PATTERNS OF LAND USE DEVELOPMENT AND SUSTAINABLE TRANSPORTATION: A SIMULATION APPROACH

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Introduction

Concerns over sustainable city planning in the last couple of decades have generated a strong sentiment against urban sprawl and its negative ramifications in North America. Sprawl is thought as dispersed and discontinuous suburban land development associated with low population density and high auto-dependence (Carruthers and Ulfarson 2002**;** Handy 2005). Critics argue that this type of development threatens the sustainability of cities due to its negative environmental, social and economic impacts. This is because it saps local resources; it destroys open space and farmland, and increases the energy consumption of mobility by promoting long commutes. The latter also contributes to high levels of traffic congestion and harmful emissions. Sprawl, critics further argue, is responsible for the decay of downtown areas due to people and firm decentralization, leading to reduced social interaction and weakening the bonds that create a healthy society (Brueckner 2000).

While the number of studies that sought to address the issue of urban sustainability and combat sprawl has been on the rise over the past couple of decades, little has been done on utilizing analytical tools to assess the future of urban transportation sustainability in North America. Questions about how particular land use development patterns or improvements in the level of transportation infrastructure are likely to impact urban sustainability remain unanswered. Such questions can be addressed with Integrated Transportation and Land Use Models (ITLUMs), which are sophisticated computer based simulation tools that allow decision makers to assess the impact of land-use and transportation infrastructure projects on the evolution of urban areas. With the exception of the work done in Europe, namely the SPARTACUS "System for Planning and Research in Towns and Cities for Urban Sustainability" (European Commission 1998) and PROPOLIS "Planning and Research of Policies for Land Use and Transport for Increasing Urban Sustainability" (Spiekermann and Wegener 2004) projects, the potential of using ITLUMs to calculate indicators for evaluating urban sustainability in North America has not been fully explored. Research is underway to utilize ITLUMs to assess the future of urban development and its relation to sustainable transportation in the Canadian Context (Maoh and Kanaroglou 2008).

This paper explores the impacts of various patterns of land development on the sustainability of the transportation system following a simulation approach. We employ IMULATE+, an integrated transportation and land use model that has been calibrated to evaluate the interaction between land use and transportation in Hamilton, to illustrate how one can assess the sustainability of the urban transportation system via a scenario simulation approach. IMULATE+ is equipped with a sustainability module (SUSTAIN) that generates a series of sustainable indicators that correspond to the three pillars of sustainability: (1) Environment, (2) Society and (3) Economy (Maoh and Kanaroglou 2008). The efficacy of the examined policies is assessed by identifying which of the simulated scenarios will result in a set of indicators that will minimize negative environmental and social outcomes while maximizing economic benefits. The analysis aims to simulate a number of scenarios that pertain to different residential land developmental patterns. The scenarios will include (1) Urban Residential Intensification (URI) scenario where all new development is allocated in the core of the city, (2) Urban Multi-Nucleated (UMN) scenario in which all new development is allocated to certain nodes or foci in the city, and (3) Urban Sprawled (USP) Scenario where all new development is allocated in the outer Suburbs. SUSTAIN will then calculate overall sustainability indices to determine the feasibility of the modeled scenarios.

To this end, the remainder of this paper is organized as follows. Section 2 provides a background discussion about concepts related to urban residential intensification, urban sprawl and smart growth strategies. Section 3 discusses the tool used to simulate and assess the residential development scenarios. Section 4 presents the devised land development scenarios and discusses the obtained results. Finally, Section 5 offers a conclusion to our study.

Background

Despite popular belief, urban sprawl is not any form of suburban growth. Brueckner (2000) defines urban sprawl as the excessive spatial growth of cities, the key word in this definition being "excessive". Although cities must grow spatially to accommodate an expanding population, the claim is that too much spatial growth occurs. Although the allocation of land is determined by competition between urban and agricultural uses, the outcome has increasingly tipped in favor of urban use, leading to substantial spatial growth of cities. Characteristics of sprawl can include unlimited outward extension of development, low-density residential developments, leapfrog development, dominance of transportation by private vehicles, lack of centralized planning or control of land uses, widespread strip commercial development and the segregation of types of land use in different zones among others (Handy 2005; Carruthers and Ulfarson 2002).

According to Downs (1999), sprawl causes, or contributes to numerous economic and social problems including traffic congestion, air pollution, large-scale absorption of open space, extensive use of energy for movement, inability to provide adequate infrastructure, shortages of affordable housing near where new jobs are being created, and suburban labor shortages. As such, it is believed that sprawl contributes to degrading the quality of life in cities and threatens the sustainability of the urban transportation system. Numerous cities have tried to alleviate congestion and emissions with varying degrees of success (Behan et al. 2008). Some of the implemented policies tries to reduce congestion through financial rewards and penalties as we see increasing / reducing taxation to encourage CBD development. Other cities also use cycle lanes to discourage commuters from vehicle usage. Cheaper and more efficient public transport offered by the local or provincial government creates another incentive to move away from private vehicle use. Other techniques in congestion reduction involve changes to infrastructure or the way in which we utilize this infrastructure. These can include the greater expansion of no-trucking routes, only allowing trucks into the CBD in the early morning or late evening, staggering of school opening times to avoid problems associated with the school run, pedestrianization of shopping areas in the CBD etc.

Whilst these solutions may provide at least temporary relief, they do not address the fundamental cause of the problem, land use. Mixed land use refers to multiple land use where no one type dominates. Multiple uses have been categorized as mixing of commercial, residential, recreational, institutional and industrial land uses, including different types of housing, owner occupied and rented accommodation, public and private uses, as well as accommodation of different social groups. To date, land use planning in most North American cities has been far from sustainable for the reasons mentioned earlier on. These trends can be addressed by encouraging relocation to the CBD through *smart growth policies*, which seek to revitalize established urban areas and provide for a greater range of housing, employment and social activities. The general idea here is to adjust for the imbalances between the distributions of households and jobs such that people live close to where they work. This can reduce commuting patterns and levels of congestion.

Smart Growth BC (2007) define smart growth as ‘a collection of land use and development principles that aim to enhance our quality of life, preserve the natural environment, and save money over time. Smart growth principles ensure that growth is fiscally, environmentally and socially responsible and recognizes the connections between development and quality of life. Smart growth enhances and completes communities by placing priority on infill, redevelopment, and densification strategies'.

A key component of smart growth strategies involves increasing population densities in the urban center. This is Urban Residential Intensification (URI), defined as a broad land-use planning concept that entails increasing the number of households/housing units in the existing or built-up area of a community. URI is that component of smart growth that deals with increasing population densities in the urban core of a city. This will result in what is known as compact urban form or the compact city. There are three distinct "methods" of residential intensification:

- **Redevelopment** – Existing structures are demolished, in most cases non-residential, and new residential structures are constructed
- **Infill** – A residential structure is constructed on a vacant lot or parcel of land and/or an existing underutilized property, building where additions or new structures have been built
- **Conversion** – Existing non-residential structures are renovated and converted to include residential dwelling units or, existing residential structures are renovated and converted to include one or more additional dwelling units

More densely populated cities are more cost efficient to manage. This has been one of the key forces in employing URI to date (Filion and McSpurren 2007). URI has been linked to environmental issues related to urban growth, and has become more publicly acceptable due to its environmental rewards, sprawl reduction, congestion reduction and the resulting emission reduction. By detracting from urban sprawl, we accommodate projected future household growth within the existing urban area and reduce pressure on greenfield areas for urban growth.

The "compact city" is a favourable sustainable urban form, not only for reduction of fuel consumption and pollution, but also for quality of life in general. Nowlan and Stewart (1991) have found that in

Toronto, Ontario, the population increases in the central area have reduced the growth rate of commuter trips, and have suggested the increase of the residential density as an alternative strategy to the construction of new transportation infrastructures.

A Simulation Tool for Sustainability Analysis

Different patterns of future residential land development can be simulated with ITLUMs. Such models can be particularly useful in disentangling the ambiguity associated with a specific urban form strategy. Given an urban center, for a variety of simulation scenarios, integrated urban models allow decision makers to isolate the potential impacts of a particular strategy by holding other characteristics of the city constant, something that is impossible to achieve otherwise. It should be noted, however, that simulation models are not decision-making substitutes but tools that aid policy makers in the decision process.

In this research, we employ IMULATE+, an operational Integrated Model for Urban Land Use, Transportation and Environmental analysis developed to study urban issues. IMULATE+ is calibrated for a one-hour period within the morning rush hour and it simulates changes in land use and travel at the zonal level over five-year intervals, the first of which corresponds to the period 1986 to 1991. IMULATE+ has been employed in several studies to date to assess the impacts of land use change and generated travel demand on the environment (see for example Kang et al. 2008; Behan et al. 2008). Recently, the model has been extended to include a sustainability module (SUSTAIN), which produces sustainability indicators (see Table 1) to assess the efficacy of a simulated scenario in reducing negative environmental and social outcomes while maximizing economic benefits (Maoh and Kanaroglou 2008).

The basic structure of the model is shown in Figure 1. Within the land use module, POPMOB is a residential location model that relates to the intra-urban household mobility and the operation of the housing market over space and time. EMPLOC, on the other hand, is a firm location model that relates to the intra-urban firm mobility and the associated location choice behavior of firms in the CMA. As for the Transportation Module, TRANDEM is a travel demand model that translates the land use information into origin-destination (OD) trips by travel mode. TRAFFIC utilizes the motorized OD trips and assigns them on the road transportation network using a Stochastic User Equilibrium algorithm to determine link flows and congested travel times. The Environmental Module translates the link flows into link emissions using emission factors that are obtained from Mobile6.2C, the Canadian version of Mobile6.2 developed by the Environmental Protection Agency (EPA) in the United States of America.

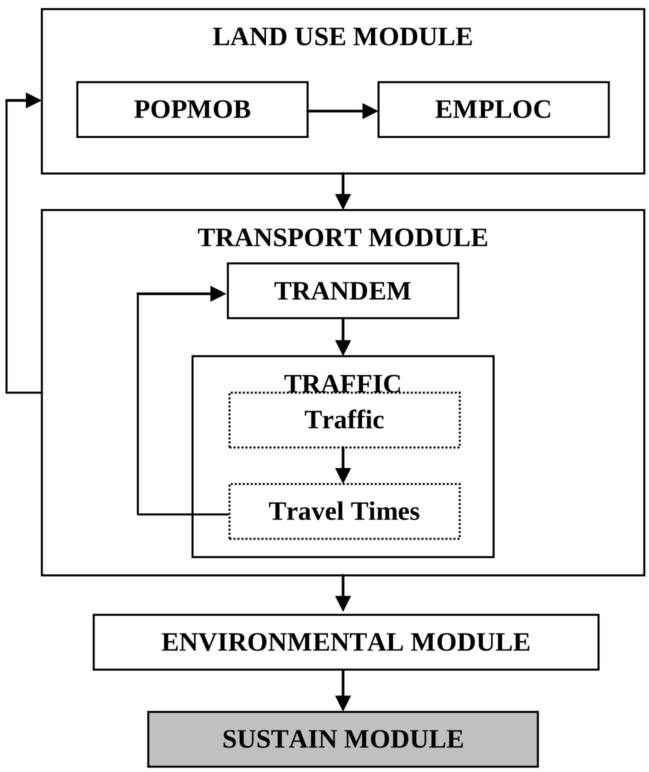

Figure 1: The IMULATE+ System

Table 1: Sustainable Indicators of IMULATE+

Pillar	Label.	Indicator
	AP1	Greenhouse gases
	AP2	Acidifying gases
Environment	AP3	Volatile organic compounds
	AP4	Fine particles PM2.5
	AP5	Fine particles PM10
	NR1	Energy use from fossil fuels
	NR2	Consumption of green space
	HL1	Exposure to NOx from transport
	HL2	Exposure to CO from transport
	HL3	Traffic injuries
Society	HL4	Traffic deaths
	OP1	Vitality of CBD
	OP2	Residential amenities
	AM1	Accessibility to CBD
	AM2	Accessibility to services
	AM3	Vehicle kilometres traveled
	AM4	Vehicle minutes traveled
	AM5	Congestion index
Economy	EC1	Transport investment costs
	EC2	Transport commuting costs
	EC3	Transport external costs such as health costs

SUSTAIN utilizes the calculated transportation usage and performance measures to generate the list of indicators shown in Table 1. The module relies on a standard multi-criteria evaluation method to calculate the contribution of each indicator x to the three pillars of sustainability. The idea is to translate the raw values of all indicators produced by IMULATE+ into standardized indices (Maoh and Kanaroglou, 2008). For any indicator x that pertains to one of the three pillars of sustainability, SUSTAIN will generate three values v_x, $v_x^{\min}$ and $v_x^{\max}$ that represent the raw, hypothetical minimum and hypothetical maximum values of the indicator, respectively, where $v_x^{\min} \le v_x \le v_x^{\max}$. The generated value v_x is normalized to a new value nv_x on a scale of 0 to 1, to be able to compare indicators directly. The normalization is achieved by using the following formula:

$$nv_x = \frac{(v_x - v_x^{\min})}{(v_x^{\max} - v_x^{\min})} \quad \ldots (1)$$

To assess the sustainability of the simulated scenario, each indicator is assigned an exogenous weight in the range of 0 to 100 percent to directly reflect its importance. For instance, an indicator with a weight of 80% is deemed more important than an indicator with a weight of 20%. Accordingly, an exogenous list of weights (w_1, w_2, …, w_k) corresponding to the k indicators of a given pillar p is provided as input to calculate sustainability index SI_p for pillar p. Multi-criteria evaluation is applied using the normalized indices nv_x to calculate an overall index SI_p using the exogenous weights. The general formula for calculating a sustainability index is given as follows:

$$SI_p = \sum_{x=1}^{k} w_x \cdot nv_x \quad \ldots (2)$$

where k is the number of indicators that belongs to pillar p, and the sum of all weights w_x for all x should add up to unity. An overall index SI is then calculated by average the SI_p values of the three pillars, where p = {1: Environment, 2: Society and 3: Economy}. SUSTAIN employs a systematic method that relies on the well-known Transportation Problem (TP) to determine the values of $v_x^{\min}$ and $v_x^{\max}$. Detailed description of this approach is provided in Maoh and Kanaroglou (2008). Such values are vital for normalizing the calculated indicators.

Analysis and Results

The performed analysis is focused on the Hamilton CMA, a region of approximately 500,000 inhabitants according to the 2001 Canadian Census. Located 60 kilometres to the south west of Toronto, Hamilton has been experiencing continual urban sprawl for more than two decades. This has been accompanied with a clear decentralization of population and jobs (Maoh and Kanaroglou 2007). Furthermore, Hamilton has an ample of road infrastructure and high level of private vehicle ownership. Using IMULATE+, one can test the ramifications of various land development patterns on the sustainability of the transportation system. In other words, we can assess which development alternative is more sustainable.

In this exploration, we simulate four scenarios that present four different patterns of residential land development in the Hamilton CMA for the time period 2001 – 2006. We assume a total of 20,000 new residential dwellings to be constructed in the Hamilton CMA in this time period. Such information forms the supply of the land market for the POPMOB model, which predicts the spatial distribution of population in the tracts of the CMA. The four scenarios are as follows:

1- **Base Case Scenario**: This is a business as usual scenario where the distribution of the 20,000 new dwellings across the tracts of the CMA follows the observed past trends published by Statistics Canada for 1991-1996 and 1996-2001.
2- **Urban Residential Intensification (URI) Scenario:** Urban residential intensification is a commonly advocated land use policy under the umbrella of new urbanism and smart growth strategies (Behan et al. 2007). To reflect urban residential intensification, we evenly assign the 20,000 new dwellings across the central tracts shown in Figure 2.
3- **Multi-nucleation Scenario:** In this scenario, we assume that the new development will mainly occur in particular nodes in the city. For this we identified three foci and evenly allocate the 20,000 new dwellings to their tracts, as shown in Figure 2.
4- **Urban Sprawl Scenario:** Land development in this scenario is assumed to follow a sprawled pattern where new development is

mainly occurring in the outer suburbs of the city. To capture this effect, we evenly distribute the new dwelling far away from the core in tracts that are at the fringe of the city, as shown in Figure 2.

The calculated indices are based on equal weights that are assigned to all the indicators of any given pillar. The results of the simulations are summarized in Table 2. It is worth noting that better environmental, social or economic conditions are achieved when the normalized value nv_x of any indicator x is closer to 0. The same applies to the SI_p indices. As such, a value close to 1 postulates an undesirable condition. The sprawl scenario appears to provide the most undesirable outcome with an overall sustainability index of 0.56. By comparison, the multi-nucleation scenario appears to provide the lowest overall index (0.4835), which appears to be very close to the indices achieved from the base and URI scenarios. The same observations apply when examining the calculated indices per pillar of sustainability. While the results from the sprawled scenario are not very surprising and points towards aggravating environmental, social and economic outcomes, those pertaining to the URI scenario are more interesting. The implementation of an URI scenario will result in better environmental conditions compared to the other scenarios. However, it fails to create better social and economic conditions when compared to the multinucleated scenario. The sources of this undesirable condition are congestion and low mix of land use density in the core, as discerned from the relatively higher values of the congestion and viability of CBD indices (0.06 and 0.008). Nonetheless, the URI scenario appears to mitigate exposure to pollution as inferred from the exposure to NO_x.

It is worth noting that the above results are partially driven by the assigned weights. Different results regarding the sustainability of the simulated scenarios would have emerged if we assigned higher weights to particular indicators. Therefore, attention should be given to the assigned weights. The latter could be based on surveys, which engage the opinions of the public as well as stakeholders from the different levels of governance, to identify the importance of each of the simulated indicators on the sustainability of the transportation system and the city.

Table 2: Estimated sustainable indices, 2001 – 2006

Indicator	**Base**	**URI**	**Multi-nucleation**	**Sprawl**
		Environmental Indicators		
AP1	0.0655	0.0680	0.0602	0.0750
AP2	0.0824	0.0849	0.0787	0.0905
AP3	0.0531	0.0547	0.0467	0.0614
AP4	0.0916	0.0949	0.0907	0.0989
AP5	0.0916	0.0949	0.0907	0.0989
NR1	0.0892	0.0926	0.0884	0.0973
NR2	0.0641	0.0000	0.0874	0.1311
SI_1	**0.5375**	**0.4899**	**0.5429**	**0.6530**
		Social Indicators		
HL1	0.0091	0.0071	0.0117	0.0126
HL2	0.0000	0.0000	0.0000	0.0000
HL3	0.0532	0.0551	0.0527	0.0574
HL4	0.0533	0.0551	0.0527	0.0574
OP1	0.0029	0.0082	0.0025	0.0021
OP2	0.0009	0.0009	0.0009	0.0009
AM1	0.0332	0.0369	0.0321	0.0427
AM2	0.0315	0.0370	0.0310	0.0434
AM3	0.0538	0.0557	0.0533	0.0581
AM4	0.0252	0.0260	0.0249	0.0327
AM5	0.0566	0.0602	0.0548	0.0609
SI_2	**0.3197**	**0.3421**	**0.3167**	**0.3680**
		Economic Indicators		
EC1	0.2114	0.2190	0.2095	0.2283
EC2	0.1695	0.1782	0.1657	0.1888
EC3	0.2178	0.2257	0.2158	0.2352
SI_3	**0.5987**	**0.6229**	**0.5910**	**0.6522**
Total SI	**0.4853**	**0.4850**	**0.4835**	**0.5578**

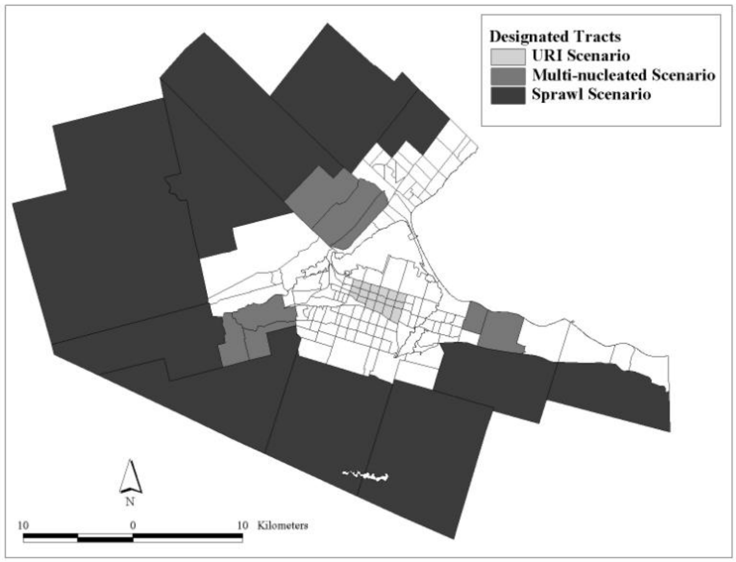

Figure 2: Designated census tracts for residential land development in the Hamilton CMA

Conclusion

Integrated urban models such as IMULATE+ allow for more informed planning decisions, and can help in the minimization of uncertainties relating to the planning process. Obviously, these models are not without their limitations, and should not be considered in isolation, but as part of a comprehensive, integrated planning process. This research employed IMULATE+ to demonstrate the value of using such tool in assessing the sustainability of alternative land development patterns.

The analysis suggests that urban sprawl development provides the least sustainable outcomes for the environment, society and economy. Furthermore, a multi-nucleation scenario in which new development is allocated to specific nodes in the city seems to provide the most sustainable outcomes when treating all aspects of sustainability equally. Interestingly, the urban residential intensification (URI) scenario would not necessarily produce the most sustainable outcomes. We found that the URI scenario improves the environmental conditions when compared to the business as usual and other simulated scenario. However, the scenario does not produce the best social and economic conditions.

The analysis in this paper demonstrates the value of using integrated urban models to simulate the sustainability of various land development patters, including urban intensification, multi-nucleation and sprawled land development. Near future research will examine various smart growth land developmental patterns to predict the most plausible outcomes of future development in the study area. It is obvious that cities have a variety of smart growth options available, some of which were explored in this paper. In a nutshell, our results reinforce previous findings, which suggest that urban sprawl is not a plausible alternative for a sustainable transportation and urbanism. The latter can only be achieved by promoting URI and multinucleated urban forms.

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Infrastructure Canada   Canada

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