DEVELOPING A SUSTAINABILITY INDICATOR WEIGHTING SCHEME FOR INTEGRATED URBAN MODELLING AND HEALTH OUTCOMES IN *SMARTPLANS*[1]

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1. Introduction

As an Integrated Urban Modeling (IUM) platform, SMARTPLANS(**S**imulation **M**odel for **A**ssessing the **R**amification of **T**ransportation **P**olicies and **LAN**d use **S**cenarios) utilizes data on local transportation, land use, economic and travel activity, as well as air pollution, health, and economic indicators, to simulate land use and transportation system changes, with the goal of assessing which decisions and policies will maximize social and economic benefits, while minimizing negative environmental and health impacts.In this paper, we describe to process to determine indicator weightings in SMARTPLANS.SMARTPLANS will help to promote healthier cities by facilitating analysis of the impacts of alternate planning and policy decisions on a variety of social, economic, environmental, and health indicators, including exposure to air pollution and health impacts of air pollution in the Canadian population. An inherent challenge in urban development and sustainability is to balance or prioritize different systems that interact over time, systems that produce distinct and individually important outcomes. The foremost goal of developing SMARTPLANS was to address this challenge by providing users with an evidence-based decision-making tool.

In order to provide users with evidence from best practices and support an analytical approach to sustainable urban development, the SMARTPLANS study team sought input from experts and stakeholders across Canada on what types of indicators should be included in scenario assessments, and furthermore, how such indicators should be weighted or prioritized to produce summary outcome measures of different scenarios. A stakeholder engagement process to receive critical feedback on a set of proposed indicators and furthermore how the final indicator list should be weighted was approached in two phases addressing complementary objectives: (1) understand how the proposed indicators were perceived by experts and stakeholders in the Canadian context, and (2) determine how the indicators should be combined quantitatively by theme and as a single composite indicator as a sustainability index. The proposed indicators included key measures on the themes of transportation and mobility; air quality; environment; health and wellbeing, and; economic outcomes of urban development processes.

2. Methods

The stakeholder engagement process to inform the types of indicators and their weighting for inclusion in SMARTPLANS was addressed through two phases of anonymous online surveys. The study was reviewed and approved by the Ryerson University Research Ethics Board. Invitations to complete the online surveys were distributed by email to experts as well as potential stakeholders that may be interested in utilizing SMARTPLANS. Experts specializing in epidemiology, environment and health, environmental quality, and environment and planning were identified by research experience and snowball sampling, while stakeholders in government and environmental organizations were identified through online directories in project study sites as well as other metropolitan areasthroughout Canada. Participants could choose to pause or end the survey at any time.

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The survey for Phase 1 was designed to understand if additional indicators should be included, as well as to get feedback on the proposed metrics and their representation in SMARTPLANS (Table 1). Proposed indicators were based on sustainability indicators from previous integrated urban models as well as health and economic outcomes of the Air Quality Benefits Assessment Tool (AQBAT) developed by Health Canada (Hatzopoulou et al. 2011;Judek et al. 2012; Maoh and Kanaroglou, 2009).

Table 1: Proposed SMARTPLANS indicators

THEME	INDICATOR	DEFINITION
Transportation and Mobility	Vehicle kilometers traveled (VKT)	Total VKT per 1000 residents
	Vehicle minutes traveled (VMT)	Total VMT per 1000 residents
	Accessibility to CBD	Average travel time to city centre
	Congestion index	Average level of congestion in the city
Air Quality	Fine particulate matter ($PM_{2.5}$)	Dissemination Block average (μg/m^3) and total level per 1000 residents (kg)
	Ozone (O_3)	Dissemination Block average (μg/m^3) and total level per 1000 residents (kg)
	Volatile organic compounds (VOC)	Dissemination Block average (μg/m^3) and total level per 1000 residents (kg)
	Nitrogen oxides (NOx)	Dissemination Block average (μg/m^3) and total level per 1000 residents (kg)
	Sulphur dioxide (SO_2)	Dissemination Block average (μg/m^3) and total level per 1000 residents (kg)
Environment	Greenhouse gases	Total level of carbon dioxide emissions
	Energy use from fossil fuels	Liters of gasoline and diesel consumed per 1000 residents
	Consumption of greenspace	Arable land (km^2) converted for urban land uses
Health and Wellbeing	Air Quality Health Index (AQHI)	Total exposed to air pollution levels with moderate, high and very high levels of risk per 1000 residents
	Vulnerability AQHI	Risk estimates weighted geographically by number of children and elderly
	AQBAT health effects	Health outcomes estimated with concentration response functions from Air Quality Benefits Assessment Tool
	Walkability index	Average and area specific levels of walkability from land use
	Traffic injuries	Number of traffic injures per 1000 residents
	Traffic deaths	Number of deaths per 1000 residents
	Accessibility to health services	Average potential accessibility
Economic	Transport commuting costs	Overall costs of commuting
	Transport external costs	Total dollars due to externalities associated with health
	AQBAT health valuations	Economic costs of air quality associated with health care utilization and lost productivity

Phase 2 followed up with stakeholders to understand how SMARTPLANS should weight the indicators to create aggregate measures of indicator themes and overall measures of sustainability. Potential participants were identified in the SMARTPLANS stakeholder database developed for Phase 1. Experts and potential end-user of the platform were asked to complete an online survey on the relative importance of indicators within each theme as well as aggregate theme indicators(i.e, comparing pollutants with one another and comparing air quality indicators with other economic indicators). The objective was to ensure that the index weights used in SMARTPLANS are representative of expert and stakeholder priorities in the Canadian context. We utilized the Analytic Hierarchy Process (AHP) to develop 'intensity matrices' based on pairwise preference for indicators and themes (Saaty, 2008). Table 2 shows the corresponding verbal judgments associated with the numeric scales presented to respondents. Note that respondentscould judge two indicators to be equally important (1) if they believed both were equally important or if they felt their expert opinion was not applicable to a given set of indicators. The survey results allowedcalculation of averaged judgement weights for indicator within each theme and the overall composite thematic indicators. These are presented in the priority matrices as<1 if the row indicator was judged less important than the column indicator, and correspondingly >1 if the row indicator was judged as more important than the column indicator. The final priority weights implemented in SMARTPLANS was calculated based on the relative priority of the indicators presented in the matrix rows.

Table 2: AHP judgement values and qualities

Verbal Judgement	Numeric Value
Extremely Important	9 8
Very Strongly More Important	7 6
Strongly More Important	5 4
Moderately More Important	3 2
Equally Important	1

3. Results and Discussion

3.1. Indicator Selection

In total, 109 recruitment letters with invitations to complete the survey were emailed and 37 individual responded. Respondents were asked to select all professional specializations that applied, and the most commonlyreported areas of expertise included environment and health (48.6%), planning and management (29.7%), environmental quality (18.9%) and epidemiology (18.9%). The respondents also included individuals specializing in policy, green development and air quality. Employees of municipal governments represented highest proportion of the sample, followed by university researchers and federal government employees (Table 3). Based on the obtained results, 43% of respondents indicated that the proposed indicators would provide a comprehensive measurement of health and sustainability to assess urban transportation and land use development. Feedback from the remaining respondents who indicated that the proposed list was not satisfactory was mixed in detail and content. Several respondents provided suggestions for additional indicators, and others provided critical feedback on how existing and/or additional indicators should be included in SMARTPLANS.

Table 3 – Stakeholder Survey Respondents by Sector

Sector	*Count*	*Percent*
Academic	8	21.6
Federal Government	7	18.9
Municipal government	18	48.6
Provincial government	2	5.4
Regional Health Authority	2	5.4

The survey provided valuable insights on the central function of SMARTPLANS to inform health impacts of transportation and land use changes. Numerous stakeholders commented on the potential challenges of utilizing AQBAT to estimate health outcomes of air pollution exposure. Specific concerns were raised around the goal of estimating health outcomes in smaller areas due to concentration response functions being based on results from large population studies, as well as the potential error of estimates in small population. These comments reflected challenges that the study team also identified early in the process, and the final version of SMARTPLANS will be based on extensive validations of health outcomes at different geographic scales The challenge of accounting for other sources of air pollution in addition to traffic as well as modeling requirements for specific sources and pollutants were also noted. Some of these comments can be attributed to a limitation of the survey, which was that participants were not provided with details on the air pollution modeling. This could not be included for practical reasons as it would require a detailed understanding of IUMs.

Table 4: Overview of SMARTPLANS indicators that were added, removed or modified

INDICATOR	ACTION	JUSTIFICATION
Congestion index	Modified	Average level of congestion as a ratio of traffic flow and capacity in zones and study area in addition to study area overall
All Air Quality indicators	Modified	Traffic emissions in addition to and land use influencesare necessary to calculate air pollutant concentrations for estimating health effects
Consumption of greenspace	Modified	Stakeholders expressed interest in differentiating between forest and vegetation land cover (km2) converted for urban land uses towards land use mix as well as impacts on GHG sequestration
Traffic composition	Added	Traffic composition in terms of personal versus commercial volumes provides relevant insight towards relative impact of transit and active transportation goals in scenario modelling
Consumption of agricultural land	Added	Initially grouped with consumption of greenspace, stakeholders expressed interest in agricultural land as a standalone indicator with reference to urban sprawl
GHG Change	Added	Total change in GHG emissions from transportation and land use change
Residential Density	Added	Residential density a key measure of sustainable urban development to support transit ridership, decrease resource demands and infrastructure costs per capita
Mixed Land Use Index	Added	Mixed land use zoning and development is frequently cited as an important feature of modernizing cities to support numerous sustainable development goals
Mortality	Added	Categorical representation of AQBAT indicators based on expert feedback
Hospital Morbidity	Added	Categorical representation of AQBAT indicators based on expert feedback
Restricted Activity and Symptom Days	Added	Categorical representation of AQBAT indicators based on expert feedback
Bronchitis	Added	Categorical representation of AQBAT indicators based on expert feedback
Congestion Costs	Added	As a complement to commuting costs and distance travelled, this provides an important measure of infrastructure capacity and relevant efforts to improve transportation efficiency
Infrastructure Costs	Added	The cost of building or maintaining road infrastructure over longer periods of time provides insight towards balancing investments in urban development
Traffic Accident Costs	Added	Based on stakeholder feedback, traffic accidents have a monetary impact on society that is currently difficult to represent over long simulation horizons
Volatile organic compounds (VOC)	Removed	Accurate emission and concentration modelling of VOC mixtures not feasible, and uncertainties in health effects of exposures as additive or multiplicative
Air Quality Health Index (AQHI)	Removed	Not appropriate as a measure of long-term health effects of air pollutant exposure
Vulnerability AQHI	Removed	Not appropriate as a measure of long-term health effects of air pollutant exposure
AQBAT health effects	Removed	Replaced by categorical representations of AQBAT indicators according to severity
Accessibility to health services	Removed	Not feasible with respect to data requirements in different cities as well as delimitation of which types of health services to include, given the diversity of health care provision regimes in different cities and provinces

More qualitative feedback can be broadly described as focused on access to active transportation infrastructure and environmental amenities, as well as urban ecosystem services. Numerous stakeholders noted infrastructure that supports active transportation such as bike paths or lanes, noting that cycling facilities simultaneously promote environmental quality and wellbeing through reduced pollution and increased physical activity. Related suggestions for integrative indicators such as streetscape configurations and compact/complete communities demonstrated a focus on how the built environment can promote both social and environmental goals. This type of indicators also promotes a systems perspective on the urban environment, which is a framework that informs the prioritization of urban ecosystem services. Ecosystem services are normally conceptualized as provisioning, regulating, or cultural in terms of their benefit to human needs.

Interestingly, suggested metrics of greenspace or natural environment were presented by stakeholders as providing different types of ecosystem services. Some stakeholders proposed access to green infrastructure and natural spaces in the context of transportation and mobility (e.g., off-road bike paths), while others framed natural areas in terms of their demonstrated health benefits when located in proximity to residential areas. These can be thought of as provisioning and cultural types of services. Others noted the benefit of indicators such as canopy cover and impervious surfaces with respect to heat island effects, climate change mitigation, and storm-water runoff management, all of which fall within the category of regulating ecosystem services. This group of suggested indicators extend SMARTPLANS beyond its function as an IUMto understand urban development effects on air quality and health, but as prioritized among potential end-users,these desired functionalities highlight important future opportunities to develop tools that promote sustainable urban development. Based on the feasibility of including additional suggested indicators and comments on proposed indicators, Table 4 summarizes the revisions to indicators in SMARTPLANS following Phase 1.

3.2. Indicator Weighting

A total of 24 responses were used to calculate indicator weights as only respondents that fully completed the relevant sections were included in the analysis. Respondents were asked to rate pairwise preferences among indicators within each theme, as well as the composite themes. Consistency indices and sensitivity analyses were not considered at this stage of the analysis due to the relatively low response rate. It should be noted that the derived weights represent a guideline for prioritizing the specific set of indicators included in SMARTPLANS, as a comprehensive study of indicator weighting for sustainability assessment through IUMs is beyond the scope of the project. Nonetheless, Phase 2 of the indicator surveys provided interesting weights with respect to novel indicator sets, and in the case of air pollutants and health, responses that predominantly reflect the current state of priorities. For instance, particulate matter and nitrogen oxides are among the criteria air contaminants for which the evidence of cardiovascular and respiratory health effects are strong(Kampa and Castanas, 2008). Somewhat surprisingly, ozone received the lowest priority weight even though it is regulated under the Canadian Ambient Air Quality Standards. This may be a reflection of several important precursors (i.e. CO and NOx) also included as indicators. As expected, mortality followed by hospital morbidity were prioritized most strongly among categorical representations of health outcomes calculated in AQBAT.

Traffic deaths were rated as more important than air pollution mortality among health indicators (Table 5). Conversely, the economic costs associated with poor air quality were rated as more important than costs of traffic accidents. Among other economic indicators, costs associated with building and maintaining infrastructure as well as congestion were prioritized over time costs of commuting. Climate change and ecosystem services as represented by changes in greenhouse gas emissions reflected the qualitative feedback in Phase 1 of the surveys and received the highest priority among environmental indicators. Notably, the high rating of the land use mix indicator was also consistent with qualitative feedback on the integrative role of built environments. Green space, residential density and agricultural land consumption received relatively even priorities. Finally, among transportation and mobility indicators, respondents weighted traffic composition (passenger vs. freight vehicles), vehicle minutes travelled and congestion as the most important indicators.

The composite indicator weights produced from rated preferences among the overarching themes or pillars demonstrated a clear differentiation between different aspects of urban sustainability (Table 6). At 32 per cent, the health theme was rated notably higher than other themes and on average more than twice as important as transportation, economic and environmental indicator themes. Air quality was rated as the second most important theme at 25 per cent. While these results may be biased by the number of experts specializing in environmental health in the sample (50%), it suggests that stakeholders such as city planners or environmental managers concerned with different aspects of urban development recognize the value of linking transportation and land use changes to environmental health. Respondents specializing in environmental quality, planning and management, and epidemiology represented 25% of this sample, with individual specializations in energy planning, environmental and public health policy. The majority of respondents worked in government (66.7%) followed by academia (28.5%).

Table 5:Sustainability Indicators and Associated Weights

Theme	Indicator	Definition (Phase 1)	Weight (Phase 2)
Air Quality	CO	Total concentrations and road link vehicular emissions	12%
	NOx	Total concentrations and road link vehicular emissions	25%
	O_3	Total secondary ozone from precursors	11%
	PM $_{2.5}$	Total concentrations and road link vehicular emissions	39%
	SO_2	Total concentrations and road link vehicular emissions	13%
Economic	Commuting Cost	Overall costs of commuting based on vehicle kilometers traveled (VKT)	12%
	Congestion Cost	Total dollars based on congestion index (ratio of volume to capacity)	18%
	Infrastructure Cost	Total dollars of building or maintaining road infrastructure	20%
	Traffic Accident Cost	Total dollars associated with traffic injuries and deaths	23%
	Air Pollution Health Costs	Economic costs of air quality associated with mortality, morbidity, health care utilization, and lost productivity based on Health Canada's Air Quality Benefits Assessment Tool (AQBAT) Health Valuations	27%
Environmental	CO_2	Total change in GHG emissions from transportation and land use change	29%
	Energy Consumption	Total litres of consumed gasoline due to vehicular mobility	14%
	Green Space Consumption	Forest and vegetation land (km^2) converted for urban land uses	11%
	Agricultural Land Consumption	Arable land (km^2) converted for urban land uses	12%
	Mixed Land Use Index	Diversity and proportion of land use categories	22%
	Residential Density	Proportion of residential land use	12%
Health	Traffic Accidents	Number of traffic injures per 1000 residents	13%
	Traffic Deaths	Number of traffic deaths per 1000 residents	26%
	Walkability Index	Zone and study area walkability scores from land use	12%
	Mortality	Air pollution exposure mortality estimated based on Health Canada's Air Quality Benefits Assessment Tool (AQBAT)	21%
	Hospital Morbidity	Health care utilization from air pollution exposure estimated based on Health Canada's Air Quality Benefits Assessment Tool (AQBAT)	11%
	Restricted Activity and Symptom Days	Restricted activity and respiratory symptom days from air pollution exposure estimated based on Health Canada's Air Quality Benefits Assessment Tool (AQBAT)	8%
	Bronchitis	Bronchitis episodes (child) and cases (adult) from air pollution exposure estimated based on Health Canada's Air Quality Benefits Assessment Tool (AQBAT)	9%
Transit and Mobility	VKT	Total vehicle kilometers traveled	15%
	VMT	Total vehicle minutes traveled	22%
	Congestion Index	Average level of congestion in zones and study area	20%
	Traffic Composition	Proportion of passenger and freight vehicle counts in zones and study area	26%
	Accessibility to CBD	Average travel time to city centre	17%

Table 6: Composite Indicator judgements and Weights

Indicator	Air Quality	Economic	Environment	Health	Transport	Weights
Air Quality	1.00	2.78	3.33	0.78	2.11	25%
Economic	0.78	1.00	0.83	0.76	1.33	13%
Environment	0.71	2.33	1.00	0.72	1.33	16%
Health	2.78	2.89	3.22	1.00	2.33	32%
Transport	0.86	0.96	0.96	0.83	1.00	13%

4. Conclusion

The stakeholder engagement process to select the final indicators and their weights for SMARTPLANS resulted in highly relevant and informative feedback. Framed as a tool to promote sustainable urban development, it became apparent that a significant proportion of stakeholders would like a platform to have more integrative indicators representative of holistic and system perspectives on sustainability. Feedback from experts in environmental health and epidemiology suggest a strong desire for SMARTPLANS to include health risk estimation capabilities based on advancing knowledge within the field recently. Taken together and implemented to the extent feasible, these two major outcomes of this phase of the stakeholder engagement process will ensure that SMARTPLANS meets the needs of a broad community that includes both researchers and practitioners.

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