

Environmental and health impacts of transportation and land use scenarios in 2061

Audrey Smargiassi^{1,2*}, Céline Plante³, Patrick Morency^{1,3}, Marianne Hatzopoulou⁴, Catherine Morency⁵, Naveen Eluru⁶, Louis-François Tétreault³, Sophie Goudreau³, Pierre Leo Bourbonnais⁵, Tanmoy Bhowmik⁶, Maryam Shekarzifard⁴, Naveen Chandra Iraganaboina⁶, Weeberb Requia¹.

1. School of Public Health, Centre of Public Health Research, University of Montreal and CIUSSS du Centre-Sud-de-l'Île-de-Montréal, Quebec, H3T 1A8, Canada
2. Quebec Institute of Public Health, Quebec, H2P 1E2, Canada
3. Montreal Department of Public Health, Quebec, H2L 1M3, Canada
4. Department of Civil, University of Toronto, Ontario, M5S 1A4, Canada
5. Département des génies civil, géologique et des mines, École Polytechnique de Montréal, Quebec, H3T 1J4, Canada
6. Department of Civil, Environmental and Construction Engineering, University of Central Florida, 32816, USA

*Corresponding Author: Audrey.smargiassi@umontreal.ca

Abstract

We compared numbers of trips and distances by transport mode, air pollution and health impacts of a Business As Usual (BAU) and an Ideal scenario with urban densification and reductions in car share (76% to 62% in suburbs; 55% to 34% in urban areas) for the Greater Montreal (Canada) for 2061. We estimated the population in 87 municipalities using a demographic model and population projections. Year 2031 (Y2031) trips (from mode choice modelling) and distances were used to estimate those of Y2061. Emissions of nitrogen dioxide (NO₂) and carbon dioxide (CO₂) were estimated and NO₂ used with dispersion modelling to estimate concentrations. Walking and Public Transit (PT) use and corresponding distances walked in Y2061 were >70% higher for the Ideal scenario vs the BAU, while car share and distances were <40% lower. NO₂ levels were slightly lower in the Ideal scenario vs the BAU, but always higher in the urban core. Health impacts, summarized with disability adjusted life years (DALY), differed between urban and suburb areas but globally, the Ideal scenario reduced the impacts of the Y2061 BAU by 33% DALY. Percentages of car and PT trips were similar for the Y2031 and Y2061 BAU but kms travelled by car, CO₂ and NO₂ increased, due to increased populations. Drastic measures to decrease car share appear necessary to substantially reduce impacts of transportation.

Keywords: Transportation, Burden, Comparative Risk Assessment, Models, Air Pollution

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1. INTRODUCTION

A large number of epidemiological studies show significant health impacts related to transport and the built environment, including traffic-related air pollution and noise and their cardio-respiratory effects and pedestrian and cyclists injuries (Van Kempen et al, 2018; Fuller and Morency, 2013; de Nazelle et al, 2011; HEI, 2010). The transportation system can also be associated with positive impacts, contributing to increased walking and cycling which can result in health benefits of active transportation such as reduced risk of diabetes, breast and colorectal cancers (Wolin et al, 2013; Lee et al, 2012; Wu et al, 2009; Jeon et al, 2007).

Understanding future health risks due to transportation and land use is crucial for disease prevention and control. Typically, future scenarios have accounted for future population distribution (Samir and Lutz, 2017; Vermeiren et al, 2012), land use (Han and Lin, 2017), and transportation infrastructures and services (Bešinović 2020), which are associated with modes of transportation, kilometers travelled per vehicle, and vehicle speed (Chaturvedi and Kim, 2015; Schafer and Victor, 2000). These models have been considered an essential part of situation analysis and long-range planning (Fuller and Morency, 2013; Tessum et al., 2014). However, these models apply better to relatively short – term periods thus a large body of the literature related to transportation and environmental health analyses has only reported estimated effects for the next 5 – 20 years (Ma et al, 2015; Chatterjee and Gordon, 2006). For example, Xue et al (2015) assessed GHGs emission and public health impacts considering road transportation strategy scenarios from 2008 to 2025 in Xiamen, China. Woodcock et al (2009) estimated health effects of alternative urban land transportation scenarios for 2030 in London and Delhi. Nicholas et al (2019) estimated the health impacts of the Los Angeles Mobility Plan 2035.

To our knowledge, few investigations have accounted for long-term land use and transportation scenarios – estimates for more than 20 years, likely due to the greater uncertainty related to such an exercise. Long-term forecasting necessarily relies on highly simplified assumptions (and increasing uncertainty with time) and only broad trends from such exercises can be expected. Nonetheless, modelling scenarios for a distant future offers the possibility of assessing the effects of societal transformations that may affect mobility and health such as the aging of the population and its growth, urban sprawl or densification, technological (e.g., electrification or automated vehicles) and behavioral changes (ex. increased working from home).

In this study, we assessed both the adverse impacts and the health benefits associated with transportation mode, land use and fleet emission scenarios in the Greater Montreal Region (GMR) in year 2061 (Y2061). Specifically, we considered negative impacts at the place of residence, related to vehicle road trips on pedestrian/cyclists and vehicle occupant injuries, as well as morbidity and mortality impacts due to residential air pollution, and the health benefits linked to active transportation. We also assessed changes in impacts from Y2031 to Y2061.

2. METHODS

2.1 Study area

The study was carried out in the GMR, which is the second largest urban region in Canada, after Toronto, and located in southern Quebec. The GMR is defined for transportation planning purposes and covers 8 327 km² (AMT, 2010). The population in the GMR is estimated to be over 4 million people in 2016, representing approximately 10% of the Canadian population (Statistics Canada, 2017).

2.2 Methodological approach

Figure S1 of the Supplemental Information (SI) outlines the methods of the present study. We compared, for a week day, the number of trips and distances by mode, and environmental and health impacts in two regions of the GMR presented in **Figure S2** (urban core and suburb), for three scenarios for the year 2061: a Y2061 business as usual (BAU), and Optimal scenarios with, and without tele-working/schooling (i.e. those conducting their activities at home and hence not performing a trip). We also compared results of Y2061 and Y2031 scenarios. The Y2061 scenarios were based on Y2031 projections for 87 municipalities (from 108 municipalities that were grouped to obtain at least 15,000 individuals per municipality). The second section of the **SI** describes the Y2031 scenarios and its **section 3**, the Y2031 modeling of the population and trips by mode; the Y2031 data is based on the 2008 Origin-Destination (O-D) survey.

To summarize the methods described below for Y2061, the Y2061 BAU was based on the BAU Y2031 modelled trips by mode, and the Y2031 BAU population; there was no additional public transit infrastructure for this scenario in Y2031 (i.e. the same infrastructure as available in 2013) and the location of the population followed past trends (reaching suburbs). The Optimal Y2061 scenarios were based on a Y2031 scenario with urban core densification (Y2031 Central scenario); all subway, tramway and train stations discussed in public documents were also included to predict the Y2031 modes of these scenarios (see **section 2** of the **SI**).

We developed the Y2061 trips by age, sex and municipality based on the increase of the population between Y2061 and Y2031 (growth factor) per municipality, age and sex (see **sections 2.4 and 2.5** for detail). Trips were then distributed by mode according to the mode share/shift of the Y2061 scenarios, and distances travelled were estimated, summing distances travelled in various municipalities.

All impacts were summarized by residential location (although risks of traumas encountered and physical activity performed occurred at other locations).

2.3 Scenarios for year 2061

As mentioned above, the three scenarios for Y2061 are based on Y2031 scenarios that are described in **the SI**. The scenarios were built based on two elements – population location and transportation modes.

We divided the population element into two parts – location of residence (urban core and suburb), and place of work/school (home, other location). Four transportation modes were considered – car mode (by private vehicle), public transit, walking or cycling, others (e.g. bi-modes and school buses). The Y2061 scenarios are described in **Table S1**.

BAU scenario

This scenario extends past trends for the increase in population that reaches a total of 1,986,089 and 3,286,524 individuals in Y2061 for the urban core and the suburbs respectively; the combined population first increased from 3,947,210 to 4,810,886 individuals from 2008 to Y2031, with an

additional increase to 5,272,613 in Y2061. The population increase in the suburbs and the urban core, from Y2031 to Y2061 (about 400,000), was calculated using demographic perspectives in Quebec between 2006 and 2061 as described below in **section 2.4** (ISQ, 2014). In the Y2061 BAU scenario, the Y2031 mode shares, as well as the non-mobile proportion, are conserved in Y2061 for the 87 municipalities (**Table S1**).

Optimal scenarios with and without teleworking/schooling

In the Y2061 Optimal scenario without change in teleworking/schooling, we maintained the same proportion of non-mobile individuals by municipality as in Y2031. In the Optimal scenario with teleworking/schooling, the non-mobile population increased from 27% to 45%. Those proportions were obtained by reducing by half the Y2031 trips of individuals who had moved for work or school. Such a high percentage of non mobile individual has been observed elsewhere (Tanguay and Lachapelle, 2018); it also corresponds roughly to members of the active (mobile) population who work/school at home approximately half of the time.

In the Optimal scenarios, the new Y2061 population i.e. the additional people since Y2031, is located in the urban core, and age and sex distributions across municipal sectors are according to the population distribution of the Y2061 Central scenario (urban core densification; see **section 2** of the **SI**). As described in **Table S1**, the car mode share for the Y2061 optimal scenarios is set to a lower value in the two regions (urban core and suburbs) compared to the Y2061 BAU for which it was unchanged from Y2031. These values are set to low car mode shares of the Y2031 Central scenario of municipal sectors in each sub-region (i.e. 34% in urban core and 62% in suburbs). In Y2061, the “removed” car trips are replaced by non-car trips (i.e. public transit, walk and bike, others), distributed in the proportions of the Central Y2031 scenario by municipality.

For sensitivity analyses, we included a scenario i) with the distribution of the BAU population (i.e. no densification in the urban core) but with the mode shares of the Optimal scenarios (i.e. mode shift to 34% and 62% car mode shares in urban and suburb areas), and ii) with only the central population distribution, but not the mode share of the Optimal scenario. Air pollutant levels and health impacts were not calculated for this scenario; only trips and distances are presented in **SI** (last section).

2.4 Y2061 population “growth factor”

The prediction of the Y2061 population was done to create weights by municipality (“growth factor”) to apply to the Y2031 aggregated “individual weights” by municipality, and to aggregated Y2031 trips. More specifically, to estimate the Y2061 population and its geographic distribution by municipality, we used the projection A from the *Institut de la Statistique du Québec* (ISQ 2014). This projection is only available for the entire province of Quebec. Thus, to obtain the Y2061 geographic distribution, we first created expansion ratios of the total population of the province of Quebec between Y2061 and Y2031 by sex and 5-year age intervals. We then created a global additional adjustment factor to account for the proportional increase in the population of the Montreal region compared to the entire province of Quebec. This yearly adjustment factor was based on the difference between the ratio of the population in Montreal vs Quebec in Y2031 and 2006, and extended to a 30-year increase. Both factors were the applied uniformly to the Y2031 population of the GMR.

In Y2031, there was significant variations in the demographic characteristics of the population residing in the suburbs and the urban core (i.e. a younger population lived in the urban core).

Therefore, an additional step was necessary to obtain population distributions that were coherent with the Y2061 scenarios (i.e. allocation of the population between sub-regions) but that maintained similar demographic characteristics (population number, age and sex) at the GMR level. Thus, final adjustments of the Y2061 BAU and Optimal “individual weights” were done with raking (Stata 13 function `ipfweight`) on the following variables: 1) the age-sex distribution of the Y2031 BAU scenario, to ensure the comparability between the two Y2061 scenarios; and 2) the center/suburb ratios (one for each scenario) of the Y2031 BAU and Central scenarios (on which the Y2061 BAU and Optimal scenarios were respectively based – see **outline** above), to ensure the targeted location of the new population from Y2031 to Y2061 (see **Table S1**). Finally, all these re-weighted Y2061 individuals were aggregated by municipality (n=87) and used to obtain the growth factor, i.e. the ratio between the Y2061 and the Y2031 populations, by age and sex.

For the estimation of the health impacts of NO₂, the Y2061 population was also needed by traffic analysis zone (TAZ) (see **section 2.6** on air pollution modeling). It was obtained by multiplying the Y2031 population per TAZ (Y2031 BAU or Central scenarios) by the ratio of the population increase between Y2061 and Y2031 by municipality, age category and sex and municipality (i.e. the growth factor).

2.5 Projection of trips, paths and distances for the Y2061 scenarios

Number of trips by mode in Y2061

As a first step, the Y2061 total number of trips (all modes included) per municipality were obtained as follows: The Y2031 total number of trips per municipality, age and sex, for each scenario, were multiplied by the population “growth factor” (i.e. ratio of the Y2061/Y2031 populations by

municipality, age and sex). The age groups used were : 0-14, 15-29, 30-44, 45-59, 60-69 and 70+ yrs old. The estimation of the Y2031 trips per mode is described in the **SI (section 3)**. The Y2061/Y2031 population ratios differed between the urban core and the suburbs for the Optimal scenarios (mean ratios 1.17 vs 1.01); the ratios for the Optimal scenarios also presented a greater variation between municipalities (0.90-1.21) than those of the BAU (0.93-1.10). For the Optimal Y2061 scenario with teleworking/schooling, we proceeded similarly, but the total number of trips of the active population (work or school) in Y2031 was first decreased by 50%, which increased to 45% the non-mobile population proportion (see **Table S1**), before applying the mode shares of the Y2061 scenarios to the trips of the remaining mobile population. Thus for all scenarios, the Y2061 new population inherited the mode share of its host municipality. This implies that in our Y2061 scenarios, modes were modified both with the mode shift (see reduction of car mode in **Table S1**), and by applying the mode share of the location of the new population.

Matrices of distances travelled by car in Y2061

In order to obtain the kilometers travelled by car (vehicle km travelled, vkt) within municipalities in Y2061, according to the population increase per municipality of residence in Y2061 vs Y2031, we used the Y2031 kilometers for each car trip on the road network made by each individual (weighted by the Y2031 individual weights to represent the population), and proceeded as follows: First, kilometers travelled on the network (i.e. the 2013 network that remained unchanged) by each Y2031 car trip were calculated and assigned to the municipality in which they were produced. For example, for a 10 km car trip made by an individual originating in municipality A, travelling through B on the way to municipality C, we calculated the km travelled in all three municipalities, i.e. 3 km in A, 2 km through B, and 5 km in C. If this individual, made an additional trip in

municipality C (ex. during lunch time), these kilometers were also added to those kilometers made in municipality C, by an individual with a residence in municipality A. Kilometers travelled by individuals in Y2031 were then aggregated by their municipality of residence and municipality of travel. Consequently, two Y2031 matrices of distances (i.e. Y2031 BAU and Central scenarios), where the lines of the matrices consisted of the 87 municipalities of residence, and the columns were 87 municipalities of travel as columns, were constructed. This step was necessary to increase the kilometers travelled based on the residential location of the Y2031 new population.

The Y2061 km travelled by cars within each municipality were then obtained by applying a ratio of the number of trips by car in Y2061/Y2031 per municipality (and scenarios, i.e. BAU2061/BAU2031 and Optimal 2061/Central 2031), on the Y2031 distances of the matrices per municipality of residence (i.e. each line of the matrix). The estimation of the Y2031 kilometers travelled by car on the road network is explained in **section 3** of the **SI**. Note that we used the kilometers travelled within municipalities of the Y2031 BAU for the Y2061 BAU, and the Y2031 kilometers travelled of the Central scenario for the Y2061 Optimal scenarios.

Distances travelled by bus

For distances travelled by bus, in contrast to distances travelled by car, we ignored the location where the kilometers were travelled. We increased the kilometers travelled by bus in Y2031 by municipality of residence, multiplying the kilometers travelled by the ratio of the number of trips by bus in Y2061/Y2031 (per municipality and scenarios). The distances travelled by bus were not used to model NO₂ levels but all new buses shall be electric after 2025 (Société de transport de Montréal, 2012).

Distances travelled by walking or biking

Distances travelled by walking and biking were calculated by municipality of residence in a similar fashion as those travelled by bus. “Expanded” (Y2061/Y2031) distances travelled were used to estimate risks of traumas (see below). In addition, to assess health benefits of physical activity (also explained below in **section 2.7**), kilometers travelled were calculated for three regions only, but by age and sex groups. Numbers of individuals walking were too small to calculate distances per municipality, age and sex. Consequently, three regions, based on an aggregation of municipalities, were created as follows: i) a central zone (see **Figure S1**), ii) the suburb municipalities with at least one train, subway, or tramway stop, and iii) the suburb municipalities without those transportation infrastructures.

2.6 Air pollution modeling

The distribution of vehicle types and ages that were assigned per municipality in Y2061 for the BAU and the Optimal scenarios were derived from 2013 vehicle registration data obtained by the Société de l’Assurance Automobile du Québec (SAAQ) for the GMR. These data capture the distribution of vehicle ownership for passenger transport only. We only consider household emissions in this study. The distribution of vehicles by age and type (see **SI, section 4**) is assumed to remain unchanged in Y2061. Therefore, in Y2061, we assume that there is an equal share of vehicles aged 10 years as in 2013, except that in Y2061, these vehicles will be model year 2051 while in 2013, they were of model year 2003. Thus, the model still catches the effect of vehicle technology on emissions. This assumption is typically valid unless there is evidence that society

is becoming more or less affluent and therefore a greater share of newer or older vehicles are available.

We used the EPA model MOVES (MOTOR Vehicle Emission Simulator) in order to generate emission factors for Y2031 for nitrogen oxides (NO_x) and greenhouse gas (GHG) in carbon dioxide equivalent (CO_{2-eq}) in g/km/veh, reflecting the distribution of vehicle ownership. The MOVES model includes a rich database of emission factors for different vehicles by type and model year and for different time horizons but up to Y2031, thus only partly embedding projections on future fuel efficiencies and emission control technologies up to Y2061. By multiplying emission factors with the total vkt travelled by municipality, we estimated emission intensities in g/km of road per municipality for the Y2061 BAU and Optimal scenarios. In both scenarios, we first assumed that all vehicles were conventional, meaning internal combustion engines (referred as veh fleet1). In addition, we added a sensitivity analysis where 50% of the vehicles were electric (veh fleet2). As such, all NO_x emissions were reduced by half. In order to estimate the GHG emissions associated with the electric vehicles, we computed an average energy consumption rate (Wang et al, 2018), which was then multiplied by the average GHG intensity of electricity production in Quebec (Hydro-Québec, 2017).

While total CO_{2-eq} emissions under the scenarios were sufficient to investigate the effect of each scenario on future regional GHG emissions, the emissions of NO_x are only useful in terms of their effect on air quality. Since in Y2061, vkt and hence NO_x emissions were estimated at the level of each municipality, it was important to distribute them across the road network in order to estimate

NO₂ concentrations using a dispersion model, at a fine level of resolution. For this purpose, we used the Y2031 vkt on the road network and assumed the same proportions in Y2061.

Finally, the CALPUFF dispersion model was used to estimate NO₂ concentrations across the study domain. The mean NO₂ concentration by traffic analysis zone (TAZ) was used to represent the exposure of the population in the TAZ (as referred to as population weighed mean in **Table A6**). The Y2061 population per TAZ was estimated by multiplying the Y2031 population per TAZ by the Y2061/Y2031 weight (explained above). Additional information is presented in Tetreault et al (2018) and Sider et al (2013).

2.7 Modeling risks for human health

We considered the negative impacts related to residential air pollution (NO₂), road traumas and the health benefits linked to active transportation, along trips, for the BAU and the Optimal scenarios with and without teleworking/schooling. To compare impacts of the scenarios, we calculated the incidence of disability adjusted life years (DALY) using the Canadian distribution by age and sex of injured and disabled people in 2008 from the Global Burden of Disease database (WHO, 2013).

Impacts of NO₂

For health impacts of NO₂ at the residence, we used a risk function for cardiovascular disease (CVD) mortality (Chen et al. 2013), and for asthma, the Tetreault et al (2016) risk function. The former was applied to the population of 16 year old and older of each municipality using average NO₂ exposure (described above), while the asthma risk function was applied to children younger

than 16 years of age per municipality. We also used rates of CVD and asthma onset as described in detail in Tetreault et al (2016). Most of the method used to calculate impacts in disability adjusted life years (DALY) of air pollution in Y2061 is similar to the method described in Tetreault et al (2018). However, we used a population attributable fraction (PAF) with a counterfactual of zero NO₂ levels for each scenario, instead of using a population impact fraction (PIF) that compares the scenarios between them directly (Hanley, 2001), because the population location within the GMR differed between scenarios and this invalidates the use of PIF for the regional comparison of the impact.

Benefits of active transportation

We estimated benefits of transport related physical activity per region of residence (Urban core and suburbs) as described in Tetreault et al (2018), using functions relating metabolic equivalents to CVD, incidence of type II diabetes, breast and colon cancers (Wu et al, 2013; Sattelmair et al, 2011; Wolin et al. 2009; Jeon et al, 2007). Briefly, log normal distributions of weekly time spent walking and cycling for transport stratified by age, sex for the three groups of municipality of residence (described in **section 2.5**) were calculated from mean distances of travelled related to physical activity. In contrary to Tetreault et al (2018), a factor of seven (instead of 3.5) was used to estimate weekly distances for bicycling. The distances were converted into time spent doing active transport using a speed of 5 km /hour for walking and 16 km/hour for cycling. The method to calculate DALY of physical activity related to transportation is described in Tetreault et al (2018), except that we used a PAF in order to enable the regional comparison of the burden, as it was done for air pollution.

Road traumas

To estimate the number of road traumas in Y2061, the km travelled per mode and municipality in the Y2061 scenarios were multiplied by the average risk of road injuries per km travelled – estimated for each mode and averaged by municipality of residence.

First, the daily risks of injuries in 2008 were estimated on the road network, for each mode, using injury data from police reports for the years 2006 to 2010 (SAAQ, 2010) and the trips of the 2008 Origin-Destination (O-D) survey (see Appendix, section 3 and 4) as follows. For each road user type, zero inflated binomial negative regression models were used to predict the daily number of injuries per crossing (at intersections) and per passenger-kilometre (on road segments) with, as predictors, the number of people using that transportation mode (car occupants, bus occupants, pedestrians, cyclists), road length (on road segments), number of cars (for pedestrians and cyclists), number of lanes, number of approaches, presence of arterials, region, and time of day (for car occupants). Injury risk on highways was computed separately as the number of observed injuries divided by total number of passenger-kilometres for each highway. Second, the proportion of severe and fatal injuries observed in 2006-2010, for each mode and according to crash location (intersections vs road segments vs highways; Montreal island vs its surrounding), was multiplied by the estimated number of injuries.

Third, severe and fatal injuries were aggregated at the trip level, and at the municipality level (of residence) taking into account the 2008 O-D survey “individual weights”. Fourth, the predicted number of severe and fatal injuries for all residents of a municipality was divided by their kilometers travelled to obtain 2008 “averaged risks of traumas” per kilometers travelled per mode

and municipality of residence. Finally, as mentioned above, these 2008 average risks of road traumas were multiplied by the kilometers travelled in Y2061 to calculate the number of traumas in Y2061.

We computed DALY for road traumas from total Canadian DALY for traumas as described in Tetreault et al. 2018, except that the Canadian DALY were prior adjusted for the age and sex of the Montreal region of Y2061.

3. RESULTS

3.1 Global and regional differences between Y2061 scenarios

Table 1 presents, for the entire study area (global results), travel modes and distances travelled in Y2061 for the BAU, where the population followed past trends and modal shares remained unchanged, and for the Optimal scenarios, with population densification in the urban core and changes in modal shares.

Compared to the BAU, walking and public transit use and corresponding distances walked were more than 70% higher for the Optimal scenario without teleworking/schooling in Y2061, while car share and distances were lower. The car share of the scenario with teleworking/schooling was however lower than without, and up to 50% compared to the BAU. These variations include those of demographic changes (i.e. aging) which are, however, identical for all scenarios.

Table 1 – Description of estimated exposures linked to transportation patterns in BAU and other scenarios for the greater Montreal in Y2061.

	Mode	BAU	Optimal without teleworking/schooling	%Δ vs BAU	Optimal with teleworking/schooling	%Δ vs BAU
Number of trips per day (per capita)	Driving or passenger	6,961,762 (1.32)	4,732,885 (0.90)	-32	3,492,829 (0.66)	-50
	Public transit	1,445,922 (0.27)	2,587,465 (0.49)	+79	1,890,762 (0.36)	+31
	Walking	1,094,693 (0.20)	1,886,817 (0.36)	+72	1,383,946 (0.26)	+26
	Cycling	128,515 (0.02)	204,174 (0.04)	+59	150,059 (0.03)	+17
	Other	558,623 (0.11)	768,434 (0.15)	+38	570,648 (0.11)	+2
	Bimodal	169,361 (0.03)	251,643 (0.05)	+49	185,571 (0.04)	+10
Km per day	Cars and light trucks passengers (drivers, drivers only)	85,020,519 (68,764,464)	50,659,487 (40,660,519)	-40 (-41)	37,522,845 (30,127,967)	-56 (-56)
	Walking to public transit	1,390,492	2,559,229	+84	1,870,515	+35
	Walk to destination	1,477,863	2,527,618	+71	1,854,698	+25
	Cyclists	603,518	944,080	+56	700,548	+16
	Public transit all (bus)	13,339,994 (7,006,066)	20,869,082 (7,234,099)	+56 (+3)	15,308,612 (5,321,539)	+15 (-24)
Minutes per week spent in active transportation (global mean, min, max among means per region, age & sex)		49 (14,108)	85 (20,152)	+75	62 (15, 110)	+20

NO2 concentration in ppb (mean, Q1-Q3)						
	veh fleet1	7.6 (6.5-8.4)	7.3 (6.3-7.9)	-4	6.9 (6.2-7.3)	-9
	veh fleet2	6.6 (6.1-7.0)	6.4 (6.0-6.8)	-3		
GHG emissions (tons/day)						
	veh fleet1	17,444	10,652	-39	7,532	-57
	veh fleet2	8,726	5,328	-39	3,768	-57

Note: Business as usual (BAU); Distances from bimodes and school bus not included.

Car trips of the Y2061 Optimal scenario without teleworking/schooling differed from the BAU due to the increase of the population of each municipality and mode share changes (note that no mode choice model is applied to estimate Y2061 modes but that the scenarios imposed mode shift). However, when applying the mode shares of the Optimal scenario without teleworking/schooling to the BAU (used as a sensitivity analysis, without the urban densification), we found that the mode share change explained an important part (i.e. 75%) of the difference in car trips of the Optimal scenario vs the BAU, i.e. more than the urban densification (i.e. 25%) also included in the Optimal scenarios (see **SI, section 4**).

NO2 levels were slightly lower in the Optimal scenarios compared to the BAU, and more importantly for veh fleet2 vs 1. More pronounced differences were seen for GHG emissions than for NO2 concentrations (**Table 1**).

There were regional variations, in the differences in car and public transit use per capita, between the Optimal scenario without teleworking/schooling and the BAU; greater contrasts in car mode share between the two scenarios were seen in the urban core than in the suburbs (urban -0.38 vs

suburbs -0.29 per capita) (**Table S6**). However, these contrasts were linked to much more pronounced differences in the absolute numbers of trips and distances by car for people of the suburbs. This was also true for the Optimal scenario with teleworking/schooling. The difference in the NO₂ between the two scenarios was however similar in the urban core and the suburbs (**Table S6**), although levels were always higher in the urban core (veh fleet1: urban core BAU 8.5 ppb vs Optimal 7.8 ppb; suburbs BAU 7.1 ppb vs 6.5 ppb).

The GHG emissions of Y2061 were lower for the BAU with high electric vehicle penetration (i.e. 50%) than for the Optimal scenario (with urban densification and decreased car mode) that only considered fuel efficiency and emission control technologies up to Y2031.

Large health benefits of active transport were seen for those with a residence in the urban core for the Optimal scenarios compared to the BAU. However, those benefits were accompanied by higher impacts of air pollution and by road traumas in the urban core (see **SI, section 5, Table S9**); on the contrary, impacts of air pollutant levels and road traumas were lower in the suburbs compared to the BAU. Globally, most of the Y2061 impacts of the BAU were due to road traumas, and the Optimal scenario would reduce these impacts by 33% DALY (see **section 5** of **SI** and **Table 2**).

Table 2. Health burden linked to transportation between the Business as Usual (BAU) and the Optimal scenarios for residents of regions of the greater Montreal in Y2061.

Health outcome	DALYS (DALY per 100,000 inhabitants) ¹			DALYS (%)
	Urban core	Suburb	Montreal region	Montreal region
Optimal vs BAU				

Road injuries	+5,110 (-27)	-7,101 (-12)	-1,991	-6
Air pollution veh fleet1	+1,247 (-19)	-1,743 (-4)	-496	-6
veh fleet2	+1,171 (-12)	-1,423 (+2)	-252	-3
Active transportation	-6,387 (-90)	-433 (-92)	-6,819	59
All outcomes veh fleet1	-52	-9,294	-9,345	-36
veh fleet2	-127	-8,975	-9,101	-33
Optimal with teleworking & schooling vs BAU				
Road injuries	+1,818 (-134)	-10,605 (-171)	-9,032	-28
Air pollution veh fleet1	+946 (-29)	-1,882 (-11)	-936	-11
Active transportation	-3674 (-2)	+657 (-43)	-3018	26
All outcomes (veh fleet1)	-917	-11,847	-12,765	-45

¹Negative DALY means a reduction of the burden

3.2 Comparisons between Y2031 and Y2061

Compared to the BAU 2031 (see **SI, section 5**), proportions of car and public transit modes of the Y2061 BAU (**Table 1**) were quite similar but kilometers travelled by car and for public transit increased. Regarding the comparison of the Y2031 Central and the Y2061 Optimal scenario (with densification in the urban core and changes in mode shares), kilometers travelled by car decreased (mostly in the suburbs) and km travelled for public transit increased (mostly in the urban core). The total health burden also increased by about **11%** from the Y2031 BAU vs the BAU 2061 (see **Table S9**).

4. DISCUSSION

We assessed the adverse impacts and the health benefits associated with transportation mode, land use (urban core densification) and emission scenarios in the metropolitan Montreal region in Y2061. According to our results, if past trends are continued (i.e. according to our BAU scenarios), kilometers travelled by car and air pollution will continue to increase from Y2031 due to the increase in the population of municipalities and corresponding mode shares. A reduction in car share accompanied with 50% electric vehicle use could marginally reduce the health impacts of air pollution, while urban core densification and decreased car use (such as in our Optimal scenario) would limit the kilometers travelled by car and increase health benefits of active transport. Teleworking/schooling may offset some of those benefits as people may become more sedentary. Reduction of GHG emissions would be highest with 50% electric vehicle penetration, and likely larger if emission factors for Y2061 (not Y2031) were used. Nonetheless, our assessments also suggest that drastic densification (all the new population would be located in the urban core) and measures to decrease car share (e.g. from 76% to 62% in the suburbs) would not substantially reduce impacts of transportation (maximum reduction of the burden by 37%). We also show that car share would be more affected by measures targeting car use, than by urban core densification. Given that most of the health burden of transportation relates to road traumas, maximum gains would thus be obtained by measures aimed at targeting car use.

These observations for the far horizon of Y2061 are in line with the current literature on the impacts of land use and transportation scenarios, for a horizon of 5 to 20 years (e.g. Woodcock et al, 2009). They reinforce the fact that major changes in urban planning practices, in addition to the supply of transportation services, are needed as early as possible, to reduce environmental and health impacts of land use and transportation. Densification in urban areas, and a stop to the

building of new roads would also be more in line with the protection of sensitive environments in the outskirts of cities thus maintaining important ecological services.

Our work is based on a number of premises. First, we assumed that it was possible for the entire new population to reside in the urban core for our Optimal scenarios, irrespective of the lodging capacity. For our Optimal scenarios, the new population in the urban core is very high (~1.3M additional individuals from 2008 to 2061) and only very drastic measures, such as an important increase in high rise buildings, could enable such Optimal scenarios. However, we could hypothesize that all the new population would be located in other areas than the current urban core but where they would contribute similar trips.

Second, we modelled future movements only considering household travel; we thus neglected impacts of commercial vehicles. Additionally, we modelled movements of the Y2061 population assuming that the mode shares by municipalities would not change from Y2031 to Y2061 by age group (except those forced by the mode shares of the scenarios). It was not possible to have reliable estimates of mode shares by municipality, age and sex, given the small number of individuals of the OD survey per age group and municipality for active and public transit modes. Therefore, total movements projected for Y2061 reflect the modification in age between Y2031 and Y2061, but neglect changes on mode shares due to the aging of the population between Y2031 and Y2061. However, for health benefits of physical transportation, grouping of municipalities allowed us to consider mode share by age and sex.

Third, given that no mode choice model was used to estimate travel mode in Y2061, we thus assumed by design that time to travel by mode and ratio of travel times remained the same between Y2031 and Y2061; this implies that we would increase public transit services and road capacity in the future to maintain those travel times. Also, none of our scenario modelled impacts of reduced road capacity. Assuming that travel times would remain the same in Y2061 is not totally unrealistic; it is in line with our mode share predictions for Y2031; indeed, mode shares by regions (i.e. urban and suburbs) predicted with a mode choice model were similar for both the BAU and the Central Y2031 scenario with urban core densification and increased transportation services (see **SI, Table S7**). This may be due to the fact that very large changes in travel times by car would be needed to induce mode changes; this may also reflect limitations of the mode choice model to predict Y2031 mode shares, and to the fact that car possession was not targeted in our Y2031 scenarios. Because travel times were assumed to be the same between Y2031 and Y2061, the Y2031 trends in mode shares were conserved in Y2061 in the BAU; in the Y2061 Optimal scenarios, we forced the mode shift to reach mode shares in line with those observed in dense areas.

Other limitations include the fact that predicted distances walked in Y2061 were based on Y2031 distances that were overestimated, as demonstrated in Tetreault et al (2018) (on average people walked 1.3 km per trip vs 0.9 km per trip according to the 2008 survey). All impacts were modelled based on the OD survey conducted in the fall of 2008, and behaviors may vary by season or by year, factors that we did not consider. Noise and associated effects were also not considered. Pollutant emissions were based in Y2061, on emission factors of Y2031, etc.

Notwithstanding these premises and limits and others that we do not enumerate here, projecting impacts for many scenarios in the far future, even if roughly estimated, are useful to determine how large, land use and transportation changes must be (i.e. exponential or enormous), to ensure future environmental and health gains. While projecting such impacts requires a sizable amount of background information (as we present here), the integration of multidisciplinary knowledge lays the foundation for future work and additional scenarios.

Our assessments suggest that in the far future of Y2061, in order to substantially reduce health impacts of transportation, drastic measures to decrease car share and to densify urban areas, where jobs and services are available, are necessary.

Supporting Information (SI): Contains outline of methods, description of scenarios, projections of population and transportation demand for Y2031 and additional results for Y2031 and Y2061.

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