Understanding resilient urban futures: A systemic modelling approach

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Making cities more resilient has become one of the most important goals of urban sustainability. This paper introduces a land use – transport – environment model which studies the city as a whole system. This can be used to evaluate city resilience under different policy scenarios, and explore the integrated solutions needed to create resilient cities.

1. Introduction

The resilience of cities in response to natural disasters and long-term climate change has emerged as a focus for researchers and policy-makers. With increasing numbers of people living in urban environments, cities now consume about 75% of total global energy and produce 80% of its greenhouse gases (GHG).1 Cities have become significant players in policies which attempt to respond to climate change. Recently such policies have emphasised the building of resilient cities. Resilient cities are believed to adapt better to change by adjusting inner systems, for example by changing their system of transport and land use to reduce energy consumption and to reduce exposure to potential natural disasters. Resilient city policies are concerned with strengthening a city’s capacity to adapt to shocks,2 such as sudden natural disasters or gradual rising sea levels. More than two-thirds of the world’s large cities are in coastal areas vulnerable to rising sea levels. It is vital to build resilience for coastal cities, which play a crucial role in world social and economic development.

A transport system is important to resilience. It is necessary for social and economic activities in a city. Transportation is also the fastest growing contributor to global climate change and urban health problems. Global transport emissions contributed an estimated 22% of direct CO\textsubscript{2} emissions in 2010, 75% of which were from road transport.3 Motor vehicles also emit other harmful gases. Urban air pollution from transport, plus traffic injuries, together kill about 2.5 million people every year.4 Transport systems are viewed as having much less adaptive capacity than other city systems. Once transport infrastructures (airports, ports, railways and highways) are built, they are hard to change. Many policies have been used to try to reduce transport emissions by changing the factors in city systems which affect transport, including land-use patterns, planning rules, city and transport network design, public transit services, parking policies, vehicle and fuel technologies, and factors related to individual travel behaviours. However, these policies are often criticised for inefficiency. A lack of integration or alignment between individual policies is a major reason for the criticisms. A systemic solution, which takes all these factors into account,
would be a more efficient way of reducing emissions from transport.\(^5\) In addition, many policies designed to reduce emissions from road transport are focused on vehicle and fuel technology. However, studies suggest that individual travel behaviour is just as important.\(^6\) Developing a model based on the travel behaviour of individuals is necessary in order to evaluate policies to reduce GHG emissions.

This paper introduces an urban model that can be used to evaluate the outcomes for city resilience under a range of policy options. It is the Wellington Integrated Land Use-Transport-Environment model (WILUTE), which is currently being developed by the New Zealand Centre for Sustainable Cities, University of Otago. The interconnectedness of urban and natural systems is a key issue for the resilience of cities. The WILUTE model considers the city as a complex system characterised by interactions between a variety of urban processes and the natural environment. It explores the dynamic relationships between:

- Human activities - geographic distribution of housing and employment, infrastructure layout, traffic flows, energy consumption;
- Environmental effects - carbon emissions, influences on local natural and ecological systems; and
- Potential natural disasters - e.g. flooding due to storms and sea level rise.

WILUTE gives insights that can be useful for policy to enhance the city’s resilience, by modelling outcomes such as the potential for reduction in transportation energy use, or changes in the vulnerability of the city’s housing stock and transport system to sea level rise.

2. The city as a system

The city is a complex system. Urban development is a complex process, involving a wide range of people, activities, sectors, and policies at a variety of geographical and administrative scales (local community, city government, region, state government, etc.). The process of urban change consists of many economic, social, spatial, cultural and institutional sub-processes, with a high level of interaction between these sub-processes. For example, urban transportation is a combined result of many sub-processes including land use and a transport network responding to social processes (changes in income and lifestyle), economic processes (commercial development and changes in oil price) and institutional processes (governance, planning and road pricing). The association between land use and transport has been widely studied. Changes in land use can result in changes in travel demand and so cause changes in transport infrastructure. Transport infrastructure and traffic characteristics such as congestion affect location accessibility, which influences land use. When time is taken into account, with some changes taking place slowly and other fast, the interactions become even more complex.\(^7\)

The urban change process has effects on urban sustainability through impacts on human well-being and on ecosystems. Urban areas, in this sense, are sites of consumption of water, energy, food, materials, land and other natural resources. The major output of an urban system is the discharge of waste and emissions. These emissions affect the environment and have many human health effects.

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While the urban change process is too complex to be fully optimised, it can be improved, for example to reduce the discharge of waste and emissions and the consequent impacts on well-being. One strategy is to increase the resource efficiency of the city system, such as by changing motor vehicle engine technology to reduce resource use and emissions. The other strategy is to reorganise the interaction between various urban sectors to minimise resource consumption, waste and emissions. This involves various policies, for example land use planning and transport planning. A typical measure is increasing density (homes, schools and workplaces are close together) and land use mix (houses, shops, community facilities and workplaces are all located in the same area) to reduce the amount of miles travelled in motor vehicles. Many studies have found that land use policies or transport planning can reduce the costs of transport and reduce GHG emissions. This way of reorganising a city system is focused on improving the sustainability and resilience of a city.

Resilience is allied to, but distinguishable from, sustainability. Resilience can mean, in an engineering sense, the ability of a system to return to an equilibrium or steady-state after a disturbance. In this sense, a city’s resilience is determined by its ability to recover from a disturbance, its capacity to rebound. To reduce the vulnerability of a city to natural hazards and disasters is often seen as one of the main goals of building a resilient city. There is also a broader way of looking at resilience. Ecological resilience refers to the size or extent of disturbance that can be absorbed before the system changes its structure. A city system’s resilience in this sense is determined by its ability to continue and adapt to a new environment. A variant on this concept is socio-ecological resilience, which takes into account human social processes as well as ecological processes, and which focuses on the changing nature of systems over time, with or without an external disturbance. Here, changes in resilience reflect the evolution of a city system. As its systems are strengthened, a city has a stronger ability to resist or adapt to new disturbances. Urban resilience can be seen as the ability of a complex social-ecological system (the city) to adapt and, when necessary, transform in response to stresses and strains.

Models of systems are used by researchers to simulate the dynamics of the urban system. Such models are based on systems thinking which considers the processes of a city as a connected whole. However, this modelling has been attempted using many different methods, measures and data. Another challenge is achieving a proper estimation of the

uncertainties in a system. An urban system and its relationship with natural systems tend to be even more complex and uncertain because of climate change and related unpredictable natural changes. This calls for new modelling tools that can take into account phenomena such as climate change.

3. Systemic approach in WILUTE

3.1. Wellington, New Zealand

Wellington is a small to medium-sized coastal city with a city region population of around 490,000. It has a fairly compact city core, confined by hills and sea, in the centre of a city region that has sprawled significantly in recent decades. The city is vulnerable to coastal hazards caused or aggravated by climate change, such as storms and sea level rise. A recent report suggests that the harbour’s relative sea level is tracking towards a 0.8m rise by the 2090s, but for planning purposes a range of plausible sea level rise estimates of up to 2.0m should be considered. New Zealand’s GHG emissions have increased 19.4% since 1990, largely due to growth in energy emissions, particularly from road transport and electricity generation. New Zealand’s road transport emissions increased by 66% over the period 1990–2009. In addition, traffic accidents and other traffic pollutants, such as NOx, SO2, other toxic waste, water pollution and noise pollution, are contributing factors in local environmental and public health challenges. A model based on Wellington is useful in illustrating resilience policies for medium-sized coastal cities in New Zealand and in other countries.

3.2. Main purpose of WILUTE

The Wellington Integrated Land Use-Transport-Environment model (WILUTE) is a model for projecting and assessing land use and transport development in the Wellington region. It is designed as a platform to test and evaluate transport or land use policies, and their interaction, with respect to environmental and public health effects. It can also be used to assess and forecast the vulnerability of the transport and land use system to sea level rise. To do this, the model measures current energy consumption and environmental pollutants from the transport system, and forecasts the effects that transport or land use policy options might have on these. It is also designed to assess the public health effects from transport policies. These public health effects include traffic accidents, and exposure of pedestrians and cyclists to pollutants (which can increase the risk of death and of respiratory symptoms and disease, and can affect fertility and birth outcomes). Currently, the WILUTE model is focused on the assessment of the impacts of the transport and land use system on carbon emissions, active travel (cycling and walking), and exposure of local residents to pollutants from road traffic. In the next stage, the WILUTE model will be used to explore other transport-related air pollution impacts and health data. Then the model will be used to examine how the transport system is exposed to sea level rise and predict the socio-economic outcomes of possible policies in response to sea level rise.

WILUTE addresses four key questions:

1. How does the existing transport and land use system influence carbon emissions and local air quality in the region?
2. How might future transport infrastructure such as new light rail or cycle lanes change current transport mode choices and promote green transportation?
3. To what extent are current transport systems and settlements vulnerable to sea level rise?
4. How can the capacity of the transport and land use system to respond to sea level rise be strengthened in future?

In the modelling process, WILUTE generates a number of indicators of urban sustainability related to the land use and transport system (Figure A), including:

- Economic sustainability indicators - travel costs in time and money, population and employment growth;
- Social sustainability indicators - housing affordability shown by price and the supply of houses in terms of types and locations, factors influencing the risk of traffic accidents such as speed and volume, percentage of walking and cycling;
- Environmental sustainability indicators - air pollution, energy consumption, CO₂ emissions, people’s exposure to sea level rise across different income and ethnic groups and in terms of residential location (environmental equity); and
- System sustainability indicators - financial capacity and cost (time, resources, social costs) for the transport and land use system to recover in the event of a disaster associated with sea level rise.

These indicators reflect the two-way interactions between the human and natural systems in a city.

Figure A. Urban sustainability indicators
3.3 System methodology in WILUTE

City system theory is applied in the WILUTE model. The model treats land use, transport and the environment in an integrated way. The model attempts to take full account of the complex interactions that occur between urban processes, including household and firm location choices, transportation choices, and land use decisions. Environmental factors such as energy use are treated as internal elements when modelling transportation choices. The environmental effects of land use and transport polices are measured.

The core of the WILUTE model is derived from the IELT model (Integrated Economy, Land use and Transport) model that was developed using data from Beijing. The WILUTE model extends the IELT model. Land use is modelled in a more precise way, a health impact sub-model is added, and an analysis is included to evaluate the resilience of the city’s transport and land use system. WILUTE has three types of indicators to measure city resilience:

1. A city’s capacity to reduce energy consumption and GHG emissions, in particular from urban transportation changes;
2. The exposure of the land use and transport system in a city to natural disaster associated with sea level rise, measured as the vulnerability of residents, traffic links and traffic flows to sea level rise, and taking into account local land features, weather conditions and infrastructure such as flood-proof dikes; and
3. Cost to reduce vulnerability to an acceptable level, including costs of relocation of residents and economic activities and of building new infrastructure to reduce the impacts of natural disasters. This also includes consideration of a city’s financial capacity - if the vulnerability and the costs are too high for its financial capacity, the city has a low resilience.

The architecture of the model (Figure B) consists of six interacting sub-models:

1. Regional economic growth model - forecasts the growth or decline of firms by sector, population by group, household incomes, and car ownership;
2. Growth distribution model - distributes the growth or decline of population to the local level (land parcel) across the whole region;
3. Land market model - transfers the economic growth into land demand and estimates land price according to demand and supply;
4. Land use and building distribution model - distributes space and housing demand to local levels;
5. Transport and environmental model - derived from the traditional “four-step” transport demand model, and a transport energy and CO₂ emissions estimation, this model transfers travel costs into area accessibility, which influences the land market and the distribution of economic growth; and
6. Environmental and health impacts model – uses estimates of trips and transport energy consumption to measure transport links’ emissions, which are transferred into site and area air quality; evaluates public health impacts by concentrations of air pollutants and by changes in walking and bicycling trips.

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18 Zhao, P. Urban Form and Transport Energy Use in Beijing: A Long-Term Prospective Analysis; Peking University: Beijing, 2009
3.4 Merits of the system approach in WILUTE

While a number of models integrate land use and transport, and some partly integrate economic development with those, the WILUTE model integrates economic development, land use and the transport system with transportation energy consumption, GHG emissions, local air quality and public health effects. The interactions between environmental effects and transport and land use are considered in connected ways. For example, exposure to traffic pollutants or vulnerability to sea level rise can affect residential location choices, which can in turn shape new patterns of traffic, which can then influence new property and infrastructure development.

WILUTE uses a discrete choice approach, which describes or predicts choices made by people among a set of alternatives, e.g. between different modes of transport. This has advantages in modelling the behaviour of individuals. This is important given that studies have found that individual travel behaviour is key to more sustainable transportation, more so than technical factors or infrastructure supply. WILUTE’s land use modelling runs calculations for residential location choice, business location choice, and developers’ location and land use choices. The model forecasts travel demand based on individuals’ travel behaviour data, so has the potential to evaluate GHG emission reduction policies more accurately than previous models.

The model has an architecture designed to be transparent to policy-makers. It has the potential to integrate other modelling approaches within its sub-models. WILUTE can also be
used to analyse at different geographical scales – from individual building sites, to land parcels and subdivisions, to neighbourhoods, communities and cities.

3.5 Operation of WILUTE

WILUTE is GIS-based (Geography Information System). It runs in annual time steps, progressing through the sub-models (Figure C). The transport sub-model simulates travel for an average working day for transport zones for one year. It provides outputs of accessibility to land uses for the model for the next year. The modelling takes into account that changes in the location of homes and businesses usually lag behind traffic changes, so a 5-year time lag is used to reflect the interaction between transport changes and land use.

Figure C. The operation of WILUTE

There are two types of input data in the modelling:
1. Base year data - including data on transport, property, land use, demographics, employment, and physical features of a region;
2. Policy intervention data - for example, land use planning, transport planning, road pricing, fuel tax, and education programmes, each of which is designed to change personal travel behaviour.

Land use or transport policy options are inputs. These can come from district plans, the urban design framework, the urban growth boundary, provision of transport infrastructure or public transport services, travel demand management such as parking and pricing, vehicle technologies, etc.

The model measures:
- Short-term transport activities (e.g., route choice, travel time, mode of transport);
• Long-term transport activities (car ownership, travel distance);
• Long-term transport effects caused by socio-economic activities (e.g., household location choice, employment location); and
• Effects of sea level rise on transport (transport links, passenger traffic), as well as possible results of policies designed to respond to sea level rise.

Output data shows indicators for urban sustainability (listed above in 3.2) and also includes two of three indicators measuring city resilience (listed in 3.3). The third, cost to reduce vulnerability to climate impacts, is not considered in WILUTE at the current stage.

4. Examples

Here are two scenarios to illustrate the model. The base year is 2006 and the scenario final year is 2031.

4.1 Transport

This example compares two development trajectories:
• Low intensification – the current pattern of low dwelling and population density continues at business as usual levels
• High intensification – four changes to business as usual:
  o Land per person is reduced for new developments. This represents intensification policies such as limits on land supply and an urban boundary, and alters the population density in each traffic zone.
  o The ratio of houses to apartments changes from 9:1 in 2006 to 1:9 in 2031 for high traffic zones. This indicates the policies of urban infill development and building high-density apartments around public transport areas.
  o Land per apartment or house changes to the minimum value in 2006 for all traffic zones. The smaller the section, the greater the intensification.
  o For individual parcels, the ratio of floor area to land area changes to simulate individual houses or apartments having more area for buildings and less for non-building or open space.

In the modelling process, people are grouped by age and income into five categories. Trips are also put into five categories, based on the purpose of the trip and its starting place, e.g. “home-based work trip” is a trip that starts at home and has the purpose of going to work.

Modelling results (Figure D) suggest high intensification could save about 20,600 trips per day compared to low intensification. It is clear that policies designed to increase urban intensification would reduce the carbon footprint of Wellington city in future.

Figure D. Population, houses and transport in the low intensification (left) and high intensification (right) scenarios

Notes:
1. Population density - persons per hectare
2. No. trips_HBW - number of home-based work trips per day
3. No. trips_HNW - number of home-based non-work trips per day
4. No. trips_NHW - number of non-home-based work trips per day
4.2 Sea level rise

In WILUTE the vulnerability of people and houses to sea level rise is calculated from the distribution of residents, land development and houses in an area in a given period. Sea level rise is measured with consideration of sea-wall and flood protection. The vulnerability of transport to sea level rise is calculated through spatial analysis of an area in a given period and by looking at vulnerability by population group.

**Figure E. Vulnerability of traffic links and flows to sea level rise**

Figure E shows the vulnerability of traffic links and flows to sea level rise, based on transport patterns in 2006. Major roads in the city are at risk of flooding, depending on the extent of sea level rise. Sea level rise scenarios above 2 metres are extremely unlikely in the period to 2031. Global mean projections for sea level rise between 1990 and 2080 range from 22 - 34 cm, though recent research suggests sea levels may be rising faster than those estimates.

The effects of sea level rise may not be equally distributed between places and between different income and ethnic groups in Wellington. Modelling suggests that 54% of people aged below 10, or over 65, or on low or no incomes are vulnerable. Only 24% of those on medium to high incomes aged 20-64 are vulnerable. In this case, “vulnerable” means living in a dwelling vulnerable to sea level rise, and excludes impacts on people’s trips to work and other forms of vulnerability.

**Conclusion**

Making cities more resilient has become one of the most important goals of urban sustainability. Planners, politicians and the public are interested in how to build a resilient city in order to respond to climate change and to possible disasters such as earthquakes and tsunamis. There are still major gaps in the research on urban resilience and in particular we lack a sound method for evaluating alternative resilience policies. Policies for resilient cities are those that strengthen the urban system’s capacity to change in response to social, economic and natural shocks. The human-built and natural systems of a city are complex, which makes it a challenge to evaluate the efficiency of policies for reducing negative environmental and health impacts.

This paper introduces an integrated land use – transport – environment model, WILUTE, which can be used to evaluate city resilience under different policy scenarios. The model is designed to estimate the complex links between urban economic activities, household and business location choices, transportation and land use. City resilience is measured by capacity to reduce energy consumption and GHG emissions, vulnerability of transport and land use to sea level rise, and costs related to reducing the vulnerability to a safe level.

There are challenges in the modelling of urban systems, such as how to model uncertainties. One way to address this challenge will be to increase the comprehensiveness of the policy alternatives and scenarios looked at; another will be to increase the flexibility of the model’s calculation processes and data. A second challenge is how to treat dynamic issues, continuously changing elements, within a model. Most models, including WILUTE, treat the dynamic features of an urban system by looking at the change from one point in time (a base year) to another (a selected year in the future). However, urban dynamics are more complicated than we can currently simulate. For example, in the WILUTE model we assume a 5-year time lag between changes in land use and changes in transport. This may not reflect faster changes (e.g. choice of travel path) or very slow changes (e.g. land use patterns). Combining various dynamic processes in one overall model continues as a work in progress.

To build or enhance a city’s resilience, individual policy actions need to be aligned and integrated. In the transportation sector, infrastructure projects, land use planning, housing policies and travel demand policies need to be integrated in order to reduce energy consumption and GHG emissions. The various aspects of city sustainability should be considered in resilient city policies, including environmental justice across different ethnic and income groups. Improving social and environmental equity is part of building a resilient city. A resilient city will reduce its ecological footprint while at the same time improving quality of life for its people. Integrated solutions, which can be explored by models such as WILUTE, need to be addressed in future policy-making in order to create resilient cities.

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