

**SMOG AND SOCIO-ECONOMICS: AN EVALUATION OF EQUITY IN TRAFFIC-RELATED AIR POLLUTION GENERATION AND EXPOSURE**

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**Abstract**

How traffic-related air pollution generation and exposure is distributed among different population groups is an important environmental justice concern. From a social equity perspective, many questions arise at the metropolitan scale: Do socially disadvantaged communities have higher exposure levels to traffic-related air pollution? Do discrepancies exist wherein neighborhoods are not exposed to similar levels of pollution than they themselves generate? And, is there a relationship between this discrepancy and social disadvantage? These questions are examined for the Montreal metropolitan region through the development of an integrated transport and emission model. Two measures of traffic-related air pollution are estimated at the traffic analysis zone level: (1) generation (average emissions per household), and (2) exposure (average residential zone concentration). A social disadvantage index is also calculated that incorporates elements of social and material deprivation. Three levels of inequity exist regarding emissions, exposure and socioeconomics. Firstly, social disadvantage was found to have a positive relationship with exposure, meaning that the most socially disadvantaged communities tend to experience the highest levels of traffic-related air pollution. Spatial discrepancies in emission generation versus exposure are also present for most of the metropolitan region. Furthermore, the communities that face a double-burden of greater disadvantage and higher exposure also tend to create the lowest quantities of pollution.

**Keywords:** emission modeling, air-pollution exposure, social disadvantage, environmental justice, polluter-pays principle

## 1. INTRODUCTION

Equity in the field of transportation and land-use planning has traditionally dealt with the equal distribution of resources in the transportation system in order to support equal levels of accessibility and mobility. At the same time, there has been a parallel stream of equity research into issues of environmental justice, which tend to focus on whether marginalized or disadvantaged communities bear the brunt of pollution, be it from energy production, waste management, or transportation externalities. With the disappearance of most industry and energy production in urban areas, transportation is now the biggest contributor to urban air pollution in the developed world (Colville et al, 2001). Traffic-related air pollution is a byproduct of the combustion process that occurs in the majority of automobiles and trucks, producing a host of pollutants such as particulate matter, nitrogen oxides, volatile organic compounds, and more. A significant amount of research over the past 10-15 years has linked exposure to the aforementioned pollutants with a host of chronic and acute health effects (Brauer et al, 2008; Gan et al, 2012; Selander et al, 2009). Furthermore, the spatial distribution of traffic-related air pollution is not uniform across urban metropolitan regions, resulting in exposure disparities across different population groups. Previous research has consistently shown that areas with higher levels of social disadvantage tend to have worse levels of air quality, creating a ‘double-burden’ of high disadvantage and high risk of air pollution related illness (Crouse et al, 2009; Fan et al, 2012; Goodman et al, 2011; Jephcote and Chen, 2012; Jerrett, 2009).

Our study is set in Montreal, Canada where a transportation model developed for the metropolitan region is extended with a capability to model emissions and evaluate population exposure to traffic emissions. In this paper, we test two hypotheses related to the distributional effects of traffic-related air pollution in a large metropolitan area. First, we test the traditional

hypothesis that individuals living in neighborhoods characterized by a high social disadvantage metric are also exposed to the highest levels of traffic emissions. In addition, the hypothesis that neighbourhoods experiencing a certain level of traffic emissions are also responsible for similar levels of emission generation (through travel behavior of inhabitants), often termed as the polluter-pays principle (PPP) is also tested. To assess these two hypotheses, two measures of traffic-related air pollution are estimated: (1) an average level of traffic-based emissions generated per household in each traffic analysis zone (TAZ) and (2) an average density of experienced traffic-based emissions, also calculated at the traffic analysis zone level. A cumulative index of social disadvantage is also estimated in order to highlight the most marginalized zones within the study area. Our analysis aims to investigate the relationships between the index of social disadvantage and traffic-related air pollution generation and exposure. Our study area includes the Montreal metropolitan region (MMR), spanning an area of 7,000 km<sup>2</sup> and a population of 3.8 million inhabitants (Statistics Canada, 2011).

## **2. CONTEXT**

Traffic-related air pollution has been an important environmental justice concern since the late 1990s, and has spurred an array of studies into the linkages between exposure and socio-economic status. Most of this research has focused on assessing whether inequities exist in the spatial distribution of air pollution across metropolitan regions. The two critical elements in such evaluations include (1) air pollution levels used for exposure estimates, and (2) socioeconomic indicators of disadvantage. The baseline for exposure in most studies is often established through measurement campaigns that collect ambient air pollution levels at specific points across urban areas. This method has been used in several cities across Canada, including Hamilton (Jerrett et al,

2001), Toronto (Buzzelli and Jerrett, 2007), and Montreal (Crouse et al, 2009), as well as in London, UK (Goodman et al, 2012). At the same time, several other studies have attempted to directly estimate traffic's contribution to air pollution through the use of emission models whereby a density of traffic emissions is used as a proxy for air pollution levels without the reliance on dispersion modelling. Outputs from an emission model are then used to estimate residential exposure levels, with this method being used in studies in Christchurch, New Zealand (Kingham et al, 2007); Leicester, UK (Jephcote and Chen, 2012); Hong Kong, China (Fan et al, 2012); and Great Britain (Mitchell and Dorling, 2003). Several studies have also used proximity to high-density roads as a surrogate for exposure to traffic related air pollution (Bae et al, 2007).

Groups and neighbourhoods with lower SES have consistently been shown to experience higher levels of air pollution, a conclusion further confirmed in a summary review by Jerrett (2009). However, there have been several exceptions to this trend. Buzzelli and Jerrett (2007) found that certain centrally located, high-status zones in Toronto were also susceptible to higher exposures, while Crouse et al (2009) had similar findings in Montreal, Canada. Mitchell and Dorling (2003) similarly concluded that the poorest experienced the worst air quality, yet the least poor did not always have the best air quality. These exceptions highlight the complexities of these interrelationships, whereby there are cases where households with higher SES trade-off poorer air quality for downtown proximity. Furthermore, there are situations wherein the 'poorer' air quality in the inner-city areas may even be considered acceptable, negating the 'trade-off' effect.

At the same time, two of the aforementioned studies attempted to address the concurrent environmental justice issue of PPP, wherein neighbourhoods with high exposure levels contribute equally high levels of emissions thereby negating the sense of inequity. Mitchell and Dorling (2003) found that the PPP was applicable to a certain percentage of high exposure zones across

Great Britain, while Jephcote and Chen (2012) found similar results for the central areas of Leicester, UK.

Meanwhile, recent years have also seen significant advances in emissions modeling. Regional traffic assignment models have been combined with refined emission simulations to generate accurate mobile link-level estimates of local pollutants and greenhouse gases (Hulsmann et al, 2009; Int Panis et al, 2011). Work has also incorporated start emissions into traffic-related pollutant estimates. This was spurred by initial estimates showing that start emissions could account for up to 28% of total emitted on-road hydrocarbons under summertime conditions (Houk, 2004). From there, the integration of start emissions into regional traffic-related emissions models has been made possible through the use of detailed trip data and expanded emission simulations (Beckx et al, 2009a; Hatzopoulou et al, 2007). Also, this additional degree of spatial resolution and separation of emission (running or start) allows researchers to further separate the effects of high automobile use rates as opposed to high rates of vehicle traffic.

Regarding the socio-economic side of equity research, there has been much interest in the identification of marginalized or disadvantaged segments of the population. The history of measuring social disadvantage (often termed deprivation) has evolved over time, leading to the creation of a measure of cumulative disadvantage through combinations of a set of socio-economic measures. Cumulative disadvantage indicators tend to incorporate factors that are linked to the independent variable being studied, for instance with car ownership for transportation equity studies, or with parental education for a study on pediatric health (Bauman et al, 2006). The motivation behind the cumulative disadvantage approach is that a combination of socio-economic factors is more representative of a population's disadvantage, in that it can account for both material and social elements. Certain studies have found that social disadvantage indicators should

be tailored to country-specific conditions (Sanchez-Cantalejo et al, 2008). Kingham et al (2007) employed a similar methodology in using a deprivation index that was unique to New Zealand. This line of research has also been extended to Quebec, and even Montreal. Langlois and Kitchen (1996) first proposed the use of a Montreal-specific index of General Urban Deprivation employing the number of young residents, low-quality housing, unemployment rate, ethnicity, and youth employment participation. Pampalon and Raymond (2000) developed a similar Quebec-specific Deprivation Index that consisted of education level, employment rate, household income, marriage status, single-parent families, and number of people living alone. Meanwhile, Apparicio et al (2007) also created a Montreal-specific index of social deprivation, again accounting for the common factors of income, lone-parent families, unemployment rate, education level, and immigration. Most recently, Foth et al (2013) developed an index of social disadvantage for Toronto that combines a weighted average of median income, unemployment rate, rate of immigration within the last 5 years, and rate of households that spend over 30% of their income on rent.

In this paper, advancements in emission modeling through the inclusion of vehicle allocation and start emissions are used to directly estimate traffic's contribution to intra-urban air pollution. This contribution is extended to capture residential exposure levels to total hydrocarbons, a common traffic-related pollutant and smog precursor, while at the same time quantifying 'responsibility' through estimating the generation of car-based hydrocarbons. The two traffic-related air pollution measures are then combined with a social disadvantage index to form a three-dimensional analysis involving social and environmental inequities. This work therefore builds on the study by Crouse et al (2009) into deprivation and air quality in Montreal by directly quantifying traffic's contribution to local air pollution and its connection to social disadvantage. Furthermore,

this study helps to shed more light on the relatively unexplored terrain of PPP in relation to Environmental Justice in a North American context, adding to initial work in the UK by Mitchell and Dorling (2003) and Jephcote and Chen (2012).

### **3. METHODOLOGY**

The Montreal Metropolitan Region (MMR) is the study area for this research and consists of the island of Montreal, the cities of Laval and Longueuil, and municipalities on the North Shore and South Shore. FIGURE 1 highlights the major boroughs on the island of Montreal as well as the cities of Laval to the northwest and Longueuil to the east. The island of Montreal contains 47 percent of the region's inhabitants and 71 percent of the region's employment opportunities (AMT, 2010). The central business district is located in the Ville-Marie borough and is primarily surrounded by dense mixed-use neighbourhoods. The region has an average vehicle ownership of 1.23 vehicles per household and a mode split of 68% car, 17% public transit, and 12% active transportation. However, the central areas surrounding downtown are much less car-reliant, with their share decreasing to 49% for passenger cars while the shares of public transit and active transportation increase to 29% and 20% respectively (AMT, 2010).

[Insert Figure 1 here]

**FIGURE 1 Map of the Island of Montreal and surrounding municipalities.**

The remainder of the methodology section contains details into the integrated transport and emissions model used to estimate emission generation and exposure. The creation of the social disadvantage index is also explained, along with the data analysis and interpretation. Further details into the integrated transport and emissions model framework are presented in FIGURE 2, and can also be found in (Reference removed for reviewing purposes).



[Insert Figure 2 here]

**FIGURE 2 Detailed framework for the integrated transport and emissions model.**

### **3.1. Emissions Model**

The generation of traffic-related emissions is estimated for both running and start emissions at the TAZ level for the entire Montreal metropolitan region. The region consists of 1,552 TAZs in total, and the average zone-size ranges from 0.53 km<sup>2</sup> in the central urban areas to 14.1 km<sup>2</sup> in the rural periphery. In addition, average population levels range from 2,230 inhabitants per TAZ in central areas to 3,030 inhabitants per TAZ on the region's periphery. The fine size of the TAZs, especially those in the central areas, confirms that the spatial unit of analysis is adequate for this study, as detailed in previous research into population health (Buzzelli, 2007).

The base data for the transport model is the 2008 Origin-Destination (OD) survey conducted by the Agence Métropolitaine de Transport (AMT), the regional transit authority for the MMR. The 2008 OD survey consists of daily travel diaries for 5% of the region's population, sampled on an average workday during the fall season (AMT, 2010). All the driving trips in the survey were expanded to account for the full population and then used to generate hourly TAZ OD matrices. The OD matrices are then input into a regional traffic assignment model of the MMR, built in a mesoscopic traffic-modeling platform (PTV VISUM). The regional traffic model includes road types ranging from expressways to local roads, with details regarding capacity, speed limit, intersection type, and turning restrictions. The OD demand is allocated onto the road network through a stochastic user-equilibrium path assignment, which ensures a probabilistic distribution of path choices between any OD pair. The main hourly outputs from the regional traffic model include a path array for every active OD pair and a congestion-related travel time matrix.

Individual vehicles (type and model year) are assigned to every driving trip in the OD survey through a vehicle allocation algorithm, primarily to maintain consistency across the running and start emission calculations. The congestion-related travel times from the regional traffic model are added to trip start times to approximate trip arrival times, which are then assumed to be the times of vehicle availability. Household-specific trips are then ordered chronologically and assigned a vehicle based on vehicle availability (time, geographic coordinates) and household vehicle ownership. The type and model year of each vehicle is then determined through probabilistic selection based on the type and model distributions of the household's residential zone. The vehicle registry data contains details on vehicle type (passenger car and passenger truck) and model year (1978-2008) at the level of the forward-sorting area (this is a Canadian geographical unit based on the first three digits of a six-digit postal code) and was obtained from the Société de l'Assurance Automobile du Québec (SAAQ). Knowing the vehicle index of each trip also allows for the approximation of the time between engine shutdown and engine ignition, known as the soak-time, which is used in the start emission model.

Concurrently, a running emission model is developed that is fed with Montreal-specific input data such as fleet distribution (age and type), ambient weather conditions and fuel composition. The software used for the emission model is the Mobile Vehicle Emissions Simulator (MOVES), developed by the United States Environmental Protection Agency. After data inputs are accounted for, MOVES outputs a look-up table of running emission factors (EFs), in grams of pollutant per km, for a set of vehicle types (passenger car, passenger truck), model years (30 years), speeds (17 speed bins), road types (expressways, arterials, local roads), and pollutants (greenhouse gases, nitrogen oxides, carbon monoxide, hydrocarbons). An emission post-processor then iterates through each driving trip in the OD survey and randomly allocates a trip to a path in its OD path

set based on the cumulative path volume distribution. Link-level emissions are then calculated by multiplying the vehicle- and road-specific emission factors by link length. Trip-level running emissions are therefore the summation of all link emissions in the assigned path.

Meanwhile, emissions from engine starts are also a crucial element in the emission model. Start emissions occur because the engine and the catalytic converter require several minutes to heat up before they reach their optimal temperatures. The excess emissions during this time are estimated to account for nearly 28-31 percent of total on-road volatile organic compound emissions (Borrego et al, 2004; Houk, 2004). Start emissions are a function of an engine's soak-time (Favez et al, 2009), and are also dependent on vehicle characteristics and ambient conditions. Ambient conditions, specifically temperature, are especially important in colder climates such as Montreal, where start emissions can account for nearly half of all on-road VOC emissions (Houk, 2004). Therefore, MOVES is also employed to output start emission factors for a set of vehicle types (passenger car, passenger truck), model years (30 years), soak-times (8 time bins), and pollutants (carbon monoxide, hydrocarbons). A start emission post-processor then iterates through each driving trip and allocates a start emission factor based on the vehicle and soak-time.

The trip-level emissions (running and starts) are then expanded using socioeconomic expansion factors to account for the full population of the region, and are then allocated to the household's residential TAZ. Therefore, the first measure regarding emission generation is the daily average emissions generated per household, calculated by normalizing total TAZ emissions by the number of households (kg/household).

### **3.2 Exposure to Emissions**

The second measure involves deriving population exposure levels to traffic-related emissions for the same set of TAZs across the Montreal region. In the absence of a dispersion model, we use the emissions occurring in the residential TAZ as a measure of population exposure. While previous Environmental Justice studies have incorporated more detailed pollutant concentrations through dispersion modeling (see Mitchell, 2005; Namdeo and Stringer, 2008), residential proximity to traffic-related air pollution is considered more than adequate given its wide use in recent population health research (Braeur et al, 2008; Gan et al, 2012; Jerrett et al, 2009; Selander et al, 2009). For this purpose, rounded buffers were created around each link to approximate dispersion effects. The buffer sizes are dependent of road type and as such are set at 10 meters for local roads, 20 meters for arterials, 30 meters for highways and 50 meters for expressways. The range of buffer sizes employed parallel findings from field measurements (Padro-Martinez et al, 2012), and is more conservative than typical residential buffers used in previous literature (Bae et al, 2007). Link-level running emissions described in section 3.1 are then spatially allocated to each TAZ based on the intersecting percentage of the road buffer. At the same time, vehicle start emissions are assumed to occur entirely in the origin TAZ of each trip. Average exposure values are then calculated by normalizing the total hydrocarbons emitted by the land-area of the TAZ to generate an average emission density ( $\text{kg}/\text{km}^2$ ). Other examples of previous work that has linked traffic, emission, dispersion, and exposure include Hatzopoulou & Miller, (2010) and Beckx et al (2009).

### **3.3 Social Disadvantage Index**

The estimation of a social disadvantage index (SDI) follows a similar methodology to the one used in Foth et al (2013), although there is a difference in spatial resolution. This index is estimated at the TAZ level instead of the census tract level in order to maintain consistency with the measures

for traffic-related emissions. At the same time, TAZs are at an even finer level of detail than census tracts, which are often delineated in order to capture relatively homogeneous socio-economic neighborhoods. The improvement in resolution should serve to provide clearer associations with exposure to traffic emissions, as has been previously found in Goodman et al (2012). The following socio-economic data from the 2006 census were retrieved at the census tract and census subdivision level (Statistics Canada, 2006):

- Median household income
- Unemployment rate (percentage of labor force that is unemployed)
- Percentage of population that had immigrated within the last 5 years (2001-2006)
- Percentage of households that spend over 30% of their income on rent

Despite the fact that no correlation was found between immigration status and disadvantage in previous studies (Crouse et al, 2009), immigration rate was still included in order to ensure that the elements of social disadvantage (unemployment and immigration) were equally as present as elements of material disadvantage (income and % of income spent on rent).

After the four variables were retrieved for all census tracts and census subdivisions in the region, the amount of habitable land was estimated for each TAZ based on land-use information for the region (all land-uses aside from ‘open water’ and ‘parks and recreation’ were considered ‘habitable’). The area of habitable land was then used to create area-based weights, and subsequently population-based weights, that were used in converting the four variables from census tract to TAZ level. Each variable was then standardized and weighted equally to create the SDI (see equation 1). For instance, a zone with a median household income of \$48,758 (Z-score = -0.196), unemployment rate of 7.8% (Z-score = 0.246), recent immigration rate of 11.4% (Z-score

= 1.567), and having 32.6% of households that spend over 30 percent of income on rent (Z-score = 1.388), has an SDI of 3.397. A correlation matrix was calculated to ensure that the index is capturing similar socio-economic groups, and the four variables were all significantly correlated with Pearson coefficients above 0.44 (significant at the 0.01 level).

$$SDI = Z_{Unemployment\ Rate} + Z_{Immigration\ Rate} + Z_{30\% \text{ of Income on Rent}} - Z_{Median\ Income} \quad (1)$$

The SDI results were then normalized and each TAZ was given a score between 1-10 based on its respective decile. There were zones with either no reported population or insignificant data available and so TAZs with populations below 1 were omitted from the analysis, resulting in a sample size of 1513 TAZs.

### **3.4. Analysis of relationships between social disadvantage and traffic emissions**

An analysis was conducted to examine the relationships between the estimated SDI and the two measures of traffic emissions (emissions generated per household and emissions occurring in a TAZ); both measures accounting for running and start emissions. Analyses were conducted using data normalized in deciles, as has been favoured in several previous equity studies (Fan et al, 2012; Goodman et al, 2012; Mitchell and Dorling, 2003). This allows for the meaningful comparison of two variables measured at different scales.

#### *Social disadvantage and exposure*

The measure of social disadvantage and exposure is calculated by taking the difference between the social disadvantage decile and the exposure decile. This measure ranges from -9 to 9, and

serves to test the relationship between disadvantage and exposure. For instance, if there are many values clustered around zero, then there is likely a positive relationship between disadvantage and exposure (ie. zones with high disadvantage have high exposure, and zones with low disadvantage have low exposure). Otherwise, a high positive value means that the zone has high disadvantage and low exposure, and a high negative value means low disadvantage and high exposure. In addition to that, the sum of SDI and exposure deciles is taken in order to spatially highlight zones that face a 'double-burden' of greater disadvantage and worse air quality.

#### *Exposure and emission generation*

The measure of exposure and emission generation is calculated that aims to capture whether the responsibility in emission generation is being matched with equivalent exposure to air pollution. This 'polluter-pays index' is calculated by taking the difference in the exposure decile and the emissions decile, with values ranging from -9 to 9. Inequity is therefore evident if there are many zones in the lowest or highest areas of that range, for instance if there are many neighbourhoods that have high exposure and low emission responsibility or vice versa. Otherwise, if a majority of zones are relatively close to zero, it could be argued that a polluter-pays principle applies.

#### *Social disadvantage, exposure and emissions*

The measure of social disadvantage, exposure and emissions involves adding the third dimension of social disadvantage to the previously explored concept of the polluter-pays principle. The measure is calculated by taking the sum of the SDI decile and the 'polluter-pays index' [ $SDI + (Exposure - Emissions)$ ]. Only the uppermost and lowermost values are of interest in this analysis. The uppermost values correspond with zones that are highly disadvantaged, have high exposure

to air pollution and generate low amounts of emissions. Meanwhile, the lowermost values are those with low disadvantage, low exposure and who generate the highest amounts of traffic-related air pollution.

### *Statistical Testing*

To determine whether the levels of emission and exposure vary significantly between social disadvantage deciles several ANOVA analyses are performed. This tests whether the means of each group's exposure and generation of traffic-related pollutants are significantly different.

Simple correlation tests are also run to quantify the relationship between social disadvantage and pollution exposure.

## **4. RESULTS AND DISCUSSION**

The distribution of raw values for the social disadvantage index is slightly skewed to the right, and range from – 13.64 to 13.54 (FIGURE 3). TABLE 1 illustrates the SDI values divided into deciles; we observe large discrepancies in the four socioeconomic factors between the lowest SDI values (1<sup>st</sup> decile) and the highest (10<sup>th</sup> decile). For example, Median Household Income ranges from \$29,800 for the most disadvantaged to \$91,300 for the least. Other variables have similarly wide ranges. The spatial distribution of the SDI deciles across the Montreal metropolitan region can be seen in FIGURE 4. The areas of highest social disadvantage are distributed across the island of Montreal with the highest concentration around the denser inner parts of the city. Other socially disadvantaged neighborhoods (8-9<sup>th</sup> deciles) are also heavily concentrated in central areas on the island, including large portions of the boroughs of Ahuntsic-Cartierville, Côte-des-Neiges, Hochelega-Maisonneuve, Le Sud-Ouest, Parc-Extension, and Ville-Marie. At the same time, the wealthy enclaves of Westmount, Outremont, and Mont-Royal are all visibly present near downtown, as well as the suburban neighbourhoods in the west part of the island. The spatial SDI



results for the island of Montreal parallel similar findings in previous research (Apparicio et al, 2007; Crouse et al, 2009; Langlois and Kitchen, 1996). Aside from Montreal, most of the region is almost entirely under the 50<sup>th</sup> percentile for social disadvantage, aside from pockets in the cities of Laval and Longueuil.

[Insert Figure 3 here]

**FIGURE 3 Histogram of the raw values of the Social Disadvantage Index.**

**TABLE 1 Comparison of socioeconomic variables between SDI deciles (mean values)**

SDI Decile	1	2	3	4	5	6	7	8	9	10
Median Household Income (1,000 CAD)	91.3	71.2	63.7	59.0	52.5	45.2	42.6	37.4	35.5	29.8
Unemployment Rate (%)	3.5	4.3	4.8	5.6	5.6	6.4	6.9	8.0	10.4	13.8
Immigration Rate (2001-2006; %)	1.3	1.4	1.4	1.8	2.5	2.8	4.8	6	7.3	13.9
Households that spend over 30% income on Rent (%)	3.0	3.8	5.6	8.9	14.5	17.6	21.3	25.4	28.1	35.8

[Insert Figure 4 here]

**FIGURE 4 Social Disadvantage Index deciles across the Montreal Metropolitan Region.**

Further examination of FIGURE 4 reveals that many of the most socially disadvantaged neighborhoods are located in close proximity to major highways that typically carry high traffic flows. Meanwhile, the majority of wealthier neighborhoods appear to be in areas that are relatively free of major highways. This initial observation suggests the existence of a socio-economic gradient in traffic-related air pollution exposure. This relationship is further explored by observing

the difference in decile rankings between SDI and exposure (FIGURE 5). We observe that 50% of zones have comparable rankings in SDI and exposure; the difference between their SDI and exposure is between -1 and +1. This suggests that a positive correlation between SDI and exposure exists; higher disadvantaged neighbourhoods tend to have higher exposure levels and vice versa. The other 50% of zones are split almost equally between areas with ‘high social disadvantage and low exposure’ (difference is greater than 1) and areas with ‘low social disadvantage and high exposure’ (difference is less than -1). Furthermore, the correlation coefficient between the SDI deciles and exposure deciles is 0.63 ( $p < 0.001$ ), again confirming the positive relationship.

[Insert Figure 5 here]

**FIGURE 5 Histogram of the difference in rankings between SDI and exposure.**

The second measure of social disadvantage and population exposure is calculated involving the summation of SDI and exposure decile rankings. The spatial distribution of the resulting measure can be seen in FIGURE 6. Neighbourhoods with combined SDI and exposure greater than 18 were of most interest, as these are the neighborhoods that experience the ‘double-burden’ of greatest disadvantage and highest traffic-related air pollution exposure. The majority of these neighbourhoods border the major highways that surround the central part of the island of Montreal. Neighbourhoods within the Plateau Mont-Royal and Rosemont boroughs also experience a similar double-burden through their proximity to high traffic densities on arterial roads. At the same time, certain neighbourhoods facing a double-burden exist outside of the central areas, as there are pockets of ‘high disadvantage and high exposure’ in the borough of Montréal Nord, northeast of Saint-Léonard, and in Longueuil.

The majority of the region outside of Montreal falls into the bracket of lowest disadvantage and exposure. However, it is interesting to note that there are several neighborhoods close to downtown, specifically Westmount, Outremont, and parts of Mont-Royal, that are categorized in the same bracket. This finding contradicts those in Crouse et al (2009), which found that the very same central neighborhoods in Montreal with higher SES also experienced relatively worse air quality. This discrepancy in findings is likely because the buffer sizes used in linking road emissions to TAZs were more conservative than other methods for generating spatially refined air quality levels.

[Insert Figure 6 here]

**FIGURE 6 Sum of social disadvantage ranking and exposure ranking across the MMR.**

Aside from direct exposure inequity, it is also important to test whether the polluter-pays principle (PPP) is in effect across the Montreal region. In order to test for PPP, a polluter-pays index that takes the difference between exposure ranking and emission ranking was calculated, and the resulting histogram is shown in FIGURE 7. Given that only 22.2% of zones have equivalent exposure and emission rankings, it would appear as if the polluter-pays principle is not generally applicable to the region. At the same time, nearly 40% of neighborhoods ‘pay’ more than they contribute in terms of traffic-related air pollution, while 38% are contributing more than they ‘pay’.

[Insert Figure 7 here]

**FIGURE 7 Histogram of the difference in rankings between exposure and emission generation.**

The polluter-pays index was mapped in order to observe whether the inequity has a spatial component as well, or whether the neighbourhoods exhibiting PPP are geographically linked (FIGURE 8). The spatial distribution across the MMR is variable yet much of the central areas near downtown and along highway corridors have higher rankings in exposure over emissions.

There are also neighbourhoods in the central business district and along the most heavily trafficked freeways with extreme gradients between exposure and emission generation (differences of 8 or 9 deciles). Neighbourhoods exhibiting PPP with a polluter-pay index between -1 and 1 are scattered across Montreal, Laval and Longueuil, with no real spatial pattern. Meanwhile, peripheral areas of the region are almost entirely on the negative side of the distribution with differences in exposure vs. emissions ranging from -2 to -9, a finding consistent with a similar study conducted in the UK (Jephcote and Chen, 2012). Therefore, not only is the polluter-pays principle absent for most of the MMR, but the inequity is also spatially biased towards central neighborhoods closer to Montreal's downtown. While this finding is important, it is not altogether surprising given that central neighbourhoods have some of the highest traffic levels while at the same time having residents who make nearly half their trips by public transit or active transportation (AMT, 2010). On the other hand, the peripheral areas of the region are much more car-reliant yet reside in neighbourhoods with light traffic volumes.

[Insert Figure 8 here]

**FIGURE 8 Ranking comparison between emission generation and exposure.**

The last measure incorporating generation/exposure ranking and SDI was calculated in order to add another dimension in combining the ideas of 'polluter pays' with socioeconomic equity. The resulting spatial distribution is shown in FIGURE 9, and confirms that there are numerous neighborhoods, primarily in the central areas closer to downtown (shown in black), that have the 'double-burden' of social disadvantage, higher traffic-related air pollution *and* contribute very little of the pollution they are experiencing. This finding contradicts several conclusions made by both Jephcote and Chen (2012) and Mitchell and Dorling (2003) who found that centrally located disadvantaged neighborhoods actually produced comparable levels of traffic-related air pollution

to those they were experiencing. The difference in findings could be due to methodological differences, although it could again be attributed to the high levels of transit use and lower car-based travel distances amongst these central Montreal neighborhoods (AMT, 2010). Again, the peripheral areas of the region are almost entirely of low disadvantage, with low exposure to traffic-related air pollution, while at the same time often generating the highest amounts of emissions.

[Insert Figure 9 here]

**FIGURE 9 Socioeconomic equity of traffic-related air pollution generation and exposure.**

Finally, to statistically test these relationships between traffic pollution emitted and exposed to across the social disadvantage gradient, multiple ANOVA tests were performed. Table 2 presents the means of emissions per household, exposure, and standardized exposure minus emission for each social disadvantage decile. Each of these relationships is statistically significant. Further, the significantly different mean values of exposure and generation are in the hypothesized direction. For example, more socially disadvantaged groups are exposed to more pollutants than they emit ( $F(9,1503) = 110.0, p < 0.001$ ). Tukey post-hoc tests further confirm that, with the exception of SDI decile 1, an increase in social disadvantage is associated with a *decrease* in the generation of transport-related emissions, an *increase* in the exposure to these pollutants, and an *increase* in the difference between generation and exposure. This relationship can also be seen in Table 2 which shows a clear trend, each increment in social disadvantage is associated with populations being exposed to more pollutants than they emit. Furthermore, levels of social disadvantage are significantly correlated with both emissions ( $r = -0.54., p = 0.035$ ) and exposure ( $r = 0.433, p < 0.001$ ).

The anomaly of SDI decile 1 is likely related to the two wealthiest neighborhoods in the region, Westmount and Outremont (See Figure 1), being situated in central locations with high

exposure but with good public transport access and walkable neighbourhoods. This points towards the importance of understanding the trade-offs that go into home location decisions.

**TABLE 2 Means of Emission and Exposure of Traffic-related air pollution by Social Disadvantage Decile**

Social Disadvantage Index	Pollutants emitted <sup>1</sup> (kg/household)	Pollutants exposed to <sup>2</sup> (kg/km <sup>2</sup> )	Standardized Exposure minus Emissions <sup>3</sup>
1	16.1	9382.7	-2.54
2	42.9	5507.3	-4.33
3	88	7057.2	-3.45
4	17.8	8825	-2.48
5	15.4	17798.8	0.41
6	17.1	16065.3	0.28
7	8.2	33473.1	2.5
8	7	26405	2.93
9	7.5	25337.9	2.79
10	5.2	36220.9	4.56

<sup>1</sup> ANOVA (F(9,1503)=1.957, p=0.041)  $\eta^2=0.01$

<sup>2</sup> ANOVA (F(9,1503)=46.074, p<0.001)  $\eta^2=0.21$

<sup>3</sup> ANOVA (F(9,1503)=110.0, p<0.001)  $\eta^2=0.39$

## 5. CONCLUSION

This paper has explored the relationships between traffic-related air pollution generation, exposure, and socioeconomic disadvantage. Two measures of traffic-related air pollution are estimated; one that captures the generation of hydrocarbon emissions per household, and another that captures location-based exposure to hydrocarbon emissions. In addition, an index of social disadvantage was developed that incorporates elements of both social and material deprivation. The findings from this study suggest the possibility of three levels of environmental injustice occurring across the Montreal region. The first is that neighborhoods with the highest social disadvantage experience the worst exposures to traffic-related air pollution, confirming similar findings across cities in North America and beyond. At the same time, these findings highlight traffic's

contribution to the ‘double-burden’ of deprivation and air pollution previously seen in Montreal (Crouse et al, 2009).

Secondly, the polluter-pays principle is mostly absent given that the majority of neighborhoods in central areas experience much higher levels of air pollution than they are responsible for. In addition, there is a subset of those same central neighborhoods that are highly disadvantaged communities who are being exposed to higher levels of emissions that they have little to no role in producing. Again, these results are illuminating in that they are observed in a North American context and parallel similar results from the UK (Jephcote and Chen, 2012; Mitchell and Dorling, 2003). Given the findings of social and environmental inequities, it would be interesting to extend the analysis to testing whether a ‘triple-jeopardy’ situation exists that includes the third dimension of health inequities.

There were a few limitations with this analysis. Commercial truck traffic was not factored into the exposure measure. However, this omission could have resulted in an under-prediction of pollution levels in the socially disadvantaged areas, given the previous associations seen between lower-income areas and heavy-duty truck traffic (Houston et al, 2008). The index of social disadvantage employed in this study does not capture elements that might show increased susceptibility to air pollution exposure such as higher presence of young children, elderly people, people with previous health issues, and even indigenous populations. Furthermore, the measure of exposure does not employ dispersion models to account for local variations in built environment or climactic conditions, nor does it account for a wholly detailed source-receptor relationship, as described in Beckx et al (2009b). Important elements concerning the housing market and tradeoffs residents make when choosing a home location (trading off, for example, increased exposure to poor quality air for a central location) were not incorporated into this analysis.

Despite these limitations, this research highlights three levels of inequity regarding socioeconomics and traffic-related air pollution in the Montreal region. An unfair burden of negative externalities from transport is being placed on the region's disadvantaged populations, many of whom emit some of the lowest levels of emissions generated.

## REFERENCES

- Agence Métropolitaine de Transport (AMT), 2010, "La mobilité des personnes dans la région de Montreal: Faits Saillants" *Enquete Origine-Destination 2008*
- Apparicio P, Cloutier M-S, Shearmur R, 2007, "The case of Montreal's missing food deserts: evaluation of accessibility to food supermarkets" *International Journal of Health Geographics* **6**(4)
- Bae C-H, Sandlin G, Bassok A, Kim S, 2007, "The exposure of disadvantaged populations in freeway air-pollution sheds: a case study of the Seattle and Portland regions" *Environment and Planning B: Planning and Design* **34** 154-170
- Bauman LJ, Silver EJ, Stein REK, 2006, "Cumulative social disadvantage and child health" *Pediatrics* **117**(4) 1321-1328
- Beckx C, Int Panis L, Arentze T, Janssens, D., Torfs, R., Broeks, S., Wets G, 2009, "A dynamic activity-based population modelling approach to evaluate exposure to air pollution: Methods and application to a Dutch urban area" *Environmental Impact Assessment Review* **29**(3) 179-185



- Beckx C, Int Panis L, Vankerkom J, Janssens D, Wets G, Arentze T, 2009a, “An integrated activity-based modeling framework to assess vehicle emissions: approach and application” *Environment and Planning B: Planning and Design* **36** 1086-1102
- Becks C, Int Panis L, Uljee I, Arentze T, Janssens D, Wets G, 2009b, “Disaggregation of nation-wide dynamic population exposure estimates in the Netherlands: applications of activity-based transport models” *Atmospheric Environment* **43**(34) 5454-5462
- Borrego C, Tchepel O, Salmim L, Amorim JH, Costa AM, Janko J, 2004, “Integrated modeling of road traffic emissions: application to Lisbon air quality management” *Cybernetics and Systems: An International Journal* **35** 535-548
- Brauer M, Lencar C, Tamburic L, Koehoorn M, Demers P, Karr C, 2008, “A cohort study of traffic-related air pollution impacts on birth outcomes” *Environmental Health Perspectives* **116**(5) 680-686
- Buzzelli M, 2007, “Bourdieu does environmental justice? Probing the linkages between population health and air pollution epidemiology” *Health & Place* **13** 3-13
- Buzzelli M, Jerrett M, 2007, “Geographies of susceptibility and exposure in the city: environmental inequity of traffic-related air pollution in Toronto” *Canadian Journal of Regional Science* **XXX**(2) 195-210
- Colvile RN, Hutchinson EJ, Mindell JS, Warren RF, 2001, “The transport sector as a source of air pollution” *Atmospheric Environment* **35**(9) 1537-1565
- Crouse D, Ross N, Goldberg M, 2009, “Double burden of deprivation and high concentrations of ambient air pollution at the neighbourhood scale in Montreal, Canada” *Social Science & Medicine* **69** 971-981

- Fan X, Lam K-C, Yu Q, 2012, "Differential exposure of the urban population to vehicular air pollution in Hong Kong" *Science of the Total Environment* **426** 211-219
- Favez J-Y, Weilenmann M, Stilli J, 2009, "Cold start emissions as a function of engine stop time: evolution over the last 10 years" *Atmospheric Environment* **43** 996-1007
- Foth N, Manaugh K, El-Geneidy AM, 2013, "Towards equitable transit: examining transit accessibility and social need in Toronto, Canada, 1996-2006" *Journal of Transport Geography* **29** 1-10
- Gan WQ, Davies HW, Koehoorn M, Brauer M, 2012, "Association of long-term exposure to community noise and traffic-related air pollution with coronary heart disease mortality" *American Journal of Epidemiology* **175**(9) 898-906
- Goodman A, Wilkinson P, Stafford M, Tonne C, 2011, "Characterising socio-economic inequalities in exposure to air pollution: a comparison of socio-economic markers and scales of measurement" *Health & Place* **17** 767-774
- Hatzopoulou M, Miller EJ, 2010, "Linking an activity-based travel demand model with traffic emission and dispersion models: Transport's contribution to air pollution in Toronto" *Transportation Research Part D* **15**, 315-325
- Hatzopoulou M, Miller EJ, Santos B, 2007, "Integrating vehicle emission modeling with activity-based travel demand modeling: case study of the Greater Toronto Area, Canada" *Transportation Research Record: Journal of the Transportation Research Board* **2011** 29-39
- Houk J, 2004, "Making use of MOBILE6's capabilities for modeling start emissions" *Proceedings of the A and WMA's 97th Annual Conference and Exhibition* **1884** 5115-5130
- Houston D, Krudysz M, Winer A, 2008, "Diesel truck traffic in low-income and minority communities adjacent to ports: environmental justice implications of near-roadway land use

- conflicts” *Transportation Research Record: Journal of the Transportation Research Board* **2067** 38-46
- Hulsmann F, Gerike R, Kickhofer B, Nagel K, Luz R, 2009, “Towards a multi-agent based modeling approach for air pollutants in urban regions” *Luftqualität an Strassen* (German Federal Highway Research Institute: Berlin)
- Int Panis L, Beckx C, Broekx S, De Vlieger I, Schrooten L, Degraeuwe B, Pelkmans L, 2011, “PM, NO<sub>x</sub> and CO<sub>2</sub> emission reductions from speed management policies in Europe” *Transport Policy* **18** 32-37
- Jephcote C, Chen H, 2012, “Environmental injustices of children’s exposure to air pollution from road-transport within the model British multicultural city of Leicester: 2000-2009” *Science of the Total Environment* **414** 140-151
- Jerrett M, 2009, “Global geographies of injustice in traffic-related air pollution exposure” *Epidemiology* **20**(2) 231-233
- Jerrett M, Burnett RT, Pope III CA, Ito K, Thurston G, Krewski D, Shi Y, Calle E, Thun M, 2009, “Long-term ozone exposure and mortality” *The New England Journal of Medicine* **360**(11) 1085-1095
- Jerrett M, Burnett RT, Kanaroglou P, Eyles J, Finkelstein N, Giovis C, Brook JR, 2001, “A GIS-environmental justice analysis of particulate air pollution in Hamilton, Canada” *Environment and Planning A* **33** 955-973
- Kingham S, Pearce J, Zawar-Reza P, 2007, “Driven to injustice? Environmental justice and vehicle pollution in Christchurch, New Zealand” *Transportation Research Part D* **12** 254-263

- Langlois A, Kitchen P, 1996, "Identifying and measuring dimensions of urban deprivation in Montreal: An analysis of the 1996 census data" *Urban Studies* **50**(6) 119-139
- Mitchell G, 2005, "Forecasting environmental equity: air quality responses to road user charging in Leeds, UK" *Journal of Environmental Management* **77** 212-226
- Mitchell G, Dorling D, 2003, "An environmental justice analysis of British air quality" *Environment and Planning A* **35** 909-929
- Namdeo A, Stringer C, 2007, "Investigating the relationship between air pollution, health and social deprivation in Leeds, UK" *Environment International* **34** 585-591
- Padro-Martinez LT, Patton AP, Trull JB, Zamore W, Brugge D, Durant JL, 2012, "Mobile monitoring of particle number concentrations and other traffic-related air pollutants in a near-highway neighborhood over the course of a year" *Atmospheric Environment* **61** 253-264
- Pampalon R, Raymond G, 2000, "A deprivation index for health and welfare planning in Quebec" *Chronic Diseases in Canada: A Publication of Health Canada* **21**(3) 104-113
- Sanchez-Cantalejo C, Ocana-Riola R, Fernandez-Ajuria A, 2008, "Deprivation index for small areas in Spain" *Social Indicators Research* **89**(2) 259-273
- Selander J, Nilsson ME, Bluhm G, Rosenlund M, Lindqvist M, Nise G, Pershagen G, 2009, "Long-term exposure to road traffic noise and myocardial infarction" *Epidemiology* **20**(2) 272-279
- Statistics Canada, 2011, *2011 Census of Population* (Statistics Canada, Ottawa)
- Statistics Canada, 2006, *2006 Census of Population* (Statistics Canada, Ottawa)