SMARTPLANS: SIMULATION MODEL FOR ASSESSING THE RAMIFICATIONS OF TRANSPORTATION POLICIES AND LAND USE SCENARIOS

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INTRODUCTION

Canadian cities experienced significant growth over the past six decades. These changes can be attributed to three main contributing factors: 1) the horizontal expansion in land development due to suburbanization and urban sprawl, 2) massive investment in road and highway infrastructure, and 3) high auto-dependency due to the affordability of private vehicles by the Canadian middle class. While the growth of cities is important for the progress of nations, it has been associated with a number of ramifications in most developed countries including Canada. For instance, most Canadian cities have experienced a noticeable increase in travel activities due to the movement of people and goods. However, this has led to daily traffic congestion in large metropolitan areas such as Toronto, Montreal and Vancouver. Increased levels of travel activities have also contributed to traffic accidents and fatalities, air and noise pollution and global warming due in part to burning fossil fuels. Expansion of urban areas has also been associated with the consumption of prime agricultural land in many suburban areas.

Ongoing suburbanization trends, urban sprawl and noticeably longer commuting patterns in many Canadian cities suggest that past and current urban development practices are far from sustainable. What is known is that cities will continue to grow in the future. As such, the question facing decision makers is what kind of future growth strategies should be promoted to achieve a more sustainable future? That is, what can be done to steer future development in a direction that will result in a healthy environment, well integrated society and a strong economy. With that in mind, recent policies for long-term urban transportation planning have been focused on promoting strategies that can achieve progress towards sustainability.

A robust method of assessing the efficacy of alternative growth strategies over the past two decades has been the development and application of Integrated Urban Models (IUMs). These models are sophisticated computer simulation programs that act as a virtual laboratory to imitate the dynamics of urban land use activities and travel patterns. They are developed as planning support systems (PSS) to test various “What if” scenarios. Example of the latter may include but are not limited to:

- What are the implications of building a new highway in the city?
- Where should future residential and/or commercial development be located?
- Will the promotion of mixed land uses lead to more sustainable futures?
- Will the establishment of Light Rail Transit (LRT) reduce traffic congestion?

To date, a number of operational IUMs have been developed for different cities around the world. These models, which began development in the mid-1960s, belong to 4 distinct schools of thought: 1) gravity-based models, 2) economic-based models, 3) bid-choice-based models and 4) agent-based microsimulation models. While each school of thought has its own advantages and disadvantages (Hunt et al. 2005), the majority of contemporary IUMs utilize the bid-choice-based modeling approach. Unlike the simple gravity-based models, bid-choice-based models are able to accurately capture the true underlying behaviors that result in land use changes, but have reasonable data requirements compared to more complex agent-based microsimulation models. Previous bid-choice based models include, but are not limited to, the IRPUD model (Wegener, 2011), MUSSA model (Martinez, 1996), the IMULATE model (Maoh and Kanaroglou, 2009), the IMPACT model (Maoh et al. 2009) and the URBANSIM model (Hunt et al. 2005).

This paper reports on the development of SMARTPLANS, a successor of the IMULATE IUM that was originally developed for the Hamilton metropolitan area. SMARTPLANS is developed as a full-fledged

IUM that can be used to simulate various land use and transportation scenarios. While it shares some features with IMULATE, it also builds on ideas from the MUSSA and URBANSIM models. On the land use side, the model can simulate the decisions affecting land development, land prices, household location and firm location, whereas the transportation system of SMARTPLANS is based on the well-known four-stage model. The User Interface (UI) of the model is developed with three features in mind: 1) fine tuning the model parameters through the user interface without the need for computer programming; 2) using the UI to extend the model by including additional land use and transportation components or categories; and 3) transferability and application of the model to different urban areas.

The remainder of the paper is organized as follows: a background section is provided at first to highlight the underlying principles that need to be considered when developing an IUM. This is followed by a section that describes the modeling framework of SMARTPLANS. The fourth section provides an empirical illustration of SMARTPLANS based on model parameters from Halifax, Nova Scotia. It also provides recommendations for future research.

BACKGROUND

The starting point in the development of an IUM is an understanding of how to model real world processes. That is, determine the processes that give rise to the dynamics and change we observe in land use and transportation. Two concepts are usually used to describe the city and the processes taking place in it. The first concept is referred to as urban form, which represents the spatial configuration of the buildings that will be occupied by different land use types (e.g. residential and commercial). Typically, if a large percentage of occupied buildings are clustered in and around the core of the city, then the urban form is said to be compact. On the other hand, if developed buildings are scattered in various suburban places, the emerging configuration will represent a sprawled or dispersed form. The second concept defining a city pertains to the spatial interaction of travel activities that are associated with the land use types occupying the buildings. It represents travel demand as a result of engaging in travel for various purposes. For example, members of a household engage in travel to go to work, shopping, or for discretionary purposes. Likewise, firms engage in commercial travel to deliver goods or provide services.

In general, four main actors (or agents of change) are responsible for the temporal changes we observe in urban form and spatial interaction. The first of those actors are public institutions (e.g. city planners and transportation ministries) who are responsible for building roads and highways, regulating transportation operation (e.g. setting travel speeds) and determining the nature of zoning within the urban area. Land developers represent the second group of actors who develop the buildings occupied by various land use types. Their decision to develop urban land use is to a large extend driven by the actions and policies set by public institutions. The third group of actors is households who occupy residential land uses and engage in travel on a daily basis. The fourth group is firms who occupy non-residential developed land. Similar to households, firms engage in commercial travel activities to deliver goods or services on a regular basis. They are also major attractors of passenger trips since the vast majority of them represent places of work and shopping.

Land use and transportation can be thought of as two separated systems yet exhibit a symbiotic relationship that integrates them to each other. The relationship can be well illustrated by an example. Consider a rural road at the edge of the inner suburbs of a city, which stretches for several kilometers from the east to the west boundary of that city. The road has one lane per direction and has a posted speed of 50 km per hour. Areas in the vicinity of this road have moderate accessibility. The latter represents the ability to reach a particular location in proximity to the road from any other location in the city. A decision is made to upgrade the road to an urban freeway with two lanes in each direction and increase the posted speed limit to 100 km per hour. The plan also includes the development of several interchanges for ease of access. Typically, the provision of a high speed and capacity freeway is going to increase the level of accessibility, which will in turn increase the land price for the sites in the vicinity of the newly developed freeway. The increase in price will trigger the interest of land developers to invest by constructing new buildings in areas close to the new freeway. This in turn will make the newly developed sites more attractive to households and firms, thus triggering them to make a move from their currently congested sites to the newly developed and easily accessible places.

The new location choice of households and firms will give rise to new patterns of spatial interactions to satisfy the demand for travel for various purposes. As such, new passenger and commercial trips will be generated from/to these new locations and that will translate into new patterns of traffic flows on the road network. As time passes, more people and firms will move into the new locations with the help of more development and this in turn will affect travel time and the levels of accessibility due to emerging congestion. Changes in accessibility will trigger more development in the outer suburbs. In other words, changes in accessibility will have an impact on land use activities and land development over time. As can be seen, there is a clear feedback loop (i.e. accessibility) between the land use and transportation systems.

A full-fledged IUM must be able to account for the various processes, triggers and feedback loops to imitate the changes observed in the real world. Figure 1 presents the general structure of such a model.

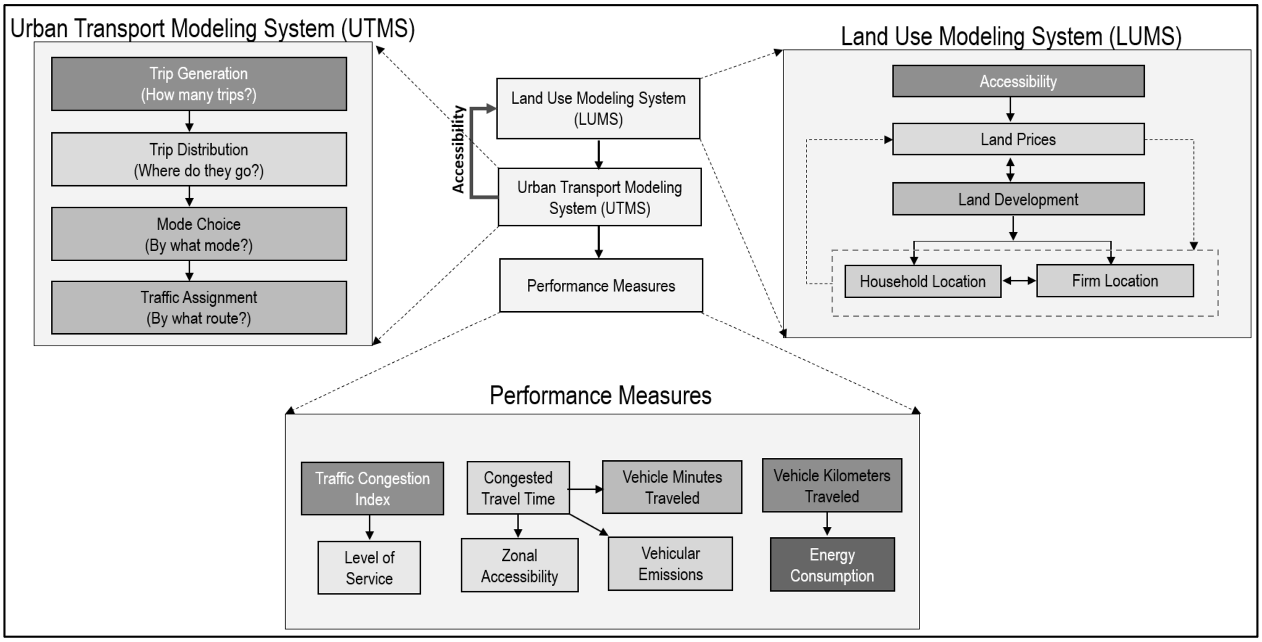

Figure 1. Basic representation of comprehensive IUM

The starting point of the Land Use Modeling System (LUMS) is an "**Accessibility Module**" that calculates zonal accessibilities to various land use activities based on the simulated inter-zonal travel times. Accessibility A_i to a specific land use opportunity for a given zone i is typically formulated as a gravity measure that depends on the quality of the opportunity Q_j and the time (t_{ij}) to travel from i to j; that is, $A_i = \sum_j Q_j \exp(\beta t_{ij})$. Estimates from the accessibility module are fed into the "**Land Price Module**" to estimate the price of land uses per zone. This model could be formulated to calculate individual property values (if disaggregate data is available) or zonal average prices per land use type. The average price per zone $R_i(t+1)$ at time $t + 1$ is typically formulated as a function of zonal accessibilities and the prices from the previous time step $R_i(t)$ (Martinez, 1996). Changes in land price as discussed earlier will have an influence on the decision of developers to construct new land uses (buildings, houses, structures, etc.). However, the change in price is also expected to influence the location choice decision of households and firms seeking a new location. The "**Land Development Module**" determines the amount of new development $ND_{i/L}(t+1)$ by land use type L in each zone i of the city. Information pertaining to land development is then used to estimate population size $K_i(t+1)$ per zone i via the "**Household Location Module**". The latter module can also be used to estimate zonal population size by age or income class (depending on the availability of data). The last module within the LUMS is the "**Firm Location Module**" which is used to estimate zonal jobs $E_i(t+1)$ for time $t+1$. As in the case of household, the firm location module can also be used to estimate zonal jobs by type of industry.

Information from the LUMS is used as an input to the Urban Transport Modeling System (UTMS). More specifically, zonal population and job estimates are used to determine the number of trips that are produced or attracted to the zones forming the study area. This is achieved via the "**Trip Generation Module**". Typically, multivariate regression models are used to determine the trip productions O_i and attractions D_j per origin zone i and destination zone j. Depending on available data, trips could be estimated by hour of the day and purpose (e.g. work trip, shopping trips, freight trips). The estimated trips from the generation module are input to the "**Trip Distribution Module**", which normally makes use of a gravity model formulation to estimate origin-destination trip matrices. Next, a "**Mode Choice Module**" is used to split the trips from the distribution module by mode of travel. The multinomial logit model (MNL) has traditionally been used to estimate the mode choice probabilities needed to split the total trips between zones. Finally, a "**Traffic Assignment Module**" is used to translate motorized inter-zonal trips into road traffic volumes. These volumes are usually simulated for each road link l of the transportation network via the User Equilibrium (UE) traffic assignment routine. In turn, the estimated traffic volume feeds back into the "**Accessibility Module**" and the updated accessibilities are used as the starting point in the LUMS for the next time period.

Traditionally, a number of performance measures are derived from the UTMS outputs. The first is the volume to capacity ratio (v_l/C_l) which can be used to determine the presence of traffic congestion. When (v_l/C_l) is less than 1, vehicles traverse the road link l at the free flow speed. However, congestion is said to be present when (v_l/C_l) is greater than or equal to 1. In such a case, the free flow travel time $t_{l/0}$ on a given road segment l is updated to estimate congested travel time $t_{l/v}$. This is achieved through the following link performance function:

$$t_{l/v} = t_{l/0}\left(1 + 0.15(v_l/C_l)^4\right)$$

Congested travel time can then be used to calculate potential zonal accessibilities A_i to various land use types. Those accessibilities are then used as input to the LUMS in the subsequent simulation. $t_{l/v}$ is also utilized to calculate vehicle-minutes-traveled $(vmt_l = v_l \,.\, t_{l/v})$ and congested travel speed $(S_{l/v} = d_l \,/\, t_{l/v}$; d_l is the length of link l in kilometers). Other performance measures include vehicle-kilometers-traveled $(vkt_l = v_l \,.\, d_l)$. Anderson et al. (1996) extended the capabilities of the IMULATE IUM to estimate vehicular emissions $e_{l/x}$ per link l and pollutant x:

$$e_{l/x} = vkt_l \;\; \varepsilon_{x/S_{l/v}}$$

where $\varepsilon_{x/S_{l/v}}$ is the amount of emissions [grams per kilometers] of pollutant type x under a given congested speed $S_{l/v}$. Finally, energy consumption per road link l can also be calculated as a function of vkt_l as in Anderson et al. (1994):

$$\Psi_l = 0.0797\, vkt_l + 0.0004725(vkt_l\,/S_{l/v})$$

MODELING FRAMEWORK

The conceptualization of SMARTPLANS borrows from the general concepts highlighted in the previous section. The first operational beta version of the model, which became available in 2014, is developed as a stand-alone application that makes use of the open-source DotSpatial Geographic Information System (GIS) library. The library provides SMARTPLANS with basic GIS capabilities to read and visualize spatial information when running simulations. The underlying theory and mathematical models governing the changes in land use within SMARTPLANS build on the approaches used to develop the IMULATE (see Behan et al. 2008; Kang et al. 2009) and IMPACT (Maoh et al. 2009) IUMs. However, unlike these IUMs, model parameters in SMARTPLANS are not hardcoded in the software. Instead, the analyst has the ability to configure these parameters through a graphical user interface.

Simulations start with a base-year (i.e. time t) dataset for the study area to predict land uses, traffic flows and emissions for a future year (i.e. time $t+1$). The platform consists of the three integrated systems shown in Figure 1 along with a fourth region wide aggregate control system. The latter consists of the following two modules: 1) a Rogers Multi-regional Demographic Model (Maoh et al. 2009); and 2) an input-output (I-O) macro-economic model (Miller and Blair, 2009). The Rogers model predicts population by age and sex in the study area using vital statistics on fertility, mortality and migration rates. On the other hand, the I-O model predicts total number of firms and associated jobs by industrial sector (Maoh et al. 2005). Information produced by this control system is fed into the LUMS.

The LUMS starts by calculating zonal accessibilities and then land prices as discussed in the previous section. Next, the "**Land Development Module**" is executed to determine the amount of new development $ND_{i/L}(\mathrm{t}+1)$ by land use type L in each zone i of the city. At first, the amount of land use $D_{i/L}(\mathrm{t})$ for time t in any given zone i is updated by subtracting it from the amount of type L land use that will be demolished in i. Given the low rate of demolished building in urban areas in general, this amount ($V_{i/L}(\mathrm{t}+1)$) can be determined exogenously. Alternatively, a logistic regression model can be used in the program to estimate the probability of demolishing land use (i.e. $V_{i/L}(\mathrm{t}+1) = P(V_D/i)\, D_{i/L}(\mathrm{t})$). On the other hand, region-wide developed land $D_L(t+1)$ for type L at time $t+1$ is determined exogenously based on past trends and official forecasts. This amount is then allocated to various zones using a multinomial logit model which predicts the probability $P(i/D_L)$ of selecting zone i for development. The utility function of the model is based on zonal variables including the price and accessibility estimates obtained from the price and accessibility modules. The total amount of developed land use of type L in zone i at time $t+1$ is calculated as follows:

$$D_{i/L}(t+1) = (D_{i/L}(\mathrm{t}) - V_{i/L}(\mathrm{t}+1)) + D_L\,(\mathrm{t}+1)\, P(i/D_L)$$

Region wide population ($K(t+1)$) (typically by class) from the Rogers demographic model is used as input to the "**Household Location Module**". The first step in this module is to calculate the proportion of the population in a given zone i who will remain in that zone between t and $t+1$. This is accomplished through a logistic regression model which calculates the probability $P(S_K/i)$ of staying in zone i. The estimated population in zone i at time $t+1$ can be calculated as follows:

$$K_i(t+1) = P(S_K/i)\, K_i(t) + ((K(t+1) - \Sigma_\mathrm{i}\, P(S_K/i)\, K_i(t))\, \Sigma_\mathrm{m}\, P_m\, P(i/K_m)$$

where P_m is the proportion of population that belongs to one of four types of migrants (intra-urban, intra-provincial, inter-provincial and external) and $P(i/K_m)$ is the probability of selecting zone i by migrant type m as a destination for residence. In a similar fashion, the number of firms (modeled by industrial sector) in zone i at time $t+1$ can be calculated as follows:

$$F_i(t+1) = P(S_F/i)\, F_i(t) + (F(t+1) - \Sigma_\mathrm{i}\, \mathrm{P}(S_F/i)\, F_i(t))\, \Sigma_\mathrm{n}\, P_n\, P(i/F_n)$$

where $\mathrm{P}(S_F/i)$ is the probability that the existing firms $F_i(t)$ from time t will remain in operation in zone i between t and $t+1$, $F(t+1)$ is the estimated number of firms in the entire region as at time t +1 (obtained from I-O model), P_n is the share of firms that belongs to one of three classes of firms searching for a location: intra-urban relocating firms, firms moving from outside the metropolitan area and newly born firms. $P(i/F_n)$ is the probability that firms from class n will select zone i as a destination. Firms per zone i are translated into jobs using a ratio on the average number of jobs per firm in a specific industry. This ratio is set exogenously by the analyst.

EMPIRICAL ANALYSIS & RECOMMENDATIONS

The empirical analysis will focus on two aspects: (1) model transferability, and (2) simulating of the impacts of land use changes

Model Transferability

In what follows, we provide an illustration on the transferability of the model from one jurisdiction to another. This is done by considering the probability of staying ($P(S_K/i)$) in a given zone *i,* which is one of the key components in the "**Household Location Module**". The probability is estimated using census data from Halifax for the year 2001. As shown in Table 1, a number of variables affect the probability of staying in census tract *i* between *t* and *t* + 1.

Table 1. Estimated model parameters for the staying probability $P(S_K/i)$ for Halifax, Nova Scotia

Variable	Beta	t Stat
Constant	-0.3520	-1.37
Distance from City Centre (km)	0.0328	5.90
Population age 24 to 35 in tract*	-1.0935	-4.83
Gross rent of dwelling in tract**	-0.0509	-1.51
Average family income in tract***	0.0625	1.89
Number of Canadian citizens in tract*	0.2281	4.99
R-square = 0.59	Number of observations = 83	

** parameter scaled by 1,000; ** parameter scaled by 100; *** parameter scaled by 100,000*

The above parameters were used to predict the number of non-movers in both in Halifax, Nova Scotia and Windsor, Ontario. The results shown in Figure 2 indicate that the transferability of the Halifax model to Windsor will produce sensible results.

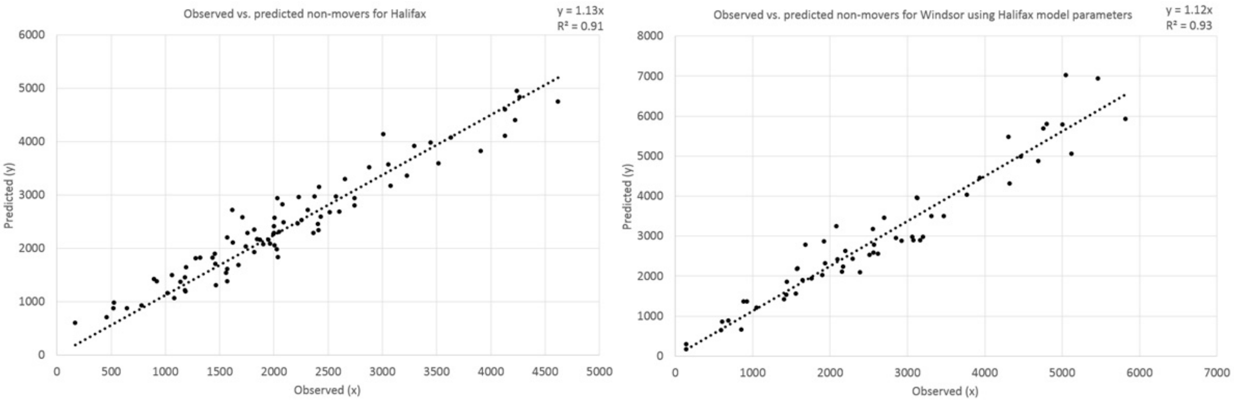

Figure 2. Model transferability and validation results

Simulating the impacts of residential land development patterns

To illustrate the capabilities of the model, we simulate residential development scenarios for Halifax, Nova Scotia for the period 2001 and 2031. Similar to Behan et al. (2008), four scenarios are examined: (a) Base case scenario which assumes a business as usual development in the future; (b) URI 100 scenario which assumes future development will be targeting the urban core; (c) URI 0 scenario which assumes sprawled future residential development in the outer suburbs; and (d) URI 50 scenario with balanced and even development between the core and suburban areas. Figure 3 presents the spatial patterns of development used in the simulations.

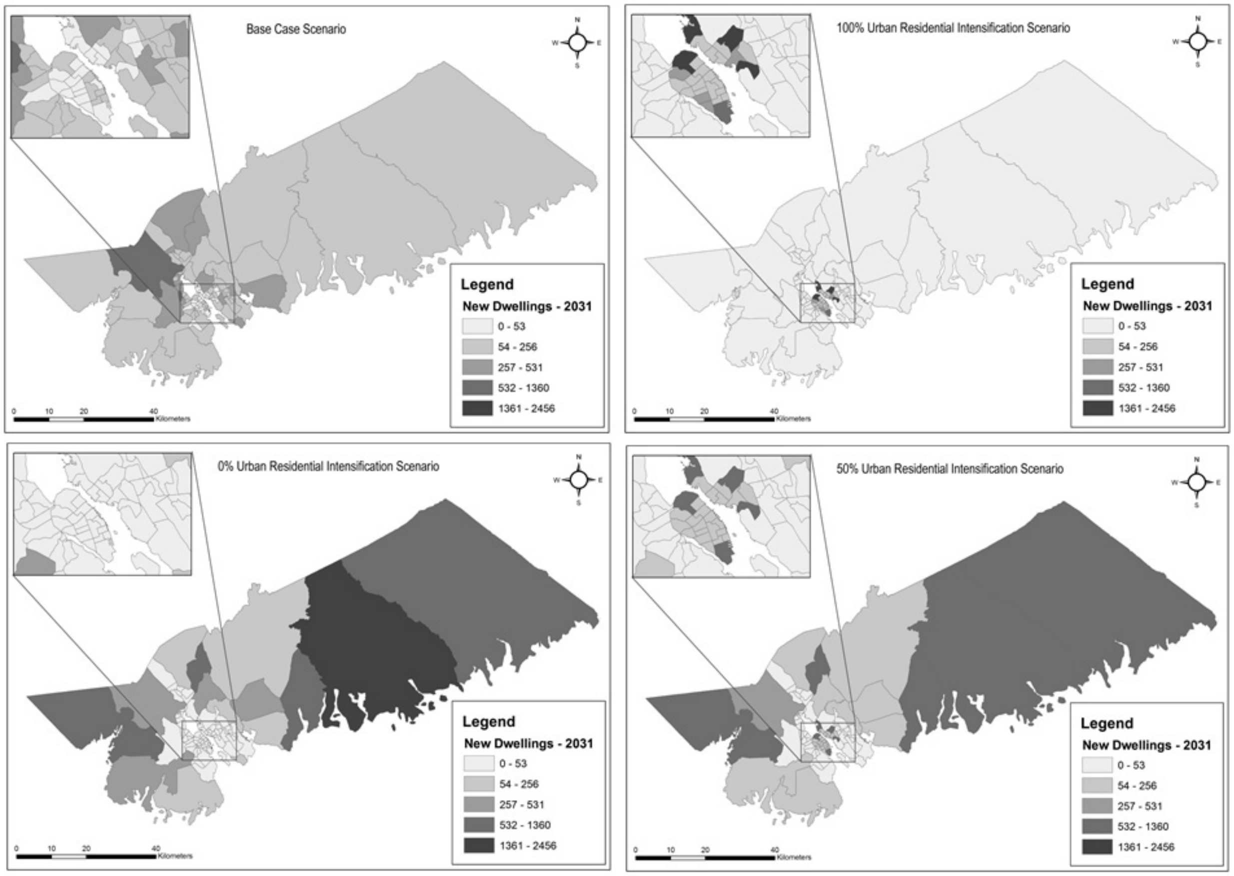

Figure 3. Residential Development Patterns used in Simulations

The results from running the above four residential developmental pattern scenarios are summarized in Table 2. As can be seen, the 100% urban residential intensification scenario (i.e. URI 100) is associated with the least amounts of VKT, VMT, energy consumption and congestion. Residential intensification will encourage non-motorized travel as can be seen from the modal split results. The increase in active modes of travel are also associated with lower vehicular emissions. On the other hand, the sprawled scenario resulted in the worst measures among all scenarios. For instance, the scenario is associated with the highest level of auto drive and total energy consumption. More specifically, energy consumption will increase by 22% and 41% relative to the base case and full intensification scenarios, respectively. Overall, the measures pertaining to the base case scenario are closest to those associated with the URI 50 scenario.

Future work on SMARTPLANS will involve extending it to include a sustainability indicators module. The objective will be to translate simulation outputs like the ones presented in Table 2 into normalized indices to assess progress towards sustainable outcomes among simulated scenarios. Tests to transfer current model parameters to a number of Canadian cities in SMARTPLANS will also be performed and the system will be applied to various Canadian metropolitan areas. Technical and user manual will be produced to provide sufficient information regarding the utilization of the model in simulating land use and transportation scenario. These documents along with data and executable files will be published online to allow researchers and city planners to download the software and use in their studies free of charge.

Table 2. Simulation outputs from future residential development scenarios in Halifax, 2031

	Base	URI 100	URI 50	URI 0
Performance Measures				
Vehicle Kilometers Travelled (VKT)	1,135,637	984,420	1,214,670	1,390,348
Vehicle Minutes Travelled (VMT)	1,158,749	992,042	1,211,795	1,390,202
Total Energy Consumed (liters of Gasoline)	91,058	78,927	97,382	111,468
Congestion Index	0.379	0.339	0.372	0.398
Emissions (kg)				
HC	932	808	1,011	1,153
CO	29,613	25,630	31,798	36,343
NOx	1,882	1,630	2,020	2,310
PM10	201	174	215	246
PM2.5	186	161	199	228
Modal Split				
Auto drive	64%	62%	63%	65%
Auto Passenger	10%	9%	10%	10%
Transit	11%	12%	11%	11%
Other	15%	17%	16%	14%

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