Energy Risk to Activity Systems as a Function of Urban Form

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Dr. André Dantas
Dr. Susan Krumdieck
Shannon Page

Advanced Energy and Materials Systems (AEMS) Laboratory, University of Canterbury, Christchurch, New Zealand

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PO Box 2840, Waterloo Quay, Wellington, New Zealand
Telephone 64-4 931 8700; Facsimile 64-4 931 8701
Email: *research@landtransport.govt.nz*
Website: *www.landtransport.govt.nz*

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Contents

Executive summary

Introduction

This project aimed to develop analytical methods for assessing energy risks due to a peak and decline in global oil production. Additionally to develop modelling capabilities to link these analyses to urban form. Our aim was to provide a new capability for long term development planning. We understand the need for communication between members of the community, councillors and practitioners with diverse backgrounds and interests. Thus, our goal in modelling was to provide accurate risk assessment and clear visual-based communication of results.

Research project outcome

The research team has produced a prototype version of a software modelling package which calculates a risk factor at a queried year in the future for a given urban form and travel demand configuration. The software is named Risk for Energy Constrained Activity and Transport Systems (RECATS).

On the energy side, the software includes interactive models for global peak in oil production, development scenarios for alternative or bio-fuels, and fuel rationing or supply management. The energy efficiency of each mode and of the vehicle fleet is modelled for the future scenario through user-input panels. RECATS calculates the future unconstrained energy use for a user-specified travel demand profile. On the transport side, RECATS allows users to specify the distance, mode, and frequency matrices, which have been determined for a given urban form using available data. One novel feature is a user-defined essentiality split, which can be made according to travel behaviour surveys.

The impact of a given energy shortage event is determined by the number of trips lost and/or changed due to a fuel shortage event and the essentiality of those trips. The loss and/or change of trips is calculated through repetition to meet the energy availability constraint. The constrained fuel supply is compared to the future energy demand, and then travel behaviour is modified according to the user-defined models, and a new energy demand is calculated. The approach allows adaptation of the travel demand to be modelled via user defined functions including preference for preserving essential trips, up-take of ride-sharing, shifting to public transport or walking. This process is repeated until the constrained travel demand profile meets the energy constraint. The constrained travel demand profile is then calculated and compared to the unconstrained profile. Lost and/or changed trips are taken to represent reduced activities, and thus have some impact.

A risk indicator is computed by multiplying the fuel shortage probability by the calculated impact. Controls on the RECATS user interface allow the processes of travel adaptation to be observed throughout the iterations. The unconstrained and constrained travel demand profiles are displayed for easy visualisation of the modelling results.

Research achievements

This research project has successfully transformed the looming worry about Peak Oil into a quantifiable set of events with a determinable probability of occurrence over a future timeline. Based on a comprehensive study of future energy supply and availability, the probabilities of energy shortage/crisis scenarios were estimated. The research team has also identified a previously un-described aspect of transport planning: essentiality of trips. For the first time, a causal link between urban form and susceptibility to fuel shortages has been established. Such a relationship has been rationally obvious, but a systematic exploration of the ramifications of various development decisions requires a rigorous analysis method. In addition, the effects of rationing plans, information systems, and public transport options can also be explored using the RECATS approach.

Strategic community planning

We have presented our results and demonstrated the RECATS modelling capability to a range of transport engineers, council employees, and commercial trucking providers. The consistent feedback is that the RECATS could provide a vital tool in long-range planning and community development.

Case study

RECATS analysis was applied to assess the risks of four future development options used in the consultation process for Greater Christchurch (2006). Various oil shortage/crisis scenarios were imposed on each 2041 urban form development options. Using RECATS, we verified that all urban forms would lose and/or change trips, but the risk to activities was very different for different future cities:

- **Option A** – The concentrated urban form would pose the lowest risk to participation in activities. Even though this option would not totally avoid the number of lost trips, it would contribute to minimize the disruption to future travel patterns. In a 20% energy reduction scenario, over 381 thousand trips would be lost;
- **Option B** – The village urban form would have the second lowest risk in all simulated scenarios. Extensive utilization of public transport would contribute to minimize the impacts of fuel shortages, but not the car trips that would be performed. In a 20% energy reduction scenario, over 401 thousand trips would be lost;
- **Option BAU** – The current development pattern would pose high risks to participation in urban activities. In a 20% energy reduction scenario, over 430 thousand trips would be lost; and
- **Option C** – The urban sprawl form would lose by far the greatest number of trips because there would be no capability for switching mode. In a 20% energy reduction scenario, over 460 thousand trips would be lost.

Limitations and recommendations for future studies

The main limitation of our study is that very limited data on travel behaviour in an energy or oil shortage/crisis is available. This limits the extent to which land use and travel demand modelling can be applied to forecast changes in behaviour and activities in a shortage/crisis event. We envisage that further research should focus on developing new methods to obtain data and information about travel behaviour under energy constraints. Also, RECATS could be applied to assess the effects of mitigation options that may reduce energy risks and assist the development of urban transport policies.

Abstract

This research investigated future fuel shortages and the associated risks to urban forms and transport systems. A method was developed in order to assess the risks posed by fuel shortages to urban activities. Particular attention was given to the relationships between different urban forms and risk. In addition, factors that could possibly mitigate the risks of fuel shortages or the impacts were identified. The risk assessment method was implemented as prototype software called RECATS. Using the software, four future development options for the Urban Development Strategy of Greater Christchurch were assessed. Various oil shortage/crisis scenarios were imposed on each 2041 urban form development options. Using RECATS, we verified that all urban forms would lose and/or change trips, but the risk to activities was very different for different future cities. Option A (concentrated and limited development) would minimize the risks to participation in activities, where Option C (urban sprawl) would pose the highest risks in all simulated scenarios. Further studies are recommended in order to obtain reliable data/information on travel behaviour under fuel constraints.

1. Introduction

Transport planners have historically assumed that fuel supply is unlimited. Recently, energy consumption has become a concern in planning (Beca, 1981; Nix and Mayes, 1983; Wright, 1986;1 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, motorised 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, Daniere, 2000). In addition, planning initiatives that have focused on changing and managing transportation systems in order to cope with future travel demand patterns, continue to assume that energy supply will always be available to meet demand.

However, over the past several years, discussion of Peak Oil has brought concerns about long-term fuel availability into the public debate (Deffeyes, 2001). International agency reports have shown that the generation of fossil fuel is declining, whereas alternative (coal, solar, wind, biofuel, etc.) energy sources do not produce enough energy to substitute economically and environmentally for traditional fossil fuel (BTRE, 2005). Recent world wide disruptions to fuel supply, due to natural disasters and labour unrest, 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/crisis 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. This is not surprising given the fact that state-of-the-art transport models and methods rarely consider energy as an integral part of transport and activity systems (Greiving and Wegener, 2001; Ortuzar and Willumsen, 1994), let alone 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). In particular, energy is not currently considered in risk-analysis or reliability assessment of transport systems, disregarding any potential shortage and/or price increase scenarios. While this may be a source of debate, it should not be ignored in planning activities (Nicholson and Dantas, 2004).

The relationship between urban form and the transport system may contribute in reducing exposure to energy availability risks in 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 behaviour. Travellers 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 behaviour 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 research investigated the future fuel shortage/crisis risks associated to urban form and transport system decisions as part of the transportation planning process.

1.1 Research objectives

The aim of this project was to develop a method to assess the risks posed to urban activities by fuel shortages. Particular attention was given to the relationships between urban form and risk. In addition, factors that could possibly mitigate the risks of fuel shortages and their impacts were identified.

Specific research objectives were determined in the early stage of the project:

- To model petroleum and alternative fuel supply availability, specifying possible availability constraints, long term shortages, supply disruption;
- To model future petroleum availability, and formulate the magnitude and probability of transportation fuel constraints;
- To assess fuel requirements for activities in urban development forms;
- To develop a method to quantify the impact and assess the risk for fuel supply scenarios;
- To develop an interactive risk assessment software tool which allows exploration of mitigation options; and
- To apply the software in a case study in Christchurch in order to assess future risks of an energy shortage/crisis.

1.2 Research method

***Phase I. Analysis of Activities as a Function of Urban Form**:* Existing travel surveys and models of various urban forms were analysed to determine the pattern of travel activities that provide goods and services for individual and community wellbeing.

Phase II. Transportation Fuel Availability Assessment: Existing data on petroleum oil reserves for New Zealand and international trading partners were assessed to characterise possible types of supply disruptions and prepare probability estimates for each category of supply disruption. Supply disruptions can be temporary constraints, long term constraints, temporary shortages, or long term shortages of varying degrees. Existing data was also analysed to determine the probability of fuel supplementation or substitution from non-petroleum sources.

Phase III. Method to assess energy risks to activity systems as a function of urban form: Based on the outcomes of the previous research phases, analytical procedures to estimate the energy risks were developed and a computer program (RECATS) was developed as a risk analysis tool.

Phase IV. Case Study: The method (***Phase III***) was applied to the particular urban forms identified in the Greater Christchurch Urban Development Strategy. Using RECATS, energy risks for each urban form were assessed.

Phase V. Analysis and Conclusion: Results of the case studies were used to evaluate the risks to activities and to determine possible mitigation measures for each urban form.

1.3 Report structure

This report is divided into six chapters. After this introduction chapter, a literature review of the theoretical concepts underpinning this research effort is presented. Chapter Three summarises the analysis of the future supply of transport fuel, based on examination of geological data and oil production figures. Chapter Four presents the method developed to assess energy risks to activity systems as a function of urban form, and Chapter Five describes the case study of the urban forms identified in the Greater Christchurch Urban Development Strategy. Conclusions, including main findings, limitations and recommendations for further research, are presented in Chapter Six.

2. Literature review

This chapter summarises the basic theoretical concepts involved in the research and is divided into four main sections. The first section presents a series of basic definitions of urban areas and urban travel. The relationships between urban form, travel demand and energy consumption are examined in the second section. This is followed by a brief review of the state-of-the art in land use and travel demand studies, with special focus on energy issues. Finally, the fourth section presents a brief summary of risk management and analysis.

2.1 Definitions

The scientific literature on urban areas and urban travel is populated with several different definitions for important concepts. In order to establish a standard for the terms used hereafter, we present a compilation of definitions from various scholars.

2.1.1 Urban area and characteristics

Khisty (1990) defines an urban area as

> "...*a locational arrangement of activities or land-use pattern, where the location of activities affects human beings and human activities modify locational arrangements...*".

This definition involves the notion that due to human needs (social, economic, political and cultural), interactions which are performed between individuals lead to the establishment of activities. Obviously, these activities are related both to spatial position in urban area (locational arrangements) and to the characteristics of the surface they are occupying (land use). Dynamically, activities and their characteristics (location and land use) affect human beings, and vice-versa (urban interactions).

Also, according to Khisty, urban form is the spatial pattern or arrangement of individual elements such as buildings, streets, parks, and other land uses (collectively termed the built environment), as well as social groups, economic activities, and public institutions within the urban area. On the other hand, urban interaction is the collective set of interrelationships, linkages, and flows that occurs to integrate and bind the pattern and behavior of individual land uses, groups, and activities into the functioning entities, or subsystems. Finally, Khisty states that urban spatial structure combines the urban form, through the urban interaction with a set of organisational rules, into a city system.

2.1.2 Urban travel characteristics

Urban travel is the result of the interaction between the transportation system and the activity system as shown in Figure 2.1. According to Manheim (1980), three kinds of relationships are generated:

(1) The travel demand (or flow pattern) in the transportation system is determined by both the transportation system and the activity system;
(2) The current travel demand will cause, over time, changes to occur in the activity systems: through the pattern of transportation services provided, and through the resources consumed in providing that service; and
(3) The current travel demand will also cause, over time, changes to occur in the transportation system. In response to actual or anticipated flow, entrepreneurs and government will develop new transportation services or change existing services

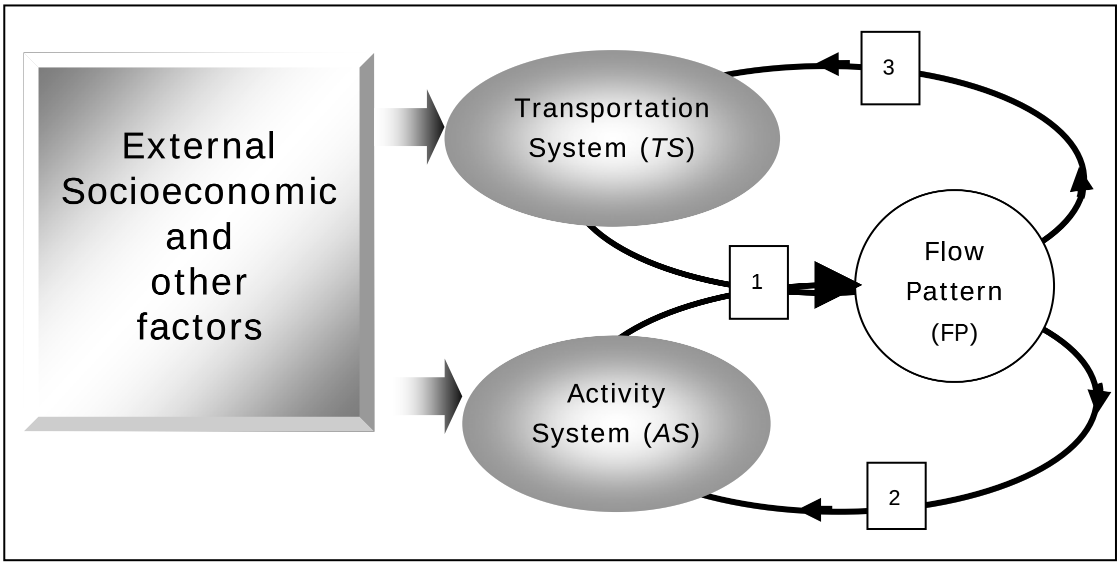


Figure 2.1 Interaction of transportation and activity systems[1].

According to Meyer and Miller (1984), urban travel has five characteristics as follows:

- Trip purpose (why people want to go from an origin to a destination);
- The temporal distribution of trip making (when trips happen over time);
- The spatial distribution of trip making (where from/to people are travelling);
- Modal distribution of trip making (which mode people use to make their trips); and
- Travel Cost (how much people "pay" to make their trips).

Various studies have attempted to measure these characteristics of urban travel. Travel demand has multiple facets due to the complexity and diversity of the phenomena which are influenced by several interconnected factors such as human behavior, location, culture and socio-economic conditions. Therefore, findings can range considerably depending on the number and details of the travel demand influencing factors examined. For instance, United Kingdom (UK) and United States of America (USA) findings (Banister *et al*, 1997; Gordon *et al;* 1988, Transfund, 2000) show considerable difference in the average number of trips per person and average trip length per person. The differences may be explained by directly related non-transport factors such as urban form and the socio-economic profile of urban areas.

[1] Adapted from Manheim (1980).

2.2 Tradeoffs: urban form, travel demand and energy consumption

In recent years there has been a growing understanding and agreement that urban form (or built environment) affects travel behaviour/demand patterns. According to Anderson *et al* (1996), urban form has a profound influence on the flows within the city, but does not determine them completely. For example, Cervero and Radisch (1996) observed, for two small USA communities with different neighbourhood design, that different mixes of land use and transport system considerably affect the mode choice and trip length of work and non-work travel. Various studies have concluded that certain urban forms may lead to motorised societies that contribute to unsustainable development (Gakensheimer, 1999). Also, Newman and Kenworthy (1999) compiled a data set of 32 major world cities and observed that transport policies, which contribute to increasing population density, are more important than economic factors in reducing the dependence on the automobile. Van de Coevering and Schwanen (2005) have recently re-examined Newman and Kenworthy's (1999) work and concluded that the space-time context of cities should be taken into account in aggregate-level comparisons of the relations between urban form and transport.

Several technical and scientific reports have also examined the direct consequence of the relationship between urban form and travel demand on energy consumption. Banister *et al.* (1997) examined empirical data on energy consumption as a function of travel demand and urban form indicators. They concluded that density is a key variable in understanding urban form and energy consumption, but data incompatibility and availability make it difficult to establish definite relationships between characteristics of travel (mode, distance and frequency) and energy consumption. Owens (1984) summarises the relationships between spatial structure and energy demand.

2.2.1 State of the art

Scientists from several disciplines have dedicated themselves to the development of urban theories and models. In order to help planners in their activities, there has been a continuous search to establish a comprehension and modelling of the urban dynamic. Qualitative and quantitative methods were originally conceived in other disciplines and then modified into new ones. These methods cover a large variety of applications such as: study of built form; study of human interactions; study of planning process and organisation structures; study of long-range trends; predicting a policy's range of effects on a community; and assessing potential problems.

2.2.2 Land use studies

Despite the multiple determinants (social, public, etc), most of the efforts on developing land use theories have been concentrated on economic analysis. Based upon the examination of economic determinants, urban economists have developed theories to explain the configuration and evolution of urban structure. As described in Chapin (1957), initial theories of urban structure advanced into three different explanations: Concentric Zone Theory (Ernest W. Burgess); Sector Theory (Homer Hoyt), and the Multiple Nuclei

Concept (Chauncy D. Harris and Edward L. Ullman). The first and the last theories deal with the entire pattern of use areas, whereas the sector system of explanation was developed primarily to explain the structure of residential areas. The zonal and sector theories are used to describe changes in the basic arrangements of land use patterns, whereas the Multiple Nuclei approach is primarily an observation of the structural form of the urban structure at a particular point in time.

Models have been constructed in order to help planners in their activities. During the urban planning process, planners have to gather information on how changes in the land use and transportation systems will affect the nature and intensity of activities. Through the application of land use models information can be organised and used in analysis and understanding of the planning problem, in plan design and in evaluation of any proposed solution (Needham, 1977). According to Ross (1988), these models show how future land use activities are to be allocated by assuming that land use is determined by location, by availability of services and amenities and by proximity to other land uses.

Batty (1971) divides these models into two types:

- Spatial interaction models: They deal with human activities in the geographical spaces that affect urban elements, about which planners might obtain information or understanding in order to conduct their activities; and
- General models of spatial systems: They are divided into two classes, optimising and non-optimising models. The former involves some process in which the model is able to predict 'best' or optimal values of its dependent variables using optimising techniques such as linear programming. On the other hand, non-optimising models are not concerned with determining optimal scenarios, being based upon systems of linear equations and non-linear models that were originally conceived considering gravity models.

In recent years, a new direction in land use studies and theories has emerged and attracted significant interest from many involved in urban planning. Called New Urbanism or neo-traditionalism, this movement attempts to change urban dynamics by introducing high density and mixed land patterns, which may contribute to reduce problems such as traffic congestion and pollution and simultaneously creates a revival of local communities (Cervero, 1998; Duany and Plater-Zyberk, 1992). In several cities around the world, New Urbanism-based settlements have been observed on the fringes of urban areas (Newman and Kenworthy, 1999), where spatially segregated communities are created without any alternative to individual transport by motorised modes of transport (Jarvis, 2003). Various scholars (Burton *et al*, 1996; Cervero, 1998; Boarnet and Sarmiento, 1998) argue that New Urbanism theories and initiatives will not create a sustainable urban environment by themselves. They conclude that changing the spatial distribution of activities without combining with transport systems planning will not be very effective in reducing or minimising currently observed problems.

2.2.3 Travel demand studies

Travel demand studies focus on obtaining knowledge about urban trip patterns. According to Ross (1988), urban travel demand studies comprise a process of collecting and analysing huge amounts of computerised data assuming that the land use pattern at a specified time in the future will dictate a corresponding demand for travel. The process involves a sequence of seven steps: inventory (of land use, population, travel, and transportation facilities); land use forecast; trip generation; trip distribution; modal split; network assignment; and evaluation (for an extensive description and details see Ortuzar and Willumsen, 1994).

Despite its extensive application worldwide and massive improvement over the years, several criticisms have been levelled at not only planning models but also the transportation planning process itself. Specifically about the models, some can be highlighted such as:

- Massive and costly requirements for application to real problems (Harris, 1996; Spear, 1996);
- Non-incorporation of the dynamic and realistic dimension of urban reality (Rodrigue, 1997);
- Irrelevancy since investment decisions are no longer driven by transportation system performance but rather by a host of public goals, such as community, environmental, and economic development. (Miller and Demestky, 1999);
- Overemphasis on the design of a linear statistical model while non-linearity prevail in reality (Fischer, 1998); and
- Rarely evaluate the accuracy of their forecasts by using past data sets to predict present conditions (Miller and Demestky, 2000).

In order to improve travel demand modelling, several different approaches have been suggested. For instance, there has been a growing notion that the temporal dimension is a decisive edge. Nihan and Holmesland (1980) state:

> “...it appears that a continuous refining of current models is not only wasteful, but may actually be counterproductive...”.

They propose an alternative to traditional cross-sectional techniques where historical data is fitted without consideration of common behavioral variables. For Ortuzar and Willumsen (1994), forecasting models should use time-series data as a reasonable way to better express urban dynamics and their consequences on transportation and this has not yet been achieved. However, Miller and Demestky (1999) verify that such an approach is complicated by the fact that longitudinal data sets for a geographical area exhibit data incompatibility, shifts in planning emphasis, temporal changes in travel characteristics and added modelling complexity.

In parallel with traditional modelling efforts, scholars have also studied the relationships between travel demand and energy consumption. Cervero (1985) presented an autoregressive-integrated-moving average (ARIMA) model for forecasting monthly highway energy consumption in the United States using data from the 1977-83 period. He argues that short-run forecasting can be used in national strategic planning. Vanek and Morlok (2000) studied freight transport energy consumption and reached two main findings: (a) commodity groups with high energy growth between 1972 and 1993 had a combination of substantial ton-mile growth and modal shift to truck, and (b) commodity groups of finished products with a high average value per ton in general have a much higher average freight energy intensity than raw materials with low average value per ton.

Also, there have been studies in understanding the implications of transport and energy policies. Wadhwa (1980) examined the consumption of energy in Australia to aid the process of energy policy design, concluding that the passenger travel demand is less likely to be contained but a combination of conservation and efficiency measures can significantly reduce the energy intensity, thereby controlling the gasoline demand in the next 25 years to present consumption levels. Litman (2005) compares four potential transport energy conservation strategies and reaches the conclusion that conventional evaluation practices often overlook mileage-related impacts and therefore overvalue strategies that increase vehicle fuel efficiency and undervalue mobility management strategies. Bester (2000) looked at incorporating energy criteria in intermodal transportation policy decisions. It presented a conceptual framework for thinking about the market behaviour of consumers and produces as cost minimisers and offered a new way to design public policies using economic and energy efficiency goals.

2.3 Risk management and analysis

Risk has been defined in various forms in the literature. On one hand, some definitions focus on the negative nature of the term. For example the Oxford Dictionary defines risk as the chance of hazard, bad consequences, loss, etc. On the other hand, others have emphasised the qualitative and quantitative nature of unexpected events and their consequences. For instance, Wharton (1992) defines risk as the measurement of the chance of an outcome, the size of the outcome or a combination of both.

Elms (1998) describes the types of risk as follows:

- Estimated risk: obtained through systematic means, often by calculating the failure probabilities or individual risks of many components or contributing events and putting them together to get an overall numeric estimate;
- Observed risk: statistical observation where there are many similar types of occurrences such as traffic accidents, fires or industrial accidents;
- Perceived risk: subjective degree of risk felt to be the case by someone; and
- “Real” risk: something we will never know, hence the inverted commas. It is the risk that would be seen if we knew all possible information about the likelihoods of future happenings and had perfect means of analysis.

The realisation of the importance of risk has led to the development of a series of concepts, methods and techniques. The following definitions summarise some of the concepts related to risk given in scientific literature:

- Risk analysis: entails determination (by much means as calculation, estimation, etc.) of the severity of the consequences and the likelihood of the short listed scenarios (Elms, 1998; Molak, 1996);
- Risk assessment: the process of estimating the probability and size of possible outcomes and then evaluating the alternative courses of action (Wharton, 1992);
- Risk communication: the process of explaining risk (Byrd and Cothern, 2000);
- Risk management: is the process of what to do about risk (Byrd and Cothern, 2000). According to Elms (1998), it comprises five steps, namely: understand the problem; determine the risk; decide strategy; set controls in place; monitor; and
- Total risk management: a systematic, statistically based holistic process that builds on a formal risk assessment and management (Haimes, 1998). Figure 2.2 depicts the total risk management paradigm.

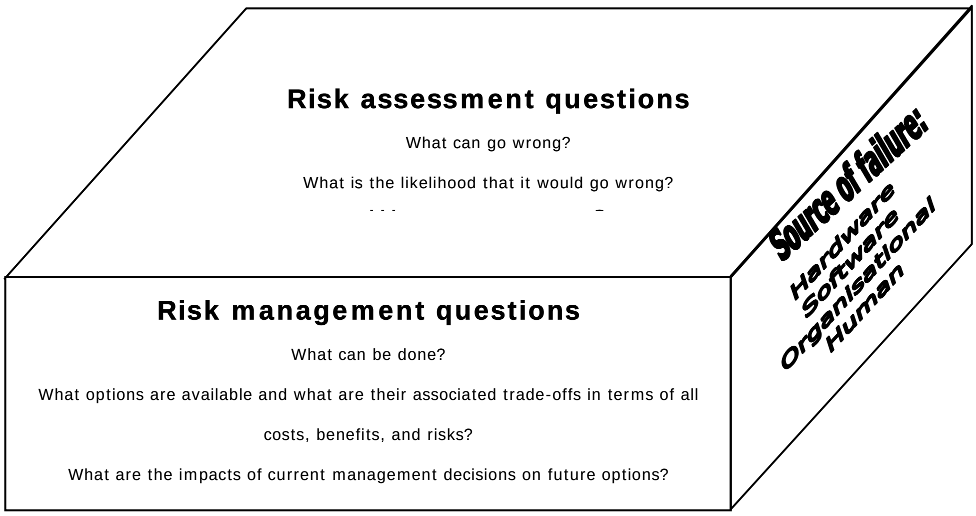


Figure 2.2 Total risk management.[2]

There have been many attempts to quantify risks as part of risk management and analysis. A commonly used approach is proposed by Haimes (1998) as follows:

- Risk is defined as a measure of the probability and severity of adverse impacts;
- The central tendency measure of risk is the expected value of risk, which is an operation that essentially multiplies the consequences of each event by its probability occurrence and sums (integrates all these products over the entire universe of events); and
- In the classic expected-value approach, extreme events with low probability of occurrence are each given the same proportional weight/importance regardless of their potential catastrophic and irreversible impact.

[2] Adapted from Haimes (1998).

Mathematically, the expected value for risk is represented as shown in equation 2.1.

$$EV[X] = \int_0^\infty xp(x)dx \qquad \text{(Equation 2.1)}$$

Where

X= continuous random variable of damages that has a cumulative distribution function $P(x)$;

$EV[X]$ = expected value, average, or mean value of the random variable X; and

$p(x)$ = probability density function of an event x.

3. Future transport energy supply analysis

Future transport fuel availability depends on the nature of the resource, the technology used to extract and process the fuel, and the history of the market. A brief overview of the origins of oil is given, followed by a review of estimates for the global total endowment. Future production is then analyzed with discussion of the history of the world's oil fields. Literature pertaining to peak production is reviewed. A probabilistic study of the estimates for the predicted date of peak production is presented and a post peak supply decline model is developed.

3.1 The geological origins and properties of oil

Crude oil is formed from high pressure heating of un-decomposed biological material which has been buried in sediments over hundreds of millions of years. The oil is usually widely dispersed in inert matrix material. In special circumstances a capstone formation allows oil to flow and accumulate into a reservoir within a higher porosity matrix rock. This particular combination of events produces a commercially viable oil field (Deffeyes, 2001).

As petroleum geologists have explored rock strata around the world, they have formulated estimates of the total amount of oil ever created. Oil bearing geologic formations are assessed to determine the size of the formation and the density of the oil trapped in the matrix rock. Every oil well has behaved in a similar manner once drilled. At first, the oil may be under pressure and easily gushes from the well. After some time the pressure is relieved and negative pressure must be applied in order to pump more oil from the formation. As more oil is removed, the production rate slows appreciably and further increasingly costly measures, including steam injection and explosive strata cracking are sometimes used to pump out further oil. However, all oil wells follow a similar pattern in that once roughly half of the recoverable oil contained in the reservoir has been removed the production rate declines, until finally, a point is reached where further extraction is not possible.

The majority of the oil that has been created in the earth's crust over hundreds of millions of years exists in matrix rocks or in geologic structures where it is not possible to extract it (Campbell, 1997). Only a fraction of the oil in a productive oil reservoir formation can be recovered. Historically, the 'recovery factor' for commercial oil fields has been around 30% of the estimated oil present in the rock.

3.2 Total global endowment of oil

The oil industry, oil geologists and governmental agencies generally agree that roughly 6,000 billion barrels (bb) of oil have accumulated in the earth's crust. The 30% recovery factor would imply that humanity will be able to remove 2,000 bb of oil and return the carbon to the atmosphere through combustion. USGS (2000) has published some substantially higher estimates that have been disputed by numerous oil industry experts (Deffeyes, 2001). Figure 3.1 summarises these predictions.

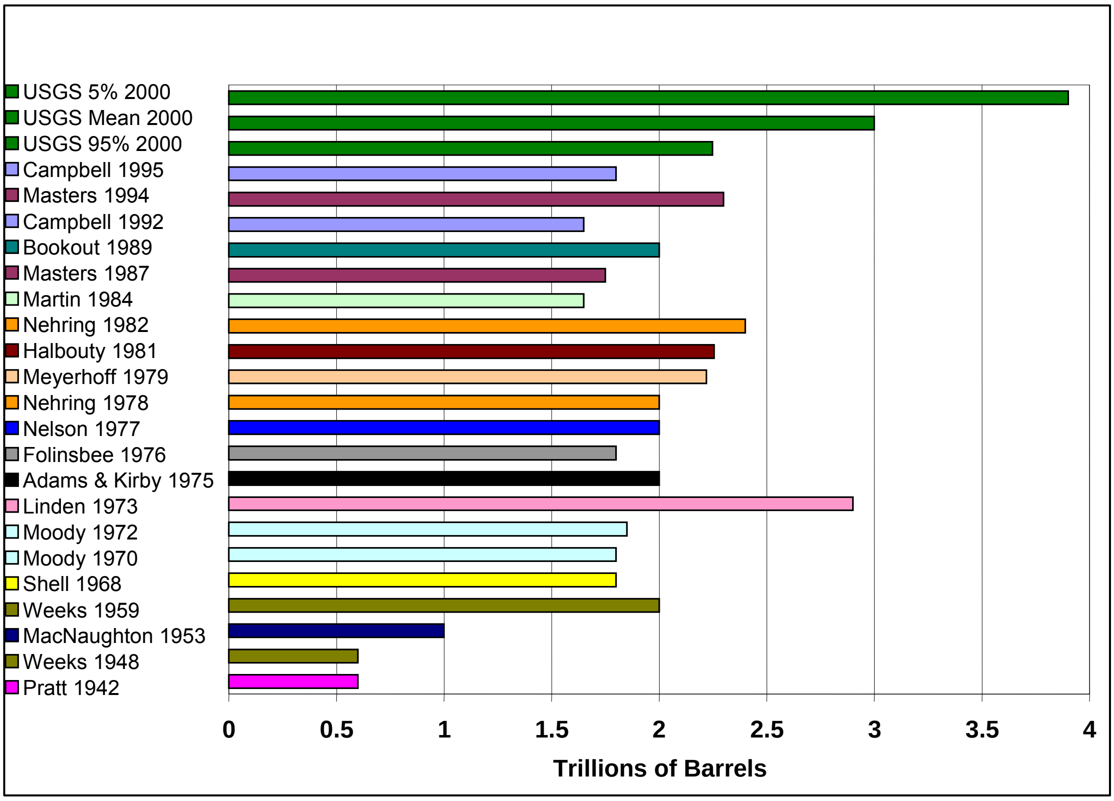


Figure 3.1 Published estimates of world oil ultimate recovery.[3]

Several experts stress that the ultimate recovery figure of 2000 bb of oil is not realistic because the first 1,000 bb was the light, sweet crude oil with flows the most easily through the rock matrix. In the 1950's, 50 barrels of oil were brought to the market for each 1 barrel of oil invested in discovery, recovery, and transport. In the early 1990's, the energy investment of oil in the USA was one barrel to recover 5 barrels (Gever *et al.*, 1991).

3.3 History of world oil production

Figure 3.2 shows oil production by region, over the past 40 years (BP, 2005). Oil production declined in 1974 due to the OPEC embargo, while oil demand dropped in the early 1980's due to high prices and global recession. Since 1983, oil production, on average, has increase by 1.6% per year.

Total oil produced to date, or cumulative production, has been estimated at approximately 1000 billion barrels by a number of sources. For example, using the USGS (2000) review of world oil production, and the British Petroleum statistical review of world energy, approximately 956 bb of oil have been produced (BP, 2005). Deffeyes (2006), who used data from the Oil and Gas Journal, gave a cumulative production figure of 1.007 trillion at the end of 2005. Given that the total global endowment of oil is around 2 trillion barrels, approximately 1 trillion barrels remains. This agrees with many predictions of remaining economically recoverable reserves for example, 1144 bb (OPEC, 2004),

[3] Source: EIA (2000).

1188 bb (BP, 2005). Oil geology experts, on the other hand, give a lower estimate of total recoverable oil, in the range 1007 bb (Deffeyes, 2001). Figure 3.2 shows the current rate of production is approximately 30 bb per year.

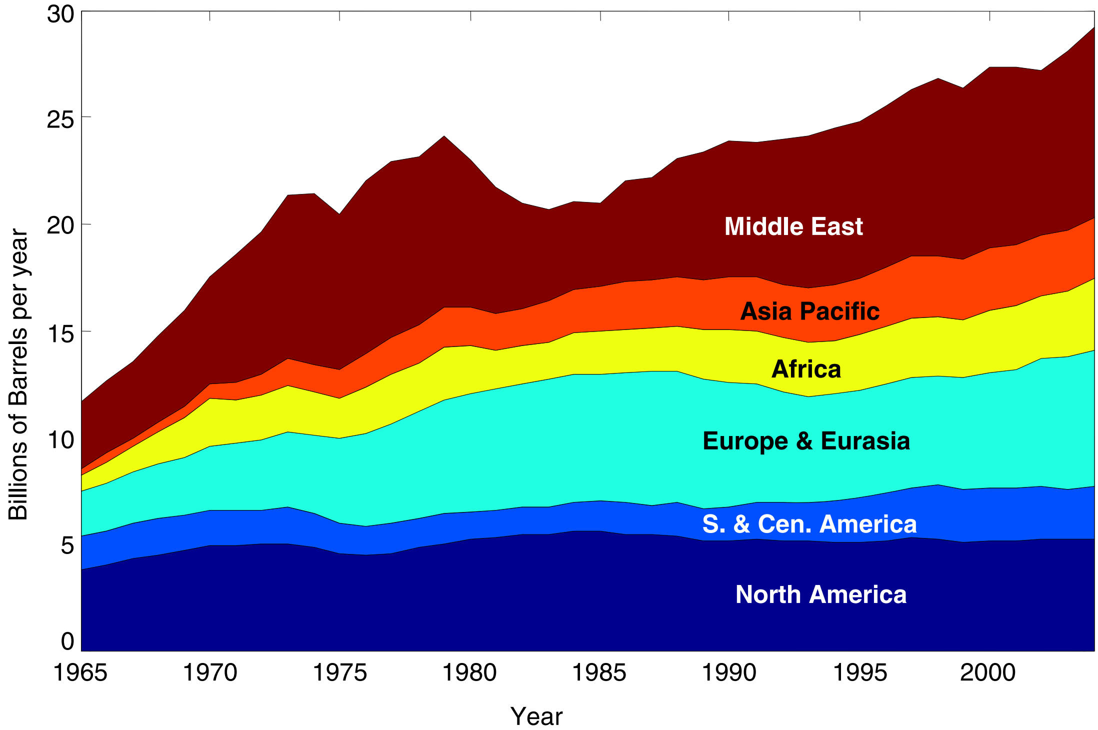


Figure 3.2 Annual world oil production.[4]

3.4 Oil production dynamics

In order to gain a technical view of future oil production, the history of the USA is examined. This represents a large geographical area, initially endowed with a significant amount of oil, with all fields developed by the early 1970's.

Oil-bearing rocks must be found before an oil well can be developed. Figure 3.3 shows the historical oil discovery and the oil production data for the USA, excluding Alaska (IEA, 2000). Most of the oil in the USA was discovered by the end of the 1930's. Oil production peaked in the early 1970's and has been in decline since that time. The steady decline in production from existing wells occurred despite extraction technology improvements, enhanced recovery and intensive exploration due to national concern about energy security.

Importantly, the unabated decline in oil production from existing oil fields in the USA occurred during a time of record world oil prices in the early 1980's.

[4] Source:BP (2005).

The increase, peak and subsequent decline in the USA was modelled and predicted before the peak was reached. In a now famous work, M. K. Hubbert carried out an analysis in 1956 that predicted a peak in USA oil production from existing fields by 1970. The analysis used data about the production to date, history of discovery, size of the reserve and current rate of 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).

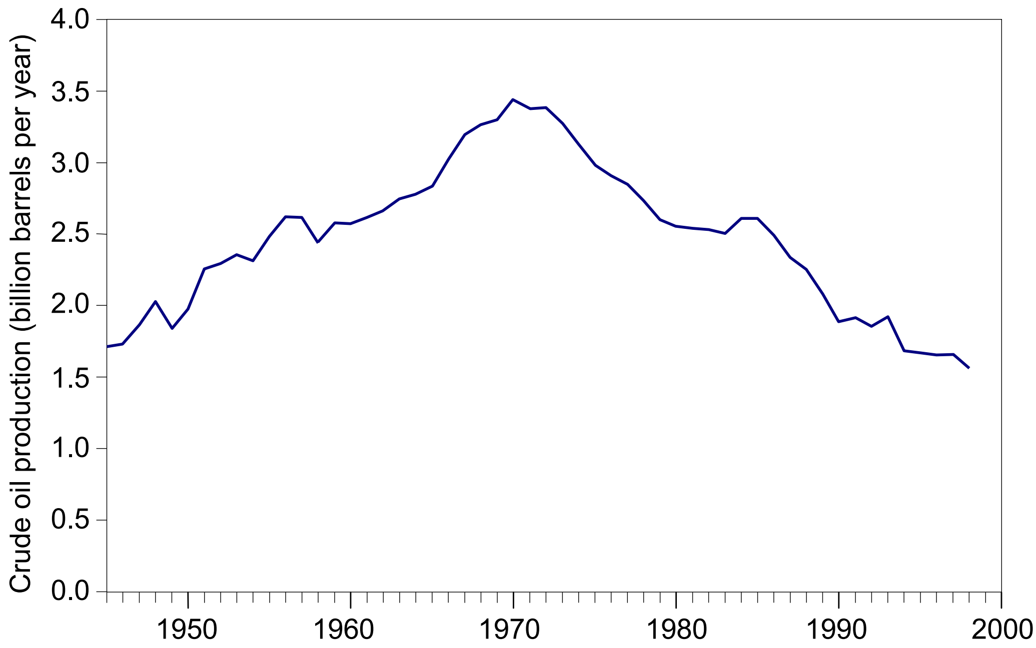


Figure 3.3 USA oil production history excluding Alaska.[5]

The production pattern of oil from resources around the world has followed the same basic pattern. The United States was one of the first oil producers to peak due to geologic constraints. Figure 3.4 shows the oil production history of most major oil producing countries that have passed peak production. The recent significant increase in oil prices since 2000 has not changed the peak and decline for these countries.

[5] Source: EIA (2000).

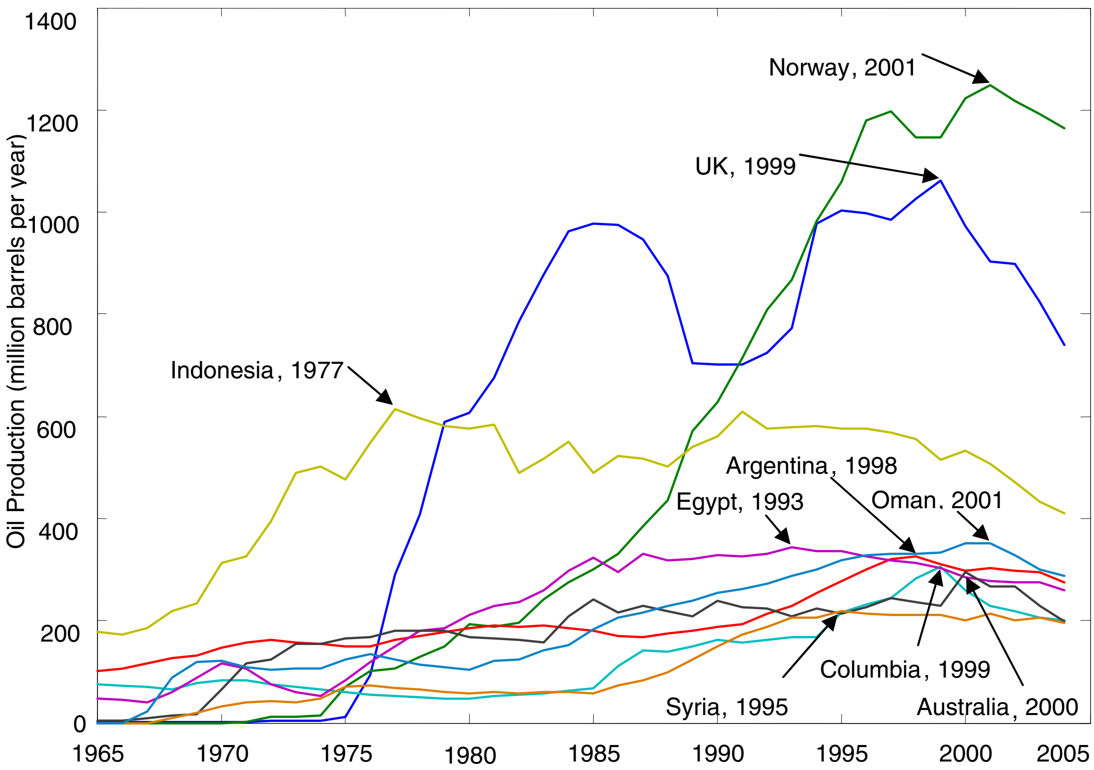


Figure 3.4 Historical oil production data for countries which have peaked.

The rate of oil discovery has declined significantly over the past two decades. Figure 3.5 gives data for the annual discovery of oil fields around the world and the subsequent production of oil. The development of an oil field to full production has historically lagged behind the discovery by several decades. The current consumption rate is four times the current rate of discovery, despite increased exploration and high prices. According to Hubbert's model, the peak in production occurs when half of the oil has been removed from the reservoir. Cumulative world oil production is currently about on half of the total known resource.

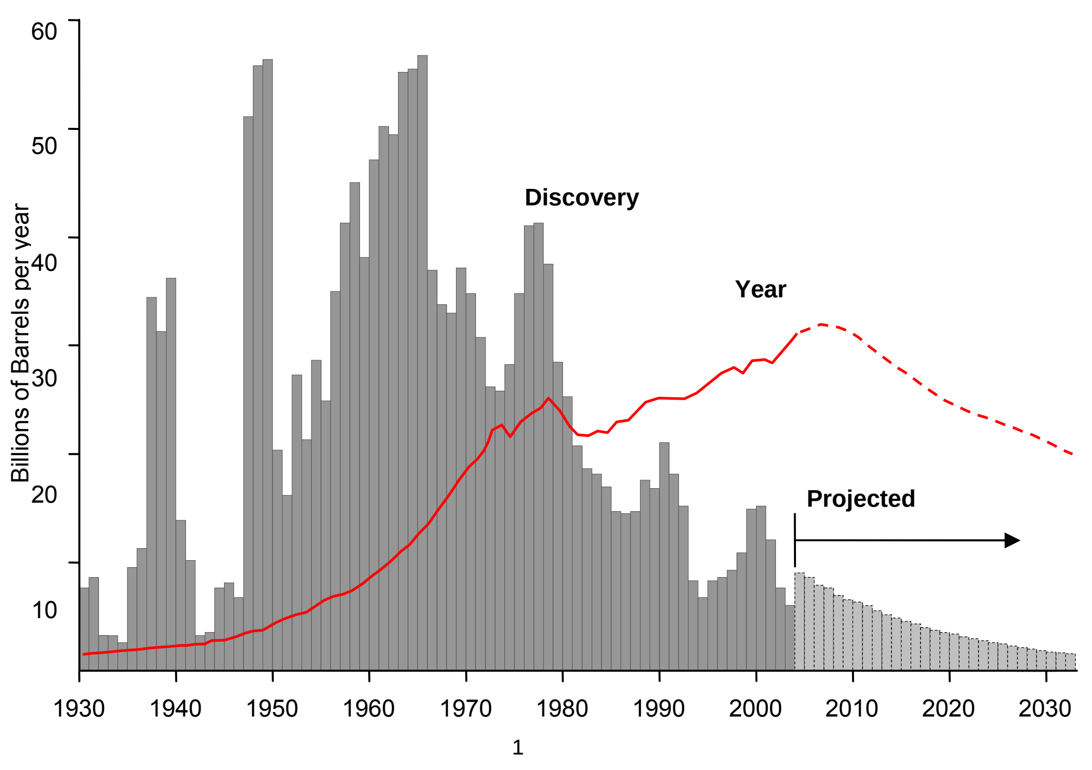


Figure 3.5 Oil field discoveries and world oil production history.[6]

3.5 Prediction of global production peak

International discussion of the topic of peak oil has intensified in the past several years. There is no question that the world oil production rate will peak and then will go into decline. The question is when, and what will the rate of decline will be. The exact timing of the reduction in world oil supply is presented in various reports and published books, but a review of scientific research publications has yielded limited analysis. Government and industry reports reviewed in this section, give the range of dates for the decline of oil supplies to be within the next twenty five years. A summary of published peak oil dates is given in Table 3.1.

Most published reports on peak oil represent the decline in supply as a bell curve mirroring the historical rate of production increase (Campbell and Laherrere, 1998). Other analysis uses a linear decline after the peak with the rate of decline equalling the rate of increase up to the point of peak (Hirsch, 2005). The USA Energy Information Authority (EIA, 2000) has 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. A much steeper decline would infer that production growth could continue to a higher level before the peak occurs.

[6] U.S. House of Representatives (2005)

Table 3.1 Published predictions of peak oil dates.[7]

Peak Oil Date	Source of Projection	Background and Reference
2006-2007	Bakhitari, A.M.S	Iranian Oil Executive
2007-2009	Simmons, M.R.	Investment banker
After 2007	Skrebowski, C.	Petroleum journal Editor
Before 2009	Deffeyes, K.S	Oil company geologist (ret)
Before 2010	Goodstein, D.	Vice Provost, Cal Tech
Around 2010	Campbell, C.J.	Oil Company Geologist (ret)
After 2010	World Energy Council	NGO
2010 - 2020	Laherrere, J.	Oil Company Geologist (ret)
2016	EIA nominal case	DOE analysis/ information
After 2020	CERA	Energy consultants
2025 or later	Shell	Major Oil Company
No visible peak	Lynch, M.C.	Energy economist

Figure 3.6 shows quite clearly that, according to Campbell, the oil supply situation is set to change from an upward trend to a downward one. Campbell (1997), Laherrere (2003), Hubbert (1956), Hirsch (2005), the IEA (2000), and Deffeyes (2001) have all examined the issue of oil depletion. Most analysis is in agreement on the nature of the decline as in Figure 3.6, with the rate of decline mirroring the historical rate of increase.

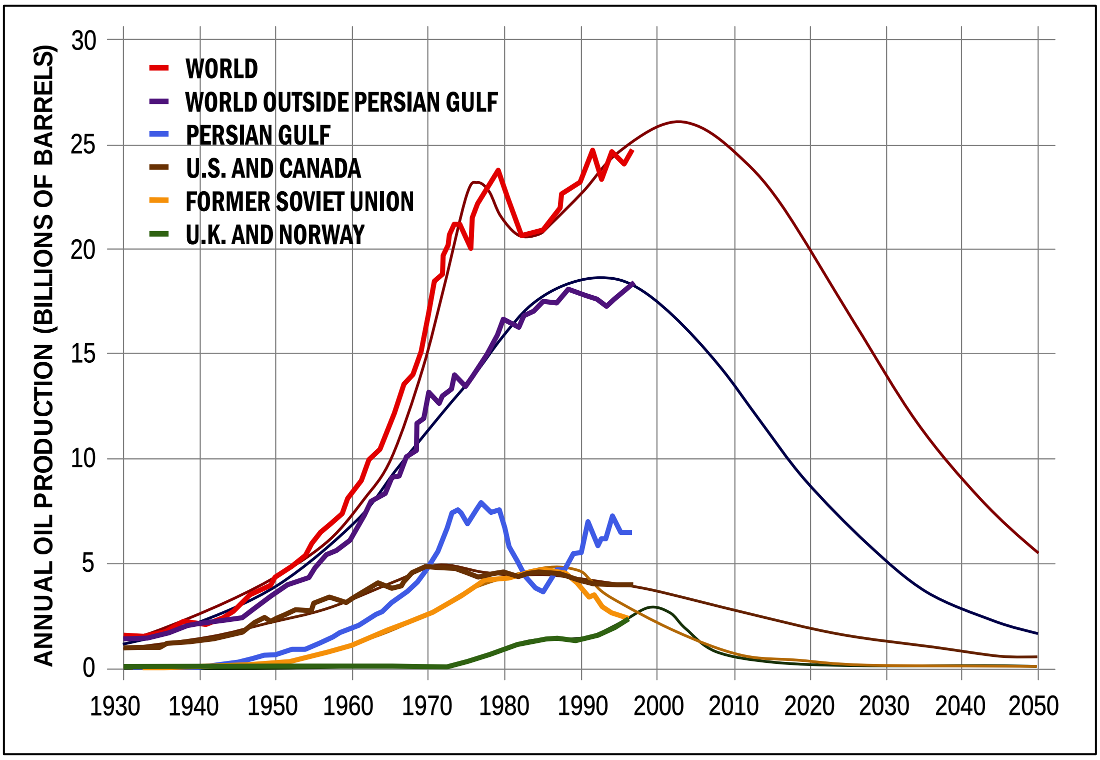


Figure 3.6 World oil production estimates.[8]

[7]Source: Hersch (2005).

[8] Source: Campbell and Laherrere (1998).

New Zealand is dependent on imported oil for all transportation fuels. In the year 2004, approximately 65% of transport fuel was refined at Marsden point, New Zealand's only refinery, which is operated by the New Zealand Refining Company (NZRC). The remaining 35% of transport fuel is imported directly as refined product. Using data from the New Zealand Energy Data File 2005, Figure 3.7 shows the flow of oil in terms of total energy. More than two thirds of refined oil products are used exclusively for domestic transportation.

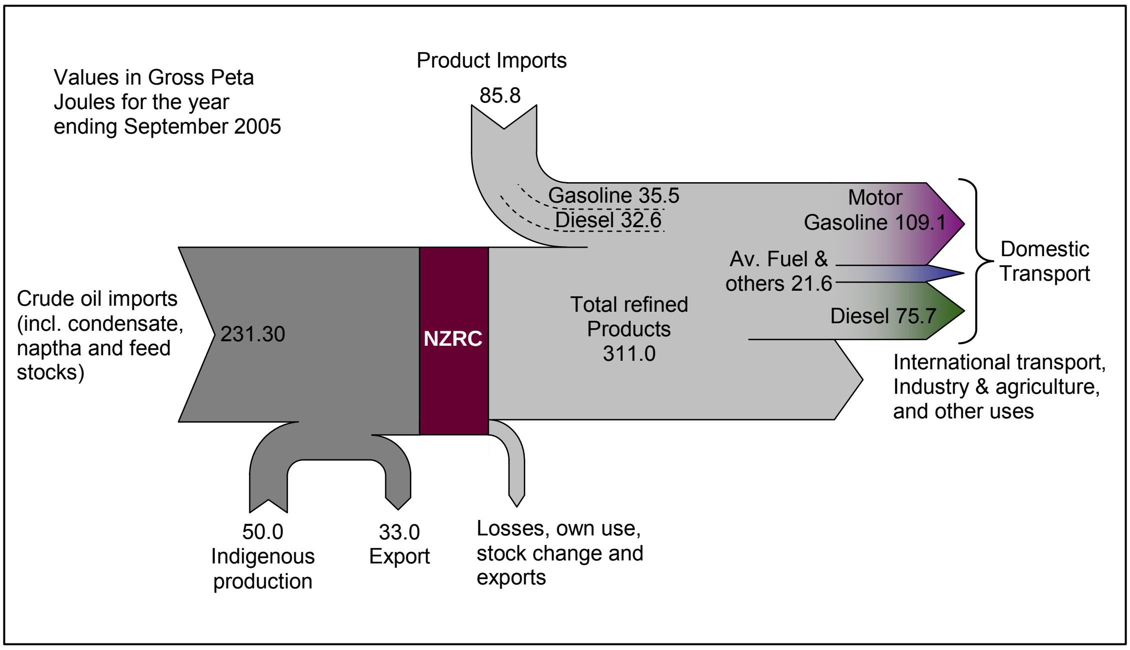


Figure 3.7 Typical transportation fuel supply and distribution for New Zealand 2005[9].

3.6 New Zealand's position for oil supplies

In any given year, around 50 – 60% of imported crude oil and refining feedstocks are sourced from the Middle East and Asia, with the remainder from indigenous production and imports from Australia (Colegrave *et al.*, 2004). New Zealand produces some crude oil, condensate and naphtha, which is predominately exported due to its light nature and high value. In 2004 indigenous production was 23% lower than 2003, and 54% lower than in 1999. This is a result of New Zealand oil peaking in 1997. Domestic oil production is now in rapid decline.

For the purposes of this report, New Zealand's oil supply situation will not differ greatly from the world situation.

3.7 Energy supply disruption events

Using the data and facts summarised in previous sections of this chapter, disruption events will be defined. The international and national regulatory mechanisms, as well as

[9] (note: 1 liter Petrol = 33 MJ, 1 liter Deisel = 36 MJ)

any oil company mechanisms, were researched to develop a picture of the nature of supply disruptions.

Temporary supply disruptions to imports are mitigated by New Zealand's fuel supply companies through storage at Marsden Point and inventories at retailers. A long-term trend of downward world oil production will be the key source of future supply disruptions. Thus, the beginning of exposure to risk from fuel shortages is the peak in world oil production.

3.7.1 New Zealand's robustness to short term supply shortages

New Zealand's system of oil refining, storage, and distribution is considered to be robust and reliable. Therefore, short term supply disruptions (such as a tanker of crude or product not arriving) will not have an impact on consumers. Part of this robustness comes from oil stocks New Zealand is required to keep. As a member of the International Energy Agency (IEA), New Zealand is required to keep 90 days worth of market consumption. Currently, New Zealand is 20 – 35 days short of this target, and lack of compliance is currently being addressed by the Ministry for Economic Development (Colgrave *et al.* 2004). Thus it can be assumed that in the future, New Zealand should hold the 90 days level of consumption.

A supply disruption to consumers caused by a global shock has a much higher chance of occurring than anything else.

> *"The likelihood of an external disruption to New Zealand supply is up to ten times greater than internal disruption."* (Colegrave et al. 2004)

Thus in predicting shortages, only global events need to be considered. The local affects of global oil shortages are to some degree directed by the IEA. New Zealand's obligations as a member of the IEA, and how these affect the manifestation of shortages, are discussed below.

3.7.2 Long-term shortages and international obligations

The IEA was formed after the global oil shocks of the 1970's. The principal purpose of the IEA is to ensure undisrupted oil supply to its 26 member countries. Effectively, the IEA facilitates cooperation among member countries in the event of an oil shortfall, thus reducing the risk to any one country. The main points of the IEA agreement are briefly discussed below.

In the event of an IEA member country suffering a supply shortfall, the IEA can instruct other member countries to reduce consumption by a fixed amount. The first level is a 7% reduction in consumer demand, and the second level is a 10% reduction in consumer demand. The IEA measures are meant to be temporary reductions enacted to keep oil prices from running away and causing economic problems. Hurricane Katrina caused a 10% reduction in supply in the US. This event influenced record oil prices, above $70 per barrel, but, the IEA did not call on members to reduce demand. Thus, an IEA call for 7%

demand reduction would signal a very significant production decline. When these events occur, this will signal the initiation of the permanent decline in oil supply rather than a temporary fluctuation.

3.8 Post peak oil supply decline model

World oil supply is actually a combination of production from many fields in many countries. It is conceivable that a natural disaster, such as recent hurricanes in the Gulf of Mexico or terrorist acts, could disrupt the production of a particular region. In the absence of disasters, the production from major oil reserves in a country will peak and go into decline as occurred in the USA in the 1970’s. After the peak in indigenous production of a country, it will then be reliant on the world oil market for any possible increase in consumption. Thus, after the peak in world oil production has occurred, all countries which have already peaked in domestic production will experience declining fuel supply.

Depending on the value used for ultimate recoverable oil reserves, between 2000 and 3000 bb, the actual date of the production peak will occur within the next 25 years. The historical global increase in world production has been 1.6% pa, which may be continued to the peak point. The world production is modelled to reduce by 1.6% pa after world peaking. As shown in Figure 3.8, the date of peak will be somewhere between now and 2025.

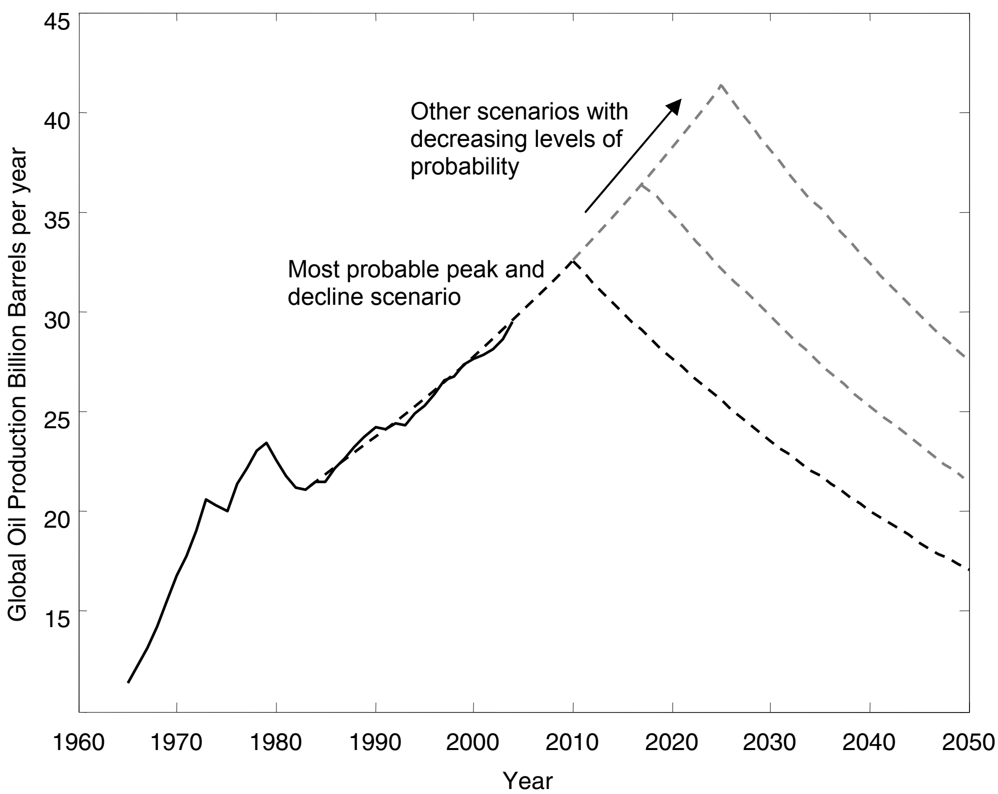


Figure 3.8 Decline model with range of peak certainty indicated.

Campbell (1997) suggests that the peak oil production may have a plateau before turning permanently downward. A plateau model would reflect very high oil prices that reduce demand even though production could possibly be increased further.

In order to assess the risk to activities that are accessed by transportation using petroleum-based fuels, the actual quantity of fuel being used is not as important as the impact due to shortages. The purpose of the fuel supply model is to determine a probability of a given fuel supply level at some point in the future which can be compared to a hypothetical demand level at that same future point. The probabilistic difference between the hypothetical demand level and the predicted supply level represents the shortage.

Once the peak in production occurs, the production rate will then decline. The probability of a 7% reduction, and any subsequent reductions 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. Table 3.2 summarizes the post-peak supply reductions according to the supply reduction model. The same time sequence would follow the peak event regardless of the peak date used

Table 3.2 Post-peak fuel reduction matrix.

Year Post-Peak	Reduction Model
0	0%
4.5	7%
6.5	10%
10	15%
13.8	20%

3.9 Probability of energy supply disruption events

In this section, a method is presented to calculate the probabilities over the next two decades of energy supply disruption events in New Zealand. We have used 0% probability that the production peak occurred in 2005. Information presented in Section 3.7 is quite clear that the peak in world oil production will occur by 2030. Discounting the one outlying USGS peak production prediction based on the ‘high scenario’ of 4 bb recoverable oil, all references available agree that oil production will peak by 2030. Thus, by 2030 there is a 100% probability that oil production will have peaked and begun to decline.

Section 3.7 gave a list of all predictions of peak oil. By mapping these predictions, in Figure 3.9, it can be seen that more experts predict the peak to occur before 2010, with fewer predictions being made out to 2025. From these predictions, a probability distribution of when peak oil will occur can be formulated, giving a cumulative probability of when peak oil is likely to occur as shown in Figure 3.10.

A distribution fit to the published peak production predictions gives a distribution function the probability, P(x), of the peak occurring in any year, x, between 2005 and 2030:

$$P(y)=\left(\frac{(r+y-1-2005)!}{(y-2005)!(r-1)!}\right)\rho^{r}(1-\rho)^{y-2005}$$ (Equation 3.3)

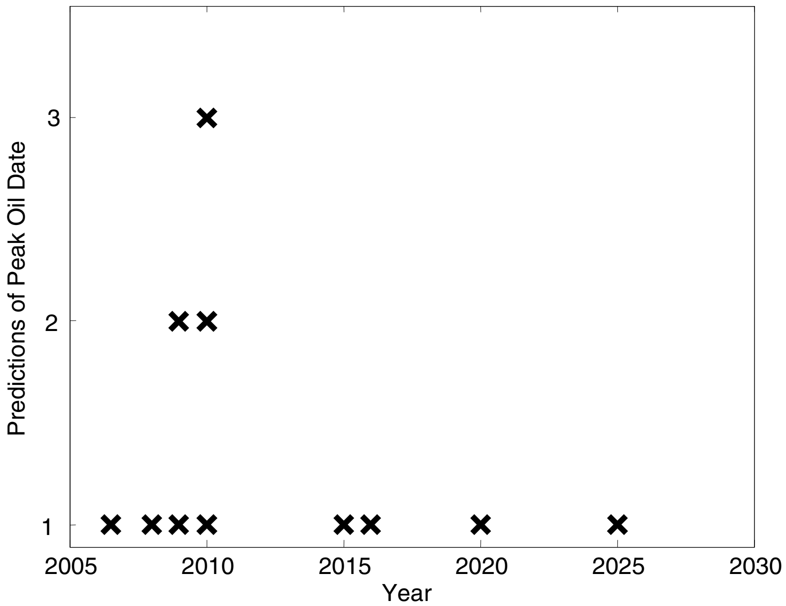


Figure 3.9 Prediction date of peak oil for all sources in table 3.1.

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

$$CP(X)=\sum_{Y=2005}^{Y}\left(\frac{(r+y-1-2005)!}{(y-2005)!(r-1)!}\right)\rho^{r}(1-\rho)^{y-2005}$$ (Equation 3.4)

Where the fit parameters of ρ = 0.44 and r = 5 are used for the distributions shown in Figure 3.10.

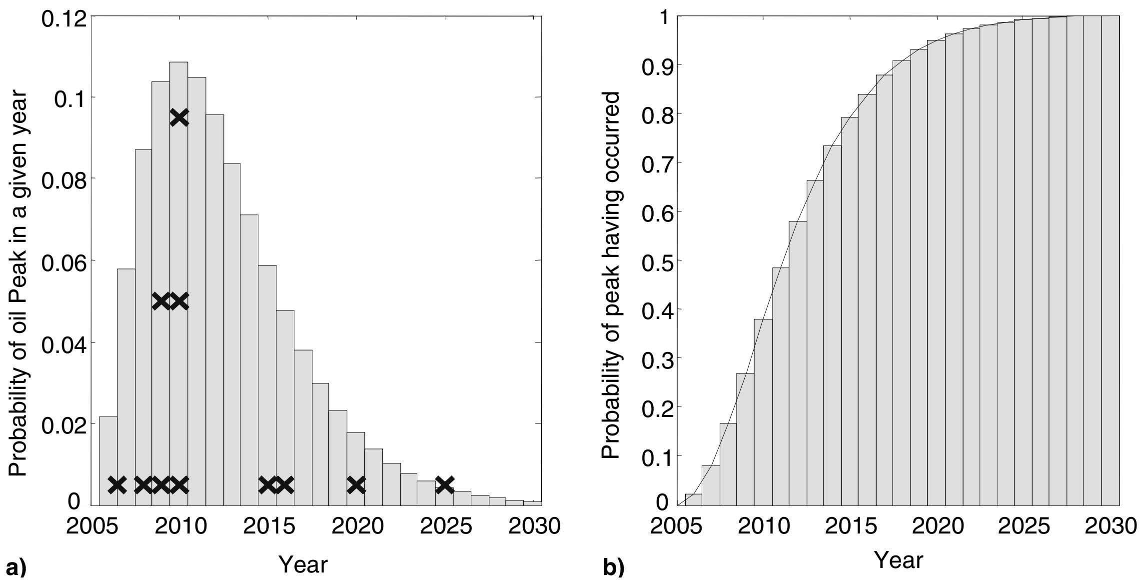


Figure 3.10 Probability model based on predicted dates: (a) probability of peak event in a given year, P(y), and (b) cumulative probability distribution with time, CP(Y).

The probabilities at five year intervals of each level of oil reduction are given in Tables 3.3 and 3.4. The forward peak matrix is based on the analysis of petroleum geology experts, and is considered to be the more accurate representation of the probability of occurrence of the peak and subsequent supply reduction trends. Thus, Table 3.4 will be used in all subsequent analyses.

Table 3.3 Peak event probability matrix.

SCENARIOS	Years					
	2005	2010	2015	2020	2025	2030
Peak Production	0%	37.8%	79.2%	94.9%	99.0%	100%
7% Voluntary Reduction	0%	3.5%	52.4%	88.4%	98.1%	99.7%
10% Ration Reduction	0%	0%	29.4%	78.1%	95.9%	99.4%
15% Ration Regulated Reduction	0%	0%	1.5%	46.1%	86.0%	97.6%
20% Ration Enforced Reduction	0%	0%	0%	7.3%	59.3%	90.7%

3.9.1 Manifestation of oil shortages to New Zealand

The model for the supply decline dynamics starts with the peak oil event at a given date. The IEA's 7% reduction signals the beginning of an irreversible decline sequence. The 7% reduction includes a voluntary compliance program aimed at all New Zealanders. A report commissioned for the Ministry for Economic Development (MED) (Denne *et al.* 2005) shows that just over 7% savings can be achieved with voluntary measures, such as car pooling, correct tyre pressure and reduced speed limits. The 7% reduction is followed within 2 years by a further 3% reduction, which is designated the Rationing Stage I.

Further reductions cannot be accomplished with voluntary compliance and will signal the beginning of the rationed supply system, which will continue indefinitely. As supplies become further reduced, the ration will adjust to Rationing Stage II with fuel supply equal to 15% below the peak value. Finally, at 13.8 years post-peak the final 20% reduction from the peak starting point is called Rationing Stage III.

Because the time between successive reduction levels is only 3.8 years, new technology and infrastructure change, such as new public transport or increased car efficiency, will not be available to alleviate the need for rationing of some kind (Hirsch 2005). Table 3.4 summarises the oil shortage events and their characteristics. The percent reduction is from the peak supply, regardless of the year in which it occurs.

The fuel supply availability for each rationing stage would reflect a percentage reduction from the peak level of consumption.

Table 3.4 Oil supply decline dynamics model.

Peak Event	Rationing Stage I	Rationing Stage II	Rationing Stage III
7% Voluntary Reduction	10% Reduction	15% Reduction	20% Reduction
Post Peak Year 4.5	Post Peak Year 6.5	Post Peak Year 10	Post Peak Year 13.8
Reduction of previous usage level for each person	New supply level equal to previous aggregate reduced by 10%	New supply level equal to previous aggregate reduced by 15%	New supply level equal to previous aggregate reduced by 20%
Implemented by media campaign and education or due to high price	Implemented through issuing of purchase allocations by petrol supply companies	Implemented through petrol suppliers and regulated by government	Implemented through petrol suppliers and regulated and enforced by government

Figure 3.11 shows the oil supply decline modelled as a series of rationing steps superimposed on the peak oil supply reduction trend from Figure 3.8.

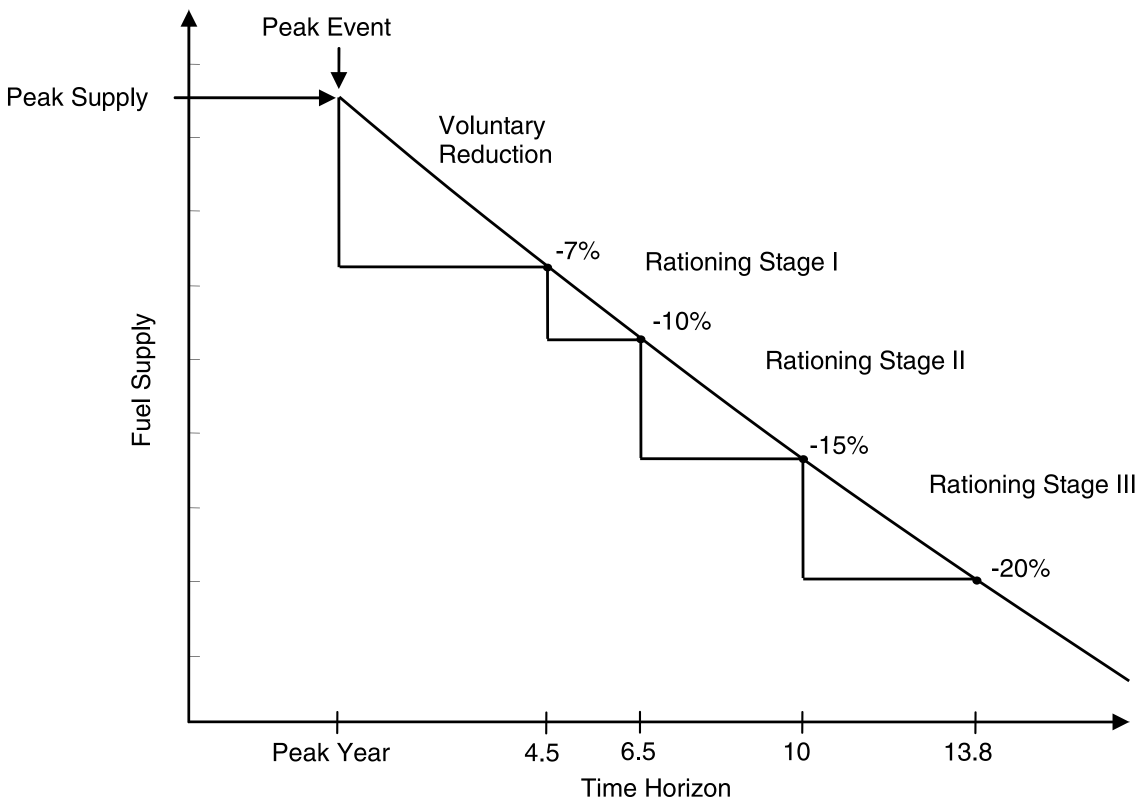


Figure 3.11 Oil supply decline curve from the peak event.

3.10 Transport fuel substitution

In this section, substitute fuel sources, new transport technologies, and additional oil from new discoveries or enhanced recovery is assessed. The preceding analysis was concerned only with oil production from existing resources according to historical oil industry practice. If alternative fuels were available for substitution at the time of an oil shortage, then the resulting disruption would be mitigated and the impact would be reduced. Biofuels, compressed natural gas and liquefied petroleum gas as fuel alternatives are reviewed. The mitigating effects of higher efficiency vehicles, enhanced oil recovery and new oil discoveries are also discussed.

3.10.1 Biofuels

Liquid biofuels are processed from biomass feedstocks that are either purpose-grown or the waste by-products of agricultural production. Biofuels are not currently used for transportation in New Zealand, but have been used for many years to various extents in Brazil, Europe and the US. There are two distinct types of biofuels; bioethanol which can be used in spark ignition engines and biodiesel which can be used in compression ignition engines.

Bioethanol, the same alcohol as in beverages, is processed from the fermentation of sugar and starch crops, for example sugarcane in Brazil and corn in the US. Bioethanol using feedstocks of cellulose, hemi-cellulose, and crop residues such as cereal straw have been proposed. However the technology is still in development, and not considered to be commercially viable without breakthrough technologies (Thiele, 2005). Due to ignition and engine component issues, bioethanol is usually used as a blend with petrol.

Biodiesel is made by reacting an oil or animal fat with ethanol, producing an alkyl-ester and glycerol as a by-product. Rapeseed is grown specifically for biodiesel production in Europe. Biodiesel can be used directly in a diesel engine, but is only available as a blend with fossil diesel.

Biofuels are commonly considered to be a renewable energy resource, with no associated net emission of CO_2. However, the process of growing the source crops, together with the processing of the crop into a biofuel requires a significant input of energy, most of which is fossil fuel sourced. For example, for bioethanol production in the US from corn the ratio of biofuel energy produced divided by the energy required for production, has been calculated to be 1.24 (Shapouri *et al*, 1995) and 1.0 (Kim and Dale, 2005). Biodiesel from rapeseed has an energy ratio 1.04 – 9.29 depending on crop productivity, processing methods, and whether the energy content of co-products is included (Janulis, 2004). The resulting cost of the biofuel is high compared to ordinary fuel, and is sustained through agriculture subsides in the US and Europe.

In 2002 the New Zealand government set an indicative target that 2PJ, about 1% of transport fuel will be renewable by 2012. A study to investigate the cost and benefits of mandatory biofuel has been undertaken (Stephenson *et al*, 2004), and recently, the government has indicated that sales targets of biofuel be set in law (Hodgson, 2005). The Government is not advocating the growing of crops specifically for the purpose of biofuel production, instead, only organic waste streams will be utilised. Therefore, the resulting biofuel is considered to be renewable and CO_2 neutral as the energy inputs have been accounted for in production of the primary produce or process.

The most promising biofuel potential in New Zealand is biodiesel sourced from tallow, an animal fat from the meat processing industry. Currently, tallow is exported to the Asian region for use in the chemical industry and for making hard soaps. New Zealand produces 150,000 tonnes of tallow per year, which if processed into biodiesel, could replace up to 5% of the current diesel consumption (Judd, 2002). Biodiesel would most likely be sold as a 5% mix with fossil diesel. The resulting blend can be used in the same way as current fuels.

New Zealand currently produces bioethanol as a by-product of the dairy industry, where whey is fermented and distilled. Most of the bioethanol is exported, and if used as a biofuel, would be sufficient for 0.3% of the current petrol market. The potential of utilizing additional waste streams could provide a maximum additional 4.3% of current consumption (Stephenson *et al*, 2004), but this relies on unproven conversion processes.

In summary, if the renewable transport energy target of 2 PJ is achieved, this is only a small fraction, less than 1%, of the total domestic transport fuel market of 213 PJ. As reviewed above, the options for increasing the amount of biofuel obtained from waste streams are low. Growing crops specifically for biofuel production is unlikely to occur, as the government does not promote this. In conclusion, the addition of biofuels into New Zealand will not significantly effect the timing and probability of reductions in oil supply presented in the analysis of Section 3.7.

3.10.2 Compressed natural gas/liquefied petroleum gas

Both compressed natural gas (CNG) and liquefied petroleum gas (LPG) are used to a limited extent in New Zealand as transport fuels. CNG consumption in automotive transport has declined drastically, from a peak of 5.85 PJ in 1986, to the current consumption of 0.22 PJ (MED Energy Data File 2005). This is largely due to the removal of subsidies in 1987.

LPG powered cars are more common than CNG, as LPG is widely available, compared to CNG which is restricted to the North Island. LPG is sold at service stations as a transport fuel and for other purposes, such as cooking and heating. Due to recent high oil prices, the interest in gas fuelled vehicles has increased, with car conversions being available and LPG cars appearing on the market. Even so, the amount of LPG currently used for domestic transport is small, approximately 1.2 PJ (MED data File, 2006). Clearly the infrastructure and technology of gas powered vehicles exists, the issue however is the future fuel availability.

Production of gas in New Zealand is currently in steep decline. Having peaked in 2001 at 265.25 PJ, production dropped to 149.3 PJ in 2005 (MED, 2005). Even with the inclusion of gas fields that are not yet in full production, such as Pohokura and Kupe, total gas production is still predicted to decline. Only with additional discoveries is gas predicted to increase gradually (1.6% pa) until an inevitable decline from 2020 onwards (MED, 2003). Some speculation has been afforded to importing liquefied natural gas (LNG). However, future global availability of LNG will likely go into decline as major LNG consuming countries have peaked in natural gas production, and are already importing increasing amounts of LNG (BP 2005). The inevitable decline of gas, together with current use to generate 16.1% of New Zealand's electricity, presents a significant probability that gas will not contribute to transport fuel requirements in the future. Thus the probability of fuel peak and decline is not affected by inclusion of substitution from gas resources.

3.10.3 Higher efficiency vehicles

It may be possible that higher efficiency vehicle technology will be available in the future. There is some evidence of the effect of higher efficiency vehicles in the sharp decline in fuel demand after the OPEC oil embargo. This was in part due to the introduction in the USA of the Corporate Average Fuel Economy (CAFE) standards and the importation of compact Japanese cars. The enactment of the CAFE standards in 1975 resulted in a near doubling of vehicle average fuel economy, measured in miles per gallon (mpg), over the ensuing decade and an increase for light trucks of over 50%. The newer efficient cars may have allowed higher travel demand using the same amount of fuel than would have been possible with the pre-1974 fleet. Despite the CAFE standards and the popularity of Japanese compact cars in the US, fuel consumption has increased at a steady rate of 1.8% per year. Raising fleet energy efficiency by 5% annually would still result in increased fuel demand given current travel demand trends (ACEEE 2006).

Considering that New Zealand's primary source of vehicles is second hand imports from Japan, the availability of new, more efficient vehicles will be delayed by four to five years, if the Japanese were to begin improving fleet efficiency now. It could be possible for the New Zealand government to effectively increase the import fleet efficiency by limiting the range of cars to include only compact and high fuel efficiency vehicles.

It might be possible that businesses and families may have several vehicles with different fuel efficiency. During a fuel shortage, people may adjust to use higher mileage vehicles without rushing out to purchase new vehicles. Over the time-frame of the first fuel reduction stage, this is the most likely scenario.

3.10.4 Enhanced oil recovery

The oil companies have invested heavily in technologies for recovering more oil from existing wells. Enhanced oil recovery (EOR) is a mature technology which has been in practice since the 1950's. EOR methods are employed once the production from an oil field has peaked. Secondary enhancement is first employed to increase the pressure in the underground reservoir by injecting water into the reservoir. EOR may then be employed, depending on site and field specific conditions and economics. The most common EOR technique is miscible flooding of the field with CO_2 which acts as a solvent to remove residual oil. EOR is relatively expensive and increases the acidity of the oil, which may lead to plant degradation (Williams 2003).

Evidence to date has shown that these measures increase the ultimate production of oil fields by no more than 10% of the original oil in place, and the increase is spread out over the last few years of the life of the well. Because EOR is becoming more widespread as oil costs rise, the effect of enhanced oil recovery is already accounted for in the decline model. However, it should be stated that the decline rate we have used is actually optimistic in that it matches the increase rate, and the production patterns from commercial oil wells indicate that the rate of decline is much faster than the rate of production increase.

3.10.5 New oil discoveries and non-conventional resources

All current oil forecasting experts indicate that the major oil resource discoveries have already been made (Deffeyes 2001). Oil discovery peaked decades ago, despite increased exploration activity. The data we have used to model the oil supply has the assessment of new oil discoveries already incorporated, and we have not included any unsubstantiated prospects for new discoveries.

Non-conventional oil includes hydrocarbon deposits which have not been converted to crude oil through geological processes. Oil-shale, for example, has not had a sufficient time at a sufficient depth and temperature to be converted to oil. Canadian oil sands have been in commercial production for decades, producing roughly half lower grade bitumen and half synthetic crude oil. Processing requires large amounts of energy for heating and processing, with an estimated energy product efficiency of less than 70% (Gray 2004).

4. Method to assess energy risks to activity systems as a function of urban form

This method brings the probability of energy supply disruption events (Section 3.9) together with travel patterns analysis to estimate the risks that different urban forms would be subject to in a fuel shortage/crisis event. The risk assessment represents how communities would be affected in terms of activities participation, because changes to travel behaviour would be required in order to cope with energy restrictions. The risk assessment method is developed to quantify how the reduction in trips is likely to impact the community.

After this introduction, we present a conceptual formulation to assess the impact of changes to activities due to fuel constraints. Next, the risk assessment method is described in the second sub-section. Finally, we introduce a prototype version of a software modelling package (RECATS) that calculates a risk factor at a queried year in the future for a given urban form and travel demand configuration.

4.1 Activities impact assessment

We propose that in a shortage/crisis event, urban communities would undergo significant transformation in order to cope with fuel 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 sub-section 4.1.1 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 the impacts of fuel shortages/crisis events are stated in sub-section 4.1.2. Sub-section4.1.3 describes how the principles are applied to determine impact for the RECATS assessment.

4.1.1 Concept of essentiality

Given a fuel constraint, certain trips would become more important to a person's wellbeing, than other trips. Surveys of travel behaviour under current unconstrained fuel availability conditions revealed that people rated up to 30% of their own trips as 'unnecessary' (Gordon et al 1988; Cervero and Radisch, 1996; Hanson, 1995; Banister et al., 1997; Banister 1980; MOT, 2000). Therefore, if a person was subject to a fuel constraint, the relative importance of each trip would play a major role in deciding which activities to participate in. For example, if a person considers maintaining income and heath as fundamental to his/her wellbeing, then work and food shopping purpose trips would be priorities over recreation travel activity.

In this context, we present the concept of **Essentiality**:

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

In a fuel shortage/crisis, 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: a certain proportion of trips which people would curtail if their fuel supply is constrained;
- Necessary trips: a proportion of trips that people would affect their or their family's wellbeing; and
- Essential trips: those trips would significantly affect the individual's survival at its most basic needs.

4.1.2 Impact principles

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

> ***Fuel constraints cause trip losses and/or changes in travel patterns.***

Travel behaviour would change from the observed (or current) travel demand with an un-constrained 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; and
- 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/crises, 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 they could not undertake those trips 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.

4.1.3 Implementation of impact principles

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

For a given scenario of urban forms, the main data inputs to conduct the impact analysis are:

- The future estimated population;
- The future estimated travel patterns, expressed in terms of demand by mode, travel distance and average number of trips per person. This data set may come from traditional travel demand modelling forecasting;
- The forecast year and the fuel reduction level, which are defined according to the values in Table 3.3;
- The relative split (%) of essentiality levels, which are adjusted to match particular survey data, taking into consideration factors like mode options, destination distances, community factors, and information systems;
- The fleet efficiency, expressed in energy consumption per travel mode; and
- The mitigation options that are expressed in terms of changes in the transportation and activity system.

Urban communities' resilience would be expressed in terms of the minimization of changes in travel patterns due to fuel shortage/crisis. 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 of fuel management systems. This complex dynamic will be the subject of future research as it has not been studied in the transport field, and because it has such a strong relationship with the impact of fuel shortage.

4.2 Risk assessment method

Given an urban form and a future energy assessment scenario, 5 steps are conducted in order to quantify the risks (see Figure 4.1).

- The travel pattern without the fuel shortage/crisis event is determined using available data expressing current/observed travel distances, mode choices and essentiality levels;
- Energy consumption is calculated;
- Considering the available energy due to future reduction levels, consumed and available energy are compared;
- If energy consumption is above the availability threshold, travel patterns are modified, then energy consumption is recalculated. The travel patterns are modified until the energy consumption levels are lower than the available energy; and
- The risk is computed considering the original and modified travel patterns and the oil crisis/shortage probability.

These steps are subsequently repeated for other urban form scenarios. The calculated risks are compared and assessed in retrospect to each scenario configuration. The following sub-sections present the mathematical description of the risk assessment method.

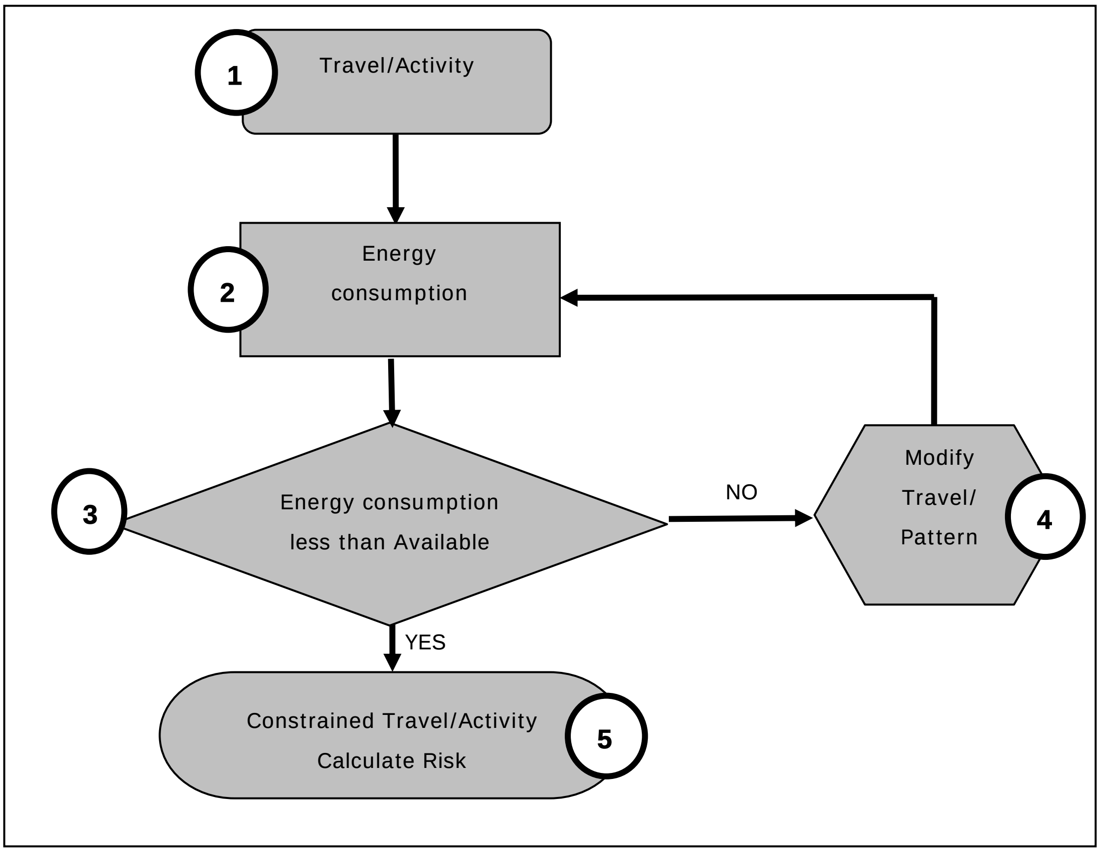


Figure 4.1 Schematic representations of the method steps.

4.2.1 Step 1 - Travel pattern without the energy shortage / crisis event

In this step, the characteristics of the urban form under analysis are converted into a travel pattern indicator (*T*) that expresses the level of activity without any disruption to energy supply, considering the Travel Demand (*TD*) for all modes and travel distance bins. Equations 4.1a and 4.1b, respectively, represent *TD* and *T* for a given urban form. Figure 4.2 shows a schematic representation of the travel pattern indicator (*T*) as a Trip Length Distribution (*TLD*).

$$TD^{m,d} = MS^{m,d} * PO * \mu \qquad \text{(Equation 4.1a)}$$

$$T^{m,d,s} = TD^{m,d} * ES^{s} \qquad \text{(Equation 4.1b)}$$

where:
T = travel demand indicator per mode and distance bin and essentiality level;
TD = travel demand per mode and distance bin;
PO = Population in the study area;
μ =Average trips per person per day;
MS = Matrix of mode split per distance bin (or range of travel that is common to a group of trips);
ES = Vector of relative split of trips essentiality; and
$^{m,\,d,\,s}$ = refer to a particular mode, distance bin and essentiality level , respectively.

4.2.2 Step 2 - Energy consumption

This step focuses on calculating the energy consumption using *TD* (from step 1), population and energy efficiency data observed in the study area. Equation 4.2 represents mathematically the energy consumption (*E*) calculation for a given urban form.

$$E = \sum_{m}\sum_{d} TD^{m,d} * EC^{m,d} DB^{d} \qquad \text{(Equation 4.2)}$$

where:
$EC^{m,d}$ = Matrix of energy consumption per mode and distance bin; and
DB^{d} = Vector of distance bins (mid distance point).

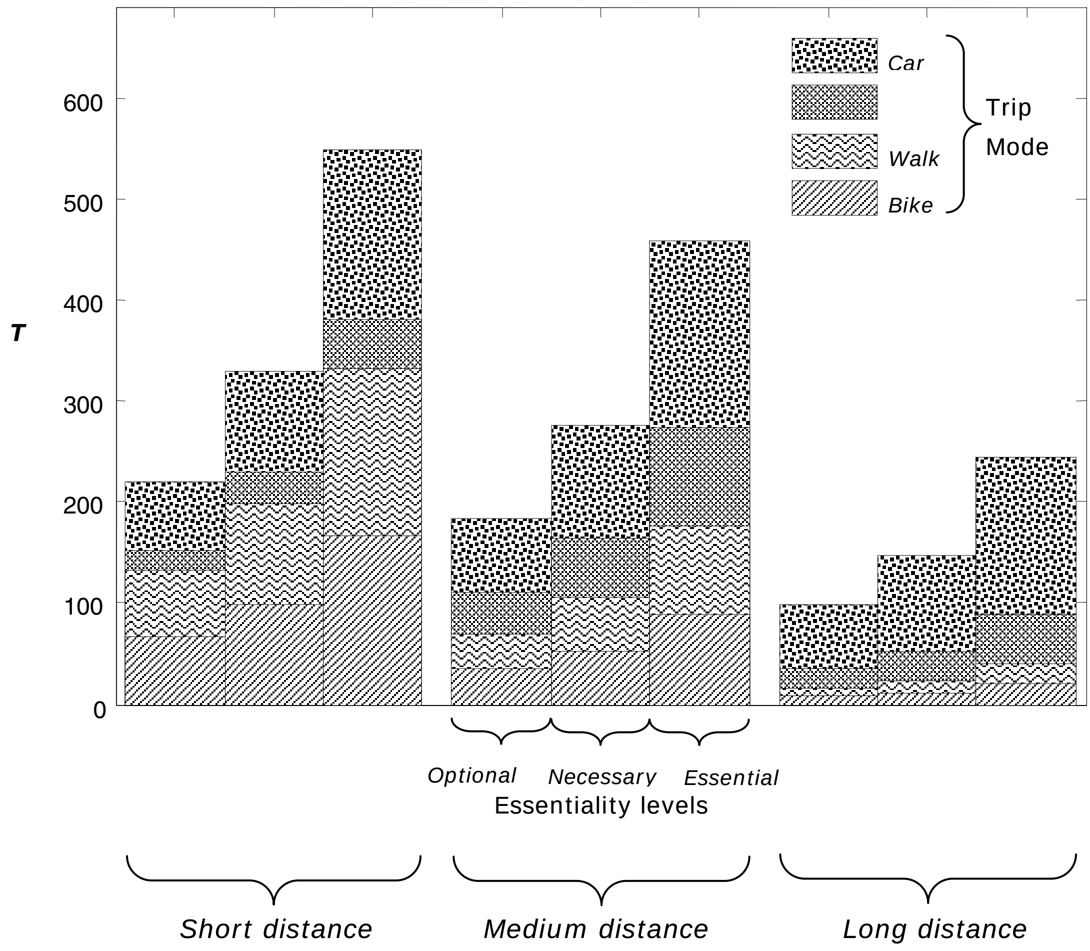


Figure 4.2 Schematic representation of the travel pattern indicator (*T*).

4.2.3 Step 3 – Comparison between consumed and available energy

The energy consumption (*E*) computed in step 2 is compared against predicted available energy (*AE*) considering future supply disruption scenarios. *AE* is calculated using Equation 4.3.

$$AE_e = (100\% - \Phi_e) * E \qquad \text{(Equation 4.3)}$$

where

AE_e =available energy in a supply disruption/shortage event e; and

Φ_e =energy reduction level, which was defined in the section 3.8 (Tables 3.4 and 3.5)

Using Equation 4.4, the need or not for changes in energy consumption is verified.

$$ME_e = \begin{cases} 0; E \leq AE_e \\ 1; E > AE_e \end{cases} \qquad \text{(Equation 4.4)}$$

where
ME_e = integer value indicating whether or not modification in travel demand pattern indicator (T) and consequently energy consumption is required in a supply disruption/shortage event e.

4.2.4 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. Thus, the following four steps are taken to modify the original travel pattern T into a modified travel pattern Ψ.

Step 4.1 - Compute trip combining considering AE_e: Two trips are combined into one, effectively reducing the number of trips without losing any activity;
Step 4.2 - Compute mode changes considering AE_e: A single trip is shifted to lower energy consumption mode, keeping the purpose and distance bin the same;
Step 4.3 - 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
Step 4.4 - Compute trip deletion considering AE_e: For 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 prioritised, where the non-essential, long distance trips are removed first.

Ψ is subsequently used to estimate the modified energy consumption (ξ) as previously defined in step 2 and equation 4.2. Travel patterns are modified until energy consumption (ξ) converges to meet the energy availability criteria (i.e. ME_e=0).

4.2.5 Step 5 – Computing the risks of energy supply disruption / shortage

Using the results from previous steps, the risk (R_e) to travel/activities due to an energy supply disruption/shortage event e is calculated. Equation 4.5 presents the mathematical formulation to compute R_e. It is the probability of an event e multiplied by an impact factor, which expresses the disparities between the participation based on travel pattern before and after disruption/shortage.

$$R_e = P_e * \left(\frac{\sum_m \sum_d \sum_s T^{m,d,s} * IW^s}{\sum_m \sum_d \sum_s \Psi^{m,d,s} * IW^s} - 1 \right) \qquad \text{(Equation 4.5)}$$

where
P_e = Probability of occurrence of an energy event e; and
IW^s = Vector of Impact Weight for each change/loss in travel patterns at the essentiality level s. These weights are defined according to the impact principles, previously introduced in section 4.1.2.

Equation 4.5 shows that if the same level of travel/activity is carried out after the oil crisis/shortage, i.e. the weighted sum of T and Ψ are the same, the estimated risk is zero. Figure 4.3 represents graphically the relationship between probability and impact affecting risk levels, i.e. the higher the probability and impact are, the higher the risk is.

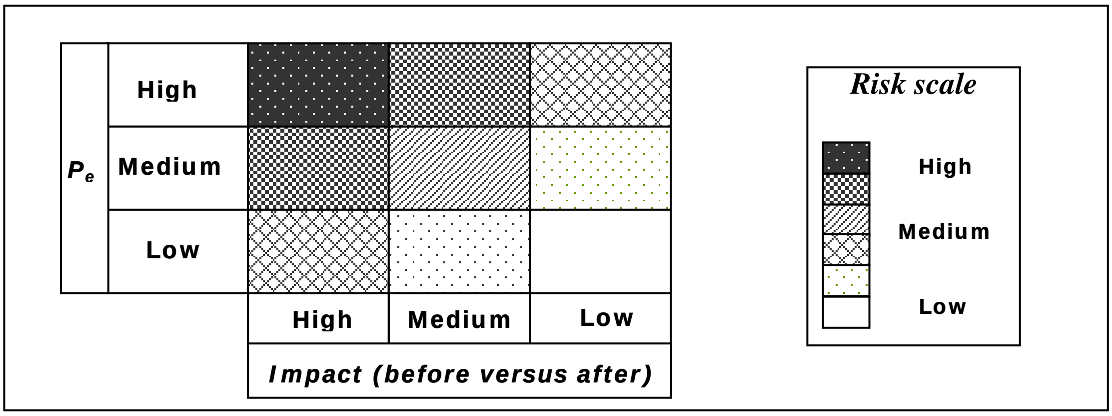


Figure 4.3 Risk levels as a function of probability and impact.

The repetition of these steps for other scenarios 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 a potential fuel shortage/crisis. At the two extremes, the highest risk would be posed if zero trips (Ψ=0) were performed after the fuel shortage/crisis. On the other hand, the lowest risk would be occur if no changes in the travel pattern (Ψ=T) were observed even after shortage/crisis. In practice, risks will be similar in magnitude and will depend on the urban area characteristics (e.g. population, travel demand characteristics, etc).

4.3 RECATS software model concept

Future oil supply data, probabilities of future reductions, and the assessment of risk method, was combined into a single, user friendly software package, called *RECATS* (Risk for Energy Constrained Activity and Transport System). This software allows the risk of an oil crisis/shortage event affecting travel/activities to be quantitatively evaluated for any urban from. Computed risks for two different forms are comparatively assessed using a user-friendly interface.

On the energy side, the software includes interactive models for the global peak in oil production, development scenarios for alternative or bio-fuels, and fuel rationing or supply management. The energy efficiency of each mode and of the vehicle fleet is modelled for the future scenario through user-input panels. Since these values are for future fleets, this feature can be used to explore various regulatory options or technology trends. RECATS calculates the current, unconstrained energy use for a user-specified travel demand profile.

On the transport side, RECATS allows the user to specify the distance, mode, and frequency matrix which has been determined for a given urban form using standard transport modelling. One novel feature is a user-defined essentiality split which can be made according to travel behaviour surveys. Another interactive feature allows the modeller to specify mode flexibility and alternative destinations, according to the layout and public transport for a given urban form.

As shown in the upper-left side of Figure 4.4, RECATS has six main input areas:

- **Mode and Distance Split**: This input area defines the percentage of daily trips expressing the travel pattern (vector *T*, section 4.2, Equation 4.1), which is in accordance with the given urban form to be analysed;
- **Energy Constraint**: For a given forecast year (e.g. 2030), the percentage reduction from non-disrupted (unconstrained) consumption is defined in the Reduction Event (e.g. 5%) drop-down option. Using these input data RECATS returns the estimate probability (e.g. 99.9%) of the energy disruption/shortage event occurring as previously defined in section 3.8 (Table 3.3). The event probability is shown graphically in the upper-right corner of Figure 4.4.
- **Relative split of trips essentiality**: This input area further divides the travel pattern (vector *T*) according to essentiality (*ES*); the resulting travel behaviour (unconstrained) is shown in the lower left trip length distribution graph of Figure 4.4;
- **Mitigation Options**: This comprises four options that rule how the travel pattern indicator (*T*) is modified (Ψ) in order to cope with the energy constraint. These options relate to allowing individuals to change the trip destinations, or mode choice, or combining (or chaining or increase in vehicle occupancy), or deletion of trips according to their level of essentiality (*ES*);
- **Urban Forms**: This allows RECATS' users to switch between pre-defined urban forms and data/results associated with each one of them; and
- **Fleet Efficiency:** This allows the consideration of different consumption rates (litres/100 km) per distance bin for different travel modes (car and bus).

Using these input data, RECATS is run (Calculate button) and after multiple iterations are made, results of the risk and impact levels for each urban form are presented on the screen (Analysis Output). The modified travel pattern indicator (Ψ) is also shown graphically (Travel Behaviour After Fuel Constraint) in the lower-right side of Figure 4.4.

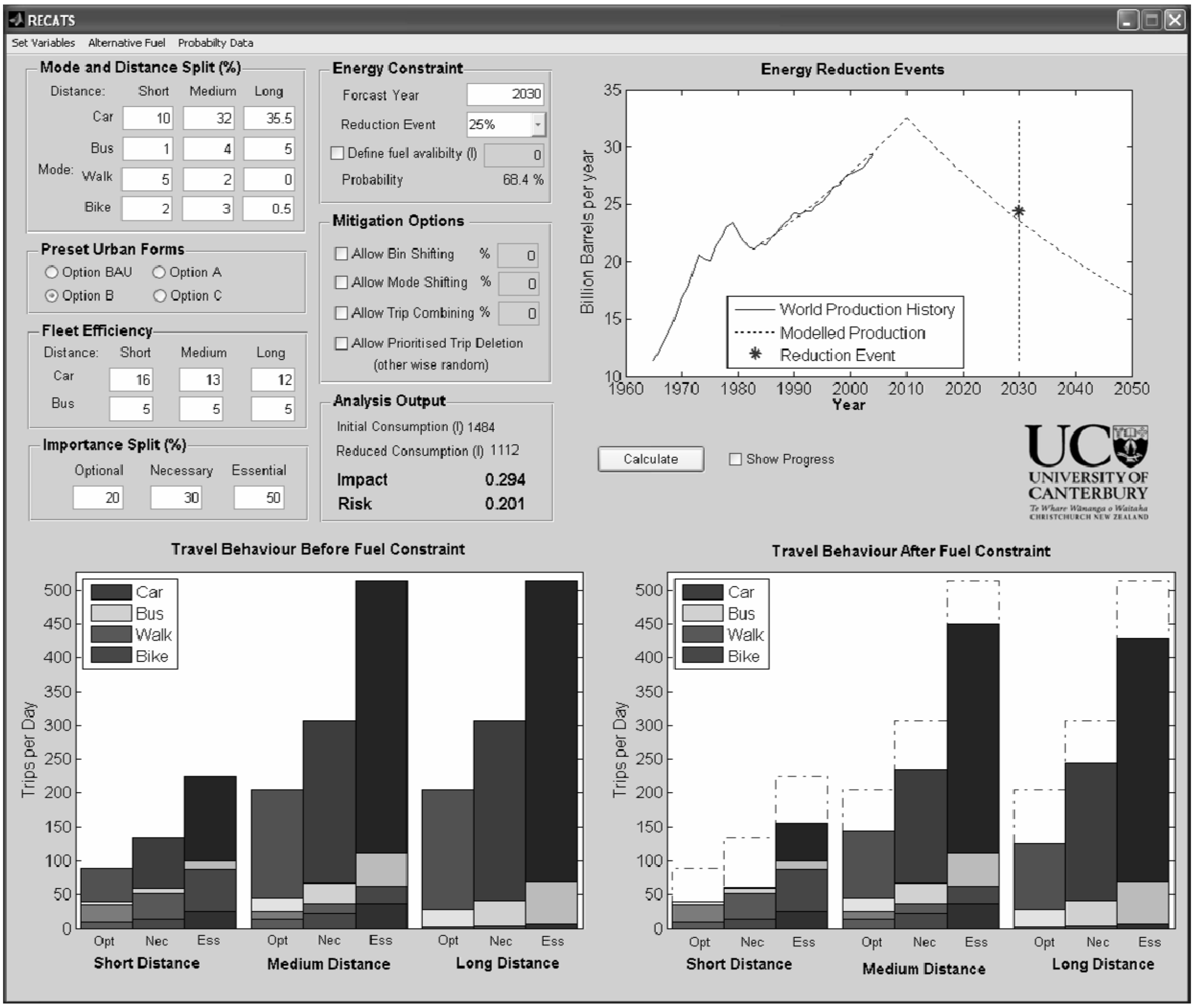


Figure 4.4 RECATS main window interface.[10]

[10] Opt=Optional Trips; Nec= Necessary Trips; Ess= Essential Trips.

5. Case study

This case study aimed to evaluate the method proposed in the previous section. We focused on analysing how the method relates urban forms to risk levels through changes in travel patterns before and after energy disruption/shortage events. In the context of the consultation process of the Urban Development Strategy (UDS) of the Greater Christchurch Urban Area, the risk assessment method was applied to assess the energy requirements and risk associated with different urban forms.

The following sub-sections present the context of the UDS and its urban form options; the characterisation 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 a considerable fluctuation in population growth, which is due to natural increase and internal and external migration. In a 10 year period (1991-2001), the estimated census population changed from 289,071, to 316,227 (CCC, 2003). Over 400 people make the city their home every month. The population in 2041 is estimated to reach 500,000 people (UDSF, 2004). Also, Buchanan (2004) has identified various changes in population and employment densities as well as significant development tendencies observed in the north part of the city. Population profile changes associated with other development tendencies are likely to eventually create extra demands in terms of basic services and utilities (housing, water, waste treatment, health, education, transport, etc.).

A UDS forum has been constituted to discuss, elaborate, assess and communicate a series of planning actions to manage the predicted growth of the Greater Christchurch area. The forum, established in 2005, is part of a multi-organisational participatory planning effort, which comprises representatives from the Christchurch City Council (including the former Banks Peninsula District Council) Selwyn and Waimakariri District Councils, Environment Canterbury (the Regional Council), Land Transport New Zealand and a cross-section of local leaders drawn from community, business and government organisations (UDSF, 2006).

As an initial step to develop the UDS, the forum has examined four options of urban forms together with their related characteristics, needs and envisaged challenges. The urban forms are very distinct in the way that future development is spatially distributed throughout the metropolitan area. Table 5.1 and Figure 5.1 summarise the characteristics of each option.

Table 5.1 Characteristics of the urban forms[11]

	Options			
	Business as Usual (BAU)	**Option A**	**Option B**	**Option C**
Development type	Non-interventionist	Concentration (Limited growth in district townships. Higher densities at some high amenity sites, particularly Sumner, New Brighton and Diamond Harbour).	Consolidation (use of existing built areas or expansion into immediately adjacent areas.)	Dispersal (low-density, separation of homes, jobs, and services; absence of strong urban activity centres; growth occurring adjacent to but outside the city centre with a general outward migration of people).
Land Use and Housing (Locations for new housing)	79% new subdivisions (Spread across districts in towns and rural subdivisions). 21% urban renewal (Christchurch inner suburbs). Mixture of housing types.	40% new subdivisions (Around edge of towns and Christchurch). 60% urban renewal (Christchurch Central City and inner suburbs; Rangiora, Kaiapoi and Rolleston). Mostly dwellings without gardens.	62% new subdivisions (Southwest of Christchurch to Selwyn, in Waimakariri around existing towns). 38% urban renewal (Urban centres in Christchurch and towns). Townhouses and apartments around urban centres with houses in new subdivisions:	90% new subdivisions (Southwest from Halswell to Rolleston, North of Waimakariri River and Lyttelton harbour). 10% urban renewal (Christchurch City). Mostly houses, some townhouses and apartments.
Transport choices	Good in some built up areas for public transport, walking and cycling-poor for subdivisions in districts.	Very good in city and inner suburbs for walking, cycling and public transport. Limited elsewhere.	Very good at urban centres for walking, cycling and public transport. Public transport to new developments.	Poor for people in new developments limited public transport, walking and cycling not practical.
Community Facilities	Few facilities for residents in new subdivisions - have to drive to existing facilities.	Good range of facilities in easy access for residents of central and inner suburbs.	Good range of facilities in easy access for residents at urban centres in Christchurch and towns.	Few facilities for residents in new subdivisions - have to drive to existing facilities.
Transport system performance	Commute takes 55% longer, 320% increase in congestion; and 58% increase in transport energy use;	Commute takes 45% longer, 190% increase in congestion, 45% increase in transport energy use;	Commute takes 50% longer, 290% increase in congestion, 57% increase in transport energy use;	Commute takes 65% longer, 630% increase in congestion, 95% increase in transport energy use.

[11] Adapted from UDSF (2004) and UDSF (2006).

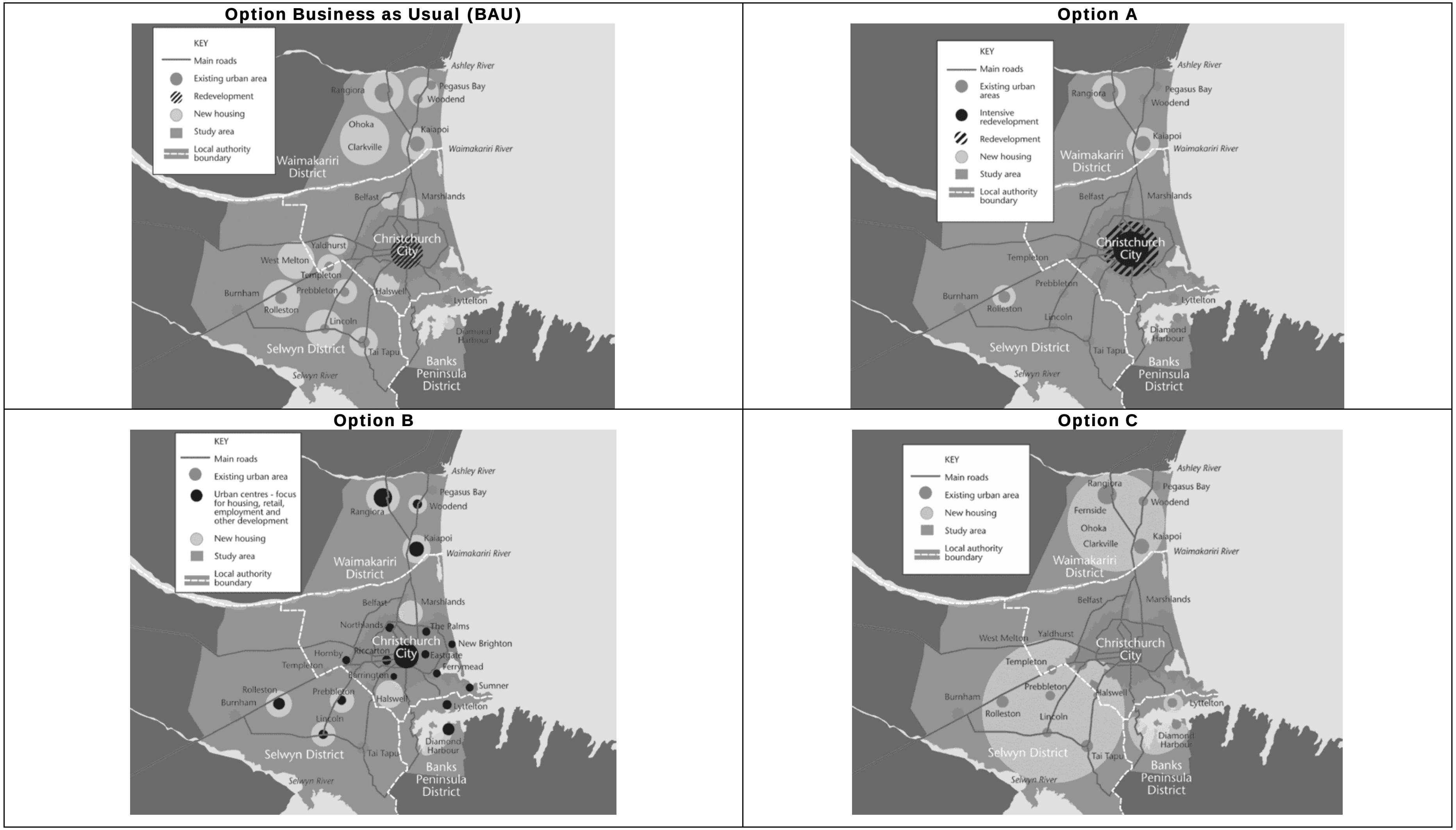


Figure 5.1 Representation of urban forms with transport options and properties compared with 2001.

5.2 Urban forms and travel demand characteristics

Considering the UDS context, the travel patterns for each urban form option were defined based upon information gathered from the various UDS documentation, international scientific and technical literature and travel demand modelling previously conducted by the Christchurch City Council.

Initially, travel distances were divided into three main distance bins. This was based on a combined assessment of all transport modes and their respective travel distances (UDSF, 2004; UDSF, 2006). For example, the Christchurch Transport Model (CTS) estimates that average vehicle travel distance will be 7.4 km in 2021, but it also acknowledges that most trips are short distances. Therefore, values shown in Table 5.2 represent a general combination of all trips by all modes and purposes.

Table 5.2 2021 estimated travel distance bins.

Distance bin	Distance (km)	Average distance per bin (km)
***d*=1**	0-1.5	0.75
***d*=2**	1.5-6	3.5
***d*=3**	>6	9.5

Based on Buchanan (2004), Transfund (2000) and Denne *et al* (2005), the relative split of essentiality levels were given as: 20% Optional (s=1); 30% Necessary (s=2); and 50% Essential (s=3).

Using the definition of the distance bins (Table 5.3), the mode split (vector *MS*) is divided into 4 main transport modes, namely: car (*MS* 1), public transport (*MS* 2) and the other non-energy consuming modes of walking (*MS* 3) and cycling (*MS* 4). Table 5.3 summarizes the mode split for each option, with the total adding up to 100 (CCC, 2003).

For example, in Option A, car mode (*MS* 1) comprises 75% (17+36.5+21.5%) of the total number of trips, whereas public transport (*MS* 2) and other modes (*MS* 3 and 4) cover, respectively, 13, 8 and 4% of the total number of trips.

Table 5.3 2041 mode split for each development option and distance bin.

Transport Mode MS	Options											
	BAU			A			B			C		
	***d*=1**	***d*=2**	***d*=3**	***d*=1**	***d*=2**	***d*=3**	***d*=1**	***d*=2**	***d*=3**	***d*=1**	***d*=2**	***d*=3**
1 (car)	12.0	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

Using Equation 4.1a, travel demand (*TD*) was calculated. Table 5.4 presents the results considering the mode slip (Table 5.3), 500 000 inhabitants in the study area and 5 trips per person per day.

Table 5.4 2041 Estimated daily travel demand (thousand trips) per mode, distance bin and urban form.

MS	Options											
	BAU			A			B			C		
	***d*=1**	***d*=2**	***d*=3**	***d*=1**	***d*=2**	***d*=3**	***d*=1**	***d*=2**	***d*=3**	***d*=1**	***d*=2**	***d*=3**
1 (car)	300.0	900.0	925.0	425.0	912.5	537.5	250.0	800.0	887.5	250.0	750.0	1275.0
2 (bus)	0.0	37.5	62.5	50.0	200.0	75.0	25.0	100.0	125.0	0.0	25.0	50.0
3 (walk)	125	12.5	0.0	175	25.0	0.0	125.0	50.0	0.0	0.0	12.5	0.0
4 (bike)	50.0	75.0	12.5	50.0	50.0	0.0	50.0	75.0	12.5	50.0	75.0	12.5

These results were subsequently used to calculate the travel demand indicators ($T^{m,\,d,\,s}$) and Trip Length Distribution (*TLD*) as shown in Tables 5.5 and Figure 5.2, respectively.

Table 5.5 2041 Estimated daily travel demand indicator per mode, distance bin, essentiality level and urban form option.[12]

Option Business as Usual (BAU)

MS	Distance Bins / Essentiality Levels								
	d=1			*d*= 2			*d*=3		
	Opt	*Nec*	*Ess*	*Opt*	*Nec*	*Ess*	*Opt*	*Nec*	*Ess*
1 (car)	60.0	90.0	150.0	180.0	270.0	450.0	185.0	277.5	462.5
2 (bus)	0.0	0.0	0.0	7.5	11.3	18.8	12.5	18.8	31.3
3 (walk)	25.0	37.5	62.5	2.5	3.8	6.3	0.0	0.0	0.0
4 (bike)	10.0	15.0	25.0	15.0	22.5	37.5	2.5	3.8	6.3

Option A

MS	Distance Bins / Essentiality Levels								
	d=1			*d*= 2			*d*=3		
	Opt	*Nec*	*Ess*	*Opt*	*Nec*	*Ess*	*Opt*	*Nec*	*Ess*
1 (car)	60.0	90.0	150.0	180.0	270.0	450.0	185.0	277.5	462.5
2 (bus)	0.0	0.0	0.0	7.5	11.3	18.8	12.5	18.8	31.3
3 (walk)	25.0	37.5	62.5	2.5	3.8	6.3	0.0	0.0	0.0
4 (bike)	10.0	15.0	25.0	15.0	22.5	37.5	2.5	3.8	6.3

Option B

MS	Distance Bins / Essentiality Levels								
	d=1			*d*= 2			*d*=3		
	Opt	*Nec*	*Ess*	*Opt*	*Nec*	*Ess*	*Opt*	*Nec*	*Ess*
1 (car)	50.0	75.0	125.0	150.0	225.0	375.0	255.0	382.5	637.5
2 (bus)	0.0	0.0	0.0	5.0	7.5	12.5	10.0	15.0	25.0
3 (walk)	0.0	0.0	0.0	2.5	3.8	6.3	0.0	0.0	0.0
4 (bike)	10.0	15.0	25.0	15.0	22.5	37.5	2.5	3.8	6.3

Option C

MS	Distance Bins / Essentiality Levels								
	d=1			*d*= 2			*d*=3		
	Opt	*Nec*	*Ess*	*Opt*	*Nec*	*Ess*	*Opt*	*Nec*	*Ess*
1 (car)	50.0	75.0	125.0	150.0	225.0	375.0	255.0	382.5	637.5
2 (bus)	0.0	0.0	0.0	5.0	7.5	12.5	10.0	15.0	25.0
3 (walk)	0.0	0.0	0.0	2.5	3.8	6.3	0.0	0.0	0.0
4 (bike)	10.0	15.0	25.0	15.0	22.5	37.5	2.5	3.8	6.3

12 Opt=Optional Trips; Nec= Necessary Trips; Ess= Essential Trips.

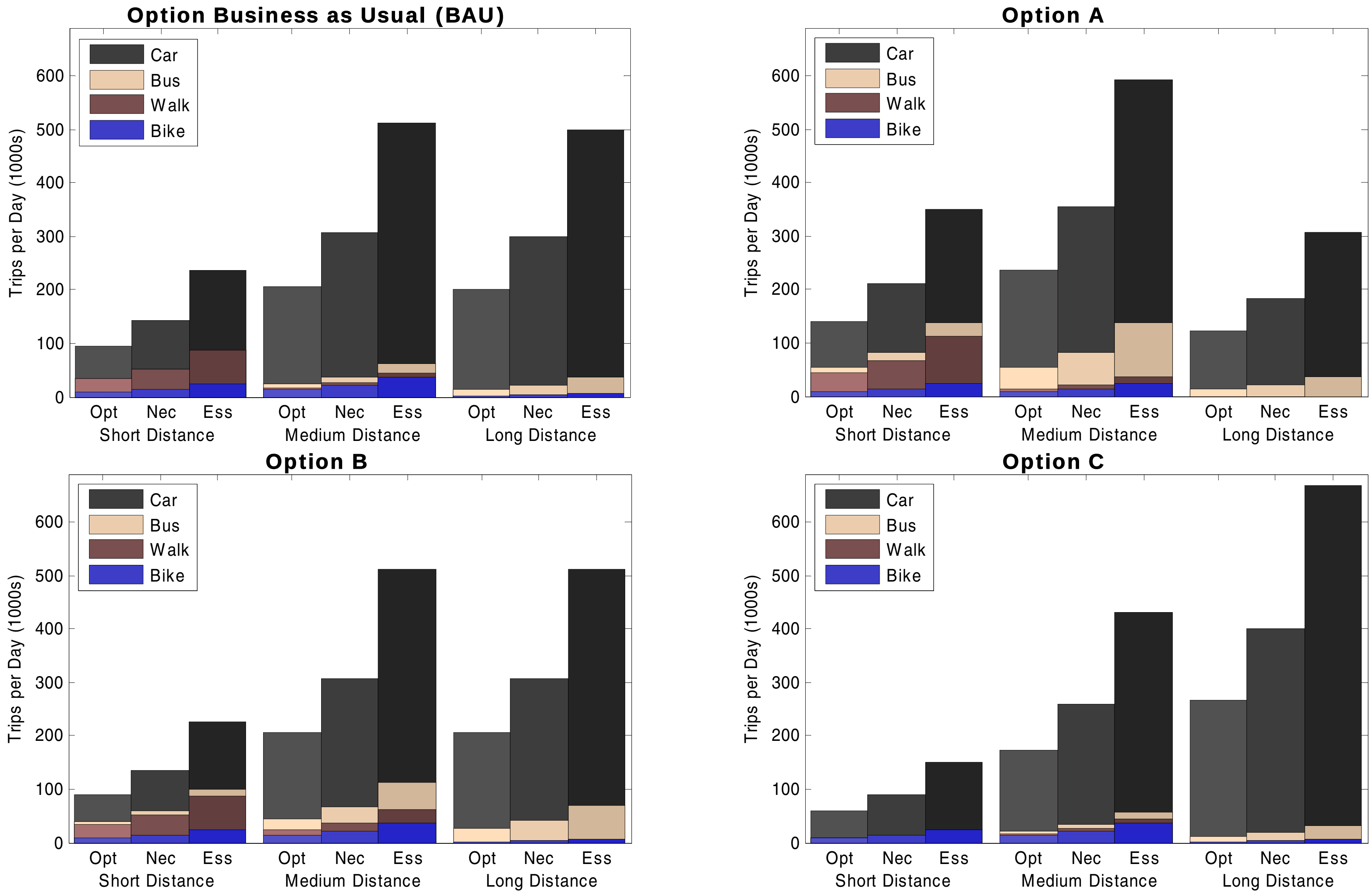


Figure 5.2 Representation of TLD for each urban form option.

Considering the impact principles, previously introduced in section 4.1.2, impact weight vector (IW^s) was defined for this case study. Trips losses were computed as follows:

- Loss in optional trips (s=1) have a impact weight of 2;
- Loss in necessary trips (s=2) have a impact weight of 3; and
- Loss in essential trips (s= 3) have a impact weight of 4.

5.3 Energy consumption

Considering the travel demand patterns (Section 5.2, Tables 5.2 to 5.4 and Figure 5.1 and 5.2) and an average petrol consumption rate (10 litres per 100 km), the energy consumption for each urban form for vehicle travel was calculated using equation 4.2. Results are shown in Table 5.6.

Table 5.6 Energy consumption for each urban form option (million litres/day).

E	**Options**			
	BAU	**A**	**B**	**C**
million litres/day	1.536	1.151	1.483	1.852

5.4 Future development scenarios using RECATS

In order to perform the simulations, major assumptions were made. They are:

- Relative split of trips essentiality would not change after the fuel shortage/crisis event;
- No special provision of fuel would be made to public transport;
- Loss of trips is prioritized on the basis of essentiality levels and impacts weights;
- Distance bins would not change after the fuel shortage/crisis event;
- Location of activities would not change after the fuel shortage/crisis event;
- Changes in travel mode and travel distance would not result in impact;
- No mitigation options would be applied after the fuel shortage/crisis event; and
- Vehicle efficiency and occupancy would not change after the fuel shortage/crisis event.

Based on these assumptions, four scenarios of future development were simulated using RECATS. For each scenario, an energy reduction event occurring in 2041 was defined according to estimated probabilities (Section 3.8, Table 3.3). Table 5.7 and Figure 5.3 present the results of the scenario simulations. For example, Scenario 1 refers to a low energy reduction event (7%), which has a 100% probability of occurrence until 2041. Scenario 1 results show that Option C would pose the highest risk to urban activities, while Option A would have the lowest risk level.

RECATS was also used to calculate changes in travel patterns due to oil unavailability. For each scenario, significant changes in the travel demand patterns are observed in modified Trip Length Distributions (*TLD*). Figure 5.4 shows the modified travel demand profiles for scenario 4 (20% energy reduction and 99.9% probability). It is observed that a significant portion of optional trips would be lost in all urban form options. Once again, Option C would experience the highest number of lost trips (90%). All these optional trips would be lost in the mode car, mostly due to energy efficiency levels of public transport travel.

Table 5.7 Risks of future development scenarios.

#Scenario	Energy Reduction	Estimated Probability (%)	Risk (*1000)			
			Option BAU	Option A	Option B	Option C
1	Low (7%)	100	24	18	23	28
2	Medium (10%)	100	34	25	33	41
3	Medium-High (15%)	100	59	56	57	63
4	High (20%)	99.9	117	105	110	126

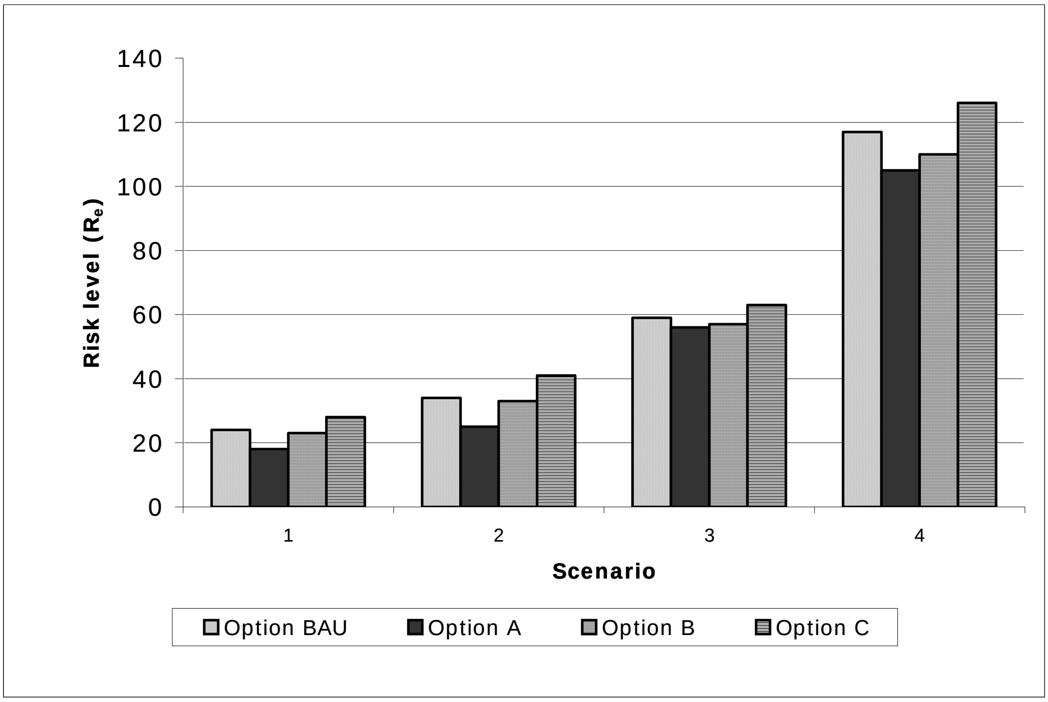
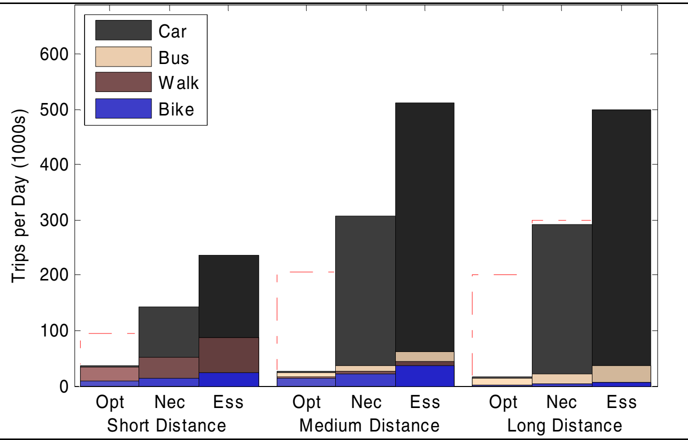


Figure 5.3 Risks results for energy reduction scenarios.

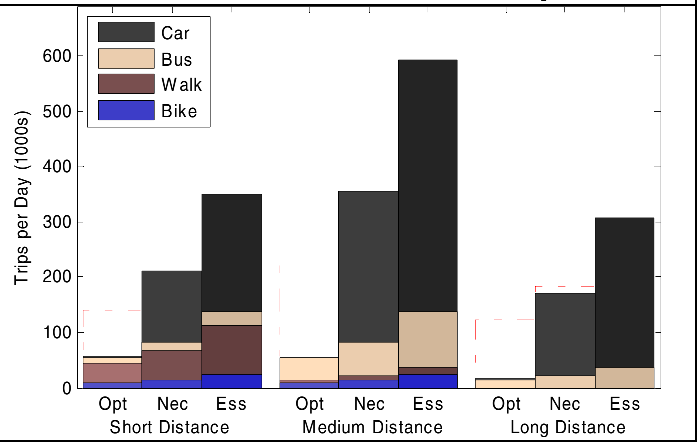
Option Business as Usual:

- Optional Trips must be reduced by 84%;
- Necessary trips must be reduced by 1%; and
- 17% reduction in car travel; and
- Loss of 430 thousand trips.



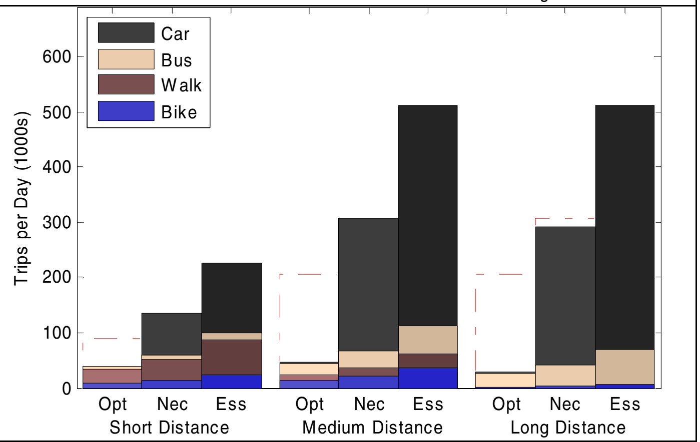
Option A:

- Optional Trips must be reduced by 74%;
- Necessary trips must be reduced by 1.9%;
- 15% reduction in car travel; and
- Loss of 381 thousand trips.



Option B:

- Optional Trips must be reduced by 72%; and
- Necessary trips must be reduced by 2%;
- 16% reduction in car travel; and
- Loss of 401 thousand trips.



Option C:

- Optional Trips must be reduced by 90%;
- Necessary trips must be reduced by 1%;
- 18% reduction in car travel; and
- Loss of 460 thousand trips.

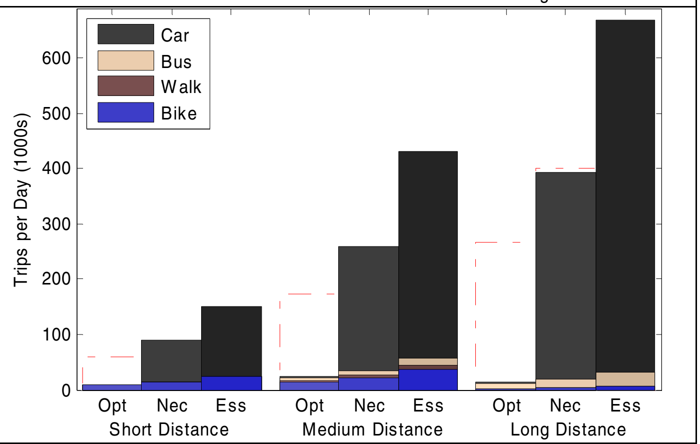


Figure 5.4 Scenario 4: Modified TLD for each urban form option.

5.5 Analysis of results

The influence of urban form in the risks of energy constraint to the participation in activities is clearly observed in the RECATS simulations. In all four scenarios, it is verified that the urban form choice would result in 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 and/or the implementation of mitigation options, daily activities in Christchurch would be destined to suffer major disruption and possible economic and social losses.

Urban form Option C would pose the greatest risks in any event of energy shortage affecting the Christchurch community. For example, in scenario 4, the combined loss of Optional (90% reduction) and Necessary trips (1%) by car would represent over 460 thousand trips out of 2.5 million trips per day. The trip losses would certainly disrupt social and economic systems throughout the metropolitan area. Furthermore, the results show that those travelling long distances (distance bin 3) would be the most affected (over 261 thousand trips lost).

On the other hand, urban form Option A would pose the lowest risk levels. As this option is based on limited growth in district townships, non-motorized travel (walking and cycling) demand would be considerably higher than in other options. Also, public transportation would also decrease the necessity for car trips. These characteristics would contribute to minimize the impacts of oil shortage/crisis. However, a significant number of trips would be lost in Option A. For example, in scenario 4, the combined loss of Optional (74% reduction) and Necessary trips (1.9%) by car would represent over 381 thousand trips out of 2.5 million trips per day. Once again, as observed in Option C, The trip losses would cause disruption mostly to those travelling long distances (distance bin 3), i.e. over 121 thousand trips would be lost.

Comparatively, in scenario 4, Option C risks would be over 20% riskier than Option A. This risk-gap (Option C-126 *versus* Option A-105) can be explained on the basis of the usage of individual transport mode (car). Option C's reliance on car travel would be extremely dependent on oil availability and any reduction would create significant disruptions to individual motorised travel. On the other hand, Option A would be less reliant on long-motorised travel, which would consequently contribute to its lower risk level. Similar considerations can be made to all other scenarios.

Options BAU and B would pose less risk than Option C. In all scenarios, Option BAU would be closest to Option C, mostly due to its tendency to provide for long distance-car travel. The most flagrant difference is that fewer long distance-optional trips would be lost in Option BAU. On the other hand, Option B would be significantly less risky than Option C, mostly because it would be based on a comprehensive public transport system, which would be much more energy efficient than long-distance car travel.

Overall, the relative performance of Options A and B reveals considerable differences due to their characteristics. For instance, Scenario 4 results show that Option A would maintain 85% of the total number of trips, while there would be enough energy to perform 84% of the total number of trips in Option B. This difference in the options performance could be attributed to loss in necessary trips. Option A would lose less necessary trips than Option B, which in turn would retain more optional trips. Also, it is observed that the original mode split also plays a role in the option's performance. In Option A, original (no fuel constraint) 75% travel by car would be reduced to 70% in a fuel shortage/crisis event. On the other hand, Option B would drop from 78 to 72% of all trips made by car, but public transport would increase from 10 to 12% of the total number of trips. While Option A would lose most car trips in both short and long distance travel, Option B would be mostly affected in terms of short distance travel. This is mostly because Option A would make more efficient use of non-motorized modes in short distance travel. In contrast, Option B would have to use fuel for both car and public transport modes.

6. Conclusions

This chapter summarises the findings of this research in order to verify if the scientific objectives (section 1.3) were accomplished. Also, we discuss the main limitations and recommendations for further research.

6.1 Main findings

The most important finding of this research is that energy shortage/crisis risks can be quantified, assessed and considered as part of urban and transportation planning decisions. Based on a future energy supply assessment and the study of travel patterns and urban forms, we developed a method to estimate the nature and magnitude of risks posed to urban activities in an event of limited or constrained access to energy. The implementation of this method as a software package (RECATS) allows planners and decision makers to assess future scenarios of urban development forms, land use, transport and energy efficiency policies in order to minimise future risks.

6.2 Main limitations

The main limitation of our study is that very limited data on travel behaviour in the event of an energy or oil shortage/crisis is available. This limits the extent to which land use and travel demand modelling can be used to forecast changes in behaviour and activities in a shortage/crisis event. As shown in the literature review, just recently a few research efforts have highlighted the need for research into travel behaviour in energy constrained events. They have also pointed out that very little data/information has been collected during recent disruption events. Therefore, this research has used Christchurch's available data sets, which are not based on any empirical evidence of disruption events.

Nevertheless, the research team's assessment is that data limitations do not compromise the quality of the findings. The case study findings using RECATS could be used in a policy-making context, which does not require a great deal of sophistication to create useful information for decision makers. Hence, additional data would increase the level of reliability of the findings, but it is expected that they would not change the nature of the findings. Nevertheless, it has to be highlighted that the risk-gap between Option C and all other options would become even larger if mitigating options, such as mode shifting, were considered.

6.3 Recommendations for further research

During the development of this research, we have identified a series of improvements to the proposed method and new research directions to be considered in the near future. The following list summarises the main recommendations for further research:

- Develop experiments to increase understanding of essentiality of trips and expand the concepts presented in section 4.1 (Activities impact assessment);
- Study land use modelling in order to represent long-term changes in activities location under energy constrained situations;

- Keep monitoring and expand energy (oil) supply availability in order to refine the event probability predictions presented in section 4.2;
- Study and incorporate further mitigation options as part of RECATS in order to simulate various ranges of policy interventions;
- Develop further communication techniques that further facilitate the understanding of the findings in this research;
- Apply the RECATS concept to other transportation systems (rail, road, air, maritime) at the regional and national level;
- Add the freight energy consumption component to RECATS in order to further represent the risks to the transport industry, with special focus on urban goods movement;
- Adapt and use RECATS to explore policies involving non-motorised travel modes (walking and cycling) as means to reduce energy dependency;
- Study the relative split of trips essentiality in order to assess how it would change after the fuel shortage/crisis event;
- Assess how special provision of fuel for public transport could affect the risk analysis results;
- Study the distance bins split in order to assess how it would change after the fuel shortage/crisis event; and
- Study how vehicle efficiency and occupancy would change after the fuel shortage/crisis event.

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8. Glossary

Abbreviations and Acronyms

ACEEE	American Council for an Energy-Efficient Economy.
ARIMA	Autoregressive-integrated-moving average.
AS	Activity System.
BAU	Business as Usual.
BP	British Petroleum.
CAFE	Corporate Average Fuel Economy.
CCC	Christchurch City Council.
CNG	Compressed Natural Gas.
EIA	Energy Information Administration.
EOR	Enhanced oil recovery.
ICT	Information and Communication Technologies.
IEA	International Energy Agency.
LPG	Liquefied Petroleum Gas.
MED	Ministry of Economic Development.
MOT	Ministry of Transport.
NGO	Non-Governmental Organisation.
NZRC	New Zealand Refining Company.
OPEC	Organization of the Petroleum Exporting Countries.
RECATS	Risk for Energy Constrained Activity and Transport System.
TLD	Trip Length Distributions.
TS	Transportation System.
UDS	Urban Development Strategy.
UDSF	Urban Development Strategy Forum.
USA	United States of America.
USGS	United States Geological Survey.

Abbreviations Meanings

AE	Available energy.
CO_2	Carbon Dioxide.
CP	Cumulative probability.
DB	Vector of distance bins (mid distance point).
E	Energy Consumption.
EC	Matrix of energy consumption.
ES	Vector of relative split of trips essentiality.
Ess	Essential Trips.
EV	Expected value, average, or mean value of a random variable.
IW	Vector of Impact Weight for each change/loss in travel patterns.
ME	Integer value indicating whether or not modification in travel demand is required.
MS	Matrix of mode split per distance bin.
Nec	Necessary Trips.
Opt	Optional Trips.
P	Probability of occurrence of an energy event.
PO	Population in the study area.
T	Travel pattern indicator.
TD	Travel Demand.
X	Continuous random variable of damages.

Units

Bb	Billion barrels
l	litre
MJ	Mega Joule (10^6 J)
PJ	Peta Joule (10^{15} J)

Symbols

μ	Average trips per person per day.
Ψ	Modified travel pattern due to oil shortage/crisis.
∞	Infinity.
ρ	Scalar input of a negative binomial probability distribution.
ξ	Modified energy consumption.
Φ_e	Energy reduction level.
E	Fuel shortage/crisis event.
D	Distance bin (or range).
M	Mode of travel.
$p(x)$	Probability density function of an event x.
$P(y)$	Probability of peak oil in any year y.
r	Scalar input of a negative binomial probability distribution.
s	Essentiality level.
Y	Event year.
y	Year.

Conversions

1 litre Petrol = 33 MJ.

1 litre Diesel = 36 MJ.