IMPLEMENTATION OF THE SMARTPLANS INTEGRATED URBAN MODEL FOR HALIFAX, NOVA SCOTIA AND LONDON, ONTARIO[1]

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1. Introduction

One of the more effective ways for assessing the efficacy of alternative urban planning policies is to develop and apply integrated urban models (IUMs) (Dimatulac et al. 2019). IUMs act as a virtual laboratory for emulating the dynamics of urban land use activities and travel patterns. They can characterize the interactions between land use and transportation to assess how such interactions will impact the future of urban sustainability. The ability to simulate land use and transportation processes can provide stakeholders with informed decisions about various futureplans. In this paper, we report on the work that was conducted to implementthe SMARTPLANS IUM for two Canadian Cities: Halifax, Nova Scotia and London, Ontario. We highlight the methods pertaining to the various part of the IUM and present the empirical results we obtained for each of the modeled parts.

The **S**imulation **M**odel for **A**ssessing the **R**amification of **T**ransportation **P**olicies and **Lan**d use **S**cenarios (SMARTPLANS) is a full-fledged IUM that has been developed to simulate the interactions between land use and transportation systems and their impacts on urban sustainability.The system is developed as a stand-alone platform that could be implemented for any metropolitan area. Majority of previous IUMs were implemented as a Blackbox as they were specific to the city for which they were developed. The modeling framework of SMARTPLANS 1.0 is shown in Figure 1.It consists of six integrated modules: Region-wide aggregate control module, Land use module, Transportation module, Spatial disaggregation module, Health benefits module, and Sustainability indicators module. Within SMARTPLANS, all Geographic Information System (GIS) layers are stored using the ESRI shapefile format. The Graphical User Interface is developed using Microsoft Visual Studio 10 and the dotSpatial GIS programmer library. The latter is a free and open source library that is developed as part of the MapWindow desktop GIS project (Ames et al., 2019). The starting point to implement SMARTPLANS is to divide the study area into a finite number of traffic analysis zones. Also, the urban road infrastructure must be presented as a planar network that consists of several links and nodes to feature the major urban arterials, highways and freeways. The user has full control over the spatial resolution of the zoning system and the number of road links of the transportation network.

In this study, the 2006 census tract delineations, as defined by Statistics Canada, were utilized to define the zonal system in the Halifax and London Census Metropolitan Areas (CMAs). The road networks for the two CMAs were derived from the CanMap Route-Logistics GIS Database developed by DMTI Spatial Inc. The GeoBase road network, produced by Natural Resource Canada, was also utilized to determine the number of lanes for the utilized roads. In total, Halifax's road network consisted of 1425 real road links and 1041 nodes. These links were connected to the centroids of 87 zones via 87 pseudo links. On the other hand, London's network consisted of 1333 road links and 952 nodes. In this case, the links were connected to the centroids of 104 zones via 104 pseudo links. Figure 2 presents the road network system for the two CMAs. The year 2006 is set as the base year for simulations, and land use predictions are performed in five-year intervals until 2041. Transportation predictions are performed for the following hours of a typical weekday: 8 AM, 12 PM and 4 PM. Estimation and calibrations of the models forming the Land Use Module were mainly based on data from Halifax. The obtained parameters were then transferred to implement the Land Use Module for London. On the other hand, estimations and calibrations of the Transportation Module were mainly based on travel data from London. Again, the parameters were then transferred to implement the Transportation Module for Halifax. Model

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transferability is performed to provide an alternative solution for not having the proper data needed to estimate the models of a given city.

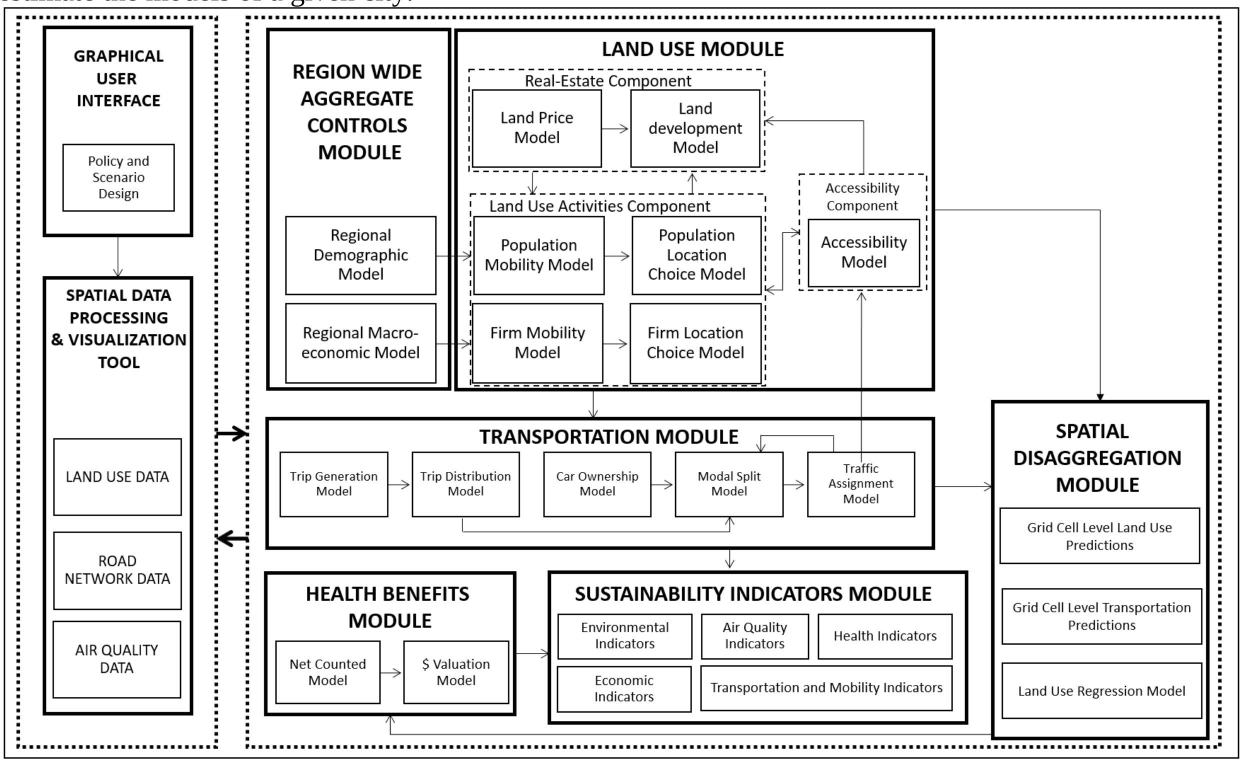
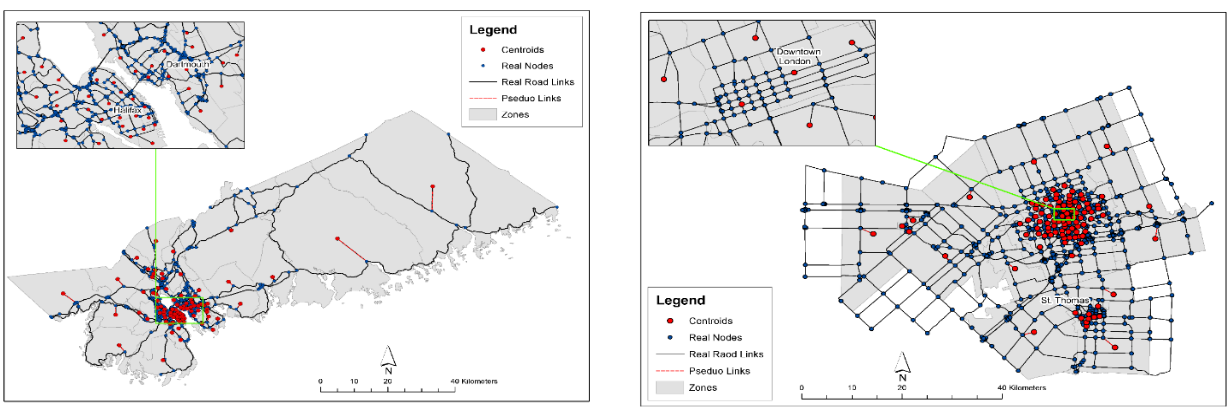


Figure 1: SMARTPLANS Modeling Framework



(a) (b)
Figure 2: Road Network System for the CMAs of (a) Halifax and (b) London

2. System Calibration and Simulation Mechanism

2.1. Region-Wide Aggregate Controls

The simulations start by considering the CMA-wide population $K(.)$ and jobs $F(.)$ as aggregate controls for simulation years t+1, t+2, t+3, …, etc. The user can provide these controls exogenously based on official forecasts, or by engaging the Region-Wide Aggregate Control Module, which predicts these aggregate controls based on demographic vital statistics and macro-economic measures. In this study, we utilized official forecasts from the two study areas as exogenous input to the simulations. Aggregate controls are fed into the Land Use Module.

2.2. Land Use Module

The starting point of the Land Use Module is to engage the land price model, which predicts the housing values and rent for a future year t+1 using data from current year t. Calibrations for the latter were based on census data from the two CMAs. The final calibrated price models were as follows:

$$HVAL_i(t+1) = 1.3505\ HVAL_i(t) \quad (1)$$

$$RENT_i(t+1) = 1.11\ RENT_i(t) \quad (2)$$

Where $HVAL_i(.)$ is the average housing price in zone i, and $RENT_i(.)$ is the average zonal dwelling rent in zone i. The latter is used as a proxy for the average zonal price for non-residential uses in the firm location model of the Land use activities module.

Next, the land development model is executed to predict the total amount of zonal non-residential floorspace developed and occupied by firms with less than 200 employees. This variable is one of the predictors used in the firm location models. The zonal floorspace was based on the 2006 firm population that was acquired from Dun & Bradstreet. While floorspace values were not part of the records making the firm data, those were synthesized using Monte Carlo simulations. The probability of allocating developed floorspace amount $D_L(t+1)$ to zone i is handled through a Multinomial Logit (MNL) model, which predicts the probability $P(i/D_L)$. The zonal utilities $V_{i/L}$ of the MNL probability model are formulated as function of type L jobs ($E_{i/L}$) that exist in zone i at time t. That is, $V_{i/L} = \beta_L \ln(E_{i/L})$. Table 1 presents the estimation results of the MNL model. The correlation coefficients between the observed and predicted values suggest an acceptable model.Newly developed residential dwellings are not modeled but rather provided exogenously by the user.

Table 1: Estimated parameters of non-residential floorspace

	Const.	Manuf.	Transp.	Wholesale	Retail	FIRE	Services	Pub. Admin
β_L	0.85007	0.87022	0.82721	0.9258	0.87843	0.91747	0.80849	0.6938
Correlation	0.85	0.98	0.96	0.99	0.95	0.95	0.98	0.86

Upon engaging the Real-Estate Submodule of the Land Use Module, the simulations move to execute the Land Use Activities Submodule to predict the spatial distribution of population and jobs at time t+1. On the population side, two models are engaged: a population mobility model and location choice model.It can be shown that population, $K_i(t+1)$, in zone i at time t+1 can be modeled as follows:

$$K_i(t+1) = P(S_K/i)K_i(t) + \Sigma_m\,(K(t+1) - \Sigma_i P(S_K/i)K_i(t))P_m\,P(i/K_m)$$

The mobility model is a logistic regression model used to predict, $P(S_{K/i})$, the probability of staying in zone i between time t and t+1. The probability is applied to time t populationof zone i, $K_i(t)$, to determine the number of non-movers in each zone. The parameters of the model for Halifax are reported in Table 2. The transferability of these parameters to London resulted in a Pearson correlation of 0.96 when comparing the observed and predicted number of non-movers.

Table 2: Parameters of population mobility model, Halifax

Variable	**Beta**
Constant	-0.3520
Number of Canadian citizens in zone *i***	0.2281
Number of people in age category 25 to 34 years old in zone *i***	-1.0935
Average housing rent in zone *i*	-0.0509
Average family income in zone *i****	0.0625
Distance between zone i and Central Business District (CBD)	0.0328
** parameter scaled by 100; ** parameter scaled by 1,000; *** parameter scaled by 100,000*	

The location choice probability $P(i/K_m)$ that migrant type m will choose zone i as a location is formulated as a destination choice MNL model.Four migrant groups are considered in the model including: intra-urban movers (IAU), intra-provincial movers (IAP), inter-provincial movers (IRP) and external immigrants (EXT). Table 3 provides the estimated parameters of the four location choice models.The zonal covariates used in the estimation of the MNL utilities for each of the four modeled groups were: amount of new dwellings (NDL), percentage of residential land use (PRES), mixed density index (MDI), distance to central business district in km (DCBD), average housing values (HVAL), average housing rent (RENT), number of non-Canadian citizens (NCIT), accessibility to schools (ASCHL) and transportation derived inclusive value (IV). The estimated parameters are sensible and meet our a priori expectations. The percent predicted right for the four respective groups were as follows: 82%, 73%, 81% and 79%. Predicted zonal population for time *t*+1 is then employed in an iterative proportion fitting algorithm to predict the breakdown of population by age class in each zone *i* at time *t*+1. These predictions are used by the Transportation Module.

Table 3: Parameters of population location choice models, Halifax

Modeled group	*LN(NDL**)*	*NDL***	*PRES*	*MDI***	*DCBD*	*HVAL*****	*RENT***	*NCIT**	*ASCHL**	*IV*
IAU	0.060	0.0080	0.079	-0.018	-	-0.4101	-0.042	0.0112	0.0234	0.243
IAP	0.056	-	-0.333	-0.009	-	-0.2163	-0.092	0.0225	0.0380	0.260
IRP	0.041	0.0109	-0.067	0.005	-	-	-0.020	0.0057	0.0239	0.362
EXT	0.083	-	-	0.012	-0.0084	-	-0.020	0.0368	0.0239	0.109
** parameter scaled by 10; ** parameter scaled by 100; *** parameter scaled by 1000; **** parameter scaled by 100,000*										

Next, the firm submodule is executed to predict the spatial distribution of firms and/or jobs of a given economic sector in future years. Similar to the population submodule, the firm submodule consists of two models: a firm mobility model and firm location choice model. The number of firms in zone *i* at time *t* +1, $F_i(t+1)$,is modeled using the following equation:

$$F_i(t+1) = SF_i(t+1) + \Sigma_n \left(F(t+1) - \Sigma_i SF_i(t+1)\right) P_n P(i/F_n)$$

The firm mobility model predicts the number of firms that will stay in zone *i* between time *t* and *t*+1 (i.e. $SF_i(t+1)$). The following linear-regression model is used to calibrate the model:

$$SF_i(t+1) = \beta F_i(t)$$

(3)

In equation 3, $SF_i(t+1)$ is modeled as a function of the total number of firms found in zone *i* at time *t*(i.e. $F_i(t)$). Table 4 provides the calibrated parameters for the model. The region-wide number of firms ($F(t+1)$) is combined with the in-situ firms (i.e. $\Sigma_i SF_i(t+1)$)to calculate the total number of firms searching for a location in the region. These could be split into newly born firms and relocating firms if the region-wide proportion P_n for each of these two segments is known. Firms pertaining to each segment *n*are then assigned to zone *i* at time *t*+1 using the location choice MNL probabilities $P(i/F_n)$.Firms are modeled by economic sector and then added to obtain the total number of firms in a given zone at time t+1. Table 5 provides the estimated parameters of the firm location choice modelsby economic sector. The firm submodule calibrations were based on Dun & Bradstreet firm data for the years 2001 and 2006.

Table 4: Parameters of firm mobility models, Halifax

	Const.	Manuf.	Transp.	Wholesale	Retail	FIRE	Services	Pub. Admin
β	0.7015	0.65	0.6312	0.7712	0.7139	0.5931	0.7189	0.5399

The firm location choice process is handled using MNL models to predict the probability of a firm selecting zone *i* as a destination. Following the literature, locational factors that affect the decision of a firm to select zone *i* as a destination include: distance to CBD (*DCBD*), travel time to CBD (*TCBD*), level of land use heterogeneity based on zonal entropy (*ENTR*), amount of floorspace available to firms in a given industry (*FLR*), level of firm agglomeration (*AGG*), proximity to population measured as accessibility to population (*APOP*), amount mixed density (*MDI*), amount of new residential development (*NDWL*), proportion of land uses such as commercial (*PCOM*), open (*POPN*) and/or residential (*PRES*), property value measured as the average rent in the zone (*RENT*), and inclusive value (*IV*) as derived from the Transportation Module. The estimated parameters shown in Table 5 are well behaved and meet our a priori expectation. Predicted jobs and employment at the zonal level are used by the Transportation Module.

Table 5: Parameters of firm location choice models, Halifax

	Const.	Manuf.	Transp.	Wholesale	Retail	FIRE	Services	Pub. Admin
DCBD	-	0.0475	-	-	-	-0.0445	-0.0233	-
TCBD	0.0301	-	-	-	-	-	-	-
ENTR	-1.0047	-	-	1.5737	-	-	-0.9351	-
LN(FLR)	0.2135	0.2547	0.3746	0.1578	0.5598	0.3624	0.5077	0.563
AGG	0.0014	0.0015	0.0031	0.0017	3.9E-05	0.0002	2.7E-05	0.0003
APOP	-	-0.0004	-0.0006	3.2E-05	0.0002	-4.1E-05	-	-
MDI	-0.0004	-	-	-0.0003	-	-0.0006	-	-
NDWL	0.0009	-	-	0.0015	0.0009	-	0.0005	0.0017
PCOM	-	-	-	-	2.0696	4.0891	3.5893	-
POPN	-	-	-	1.8117	-	-	-	-
PRES	-	-	-	-	-0.8853	-	-0.5219	-
RENT	-	-0.0016	-0.0013	-0.0015	-0.0009	-	-0.001	-0.0036
IV	-	-	-	-	-	0.2225	-	-

2.3 Transportation Module

The Transportation module is executed next. Trips in this module are modeled for work and non-work purposes. The calibration of the work trips was based on the 2006 Journey-to-Work data produced by Statistics Canada. The non-work trip generation models were derived from a 2009 household survey that was conducted in London, Ontario. The formulation of work trip production and trip attraction models are shown in equations 4 and 5.

$$O_i^w = \beta_1 A_{1i} + \beta_2 A_{2i} + \beta_3 A_{3i}$$
(4)

$$D_j^w = \beta_1 E_{1j} + \beta_2 E_{2j} + \beta_3 E_{3j}$$
(5)

The formulation of non-work trip production and trip attraction models are provided in equations 6 and 7.

$$O_i^{nw} = \beta_1 A_{4i} + \beta_2 E_{Ti}$$
(6)

$$D_j^{nw} = \beta_1 A_{Tj} + \beta_2 E_{2j} + \beta_3 E_{sj}$$
(7)

The trip distribution models for work and non-work trips are executed next. These models were based on the doubly constrained gravity model (de Dios Ortuzar and Willumsen, 2011). Table 6 presents the calibrated parameters for the Halifax and London trip generation and distribution models.

Table 6: Calibrated work and non-work trip generation models for Halifax and London

Trip Production Model	O_i^w (Halifax)	O_i^{nw} (Halifax)	O_i^w (London)	O_i^{nw} (London)
A_{1i}: *Population ages 15 to19*	0.905	-	0.683	-
A_{2i}: *Population ages 20 to 34*	0.696	-	0.542	-
A_{3i}: *Population ages 35 to 64*	0.533	-	0.604	-
A_{4i}: *Population ages 15 and up*	-	0.753	-	0.719
E_{Ti}: *Total jobs*	-	1.451	-	1.385
Trip Attraction Model	D_j^w (Halifax)	D_j^{nw} (Halifax)	D_j^w (London)	D_j^{nw} (London)
E_{1j}: *Const., Manuf., Transp., & wholesale jobs*	0.799	-	0.857	-
E_{2j}: *Retail jobs*	0.828	2.126	0.759	2.010
E_{3j}: *FIRE, services & Pub Admin jobs*	0.902	-	0.879	-

A_{Tj}: Total population	-	0.861	-	0.814
E_{sj}: Services jobs	-	1.440	-	1.362
Calibrated Impedance parameters of Trip Distribution Models				
Morning Peak	-0.0735	-0.0871	-0.1356	-0.1605
Day	-0.0445	-0.2095	-0.082	-0.3862
Afternoon Peak	-0.014	-0.1601	-0.0258	-0.2951
Night	-0.0064	-0.1601	-0.0117	-0.2951

Next, the vehicle ownership model is executed to predict the total number of private vehicles (Veh_i) and bikes ($Bike_i$) owned in zone i. The calibrated models are as follows:

$Veh_i = 230.08\, PH_i + 1.031\, EP_i$ (8)

$Bike_i = 154.03\, PH_i + 2.09\, YP_i$

(9)

Where PH_i is the average household size in zone i, EP_i is the number of employed people living in zone i, and YP_i represents population ages 14 and younger in zone i. Information from the vehicle ownership and trip distribution models are then fed into the modal split component. Table 7 presents the calibrated parameters for the modal split models. The modal split component is based on the MNL framework and was calibrated to predict the OD trip matrices of four modes: auto driver (D), auto passenger (P), transit (T), and other (O). The "other" mode comprises the walk and bicycle modes.

Table 7: Estimated parameters of modal split models

	Work Trips			*Non-Work Trips*	
Variables	*V^w*	*Halifax*	*London*	*V^{nw}*	*London*
Constant	O	1.404	1.027	D	1.434
Average number of vehicles per household	D, P	0.078	0.35	D, P	0.2
Average number of bicycles per household	-	-	-	O	0.612
Number of bus stops	T	0.01	0.009	-	-
In-vehicle travel cost ($)	D, P, T	-0.052	-0.072	D, P	-0.186
	-	-	-	T	-0.032
In-vehicle travel time (min)	P, T	-0.002	-0.04	P, T	-0.016
Euclidean distance (km)	O	-0.304	-0.364	O	-0.182
Distance to CBD (km)	O	-0.025	-0.008	T, O	-0.009
Number of full-time employees	D, P	1.30E-03	5.50E-04	D	5.70E-04
	-	-	-	P	3.70E-04
Number of part-time employees	O	6.50E-04	9.20E-04	T	7.20E-04
	-	-	-	O	6.20E-04
Average household income ($1,000)	D	0.018	0.011	D	0.001
Number of individuals ages 19 and younger	-	-	-	P, T, O	2.80E-04
Number of individuals ages 15 to 24	T, O	0.002	7.00E-04	-	-
Number of individuals ages 30 to 44	D	4.00E-04	8.40E-04	-	-
	T	5.60E-04	7.90E-04	-	-
Number of individuals ages 65 and older	-	-	-	D	3.80E-04
	-	-	-	P	5.30E-04
	-	-	-	O	5.00E-04
Number of individuals living in apartments	-	-	-	T	1.00E-04
	-	-	-	O	1.90E-04

The calibration of the two modal split models for the work trip models shown in Table 7was based on the Journey-to-Work data. However, data for non-work trips were only available for London from the 2009 household travel survey. As such, a non-work modal split model was developed for London (see Table 7) and the parameters were transferred for Halifax. The estimated parameters of the modal split models are well-behaved and in line with previous studies in the literature.

The OD matrices for work and non-work trips for the motorized mode are combined and fed into the traffic assignment model. The latter, which is based on a stochastic user equilibrium algorithm (SUE), translates the OD trips into actual traffic volume on the road network. The SUE produces an inter-zonal travel times matrix that is fed back into the modal split model to generate a new set of motorized OD matrices. A new SUE assignment is then performed and the changes in the inter-zonal travel times are assessed. The feedback loop between the modal split and traffic assignment models will terminate when the inter-zonal travel times stabilize, or the maximum number of iterations are reached.

2.4 Spatial Disaggregation Module

Land use and transportation predictions are processed by the spatial disaggregation module to create grid cell level land use and traffic flow measures. The conversion of zonal data to grid cells is done through a spatial intersection procedure which matches grid cells to their respective zones. Grid cell level estimates are then used as input to the Land Use Regression (LUR) model responsible of estimating the concentration of several harmful pollutants including nitrogen dioxide (NO2), fine particulate matters (PM2.5), ozone (O3) and sulfur dioxide (SO2). Concentrations of these pollutants are estimated at a grid cell level of 600×600 meters. Table 8 provides the calibrated LUR models used for Halifax and London.

Table 8: Calibrated LUR models at grid cell level g

Pollutant (ppb)	LUR Model
$NO2_g$	2.52+9.21E-9 VKT_g+1.50E-3 $Population_g$
PM2.5	0.94+1.53E-9 VKT_g+8.29E-5 $Population_g$ -1.11 $PRLAND(1600)_g$
$O3_g$	101,959 – 1.791 $NO2_g$
SO2	exp(-0.33465 $NO2_g$)

2.5 Health Benefits Module

The Health Benefits Module is engaged upon estimating pollution concentrations at the grid cell level. The model is based on the framework developed by Health Canada called Air Quality Benefit Assessment Tool (AQBAT) (Judek et al., 2012). SMARTPLANS starts by calculating the change in the level of pollution concentration between a status quo scenario and an alternative scenario. The change in concentration is then used to calculate the number of people that will be at risk of a specific health outcome. Here, the model considers 18 health end-points that belong to the following four major health groups: mortality, hospital morbidity, restricted activity and symptom days, and bronchitis. The monetary value for each of the 18 health outcomes is also calculated to derive an overall health cost factor “air pollution health cost”. Details on Health Benefits Module of SMARTPLANS 1.0 are provided in Maoh et al. (2019). The health outcomes and monetization are based on AQBAT valuation.

2.6 Sustainability Indicators Module

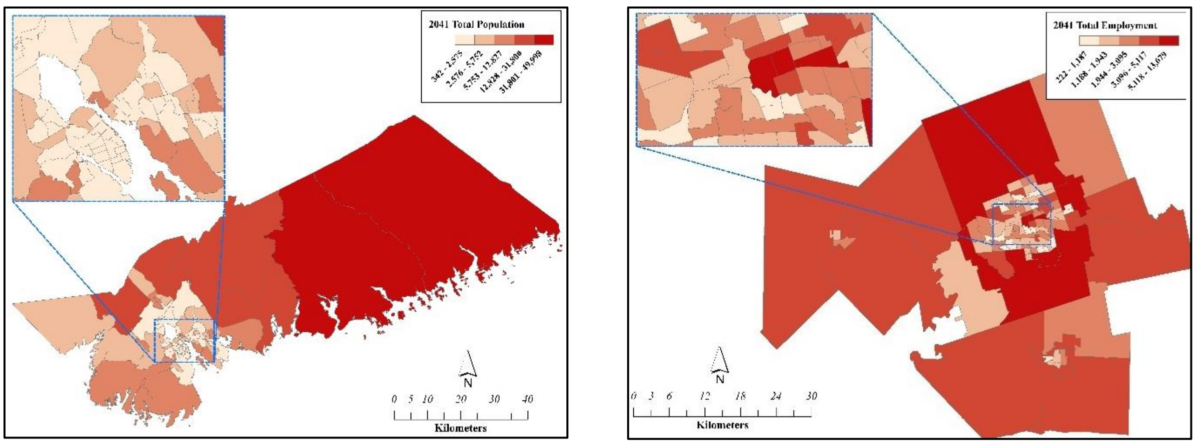
Lastly, the sustainability indicators module in SMARTPLANS is executed to estimate normalized values nv_x for several indicators $x$that pertain to the following five pillars of sustainability: air quality (4 indicators), economic cost (5 indicators), environmental outcomes (4 indicators), health outcomes (7 indicators), and transportation and mobility (4 indicators).SMARTPLANS uses predefined weights w_x associated with each indicator x belonging to a given pillar$p$to calculate an overall index SI_p per pillar$p$:

$$SI_p = \sum_x w_x nv_x$$

While SI_pvalues will range from 0 to 1, the system is setup such that value closer to 1 suggest less progress towards sustainability.Details on the sustainability indicators of SMARTPLANS and their weighting scheme is provided in Oiamo et al. (2019).

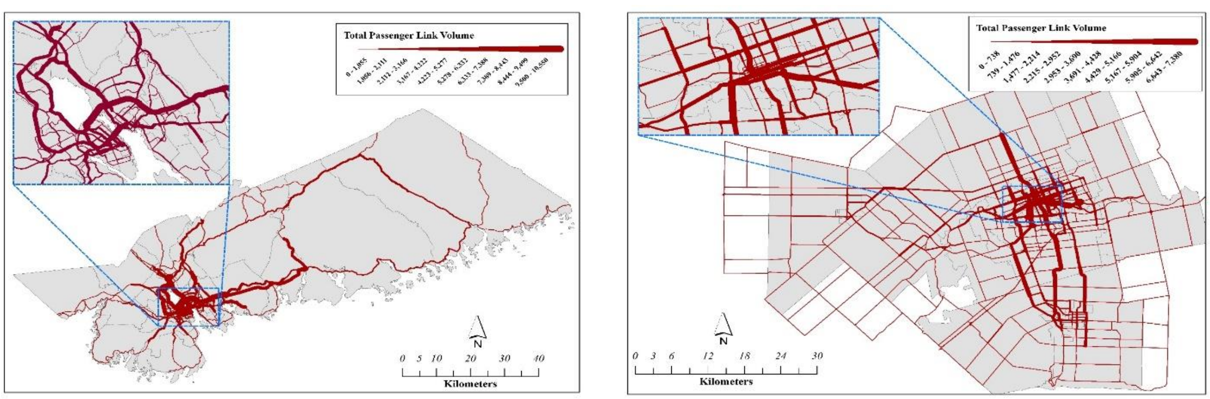
3. Sample Outputs & Concluding Remarks

SMARTPLANS produces a wide array of outputs upon completing a full simulation. For instance, Figure 3 presents zonal estimates of population and jobs for a future simulation. Other zonal measures include accessibilities, prices and the amount of developed land by modeled categories. Figure 4 presents the simulated traffic flows for a future year. The model also produces modal split shares, congested travel times and speeds, Vehicle Kilometres Traveled (VKT), Vehicle Minutes Traveled (VMT), congestion index, amount of energy consumed and road link emission levels.The model also produces outputs for 24 sustainability indicators (Oiamo et al. 2019). Our efforts to implement SMARTPLANS for Halifax and London were successful. The transferability of the land use models from Halifax to London produced the expected results. Likewise, the transferability of the transportation models from London to Halifax was successful. The work in Dimatulac et al. (2019)provides an application of the implemented models toillustrate the capabilities of SMARTPLANS when it comes to assessing future transportation development strategies.



(a) (b)

Figure 3: Simulated Status Quo zonal (a) population of Halifax, and (b) jobs of London in 2041



(a) (b)

Figure 4: Simulated Status Quo Passenger Volume in 2041 during 8–9 AM Peak Hour in (a) Halifax, and (b) London

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