EXTENDING THE *SMARTPLANS* INTEGRATED URBAN MODELING FRAMEWORK TO EVALUATE THE IMPACTS OF AIR QUALITY ON HEALTH OUTCOMES[1]

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Introduction

The practice of developing and using Integrated Urban Models (IUM) to forecast the impacts of air quality on health outcomes under future urban growth scenarios is not common in the literature. Existing studies have focused on determining the level of exposure by counting the number of people of a specific age group who are living in areas with high levels of pollution concentration. Example of such work can be found in Hatzopoulou and Miller (2010). While these studies are useful for identifying the susceptible groups in an urban area, the followed approach does not provide an estimate of the likely health outcomes that would be associated with such exposure. The Air Qualify Benefits Assessment Tool (AQBAT), a simulation program developed by Judek et al. (2012), addresses the latter by estimating the potential benefits or damages caused by changes in national air pollution concentration. The program considers 18 health end-points that belong to the following four major health groups: mortality, hospital morbidity, restricted activity and symptom days, and bronchitis.

In this paper, we adapt the AQBAT modeling framework and integrate it within the SMARTPLANS Integrated Urban Modeling system—see Maoh et al. (2019). The objective is to determine the health outcomes from changes in air quality under a given urban growth scenario. The integrated module, called Health Benefits Module, is engaged once the land use, transportation and spatial disaggregation modules are executed as discussed in Maoh et al. (2019). The Health Benefits Module of SMARTPLANS is first used to simulate the levels of pollution concentration across the metropolitan area for a base case (i.e. reference) scenario. Here, Land Use Regression (LUR) models are employed to obtain the concentration surfaces for fine particulate matter (PM2.5), nitrogen oxide (NOx), sulfur dioxide (SO2), and Carbon monoxide (CO). These LUR models utilize land use and road traffic estimates that are generated by SMARTPLANS for the reference scenario. An average concentration value per pollutant is then calculated from the generated surfaces. Next, the urban growth scenario in question is simulated in which average metropolitan-wide concentrations of the various air pollutants are determined. The Health Benefits Module then compares the simulated concentrations from the urban growth and reference scenarios. Such comparison allows the system to determine the benefits or damages associated with the examine growth scenario. To our knowledge, the approach followed in this work is novel and no other IUM has been extended in a similar fashion.

The remainder of this paper is organized as follows. In the next section we present the modeling framework adopted from the AQBAT system to develop the Health Benefits Module of SMARTPLANS. The discussion will focus on the steps leading to the calculation of the health outcomes pertaining to mortality, hospital morbidity, restricted activity and symptom days, and bronchitis. We also discuss how these estimated health outcomes are translated into dollar valuations.

[1] 54th Annual Meetings of the Canadian Transportation Research Forum, May 26 - 29, 2019 at Vancouver, British Columbia

Health Benefits Module (HB) of SMARTPLANS

Baseline Population Count

The HB module starts by calculating baseline counts *bc* for the 18 health endpoints originally used in AQBAT. These health endpoints are shown in Table 1.

Table 1: Relation of Health Endpoints, Pollutants and Affected Population Segments

HIDs	Health Indicator Name	Pollutant	Population Age	Health Group*
1	Acute Exposure Mortality	O3, SO2, NOx	All	G1
2	Acute Respiratory Symptom Days	Acute PM25, O3	All	G3
3	Adult Chronic Bronchitis Cases	Chronic PM25	25+	G4
4	Asthma Symptom Days	Acute PM25, O3	All	G4
5	Cardiac Emergency Room Visits	Acute PM25	All	G2
6	Cardiac Hospital Admissions	Acute PM25	All	G2
7	Child Acute Bronchitis Episodes	Chronic PM25	Under 20	G4
8	Chronic Exposure Mortality	Chronic PM25	30+	G1
9	Elderly Cardiac Hospital Admissions	CO	65+	G2
10	Minor Restricted Activity Days	O3	All	G3
11	Respiratory Emergency Room Visits	Acute PM25, O3	All	G2
12	Respiratory Hospital Admissions	Acute PM25, O3	All	G2
13	Restricted Activity Days	Acute PM25	20+	G3
14	Chronic Exposure Cardiovascular Mortality	Chronic PM25	30+	G1
15	Chronic Exposure Respiratory Mortality	Chronic PM25, O3	30+	G1
16	Chronic Exposure Cerebrovascular Mortality	Chronic PM25	30+	G1
17	Chronic Exposure Ischemic Heart Disease Mortality	Chronic PM25	30+	G1
18	Chronic Exposure Lung Cancer Mortality	Chronic PM25	30+	G1

* G1: mortality, G2: hospital morbidity, G3: restricted activity and symptom days, and G4: bronchitis

Baseline rates $br_{i/h,a}$ per million for traffic analysis zone *i* for a given health endpoint *h* and affected age group *a*are derived from the AQBAT database as follows:

$$br_{i/h,a} = br_{I/h,a}\left(\frac{K_{i/a}}{K_{I/a}}\right) \quad (1)$$

Where $br_{I/h,a}$ is the base rate obtained from the AQBAT database for study area *I*(defined in the original AQBAT as the Census Division), health endpoint *h* and age group *a*. On the other hand, $K_{i/a}$ and $K_{I/a}$ are the population size of age group *a* in zone *i* and study area *I*, respectively.

During simulations, base counts $bc_{i/h,a}$ in zone *i* for a given health endpoint *h* and affected age group *a*are calculated as the product of the derived baselines rates from equation 1 and the zonal population size estimated by the Land Use Module of SMARTPLANS:

$$bc_{i/h,a}(t+1) = \frac{br_{i/h,a}}{1{,}000{,}000} K_{i/a}(t+1) \quad (2)$$

Next, a metropolitan-wide base count measure is calculated for each of the 18 health endpoints as follows:

$$bc_h(t+1) = \sum_i \sum_a bc_{i/h,a}(t+1) \quad (3)$$

The result is a vector of 18 values for the 18 health endpoints.

Concentration Response Functions (CRF)
Health endpoints (outcomes) can be attributed to the exposure to certain pollutants and can be measured in terms of the percentage of cases that are affected by the exposure. Epidemiological studies utilize a Concentration Response Function (CRF) to quantify how a certain health outcome will be impacted by the change in air pollution concentration (Judek et al., 2012). More specifically, a CRF estimates how a unit change in the concentration of pollutant *p* will increase or decrease the percentage of cases associated with a health endpoint h (i.e., percent excess $PctXS_{h,p}$). In the HB module of SMARTPLANS CRF are set to either Linear (*L*) or Poisson (*P*). A linear CRF is expressed as follows:

$$PctXS_{h,p} = \beta_{h,p}\ [\max(CA_p, \varepsilon_p) - \max(CR_p, \varepsilon_p)] \quad (4)$$

and a Poisson CRF is expressed as follows:

$$PctXS_{h,p} = \exp\left(\beta_{h,p}[\max(CA_p, \varepsilon_p) - \max(CR_p, \varepsilon_p)]\right) - 1 \quad (5)$$

Where CR_p is the average concertation of pollutant *p* for the status quo (i.e. reference) scenario, CA_p is the average concentration of pollutant *p* for the simulated alternative (i.e. urban growth) scenario, ε_p is threshold per pollutant *p*, and $\beta_{h,p}$is a CRF parameter associated with health endpoint h and pollutant *p*. Other functional forms for the CRF may include log-linear (LL) or log-Poisson (LP). Table 2 provides a list of the $\beta_{h,p}$ parameters adopted by Health Canada. The listed parameters are adopted from a variety of epidemiological studies (Judek et al., 2012).

Table 2: CRF $\beta_{h,p}$ parameters used in SMARTPLANS (Source: Judek et al. (2012))

Health Endpoint *h*	**Symbol**	**Polt.** *p*	**HID**	**CRF**	$\boldsymbol{\beta_{h,p}}$	$\boldsymbol{\theta_{h,p}}$
Chronic Health Endpoints						
Child Acute Bronchitis Episodes	ChAcBro	PM2.5	7	*L*	0.0272	0
Adult Chronic Bronchitis Cases	AdChBro	PM2.5	3	*L*	0.0132	0
Chronic Exposure Mortality	ChExMor	PM2.5	8	*L*	0.005856	8.34
Cardiovascular Mortality	ChExCar	PM2.5	14	*L*	0.005856	2.75
Respiratory Mortality	ChExRes	PM2.5	15	*L*	0.005856	0.764
Cerebrovascular Mortality	ChExCer	PM2.5	16	*L*	0.013094	0.537
Ischemic Heart Disease Mortality	ChExIsc	PM2.5	17	*L*	0.025462	1.56
Lung Cancer Mortality	ChExLun	PM2.5	18	*L*	0.012995	0.911
Acute Health Endpoints						
Restricted Activity Days	ReAcDay	PM2.5	13	*P*	0.00481	0
Cardiac Emergency Room Visits	CaEmRoo	PM2.5	5	*L*	0.000711	0
Cardiac Hospital Admissions	CaHoAdm	PM2.5	6	*L*	0.000711	0
Respiratory Emergency Room Visits	ReEmRoo	PM2.5	11	*L*	0.000754	0
Acute Respiratory Symptom Days	AcReSym	PM2.5	2	*P*	0.00266	0
Respiratory Hospital Admissions	ReHoAdm	PM2.5	12	*L*	0.000754	0
Asthma Symptom Days	AsSym	PM2.5	4	*L*	0.0793	0
Respiratory Mortality	ChExRes	O3	15	*P*	0.00392	0
Acute Exposure Mortality	AcExMor	O3	1	*P*	0.000839	0
Minor Restricted Activity Days	MiReAct	O3	10	*P*	0.00053	0
Respiratory Emergency Room Visits	ReEmRoo	O3	11	*P*	0.000791	0
Acute Respiratory Symptom Days	AcReSym	O3	2	*P*	0.000786	0
Respiratory Hospital Admissions	ReHoAdm	O3	12	*P*	0.000791	0

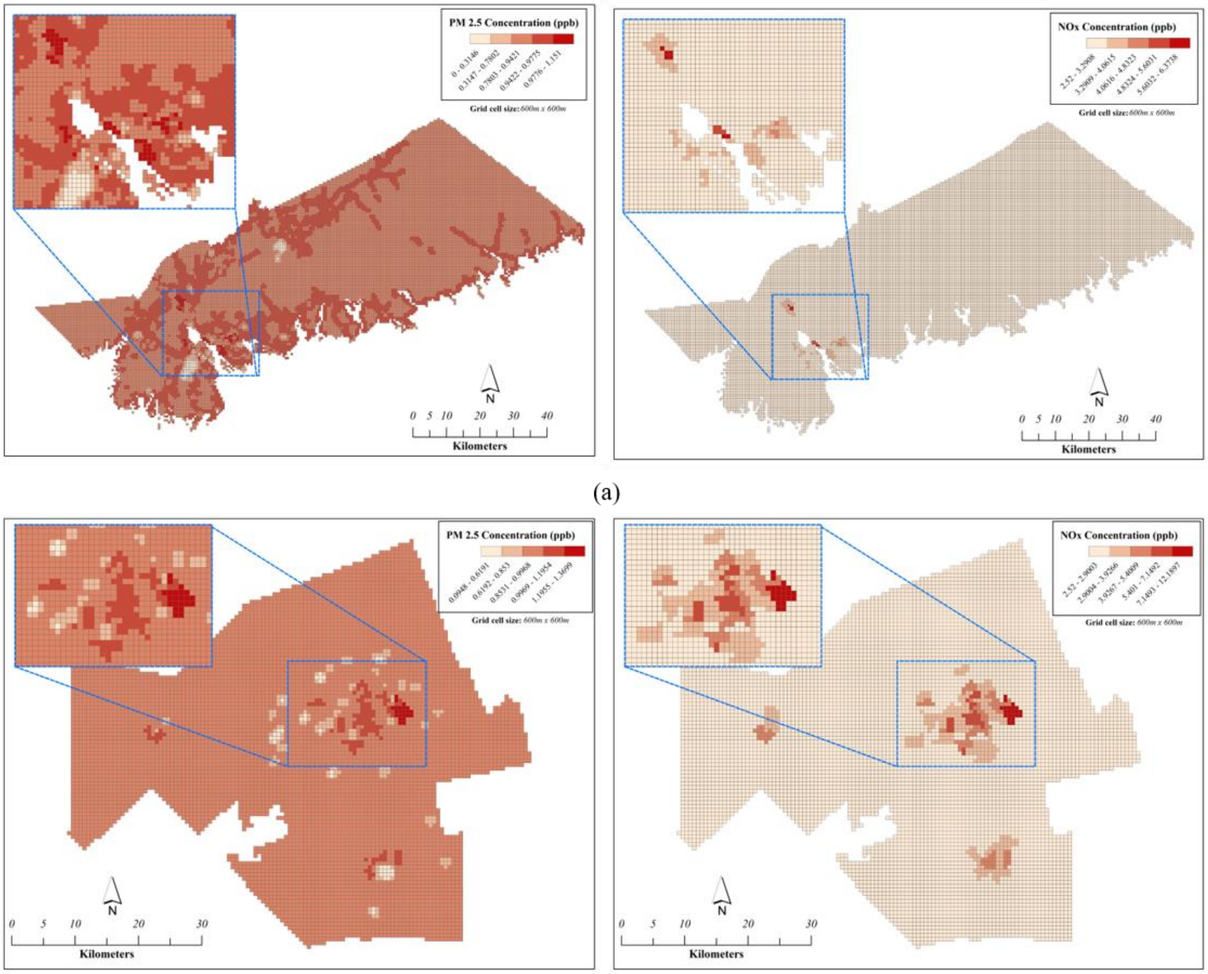
Asthma Symptom Days	AsSym	O3	4	*P*	0.00177	0
Acute Exposure Mortality	AcExMor	NOx	1	*P*	0.000748	0
Acute Exposure Mortality	AcExMor	SO2	1	*P*	0.000459	0
Elderly Cardiac Hospital Admissions	ElCaHos	CO	9	*P*	0.0277	0

Pollution concentration

The $CR_p$and CA_p values used in equations 4 and 5 of the HB module of SMARTPLANS are based on the outputs from running several Land Use Regression (LUR) models.Land use and transportation predictions are processed by the spatial disaggregation module of SMARTPLANS to create grid cell level g land use ($Population_g$) and traffic flow (VKT_g) 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 grid cell level (600 × 600 metres) concentrations of several harmful pollutants including nitrogen dioxide (NO2), fine particulate matter (PM2.5), ozone (O3) and sulfur dioxide (SO2). Concentrations of these pollutants must be averaged over time (e.g. daily 1-hour max, 8-hour max, 24-hour average) to match their corresponding CRFs. Table 3 provides the calibrated LUR models used for Halifax and London. Figure 2 presents a sample of the estimated pollution concentrations at the grid cell level. Upon estimating the grid cell level concentrations for a reference scenario, the $CR_p$is calculated by averaging over all grid cells for pollutant p. The same is also done to obtain the CA_p value.

Table 3: Calibrated LUR models at grid cell level g

Pollutant (ppb)	**LUR Model**
$NO2_g$	2.52+9.21E-9 VKT_g+1.50E-3 $Population_g$
$PM2.5_g$	0.94+1.53E-9 VKT_g+8.29E-5 $Population_g$ -1.11 $PRLAND(1600)_g$
$O3_g$	101,959 – 1.791 $NO2_g$
$SO2_g$	exp(-0.33465 $NO2_g$)



(b)

Figure 2: Estimated Pollution Concentration of PM2.5 and NOx in (a) Halifax, and (b) London in 2041

Netted Counts and Dollar Valuations

Once the $PctXS_{h,p}$ values are estimated, the HB module proceeds to calculate the life years gained ($LYG_{h,p}$) using the slope $\theta_{h,p}$values listed in Table 2, that is:

$$LYG_{h,p} = \theta_{h,p} PctXS_{h,p} \tag{6}$$

Next, the gross count ($GC_{h,p}$) per pollutant $p$and corresponding health endpoints $h$for the following pollutants Chronic PM25, Acute PM25, O3, SO2, NOX, CO are calculated as follows:

$$GC_{h,p} = PctXS_{h,p} bc_h(t+1)\; paf \tag{7}$$

where *paf* is 0.4192 for O3 (May – Sep.) and 1 for all other cases. Equation 7 can also be used to calculate the percentage gross count for pollutant p and health endpoint h:

$$PrGC_{h,p} = GC_{h,p}/bc_h(t+1) \tag{8}$$

To avoid double counting, the gross count values are adjusted for overlapping health endpoints. That is:

$$AGC_{h,p} = GC_{h,p} - \sum_{h'} \sum_{p'} GC_{h',p'} \quad (9)$$

Where *h'* represents the class of all endpoints that has to be netted, and *p'* represents the class of all pollutants that are related to pollutant *p*. Table 4 provide the overlapping pollutants along with the endpoints that need to be netted:

Table 4: Health endpoints subjected to gross count adjustments

Acute PM25	**O3**
AcReSym= AcReSym– ReAcDay CaEmRoo= CaEmRoo–CaHoAdm ReEmRoo= ReEmRoo–ReHoAdm	AcReSym= AcReSym– MiReAct ReEmRoo= ReEmRoo– ReHoAdm

The HB module then calculated the Netted Counts as follows:

$$NC = \begin{cases} \min(\max(GC, AGC), 0) & GC < 0 \\ 0 & GC = 0 \\ \max(\min(GC, AGS), 0) & GC > 0 \end{cases} \quad (10)$$

Finally, the dollar valuation *N$* for the net count is estimated using monetary conversion factors (*mcf*), as follows:

$$N\$ = NC \times mcf$$
(11)

Where *mcf* is the monetary conversion factor value and is calculated as follows:

$$mcf = \frac{CPI(y)/CPI(b)}{(1+DR)^{(y-b)}}$$
(12)

Where*CPI*(*y*) is consumer price index in simulation year *y* whereas *CPI*(*b*) is the consumer price index in the base year, which is set to 2006 in this project. *DR* is the discount rate in simulation year *y*. Table 5 provides the estimated *CPI*, *DR* and *mcf* values for Halifax and London.

Table 5: Estimated *CPI*, *DR*, and *mcf* values used for Halifax and London

Year	**Halifax**			**London**		
	CPI	***DR***	***mcf***	***CPI***	***DR***	***mcf***
2006	100.00	0.03038	1.0603	100.00	0.03038	1.0560
2011	110.84	0.00890	1.1207	110.39	0.00890	1.1302
2016	118.21	0.00535	0.9477	119.21	0.00535	0.9471
2021	128.11	0.02030	0.6942	128.04	0.02030	0.6932
2026	137.59	0.03480	0.4416	137.40	0.03480	0.4407
2031	147.07	0.04930	0.2448	146.77	0.04930	0.2442
2036	156.55	0.06380	0.1187	156.14	0.06380	0.1183
2041	166.03	0.07830	1.0603	165.50	0.07830	1.0560

HB Module Simulation Output Files

The HB module of SMARTPLANS is programmed to produce several outputs that can be used to calculate the health-related inputs required by the Sustainability Module discussed in Oiamo et al. (2019). Outputs pertaining to pollutants *p* (*p* = PM25A, PM25C, NOX, SO2, O3 and CO) include the following:

File Name	**Description**
p_taz.csv	A vector of 1 × (2+*k*) values containing the average concentrations for the reference and alternative scenarios for pollutant *p* in the first two entries and percentage excess for the *k* health endpoints associated with *p*
p_GC.csv	A vector of 1 × *k* values containing the gross count pertaining to the *k* health endpoints associated with pollutant *p*
p_PrGC.csv	A vector of 1 × *k* values containing the percentage gross count pertaining to the *k* health endpoints associated with pollutant *p*
p_NC.csv	A vector of 1 × *k* values containing the netted count pertaining to the *k* health endpoints associated with pollutant *p*
p_DV.csv	A vector of 1 × *k* values containing the dollar valuation pertaining to the *k* health endpoints associated with pollutant *p*

Notice that in the case of particulate matter (PM2.5), the software will produce outputs for PM2.5 Acute (i.e. PM25A) and PM2.5 Chronic (i.e. PM25C). The software also produces output files with adjusted counts for Acute PM25 and O3:

File Name	**Description**
O3_AGC.csv	A vector of 1 × 7 values containing the adjusted gross count pertaining to the 7 health endpoints associated with O3, namely, HID = 1, 2, 4, 10, 11, 12, and 15
PM25A_AGC.csv	A vector of 1 × 7 values containing the adjusted gross count pertaining to the 7 health endpoints associated with PM25A, namely, HID = 2, 4, 5, 6, 11, 12, and 13

Also, the outputs include the following summary files:

File Name	**Description**
bc.csv	A vector of 1 × 18 values with estimated base count for the 18 health endpoints
LYG.csv	A vector of 1 × 6 values with estimated life years gained due to the changes in the pollutants affecting 6 health endpoints, namely HID = 8, 14, 15, 16, 17 and 18

It is worth noting that the information generated in the bc.csv file is obtained from 18 files (HENDP*h*.csv) pertaining to the estimated base count of the 18 endpoints (*h*=1, 2, …, 18). Each file contains the base count of the affected population segments. The latter are broken into the following age classes:

poplt20	Population age 0 – 19
pop20plus	Population age 20 – 24
pop25plus	Population age 25 – 29
pop30plus	Population age 30 – 39
pop40plus	Population age 40 – 49
pop50plus	Population age 50 – 59
pop60plus	Population age 60 – 64
pop65plus	Population age 65 and above

The sum of the values reported in each of the HENDP*h*.csv for the above population segments is also reported under the header total that also exists in the file. This total is what the program uses to create the values in the bc.csv file. Finally, the program produces the outputs required by the Sustainability Module in the following files:

File Name	**Description**
HBHSI_NC.csv	A vector of 1 × 4 values containing the estimated netted count pertaining to the following health groups: mortality, hospital morbidity, restricted activity and symptom days, and bronchitis
HBHSI_DV.csv	A vector of 1 × 4 values containing the estimated dollar valuation associated with the following health groups: mortality, hospital morbidity, restricted activity and symptom days, and bronchitis

Conclusion

This paper described the work that was done to extend the capabilities of the SMARTPLANS integrated urban model, to estimate the health impacts that are associated with exposure to air pollution. The AQBAT system developed by Health Canada was adapted to create the new extension. As such, the Concentration Response Function (CRF) parameters of AQBAT were transferred for use in SMARTPLANS. However, work is currently underway to test the transferred parameters and to perform calibrations whenever needed to ensure that the developed extension is capable of producing meaningful results.

Acknowledgment

The research work in this paper is enabled through funding from Health Canada.

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