oil Production: Impacts, Mitigation, & Risk Management*, U.S. Department of Energy Report: DOE NETL available at: http://www.netl.doe.gov/publications/others/pdf/Oil_Peaking_NETL.pdf

IEA (1974) *The IEP Agreement*, IEA, available at www.iea.org/Textbase/about/IEP.pdf

IEA (2005) *World Energy Outlook 2005*, International Energy Agency, Paris, pp. 83, Available at www.iea.org/Textbase/publications/free_new_Desc.asp?PUBS_ID=1540

Lim, C.C. (1997) The status of transportation demand management in Greater Vancouver and energy implications," Greater Vancouver Regional District, Burnaby 1997.

MED (2006) *Energy Outlook to 2005*, New Zealand Ministry for Economic Development, pp. 55.

Mindali, O., A. Raveh, I. Salomon, Urban density and energy consumption: a new look at old statistics, *Transportation Research Part A*, 38 (2004) 143-162

Newman, P. and Kenworthy, J (1999) *Sustainability and cities: Overcoming Automobile Dependence*, Island Press, Washington, DC, USA.

Nicholson, A. and Dantas, A. (2004) (Eds) *Proceedings of the Second International Symposium on Transportation Network Reliability (INSTR)*, University of Canterbury Press, Christchurch, New Zealand

Nix, F. and Mayes, R. (1983) *Modelling Transport Energy Conservation Policy Options: A User's Perspective*; Transport Canada & York University, Canada.

Ortuzar, J. D., Willumsen, L.G. (1994) *Modelling Transport*, John Wiley&Sons, Chichester.

Shell (2005) *Shell Global Scenarios to 2025*, Shell International Limited (SIL).

Transfund (2000) *Person Travel Characteristics of New Zealanders: Analysis of Home Interview Survey Data*; Transfund New Zealand Research Report No. 183, Wellington, New Zealand.

Transport Canada (1982) *Transportation Demand & Oil Use to 1990*; Ottawa, Ontario, Canada.

UDSF – Urban Development Strategy Forum (2004) *Report #5 – technical report on assessment of options and appendix – 13*; December, Christchurch, New Zealand.

UDSF – Urban Development Strategy Forum
(2006) <http://www.greaterchristchurch.org.nz/>; Last accessed on May 2006.

Waters, M.H.L. (1992) *Road vehicle fuel economy*; Transport and Road Research Laboratory; London, UK.

Wright, J. (1986) *Conservation of transport fuel in New Zealand: a review and research recommendations for the Liquid Fuels Trust Board*; Centre for Resource Management Lincoln College & University of Canterbury, New Zealand.

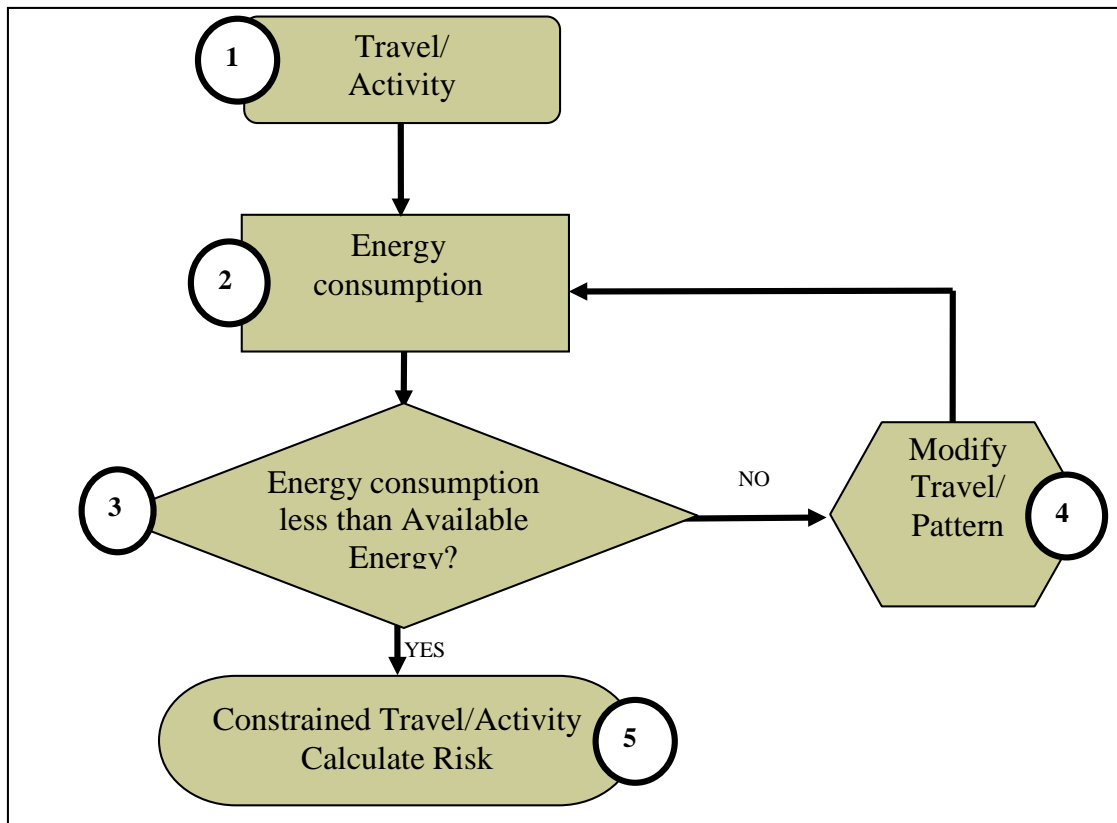


Figure 1. Schematic representation of the risk analysis method steps. (1) model unconstrained travel activity for a given urban form, (2) calculate the unconstrained energy consumption, (3) compare the unconstrained energy consumption to the probable fuel shortage, (4) modify travel behaviour and calculate energy consumption, (5) iterate until the constrained travel demand has the constrained fuel consumption level.

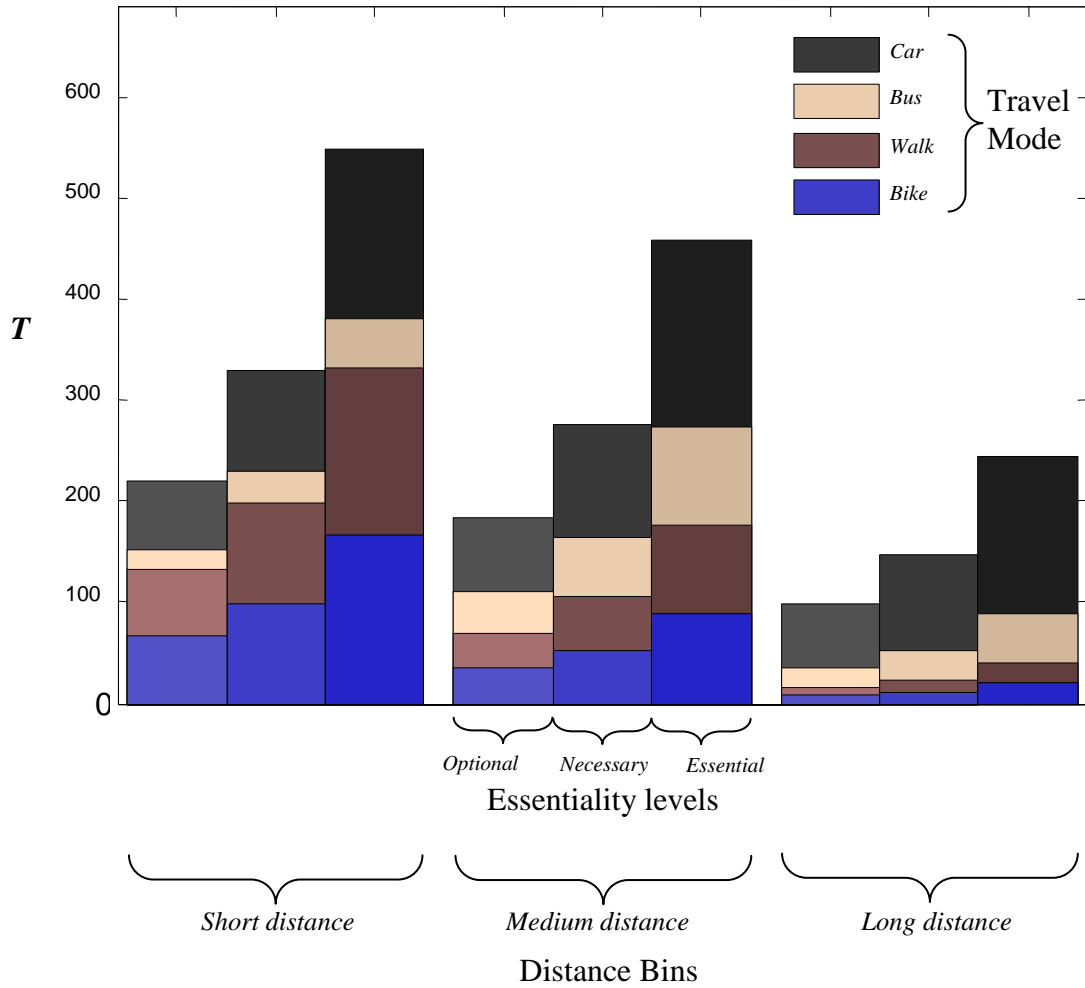


Figure 2. Schematic representation of the travel pattern indicator T including distance, mode, and essentiality splits.

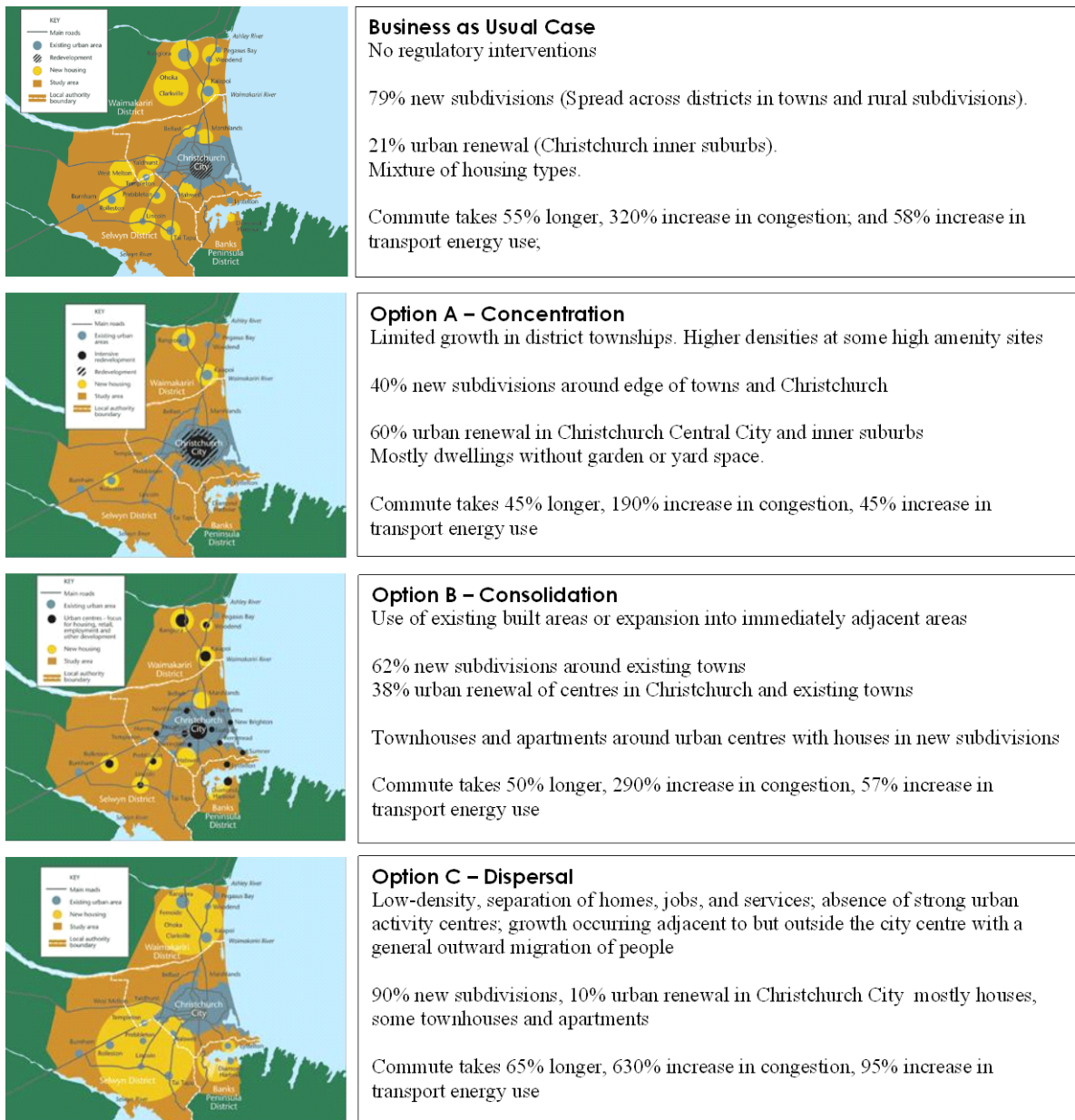


Figure 3. The four Greater Urban Christchurch development scenarios to 2041 with basic land use and transport characteristics.

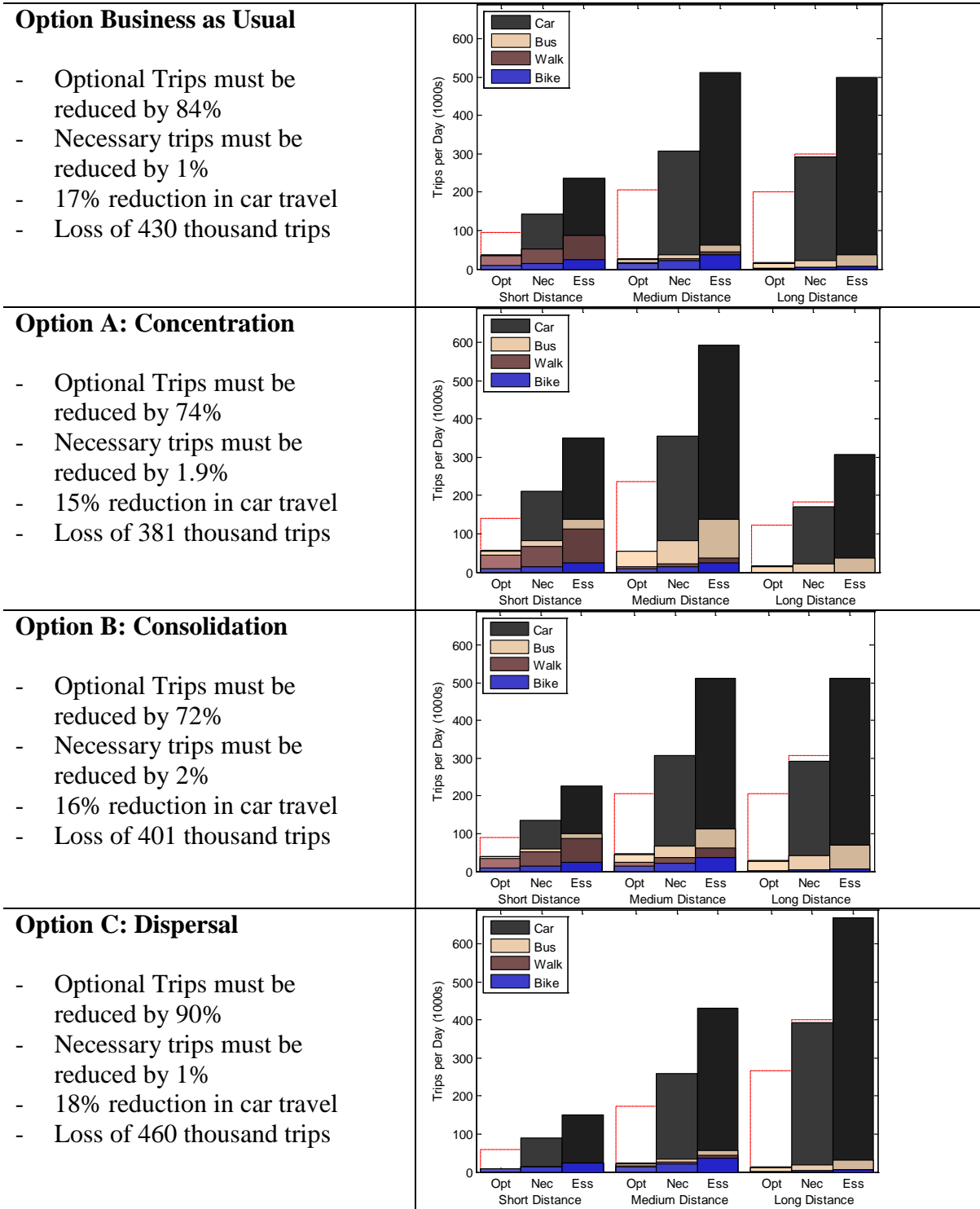


Figure 4. Modified travel demand distributions for each growth option considering a 20% fuel shortage.

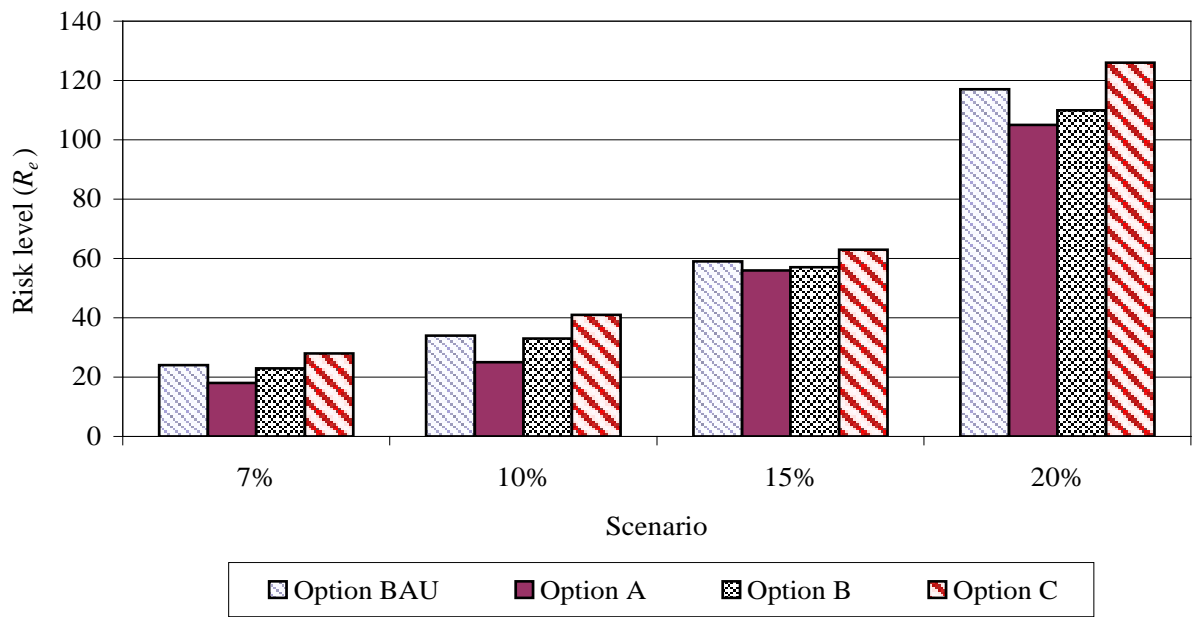


Figure 5: Results of risk analysis for different fuel reduction level for each case study development option showing a non-linear trend in risk with increasing fuel shortfall event.

Table 1. Mode and distance

MS	Option BAU			Option A			Option B			Option C		
	<i>d=1</i>	<i>d= 2</i>	<i>d=3</i>	<i>d=1</i>	<i>d= 2</i>	<i>d=3</i>	<i>d=1</i>	<i>d= 2</i>	<i>d=3</i>	<i>d=1</i>	<i>d= 2</i>	<i>d=3</i>
1 (car)	12.	36.0	37.0	17.0	36.5	21.5	10.0	32.0	35.5	10.0	30.0	51.0
2 (bus)	0.0	1.5	2.5	2.0	8.0	3.0	1.0	4.0	5.0	0.0	1.0	2.0
3 (walk)	5.0	0.5	0.0	7.0	1.0	0.0	5.0	2.0	0.0	0.0	0.5	0.0
4 (bike)	2.0	3.0	0.5	2.0	2.0	0.0	2.0	3.0	0.5	2.0	3.0	0.5

Table 2. Risk assessment of alternative growth options for Christchurch in 2041.

Energy Reduction	CP(2041) (%)	Risk (*1000)			
		BAU	Option A	Option B	Option C
Low (7%)	100	24	18	23	28
Medium (10%)	100	34	25	33	41
High (15%)	100	59	56	57	63
Extreme (20%)	99.9	117	105	110	126