Traffic-Related Air Pollution and Health:

A Canadian Perspective on Scientific Evidence and Potential Exposure-Mitigation Strategies

FINAL REPORT, MARCH 1, 2012

Michael Brauer, ScD

Conor Reynolds, PhD

Perry Hystad, MSc

The University of British Columbia, School of Population and Public Health

Prepared for:

Health Canada – Santé Canada

Water, Air and Climate Change Bureau – Bureau de l'eau, de l'air et des changements climatiques

TABLE OF CONTENTS

1. Summary

While urban areas in Canada generally experience relatively good air quality, exposure to outdoor air pollution still elicits considerable public health impacts. Recently, a growing body of evidence has emerged that specifically links traffic-related air pollution (TRAP) with health effects, including cardiovascular disease and cardiovascular mortality, respiratory disease, adverse pregnancy outcomes and lung cancer. This understanding of the importance of TRAP requires renewed focus on options to reduce population exposure, including integration with urban and transportation planning.

The objectives of this document are: (a) to present an overview of the international scientific evidence linking TRAP exposure to adverse human health effects, highlighting Canadian studies and new research findings published since the completion of a critical systematic review of the literature (HEI, 2010); (b) to estimate the exposure of Canadians to TRAP and identify its potential public health implications in Canada; (c) to review current legislation and guidelines regarding urban planning, the built environment and traffic exposure; and (d) enumerate potential options to mitigate population exposure to TRAP.

Canadian researchers have made important contributions to the body of evidence linking TRAP exposure with health effects, and findings from these studies have been highlighted and reviewed in detail. Recent Canadian published epidemiologic studies support the conclusions reached by the HEI panel in describing effects of TRAP exposure on respiratory heath, adverse pregnancy outcomes, cardiovascular disease and cancer. Therefore, Canadian scientific data indicates that exposure to traffic-related air pollution is a significant public health issue in Canada.

Spatial analysis of the number of Canadians living in proximity to major roads quantifies the scope of potential impact of TRAP as a public health

concern in Canada. We applied the finding from the HEI (2010) literature review of roadway gradients to estimate TRAP exposure and found that approximately 10 million individuals (32% of the Canadian population) live within 100m of a major road or 500 m of a highway. In addition, recent research has estimated that approximately one-third of Canadian urban elementary schools are located in zones of high traffic proximity. These estimates highlight the large proportion of the Canadian population exposed to TRAP and confirm its public health importance.

Four categories of exposure-mitigation options for TRAP are described: (1) Land-use planning and transportation management; (2) Reduction of vehicle emissions; (3) Modification of existing structures; and (4) Encouraging behaviour change. Real-world implementation of policies and actions – within Canada and internationally – have been examined. These strategies tend to either reduce TRAP exposures uniformly (e.g. identifying and repairing high-emitting vehicles or making improvements to public transit), or reduce TRAP exposure spatially (e.g. separation of buildings and active transit infrastructure from busy roads, low emission zones, or the use of HVAC to reduce TRAP infiltration in buildings). In addition, the time-horizon within which a reduction in TRAP exposure is expected to take place following a specific action varies from less than a year to decades. It is recommended that municipal and local governments take these considerations into account when choosing which TRAP exposure-reduction measures to implement. Recommended approaches include the following, grouped according to the time-horizon of their expected impact.

"Near-term" time horizon (months to years):
- Install HVAC filter systems in buildings that house susceptible populations within 150m from busy roads (>15,000 AADT);
- Limit heavy truck traffic to specific routes and times;
- Target high emitting vehicles for retrofit or removal with inspection and maintenance programs;

- Separate active commuting from busy roads (e.g. create bicycle routes on minor roads);
- Implement anti-idling bylaws;
- Implement traffic congestion reduction policies (e.g. tolls, parking restrictions, low emission zones, car-share programs, increased public transportation) to increase traffic flow (evidence suggests higher TRAP exposures with stop-and-go traffic).

"Long-term" time horizon (years to decades):
- Conduct integrated land use planning that incorporates health impact assessments (HIA's);
- Site buildings that house susceptible populations (e.g. schools, daycares, retirement homes) at least 150m from busy roads (>15,000 AADT);

It is likely that a bundle of complementary mitigation options will be required to protect the most susceptible sub-groups as well as those most highly exposed to TRAP, and to enable both near-term as well as long-term results.

2.   Glossary

AADT	annual average daily traffic (unit of traffic volume)
AQHI	air quality health index
BC	black carbon
CHD	coronary heart disease
CI	confidence interval
CO	carbon monoxide
DM	diabetes mellitus
DMTI	Canadian road network classification system developed by DMTI Spatial, Inc.
DRA	Digital Road Atlas for British Columbia
eNO	exhaled nitric oxide
GIS	geographic information systems
HEI	Health Effects Institute
HR	hazard ratio
HVAC	heating, ventilating, and air conditioning
IARC	International Agency for Research on Cancer
IgE	immunoglobulin E
IRR	incidence rate ratio
IUGR	intrauterine growth retardation
km	kilometre
kph	kilometres per hour
LBW	low birth weight
LUR	land use regression
m	metre
MERV	minimum efficiency reporting value
MI	myocardial infarction
mph	miles per hour
NO	nitrogen monoxide (also known as nitric oxide)
NO_2	nitrogen dioxide
NO_X	oxides of nitrogen (NO plus NO_2)
OC	organic carbon
OR	odds ratio
PAH	polycyclic aromatic hydrocarbon
ppb	parts per billion
ppm	parts per million
PSD	petrol station density
PM	particulate matter
SES	socio-economic status
SGA	small for gestational age
TRAP	traffic-related air pollution
VkmT	vehicle kilometres travelled

3.   Traffic-related air pollution: Evidence of adverse health effects

While Canada is known for its relatively good air quality (WHO, 2011a), there is a growing body of evidence that specifically links exposure to traffic-related air pollution (TRAP) in urban areas with a diverse array of health impacts, including respiratory disease, cardiovascular disease and cardiovascular mortality, adverse pregnancy outcomes and lung cancer. For example, an analysis of motor vehicle contributions to air pollution in Toronto estimated 440 premature deaths and 1700 hospitalizations per year with the mortality impacts estimated to cost more than $2 billion annually (McKeown, 2007).

In May 2009, the Health Effects Institute[1] (HEI) published a comprehensive critical review of the literature on emissions, exposure, and health effects of traffic-related air pollution (HEI, 2009, updated in January 2010 [HEI, 2010]). The HEI (2010) review builds on established efforts to assess and communicate the health effects of exposure to outdoor air pollution (e.g. WHO, 2005). The goal of this section is to summarize the HEI report findings on the health effects of TRAP exposure, to update the state of evidence with research published after the October 2008 cut-off for the HEI (2010) review and to provide a synthesis of Canadian evidence examining TRAP and health effects.

The Health Effects Institute (2010) state of evidence review included literature on emissions, exposure, and health effects of TRAP. The goal of the review was to summarize and synthesize relevant information on TRAP and its health affects in a coherent framework that linked exposure to traffic pollutants with human health effects, considering biological mechanisms. In order to infer whether associations between TRAP exposure and health outcomes were

---

[1] HEI (www.healtheffects.org) is a nonprofit corporation chartered in 1980 as an independent research organization to provide high-quality, impartial, and relevant science on the health effects of air pollution. Typically, HEI receives half of its core funds from the US Environmental Protection Agency and half from the worldwide motor vehicle industry.

causal, criteria were adapted from those used by the U.S. Surgeon General in the report "The Health Consequences of Smoking: A Report of the Surgeon General" (U.S. Department of Health and Human Services, 2004). For each health outcome posited to have adverse health outcomes, the HEI concluded that the evidence was:

A. sufficient to infer a causal association;

B. suggestive, but not sufficient to infer a causal association;

C. inadequate and insufficient to infer the presence or absence of a causal association, and;

D. suggestive of no causal association

The HEI review identified the evidence regarding TRAP exposure and asthma exacerbation as sufficient to infer causality and that the evidence for TRAP causing new cases of childhood asthma was on the borderline between sufficient and suggestive but insufficient. Evidence for adult onset asthma, lung function decrements, cardiovascular mortality, myocardial infarction onset and progression of atherosclerosis was deemed to be suggestive but insufficient to infer causality. The evidence for all other health effects (i.e. adverse pregnancy outcomes, lung cancer, etc.) was considered inadequate and insufficient. In the following sections more detail is provided on key studies in each health outcome category, including new research findings and Canadian evidence. Although evidence from both epidemiologic and toxicologic studies was considered, the larger body of evidence was from the field of epidemiology.

3.1   *Epidemiological evidence*

3.1.1 *Respiratory disease*

A number of respiratory effects were examined for children and adults, using a variety of different outcome measures, including asthma exacerbation

and development, wheeze and lung function. The HEI (2010) report noted considerable variability in the definitions of these outcomes used in the epidemiologic literature. The HEI (2010) report reviewed seven studies conducted in four separate cohorts and one case-control study that examined TRAP and asthma incidence in children, while eleven studies examined asthma prevalence in children. A number of these studies used proximity to roads or traffic density to represent TRAP exposure. For example, Zmirou *et al.* (2004) found that for children during the first 3 years of life, proximate traffic density was significantly associated with asthma diagnosis, specifically for children exposed to roadways with ≥30 vehicles/day per metre of roadway. In another study, older children (age 4 to 6 years) living within 50 m of a busy road were more likely to be doctor-diagnosed as asthmatic (Odds Ratio [OR] 1.66, 95% Confidence Interval [CI]: 1.01–2.59), where "busy road" were defined as motorways, federal roads, or state roads (Morgenstern *et al.,* 2008). The HEI (2010) report concluded that living close to busy roads appears to be an independent risk factor for the onset of childhood asthma, classifying the evidence for a causal relation in a gray zone between "sufficient" and "suggestive but not sufficient" (HEI, 2010).

In terms of studies examining TRAP exposure and wheezing in children, the review found a high level of consistency in positive findings within the 20 cohort and cross-sectional studies examined. Again, most studies used proximity to represent TRAP exposure. For example, Morgenstern *et al*. (2007) identified an association between living within 50 m of a major road in the first 2 years of life and an increase in the risk of wheezing and asthmatic/spastic/obstructive bronchitis. Ryan *et al*. (2005) investigated the association between wheezing (without the child having a cold) and traffic pollution among children 6 months old. Among those living in proximity to stop-and-go traffic (<100 m from a bus route or within 100 m of a state route with a speed limit of < 50 mph [80 kph]), the odds of wheezing was 3 times higher than among the unexposed children. The HEI (2010) report concluded that the evidence is "sufficient" to infer a causal

association between traffic exposure and exacerbations of asthma but that it is "inadequate and insufficient" to infer a causal association between exposure and respiratory symptoms in children without asthma. An additional nine studies examined TRAP and health-care services (primarily hospital admissions), from which the HEI (2010) report found "inadequate and insufficient" evidence to infer a causal association, primarily due to methodological limitations of the studies. In terms of adult onset respiratory effects, only one study was identified that examined adult onset asthma, while 17 studies examined adult respiratory symptoms. Due to the limited number of studies and exposure assessment limitations the evidence was considered "inadequate and insufficient" and "suggestive but not sufficient" for adult onset asthma and adult respiratory symptoms, respectively.

A large number of studies have examined lung function in both children and adults, but have used a diverse range of study designs and lung function measures, which limits their comparability. The HEI (2010) review concluded that while several studies demonstrate that living in proximity to high traffic roads is associated with reduced lung function, in both children and adults, the evidence is "suggestive but not sufficient" to infer causality. Chronic obstructive pulmonary disease (COPD) was also examined; however, only two studies fulfilled the HEI review criteria. Due to the lack of studies, the HEI (2010) report concluded that the evidence is "insufficient" to infer a causal association.

Since the HEI review, the most significant new information is the number of studies that have strengthened the state of evidence surrounding TRAP exposure and new onset asthma. For example, Gehring *et al.* (2010) reported robust associations between LUR estimates of TRAP and asthma incidence in an extended follow-up of a Dutch birth cohort. Evidence that this association is causal is strengthened by a sub-analysis, in which the risk of TRAP-related asthma was found to be influenced by variant alleles of the TLR2 and TLR4 genes that are involved in the innate immune response (Kerkhof *et al.*, 2010). In

addition, McConnell *et al*. (2010) demonstrated that TRAP exposure at schools contributed to the development of asthma in the Southern California Children's Health Study. As part of the International Study of Asthma and Allergies in Childhood (ISAAC), Brunekreef *et al.* (2009) conducted a global analysis involving more than 100,000 children from 21 countries. After controlling for sex, region of the world, language, gross national income, and 10 other subject-specific covariates, self-reported frequency of truck traffic on the street of residence was positively associated with the prevalence of symptoms of asthma, rhinoconjunctivitis, and eczema with an exposure-response relationship amongst the 6–7 and 13–14 year old children.

Adult-onset asthma has also been examined in a number of recent studies, and positive associations with exposure to TRAP have been observed (Künzli *et al.*, 2009; Modig et al., 2009). As with childhood asthma, higher risks were observed in subsets of study populations with polymorphisms in genes involved in the oxidative stress response, adding to the strength of evidence for a causal relationship (Castro-Giner *et al.*, 2009).

A number of review articles have concluded, based on descriptive analysis of the literature, that TRAP is associated with incident childhood asthma (e.g. Braback and Forsberg, 2009; Salam *et al*. 2008). The best summary of the available evidence, however, is a recent quantitative systematic review regarding incidences of asthma and TRAP exposure (Anderson *et al.*, 2011a). Most of the studies included in this meta-analysis were based on within-community exposure contrasts dominated by traffic pollution. Twelve of 17 cohorts reported at least one positive statistically significant association between air pollution and a measure of asthma. For the 13 studies with estimates for nitrogen dioxide (NO_2), the random effects odds ratio was 1.07 (95% CI: 1.02–1.13) per 10 $\mu g/m^3$. For five studies with estimates for particulate matter with aerodynamic diameter <2.5 μm ($PM_{2.5}$), the random effects estimate was 1.16 (95% CI: 0.98–1.37) per 10 $\mu g/m^3$. The authors concluded that the results were consistent with an effect of outdoor air pollution on asthma incidence.

Another important respiratory health outcome that has been studied more recently is chronic obstructive pulmonary disease (COPD). Although the evidence base is still small and inconsistent, some studies have suggested that TRAP contributes to the progression of COPD (Lindgren *et al.*, 2009; Andersen *et al.*, 2011b; Pujades-Rodríguez *et al.*, 2009; Eisner *et al.*, 2010). The most relevant of these is a recent Danish cohort study of 57,000 individuals that reported an association between traffic-related NO_2 and the first hospital admission for COPD, with stronger associations in subjects with prior diabetes and asthma (Andersen *et al*., 2011b). A large, population-based, cross-sectional survey in the UK, however, found no association between traffic-proximity and COPD (Pujades-Rodríguez *et al*., 2009), and a summary review of COPD risk factors came to the conclusion that traffic was associated with COPD, but that the evidence was not at a level where causality could be concluded (Eisner *et al*., 2010).

Canadian studies of respiratory disease:

A number of Canadian studies have been published that examined respiratory effects, including several published since the HEI (2010) report. In the largest of these studies, Clark *et al.* (2010) examined the effect of early-life TRAP exposures on the development of childhood asthma. In a birth cohort of children born in Southwestern British Columbia in 1999/2000 (n=37,401), asthma diagnoses up to 3-4 years of age were assessed using administrative health databases. High-resolution models of traffic-related NO, NO_2, $PM_{2.5}$ and BC were used to estimate exposure at mothers' residential histories during pregnancy and the children's addresses during follow-up. Results found that these traffic-related pollutants were associated with the highest risks of asthma diagnosis, for example an adjusted OR of 1.12 (95% CI: 1.07–1.17) for a 10µg/m^3 increase in NO_2.

Carlsten *et al.* (2011) examined TRAP and incident asthma in a high-risk birth cohort (272 high-risk infants during born during 1995) in Vancouver. High risk was defined as having at least one first-degree relative with asthma or two first-degree relatives with other IgE-mediated allergic disease (according to parental report). NO, NO_2 and $PM_{2.5}$ LUR models were applied to birth-year residential addresses and asthma was assessed by pediatric allergists at age 7. , and adjusted for a number of known risk-factors. Exposure estimates were available for 184 children (23 diagnosed with asthma and 68 with bronchial hyper-reactivity). For each IQR increase ($4.1mg/m^3$) of $PM_{2.5}$ at birth residence there was a significant increase in the risk of asthma (OR: 3.1; 95% CI 1.3–7.4). Elevated (non-significant) associations were also seen for NO and NO_2, while little association was seen for BC.

In addition to these studies of incident asthma, a number of Canadian studies have evaluated exacerbation of respiratory and allergic disease. Chen *et al.* (2008) examined interactions between exposure to TRAP and stress on biological and clinical outcomes of asthma for asthmatic children (n=73, 9–18 years of age) located in Vancouver. NO_2 LUR models were used to estimate TRAP, information about life stress was collected in interviews, and asthma-relevant inflammatory markers were measured. Significant NO_2 by stress interactions were found for interleukin-5, immunoglobulin E (IgE), and eosinophil counts. These interactions showed that higher chronic stress was associated with heightened inflammatory profiles as pollution levels decreased.

Included in the HEI (2010) review was a study by Dales *et al*. (2008), which assessed the effect of living near local residential roadways on children's objective indicators of ventilatory function and airway inflammation (1,613 children age 9-11 years in Windsor, Ontario). The length of roadways within a 200 m radius of each child's neighbourhood was summed, and measurements of both air pollution exposure, spirometry, and exhaled NO (eNO, which indicates an inflammatory response in the subject) were collected. For every 1km increase

in combined length of roadways within a 200 m radius of the neighbourhood, there was an associated 10.1% increase in eNO. A positive effect was also seen for local roadways near the home, after major roadways and highways were excluded (each 1km increase in local roadways was associated with a 6.8% increase in eNO). An additional analysis using similar exposure data applied to 2,328 9-11 year old children in Windsor (Cakmak *et al*., 2012), reported significant associations between truck turning counts on roads within 200 meters of the children's neighbourhouds and chest congestion, with larger effects observed in children with asthma. In addition, an interquartile range increase in truck turning counts was associated with a 1.84% (95% CI 0.07, 3.61) decrease in percent-predicted FEV while an interquartile increase in simple traffic counts (33,787 vehicles daily) was associated with a 0.68%, (95% CI 1.32, 0.03) decrease in percent-predicted FVC. In contrast to this observed relationship between TRAP and lung function, and unlike the earlier analysis, no statistically significant change was detected between traffic measures and eNO.

In a follow-up study, Dales *et al*. (2009) investigated the respiratory health effects of living near roadways in 12,693 Windsor school children, enrolled in grades 1 through 8. Increased associations were statistically significant for the highest versus the lowest roadway density exposure quintiles (calculated for 200 m radius around children's households) for wheeze (OR 1.23; 95% CI: 1.07–1.41) and wheeze with dyspnea (OR: 1.27; 95% CI: 1.05–1.52).

In a cross-sectional population-based survey of asthma exacerbation in 6-12 year old Montreal children, Deger *et al.* (2010) reported that children living along high-traffic density streets (OR: 1.35; 95% CI: 1.00–1.81) were found to be at increased risk of poor asthma control.

Wang *et al.* (2010) in an analysis of five Canadian cities (Vancouver, Saskatoon, Winnipeg, Hamilton and Halifax) participating in the International Study of Asthma and Allergies in Childhood (ISAAC) analysis found associations

(in multivariate analysis) between heavy exposure to traffic exhaust (by self-reported questionnaire) and wheezing, rhinoconjunctivitis and eczema.

A cross-sectional analysis of ~1500 elementary school children in Hamilton (Sahsuvaroglu *et al*., 2009) linked survey responses to multiple measures of traffic pollution exposure including roadway distance and a land use regression model. No significant associations between any of the exposure estimates and asthma were found for the whole population, but in the subgroup of children without hayfever (predominately in girls) large asthma effects were detected for elevated NO_2 exposures (as estimated from the LUR model).

A study on Montreal evaluated the relationship between TRAP exposure, socioeconomic status and respiratory disease (Smargiassi *et al.,* 2006). Respiratory disease hospitalizations were associated with traffic intensity near subjects' residences, even after adjustment for high-resolution measures of housing value calculated from property assessment data (as a measure of socioeconomic status). These results indicate that health impacts related to TRAP are unlikely to be an artefact of associations between TRAP exposures and socioeconomic status.

Recent Canadian studies have also linked TRAP to respiratory infections. A case-control study in Vancouver (Karr *et al*., 2009a) reported associations between physician visits and hospitalizations for bronchiolitis among infants with TRAP, but also with other air pollution sources, such as woodsmoke. A companion study conducted in Seattle, also reported weak associations between bronchiolitis and traffic proximity (Karr *et al*., 2009b). Finally, following from an earlier study conducted in Europe (Brauer *et al*., 2006) in which TRAP was associated with middle ear infections (otitis media) in two birth cohorts, MacIntyre *et al.* (2011) examined TRAP exposure during the first two years of life and risk of otitis media in a large population-based birth-cohort in Southwestern British Columbia. Children born during 1999-2000 were followed using administrative health databases until the age of 2 years. TRAP was estimated using high spatial

resolution land use regression (LUR) NO, NO$_2$, PM$_{2.5}$, BC and woodsmoke models that were applied to all children's residential locations. Exposure was estimated from NO LUR models. After adjusting for a number of known risk factors, exposure was found to be significantly associated with risk of Otitis media (RR 1.10; 95% CI: 1.07–1.12). Other LUR estimates showed weak associations, as did proximity measures to highways and majors roads. Larger effects, however, were observed for exposure to woodsmoke.

3.1.2 Cardiovascular effects

The association between cardiovascular effects and long-term and short-term TRAP exposure were considered "suggestive but not sufficient" by the HEI review. These conclusions were reached due to a relatively small number of epidemiologic studies, which did not address all potential key confounders, in particular traffic-related noise and stress (HEI, 2010). Four studies specifically made a convincing case for an association between TRAP and cardiovascular effects (Rosenlund *et al.*, 2006; Tonne *et al.*, 2007; Hoffmann *et al.*, 2007; Kunzli *et al.*, 2005). For instance, Hoffmann *et al.* (2007) examined the association between coronary atherosclerosis and long-term exposure to TRAP (estimated using proximity to major roads) in a cohort of adults 45 to 75 years old in two German cities. After adjusting for socioeconomic status (SES, based on household income and educational level) and smoking, individuals living within 150 m of a major road were at increased risk of coronary atherosclerosis (OR: 1.85; 95% CI: 1.21–2.84) compared in individuals living farther away.

New longitudinal evidence supports earlier cross-sectional studies that TRAP exposures are associated with progression of atherosclerosis. Arguably the most important new study is longitudinal cohort analysis of data from Los Angeles, indicating an association between atherosclerosis progression and traffic proximity. The rate of progression among those living within 100 meters of

a freeway was twice that of the rate of progression in the general population (Kunzli *et al*., 2010). The relationship between TRAP and atherosclerosis progression is also supported by an additional cross-sectional study of measures of atherosclerosis (Bauer *et al.*, 2010). The recent American Heart Association statement on the cardiovascular health effects of particulate matter (Brook *et al*. 2010) concluded that, "many studies have found a strong association between metrics of traffic-related air pollution exposure and elevated cardiovascular risk." and that "traffic-related pollution as a whole appears to be a specific source associated with cardiovascular risk". Supporting this conclusion are recent studies reporting associations between TRAP and hypertension (e.g. Fuks *et al.*, 2011) and studies of vascular effects such as stroke (Andersen *et al.*, 2011c) and deep-vein thrombosis (Baccarelli *et al.*, 2009). Further, new evidence strengthens the links between short-term TRAP exposure and onset of myocardial infarction (MI) (von Klot *et al.*, 2011). An analysis of multiple MI triggers suggested that traffic exposure, while not having the highest individual risk, was the risk factor with the largest population-level risk, due to the high proportion of the population that is exposed to traffic (Nawrot *et al.*, 2011).

A body of evidence is also emerging that links TRAP exposure to preclinical indicators of cardiovascular disease risk. The associations between TRAP, estimated with validated Black Carbon LUR models, and markers of inflammatory and endothelial response were examined in 642 elderly men between 1999-2008 participating in the Veterans Administration Normative Aging Study (Alexeeff *et al.*, 2011). Statistically significant positive associations were found for one marker and suggestive positive associations for the other. Results suggest that medium-term exposure to TRAP may induce an increased inflammatory/endothelial response, especially among diabetics and those not using statins.

Delfino *et al*. (2011) evaluated whether TRAP exposure (using primary organic aerosols and ultrafine particle markers) were more strongly associated

with ST-segment depression of ≥1mm in 38 subjects than secondary organic aerosols or $PM_{2.5}$. Significant positive associations were found with markers of combustion-related aerosols and gases, but not for secondary aerosols or ozone.

Another study examined whether bicycle commuting along a busy road in Antwerp, Belgium would induce changes in biomarkers of pulmonary and systematic inflammation in 38 health volunteers (Jacobs *et al*. 2010). The study found that TRAP exposure during exercise caused a small increase in the distribution of inflammatory blood cells in healthy subjects (measured using blood neutrophils).

Canadian studies of cardiovascular effects:

A number of new Canadian studies have strengthened the associations between TRAP and cardiovascular effects. Most importantly, a series of analyses in Vancouver have provided further evidence to suggest a causal association between cardiovascular mortality and exposure to TRAP. In a population-based cohort of 452,735 individuals (45-85 years of age) created from administrative health record linkages in 1999, living close to a major road was associated with increased coronary heart disease (CHD) mortality, while changes in distance of residences in relation to major roads were associated with altered CHD mortality risk in an exposure-response fashion (Gan *et al*., 2010; Gan et al., 2011). The most recent analysis of this cohort suggests that the increased CHD risk appears to be independently related to both exposures to BC and to traffic noise (Gan *et al.*, 2011).

Jerrett *et al*. (2009) examined mortality in 2,360 individuals from a respiratory clinic in Toronto and assigned TRAP exposures using NO_2 LUR models. After adjusting for a number of covariates, a significant association was found between circulatory related deaths and NO_2 (RR: 1.39; 95% CI: 1.05–1.85), but not for proximity to traffic. Canadian data also provide further evidence for increases in subclinical indicators in relation to traffic pollution exposure. In a

case-crossover study of 42 cyclists in Ottawa, exposures to NO_2 and ultrafine particles along a high traffic route (compared to a low traffic route or indoors) were associated with altered heart rate variability (Weichenthal *et al*., 2011). In a double-blinded randomized crossover study of 31 subjects in Toronto, particle exposure was associated with significantly increased diastolic blood pressure, and impaired endothelial function, while no affects were seen for ozone (Brook *et al*., 2009).

3.1.3 Cancer

The HEI (2010) report concluded that there was "inadequate and insufficient" evidence to infer a causal relationship between TRAP exposure and cancer in both adults and children. Four studies examined adult cancers (lung, breast, and multiple cancers) and five studies examined childhood cancers (leukemia, lymphomas, and brain cancers). Results for lung cancer associations with TRAP were mixed. For example, Nyberg *et al*. (2000) modeled NO_x/NO_2 exposures for 1,042 lung cancer cases and 2,364 controls in Stockholm and found significant associations between average 20 year traffic-related NO_2 exposures and lung cancer (OR: 1.4; 95% C: 1.0–2.0). In a case-cohort study on diet and cancer in the Netherlands (Beelen *et al*., 2008), including 114,378 individuals with follow-up from 1986 to 1997, traffic intensity in a 100 m buffer and living within 100 m of a motorway were not associated with lung cancer incidence in smokers. In non-smokers (n=252), traffic intensity in a 100 m buffer was marginally associated with lung cancer incidence (OR: 1.36; 95% CI: 0.99–1.87). In terms of childhood cancers, the associations with TRAP were not consistent.

Since the HEI review, there have been a number of studies that have added to the associations between TRAP and cancer, particularly lung cancer. Raaschou-Nielsen *et al*. (2011) examined 592 lung cancer cases in the Danish

diet, cancer and health cohort and applied NO_X concentrations estimates from a dispersion model to residential histories from 1971 to time of diagnosis. After adjusting for smoking (status, duration and intensity), environmental tobacco smoke, length of school attendance, occupation and dietary intake of fruit there was a significant association (Incidence Rate Ratio [IRR]: 1.30, 95% CI: 1.05– 1.61) with lung cancer for the highest compared with the lowest quartile of NO_X. Living within 50 m of a major road (>10,000 vehicles/day) was also associated with an increased, though insignificant, risk (IRR 1.21, 95% CI: 0.95–1.55). Rasschou-Nielsen *et al.* (2010) also examined 679 lung cancer cases (identified from two prospective cohort studies in Demark plus the Netherlands cohort study on diet and cancer) and estimated NO_X concentrations using the same dispersion model applied to residential histories from 1971 to lung cancer diagnosis. A 37% (95% CI: 6–76%) increase in lung cancer incidence was observed per 100 µg/m^3 increase in NO_X after adjustment for smoking (status, duration, and intensity), educational level, body mass index, and alcohol consumption.

In addition to lung cancer, several studies have recently been conducted examining TRAP and other cancer sites. Raaschou-Nielsen *et al.* (2011) examined the associations between NO_X air pollution exposure and twenty cancers (not including lung cancer) in the Danish cohort on diet and cancer. Enrolment in the cohort occurred from 1993-1997 and follow up was conducted until 2006. NO_X was estimated using a dispersion model applied to all residential addresses from 1971 onwards and the amount of traffic at all residential locations was estimated. NO_X was significantly associated with risks for cervical cancer (IRR, 2.48; (95% CI: 1.01–5.93) and brain cancer (IRR, 2.28; 95% CI: 1.25–4.19) per 100µg/m^3 increase in NO_X. Each specific cancer analysis was adjusted for known or suspected risk factors. Increased, though non-significant, associations were also seen for other cancers, including those in the Buccal cavity and pharynx, Esophagus, Liver, Breast, Uteri, Kidney, Bladder, and Non-Hodgkin Lympohoma.

Canadian studies of cancer:

There have been two studies of air pollution and lung cancer conducted to-date in Canada. Jerrett *et al*. (2009) attempted to examine lung cancer and TRAP, estimated with NO_2 LUR models in Toronto; however, there were only 35 lung cancer deaths, which resulted in positive estimates with large confidence intervals. Recently, Band *et al*. (2011) examined NO_2 and SO_2 exposures for 711 lung cancer cases and 711 controls in Windsor Ontario. Significant associations were found between NO_2 and lung cancer in males only after adjustment for age, residence duration, and duration of smoking and cigarettes per day (OR 5.49; 95% CI: 1.04–29.0 for the highest versus lowest NO_2 exposure quintile).

Crouse *et al*. (2010) examined TRAP and postmenopausal breast cancer in a Montreal in a case-control study conducted in 1996–1997. NO_2 exposures were estimates for the 383 cases and 416 controls (other incident cancer cases) using back-extrapolated LUR models linked to subjects' residence at time of interview. After adjusting for known and suspected breast cancer risk factors, a 5 ppb increase in NO_2 (estimated in 1996), was associated with a 31% increase (OR 1.31, 95% CI: 1.00–1.71) in breast cancer incidence.

3.1.4 Pregnancy and developmental effects

The HEI (2010) report identified only four studies of TRAP exposure and pregnancy outcomes (Wilhelm and Ritz, 2003; Ponce *et al.*, 2005; Slama *et al.*, 2007; Brauer *et al.*, 2008), which led to their conclusion of "inadequate and insufficient" evidence to infer causality. These four studies provide evidence for a positive association between TRAP exposure and preterm birth, low birth weight and small for gestational age. One of these, a Canadian study of 70,249 births from 1999 to 2002 in Vancouver (Brauer *et al.*, 2008), identified small but

consistent higher associations between exposure to NO, NO_2, and $PM_{2.5}$ during the entire period of gestation, as well as residence within 50 m of a highway, and small-for gestation-age birth weight. There were no associations observed with living within 150 m of a highway. As well, associations were noted between exposure to specific traffic-related pollutants and preterm births.

A small number of studies have been published since the HEI (2010) report that examine TRAP and birth outcomes. Wilhelm *et al.* (2011) conducted a separate analysis of a large birth registry in Los Angeles, and found relatively consistent associations between a variety of measures of traffic-related air pollution and term low birth weight. Malmqvist *et al.*, (2011) examined 81,110 births in Scania, Sweden for associations between low-level exposure to NO_X and proximity to roads and prematurity and fetal growth. An increased risk for SGA babies was found for the highest versus the lowest NO_X quartiles, adjusting for maternal age, smoking, sex, and year of birth; however, in the fully adjusted models, the associations were no longer significant. In subgroup analyses, an increased risk for SGA for girls was seen as well as an increased risk among mothers who had not changed residency during pregnancy (OR: 1.09; 95% CI, 1.01–1.18). A study from Japan reported an association between proximity to major roads and preterm births at all gestational ages (Yorifuji *et al.*, 2011). Living within 200 m increased the risk of births before 37 weeks by 1.5 times (95% CI = 1.2–1.8), birth before 32 weeks by 1.6 times (1.1–2.4), and births before 28 weeks by 1.8 times (1.0-3.2). Analysis of the same population for low birthweight, however, reported no association with several measures of traffic proximity (Kashima *et al.*, 2011). A unique study from Spain reported an association between TRAP measures and fetal head circumference, suggesting that prenatal exposure to traffic-related air pollution may reduce fetal growth (Ballester *et al.*, 2010).

While these new studies support an association between traffic pollution exposures and adverse reproductive outcomes the literature is not consistent. For example, a small study from Australia (Barnett *et al.*, 2011) showed

associations between shortened gestational time and road density around the mother's residence but did not find associations with road proximity or with birth weight, birth length or head circumference. Other largely negative studies were reported from populations in Japan (Kashima *et al.,* 2011) and the Netherlands (Gehring *et al.*, 2011).

Canadian studies of pregnancy and developmental effects:

As well as the study mentioned above (Brauer *et al.*, 2008), one additional Canadian study, conducted in Montreal (Genereux *et al*., 2008) examined whether proximity to highways (defined as residing within 200 m of a highway that had a speed limit of at least 70 kph and no stop signs or traffic lights) interacts with individual and neighbourhood socio-economic status (SES, indicated by maternal education) to influence birth outcomes. All live singleton births on the island of Montreal, from 1997–2001, were included in the analysis (n=99,819). After for a number of known risk factors, highway proximity was associated with adverse birth outcomes in the study population as a whole, with mothers residing within 200 m of a highway having a 14% increased odds of preterm birth (OR: 1.14; 95% CI: 1.02–1.27) and a 17% increased odds of low birth weight (LBW) (OR: 1.17; 95% CI: 1.04–1.33) compared to mothers who did not reside close to a highway.

3.1.5 All cause mortality

Studies of all-cause mortality, although large in quantity, tended to lack specificity in regards to possible mechanisms and physiologic systems. Therefore, the evidence was considered "suggestive but not sufficient" to infer a causal association between mortality and both short-term and long-term exposure to traffic-related air pollution (HEI, 2010). Two of these were Canadian studies: Finkelstein *et al.* (2004) examined 5,228 study subjects who underwent

pulmonary function testing at a clinic in Hamilton, Ontario, Canada, from 1985-1999 and follow-up was conducted from 1992-2001. Exposure to TRAP was estimated using residence within 50m of a major urban road or 100 m of a highway. Subjects living near a major road had significantly increase risk of mortality (RR=1.18; 95% CI: 1.02–1.38), after adjusting for sex, age, forced vital capacity, forced expiratory volume, BMI, and household income. Similarly, Jerrett *et al.* (2009) examined mortality using administrative health databases from 1992-2002 for 2,360 subjects enrolled from a respiratory clinic in Toronto. NO_2 LUR models for Toronto were used to estimate TRAP exposures. After controlling for age, sex, lung function, obesity, smoking, and neighbourhood deprivation, a relative risk of 1.17 (95% CI: 1.01–1.35) for all non-accidental causes of mortality was found for each 4 ppb increase in NO_2. Given the conclusions of the HEI review indicating that all studies of this type are only suggestive given their lack of specificity, no more recent studies are reviewed here. Instead, more weight should be placed on the recent studies of cardiovascular mortality, including a recent series of Canadian studies reviewed above (Gan *et al.*, 2010, 2011).

3.1.6   Other health outcomes

Given the growing weight of evidence associating TRAP with a range of health outcomes, especially those related to systemic inflammation (e.g. Hart *et al.*, 2009), additional health impacts have been explored in recent years. Perhaps the most important of these from a public health perspective are several studies in which TRAP has been associated with incidence of diabetes (Andersen *et al.*, 2011d; Krämer *et al.*, 2010; Brook *et al.*, 2008).

A small number of recent studies have also reported associations between TRAP and measures of cognition in both adults and children (Power *et al.*, 2011; Ranft *et al.*, 2009; Freire *et al.*, 2009). Further, a single (but highly provocative)

study reported an association between highway proximity and autism (Volk *et al*., 2011).

<u>*Canadian studies of other health outcomes:*</u>

Among the diabetes studies mentioned above is a Canadian study (Brook *et al*., 2008) where the association between diabetes mellitus (DM) and TRAP was evaluated in patients who attended two respiratory clinics in Hamilton (n=5,228) and Toronto (n=2,406) from 1992–1999. NO_2 LUR models were used to assign TRAP exposures in both cities and administrative health databases were used to diagnose DM. After adjusting for age, body mass index, and neighbourhood income, the odds ratio for DM in women for a 1 ppb increase in NO_2 exposure increased in Toronto (OR 1.06; 95% CI: 0.99–1.11) and Hamilton (OR 1.03, 95% CI: 0.98–1.08). No associations between NO_2 and DM were seen in men.

Finkelstein and Jerrett (2007) examined the associations between Parkinson's disease (PD) and TRAP among a cohort of 110,000 subjects recruited from five university-affiliated primary care clinics in Toronto and Hamilton. Overall, no consistent associations between TRAP and PD were observed.

3.2   *Toxicological evidence*

Toxicological evidence can help provide information on biological mechanisms by which TRAP may impacts specific health outcomes, thus adding to weight of evidence when considering causality. The HEI (2010) review concluded that the toxicological evidence supports the hypothesis that oxidative stress in an important determinant of the health effects associated with ambient air pollution, but evidence linking specifically TRAP exposure to oxidative stress remains less clear. The review did note a growing body of evidence that

demonstrates oxidative stress in response to exposure to components of TRAP, of which the majority of studies focused on PM from diesel engine exhaust and the presence of surface-absorbed transition metals and polycyclic aromatic hydrocarbons.

In terms of toxicological evidence specific to certain health effects, the HEI (2010) review found that the toxicological literature is supportive of a possible association between TRAP and asthma, while very few studies were available for lung function in both children and adults. Exposure to TRAP components (principally PM and diesel) resulted in mild acute inflammatory responses in healthy individuals and enhanced allergic responses in individuals with asthma (HEI, 2010). In terms of cardiovascular effects, the recent toxicological evidence provides suggestive evidence that TRAP components alter cardiovascular function (HEI, 2010). There is also evidence for acute effects on vascular homeostasis and suggestive evidence in animal models that repeated or chronic PM exposure enhances the development of atherosclerosis (HEI, 2010). Toxicological studies have also shown that specific components of TRAP are mutagenic and genotoxic, likely through the production of oxidative DNA damage; however, caution must be used when extrapolating these data to ambient concentration and human risks (HEI, 2010). Similarly, a limited body of toxicological evidence was available for TRAP and reproductive outcomes and while a small number of TRAP animal and in vivo studies have been conducted, findings must be interpreted with caution (HEI, 2010).

In addition to toxicological studies, the HEI (2010) report reviewed a number of human exposure studies, which provide additional insights into biological mechanisms, as well as evidence for primary prevention activities to reduce exposures. A number of controlled human exposure studies using real-world TRAP exposures show decrements in lung function and enhanced response to allergens in subjects with asthma (HEI, 2010). Studies capitalizing on different real-world exposure scenarios were also reviewed. For example,

important insights into lung function effects were revealed in a randomized crossover study that was conducted in London (McCreanor *et al.*, 2007). Sixty adults with mild or moderate asthma walked for two hours along a heavily trafficked London street where only diesel-powered vehicles were permitted, and on a separate occasion through a nearby park. Elevated exposure to TRAP on busy streets was associated with significant reductions in lung function, compared to the effects when walking through the park. These lung function changes were accompanied by increases in measures of neutrophilic, but not eosinophilic, inflammation in sputum and exhaled breath condensate. The inflammatory effects were most consistently associated with exposures to BC and ultrafine particles. Similarly, in a series of studies conducted in Sweden, mild allergic asthmatics were exposed to traffic pollution for 30 minutes while in a car traveling in a road tunnel (Svartengren *et al.*, 2000). Subjects' responses to an inhaled allergen challenge were assessed, and compared to their allergen response following a control period in a low-pollution suburban area. Subjects experienced decreased lung function and more asthma symptoms following the tunnel exposure compared to the control scenario. Such real-world exposure studies provide important policy relevant information on the health effects of TRAP and how to mitigate exposures.

3.3   Conclusions on the state of evidence

The HEI (2010) report concluded that the epidemiologic and toxicologic evidence is sufficient to support a causal relationship between exposure to traffic-related air pollution and exacerbation of asthma. It also concluded that there was between sufficient and suggestive evidence for a causal relationship with onset of childhood asthma, and suggestive but not sufficient evidence for non-asthma respiratory symptoms, impaired lung function, total and cardiovascular mortality, and cardiovascular morbidity. For the other health outcomes examined, the

evidence was considered inadequate or insufficient (HEI, 2010). Table 1 updates these conclusions based on the more recent evidence reviewed above. The table also provides references to whether Canadian studies support the conclusions of the HEI (2010) report. While Canadian cities generally experience comparatively low levels of ambient background air pollution (WHO, 2011a), numerous studies conducted in Canada indicate that impacts of TRAP on the health of Canadians are similar to those experienced in other urban areas throughout the world.

> **Recent and Canadian published epidemiological studies support the conclusions reached by the HEI panel in regards to the effects of traffic related air pollution (TRAP) exposure, indicating a causal relationship between exposure to TRAP and exacerbation of asthma, as well as onset of childhood asthma. Evidence also suggests the potential for causal relationships between exposure to TRAP with cardiovascular mortality and morbidity, non-asthma respiratory symptoms and impaired lung function, and lung cancer. Canadian scientific data clearly indicates that exposure to TRAP is a significant public health issue in Canada.**

Table 1. Summary of the strength of evidence between exposure to TRAP and health outcomes. Revised conclusions are presented based on the HEI (2010) conclusions as well as new evidence since 2009. A summary of whether Canadian-specific studies support each conclusion is also presented.

Health Outcome	HEI Conclusion on Strength of Causality	Updated Conclusion on Strength of Causality	Canadian Literature Supports Conclusion on Causality
Respiratory			
Asthma exacerbation	Sufficient	(No change)	Supports
Respiratory symptoms (non-asthmatic children)	Inadequate and insufficient	(No change)	Supports
Asthma onset			
Adults	Suggestive, but insufficient	Sufficient / Suggestive, but insufficient	No Studies
Children	Sufficient / Suggestive	Sufficient	Supports
Lung function	Suggestive, but insufficient	(No change)	Supports
COPD	Inadequate and insufficient	(No change)	No Studies
Allergy	Inadequate and insufficient	(No change)	No Studies
Cardiovascular			
CVD mortality	Suggestive, but insufficient	(No change)	Supports
MI onset	Suggestive, but insufficient	(No change)	No Studies
Atherosclerosis	Suggestive, but insufficient	(No change)	No Studies
Cancer			
Lung cancer	Inadequate and insufficient	Suggestive, but insufficient	Supports
Other (non-lung) cancer	Inadequate and insufficient	(No change)	Supports
Childhood cancer	Inadequate and insufficient	(No change)	No Studies
Pregnancy/Birth Outcomes	Inadequate and insufficient	(No change)	Supports
All Cause Mortality	Inadequate and insufficient	(No change)	Supports

4. Canadian population exposure to traffic-related air pollution

4.1 Distance from major roadways as a measurement of pollution exposure

Of the epidemiological studies reviewed above, the majority used TRAP exposure estimates derived from residential locations, due primarily to data availability (work, commute and recreation locations are rarely available for large populations). Here, we follow the same approach to assess the number of Canadians potentially exposed to TRAP. Residential location is a reasonable proxy for exposure assessment, since it is the location where individuals spend the majority or their time, and it is straightforward to quantify proximity to highways and major roads. In addition, we discuss locations of Canadian schools in relation to TRAP sources.

Relatively few studies have evaluated the relevant period(s) of exposure duration, but there is some evidence to suggest that exposure may not need to be very long to impact health. For example, heart attacks may be triggered by short-term (hour to day) exposure to TRAP (Brook *et al.,* 2010), asthmatic responses are precipitated by exposures of one hour or less (Svartengren *et al.*, 2000; McCreanor *et al.*, 2007) and the study of coronary heart disease mortality conducted in Vancouver (Gan *et al.,* 2010) found that those who modify their TRAP exposure by moving have nearly the same risk as those with more constant TRAP exposure, suggesting a relatively short (several years) duration exposure impact.

While residential, school and workplace locations are important determinants of exposure to TRAP, specific activities may also lead to elevated

exposures that are not well-characterized by home or school/work location. Therefore, in addition to those at risk of TRAP health impacts due to location, outdoor workers, individuals with long commutes in traffic and those engaging in active transport or exercise in proximity to TRAP may also be considered sub-populations at increased risk. Personal exposure measurements which may elucidate the role of high-exposure activities and offer important insights into sources and determinants of TRAP are feasible for small exposure studies. Specific personal monitoring studies that could inform mitigation strategies are reviewed in Section 3.

A number of pollutants (e.g. CO, NO_X, BC) can be used to represent exposure to TRAP, and these pollutant species are routinely measured at fixed monitoring sites in many urban areas. However, more detailed measurements or models are required for exposure assessment, since fixed-site monitoring data cannot capture the fine-scale spatial pollutant gradients associated with vehicle emissions. Land-Use Regression (LUR) models have become a common method for estimated TRAP in epidemiological studies (9 cities in Canada now have LUR models complete, see Appendix B for summaries and maps of existing models). These models can be useful information sources for local transportation and air quality management planning and can help inform the public on locations of high TRAP levels, but proximity measures remain the most common (and easily applied) method for estimating exposure to TRAP within large populations and geographic areas.

Based on a synthesis of the best available evidence, the Health Effects Institute (HEI) concluded that TRAP gradients are present up to 300-500 m from a major roadway. Probably the most important driver of TRAP gradients in LUR models are the strength of the pollutant source, i.e. traffic volume, normally expressed in units of annual average daily traffic (AADT), as well as the proportion of heavy-duty vehicles on a given roadway. Because the majority of gradient studies were conducted on highways (with traffic volumes over 100,000

AADT), gradients with 500 m width are unlikely to be observed adjacent to roads with lower traffic volumes. However sufficient evidence exists that TRAP gradients are present up to 100 m from major roads, which are defined in this report as roadways with relatively large traffic volumes (>15,000 AADT), two or more lanes spanning several kilometres, and speed limits above 50 kph. More detail on the relationship between traffic volume and TRAP gradients is given in the following sections.

In addition to the type and amount of traffic on a road, other factors that influence the specific gradient distance is the pollutant type being examined (and whether it is a primary or secondary pollutant), local topography, urban form, and metrological conditions. Below is a brief summary of each of the main factors that affect TRAP gradients around roadways.

4.1.1 Spatial extent of TRAP components

The physical and chemical properties of different TRAP substances influence the spatial scale of roadway gradients. These scales can range from tens of meters to entire airsheds depending on the substance of interest. Primary pollutants, such as NO and BC, are formed directly from combustion and typically have small scales of influence, while secondary pollutants, such as NO_2 or O_3, are formed in the atmosphere through chemical and physical conversions of gaseous precursors and will have larger scales of influence. Zhou and Levy (2007) conducted a systematic review of measured and modeled pollutant gradients from roadways and found large differences in the spatial extent of gradients by pollutant type (see Figure 1). Inert pollutants with low background concentrations and reactive pollutants that are removed close to the roadways had the smallest spatial scales, with mean spatial extents below 200 m. Reactive pollutants that formed close to roadways demonstrated a mean spatial extend of approximately 400 m, but extended to 500 m in some studies.
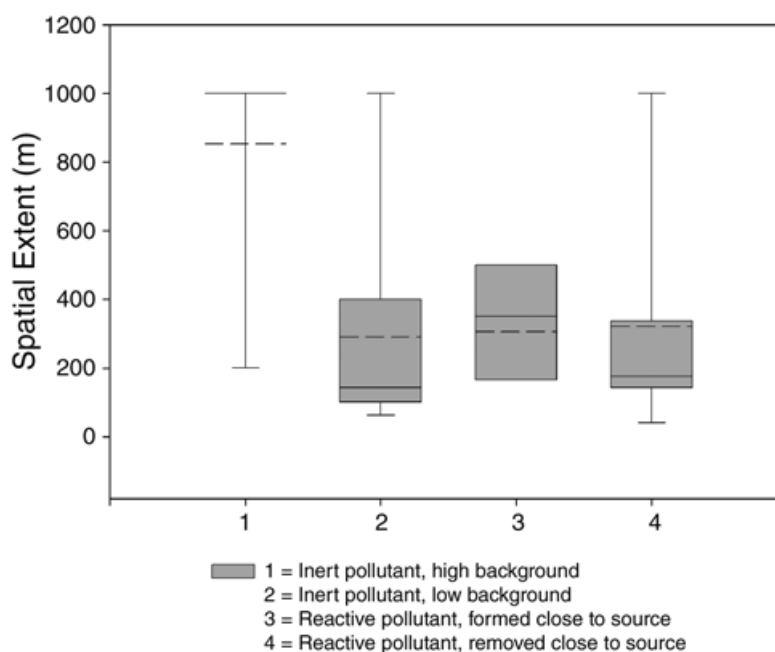
Figure 1. Results of a meta-analysis on the spatial-extent of traffic air pollution, stratified by pollutant type (Zhou and Levy, 2007). Boxplots indicate mean (dashed line), median (solid line in box), 25th and 75th percentiles (upper and lower ends of boxes) and 10th and 90th percentiles (upper and lower whiskers). Examples of pollutant types are 1: CO, benzene, Black Carbon, 2: PM mass concentration 3: NO_2 4: NO, ultrafine particles

More recently, Karner *et al.* (2010) also synthesized findings from 41 monitoring studies of traffic-related pollutant gradients and found gradients ranged from 100–500 m depending on the pollutant (Figure 2). CO had the smallest spatial gradient while secondary VOCs and fine and course particles had the largest spatial gradients.
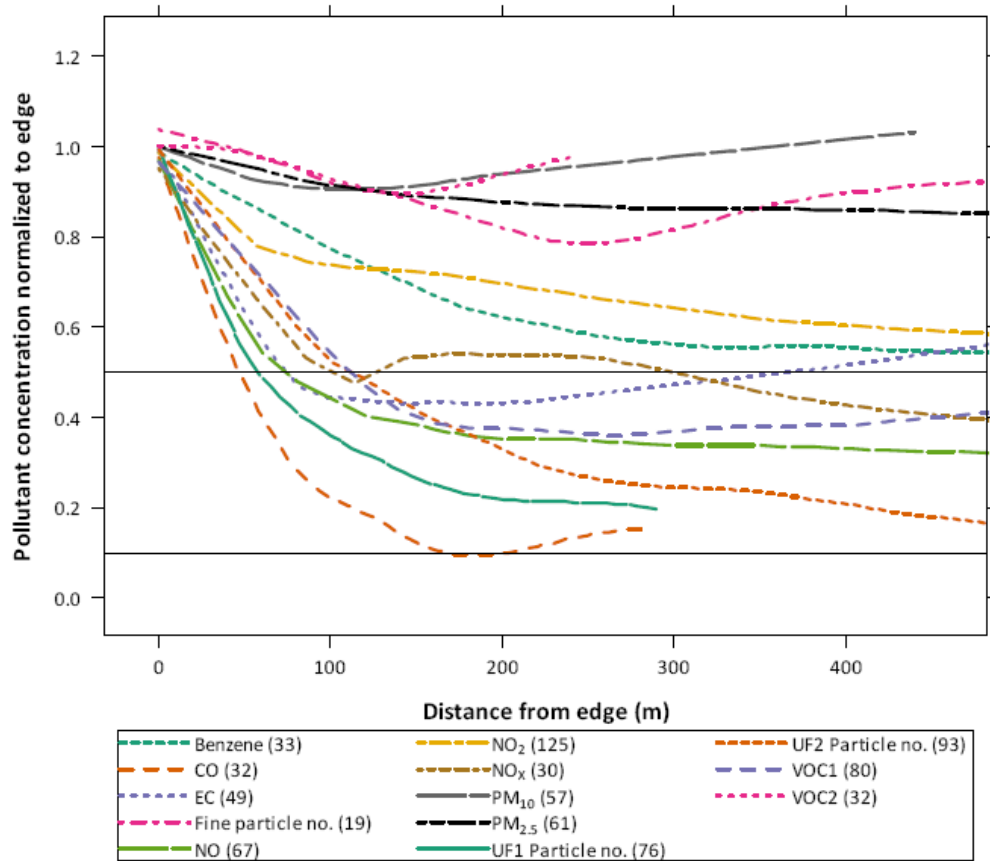
Figure 2. Estimated traffic pollutant gradients (Karner *et al.*, 2010). The horizontal black lines show a reduction from the edge of road concentration of 50% (at 0.5) and 90% (at 0.1). The number of published measurements (n) used to estimate the curve is given in parentheses after each pollutant.

4.1.2 Meteorological conditions and the street canyon effect

Meteorological conditions (especially wind strength and direction) and urban topography (in particular street canyons) are also major factors affecting TRAP gradients (Reponen *et al.*, 2003). Typically, pollutant gradients will differ on the upwind and downwind sides of major roads. For example, Beckerman *et al.* (2008) examined NO_2 and VOCs downwind and upwind at two transects of

Highway 401 in Toronto (with traffic volume of approximately 400,000 AADT) and found that both pollutants were elevated from 250–400m downwind from the roadway compared with upwind distances of 200 m (see Figure 3). Gilbert *et al.*, (2003) also documented NO_2 concentrations that were systematically higher on the downwind than upwind side of a busy highway in Montreal and found that concentrations decreased with the logarithm of distance. These Canadian results correspond to the HEI (2010) review of distance-decay gradients and the conclusion that on the upwind side of busy roads, TRAP concentrations drop off to near background levels within 200 m (except for particles, which drop to background within 100 m or less), and that on the downwind side, concentrations do not generally reach background levels until 300–500 m.
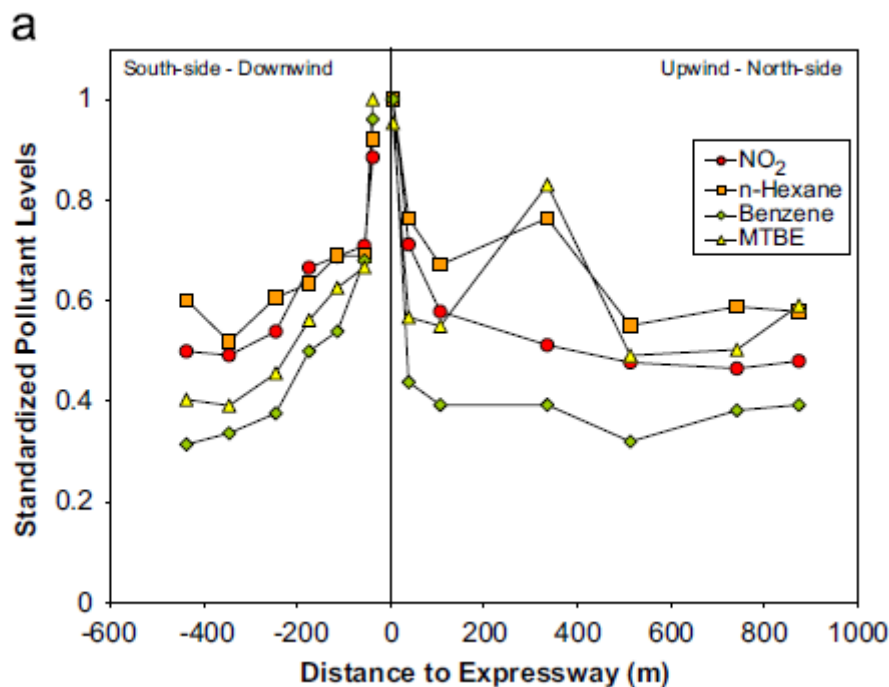
Figure 3. NO$_2$, and VOC concentrations upwind and downwind of an expressway in Toronto (Beckerman *et al*., 2008).

In addition to wind, other meteorological conditions that influence pollution concentration gradients include solar radiation (photochemical pollutant formation/transformation) and precipitation, which increases the rate of PM removal.

In urban areas, it is also important to consider the effect of physical infrastructure on TRAP concentrations. Tall, continuously adjoining buildings can create "street canyons", which may restrict the movement of air and result in increased concentrations of air pollutants that would otherwise be more rapidly dispersed (Raaschou-Nielsen *et al*., 2000). The street canyon effect is unlikely to be as important as meteorological conditions, but may influence TRAP concentrations in low- or no-wind conditions, or in situations where the prevailing wind direction is perpendicular to the street. A potential street canyon can be identified by calculating the ratio of the height (H) of buildings adjacent to roads to the road width (D). An H/D ratio above 0.7 suggests a canyon road with the

potential for TRAP accumulation (ADEME, 2002; Wehner *et al.*, 2002). The topic of using purpose-built infrastructure, or vegetative barriers, to shield populations from major roads is discussed in more detail in Section 3.

4.1.3 Traffic volumes

As mentioned above, the source strength of TRAP from a road is directly related to traffic volume and type. Thus, the absolute spatial scale of roadway gradients, and the concentration of pollutants at any given point, is ultimately determine by the number of vehicles on a roadway as well as the proportion of light-duty to heavy-duty vehicles in the traffic mix. For example, Figure 4 illustrates the difference in BC concentrations near two different freeways and the associated gradients (Zhu *et al.*, 2002).
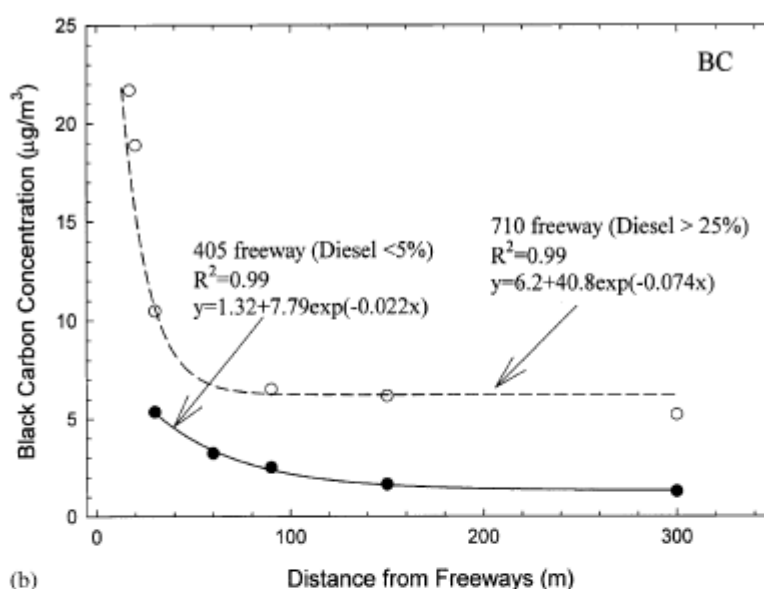
Figure 4. Black carbon gradients adjacent to two freeways (Zhu *et al.*, 2002).

Table 2 also illustrates the relationship observed between traffic volumes on several major roads and freeways, and the fractions of NO_2, BS, and $PM_{1.0}$ that

remain at 150 m from those roads (BC MOE, 2006a). The fraction of each pollutant and the % above background concentrations both varied significantly with traffic volumes.

Table 2. Fractions of pollutant concentrations (NO_2, black smoke, $PM_{1.0}$) at a distance of 150 m from major roads (from BC MOE, 2006a). The first 4 lines refer to NO_2, the next 3 to Black Smoke and the last line to $PM_{1.0}$

Study and Location		% Fraction of Maximum (close to road)	% Above Background (steady-state)	Traffic Data at Nearby Road (vehicles/day)
Singer et al., 2007 (LA)		0.55	0.5	200,000
Kodama et al., 2002 (Tokyo)		0.78	0.15	60,000
Gilbert et al., 2003 (Montreal)	NO_2	0.75	0.3	100,000
Roorda-Knape et al., 1998 (Netherlands)		0.6	0.1	100,000
Roorda-Knape et al., 1998 (Netherlands)		0.55	0.1	120,000
Zhu et al., 2002 (LA; high diesel)	Black Smoke	0.3	0.3	200,000
Zhu et al., 2002 (LA; low diesel)		0.3	0.5	200,000
Zhu et al., 2002 (LA; both)	$PM_{1.0}$	.15	n/a	200,000

Most of the distance-decay measurement studies conducted to-date have been on major highways (with traffic volumes above 100,000 AADT) and the scale of the resulting gradients are unlikely to apply to roads with less traffic

volume. In studies of TRAP exposure, variations exist in the procedures by which roads are classified, and how traffic activity is quantified. Traffic volume data are typically collected by municipalities in Canada and are difficult to obtain in standardized and systematic formats for large geographic areas.

For these reasons, road classifications are often used as surrogates for traffic volume (and this is the approach taken to estimate Canadian population exposures to TRAP in this document). Approximate traffic volume data by road class for two national road network classification systems (DMTI and DRA) are given in Table 3. Based on this information, all major roads (sometimes classified as secondary highways or arterials) with annual average daily traffic levels of ~15,000 AADT are considered important local sources of TRAP. Since the total area impacted by TRAP increases as the traffic volume increases, where traffic count data are available in general they will provide a better indicator of TRAP exposure than simple road classification. Data sources for a selection of regions and municipalities are listed in Table 4. Permanent counts are available at selected locations on highways and some major roads (e.g. from the Ministry of Transportation in BC), while municipal data is usually for much shorter averaging periods, such as for peak morning (two hours) or evening traffic periods. There is, however, only a moderate relationship between these shorter-term measurements and the longer-term averages that are most relevant for health assessment, because traffic volumes vary dramatically on a diurnal basis.

Table 3. Road categories for and traffic volumes for Metro Vancouver, based on two Canadian road network classifications (BC MOE, 2006b). Shaded rows show roads considered to have important TRAP influence, based on traffic volumes.

DMTI Class	*AADT (mean)*	DRA Class	*AADT (mean)*
Local	6,500	Local	4,000
Major	15,000	Collector	9,000
Highway Secondary	18,000	Arterial	18,500
Highway Principal	21,000	Highway	28,000
Expressway	>115,000	Freeway	>115,000
Expressway (Toronto) *	>350,000	N.A.	>400,000

* Traffic volume on Highway 401 through Toronto included for comparison.

Table 4. Examples of traffic volume data sources for selected Canadian provinces and municipalities

| Region	Details	Data available at:
British Columbia	AADT from permanent and "short counts" (48 hour)	www.th.gov.bc.ca/trafficData/index.asp
Ontario	AADT by road-section	www.mto.gov.on.ca/english/pubs/trafficvolumes.shtml
Alberta	AADT by road-section	http://www.transportation.alberta.ca/3459.htm
City of Vancouver	Automatic counts (24 hour), both directions	http://data.vancouver.ca/datacatalogue/trafficCounts.htm http://vancouver.ca/vanmap/t/trafficCounts.htm
Toronto	Average Weekday, (24 Hour average)	www.toronto.ca/transportation/ publications/brochures/24hourvolumemap.pdf

4.2 *Estimates of Canadian populations' exposure to TRAP*

The HEI (2010) report estimated exposure to TRAP for Toronto and Los Angeles populations residing within 500 m of a highway and within 100 m of a major road. These distances were determined from their review of the literature and are meant to represent TRAP gradients around highways and major roads (HEI, 2010). The distances represent conditions without significant influence from meteorology, buildings and other topographic features. In Metro Toronto it was estimated that approximately 45% of the total population are exposed to TRAP and 44% in Los Angeles.

Here we have applied the same distance criteria to estimate the Canadian population that is exposed to TRAP, defined as those living within 500m of a highway or 100m of a major road. The national road network provided by DMTI CanMap® Street was used with expressway, primary and secondary highway classifications representing "highways" and the major road classification representing "major roads". Statistics Canada 2006 block-point data, each of which represents the location of approximately 89 individuals, was used to locate the Canadian population within 500 and 100 m buffers around highways and major roads respectively. Figure 5 and 6 illustrate the resulting exposure areas considered to be significantly influenced by TRAP for Vancouver and Toronto. Table 5 summarizes these population exposure results, reported by Province. Nearly one-third of the Canadian population (10 million individual) are exposed to TRAP.
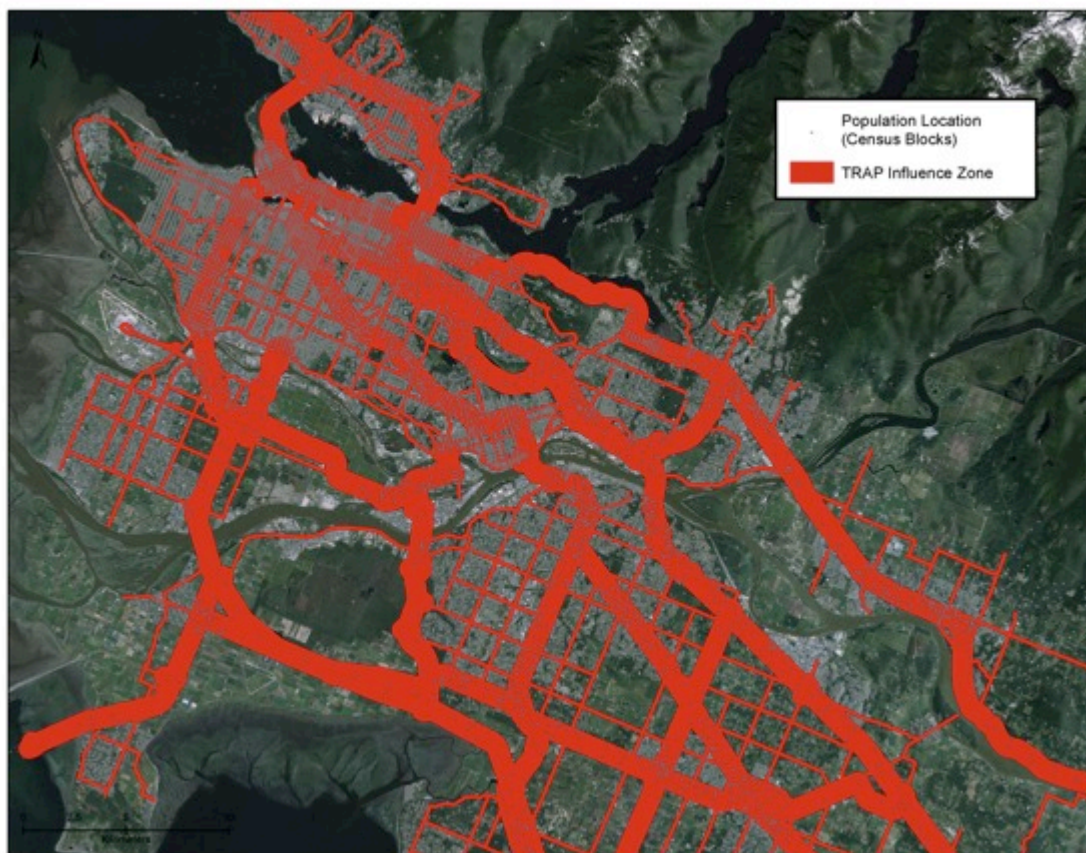
Figure 5. TRAP influence zones in Vancouver.
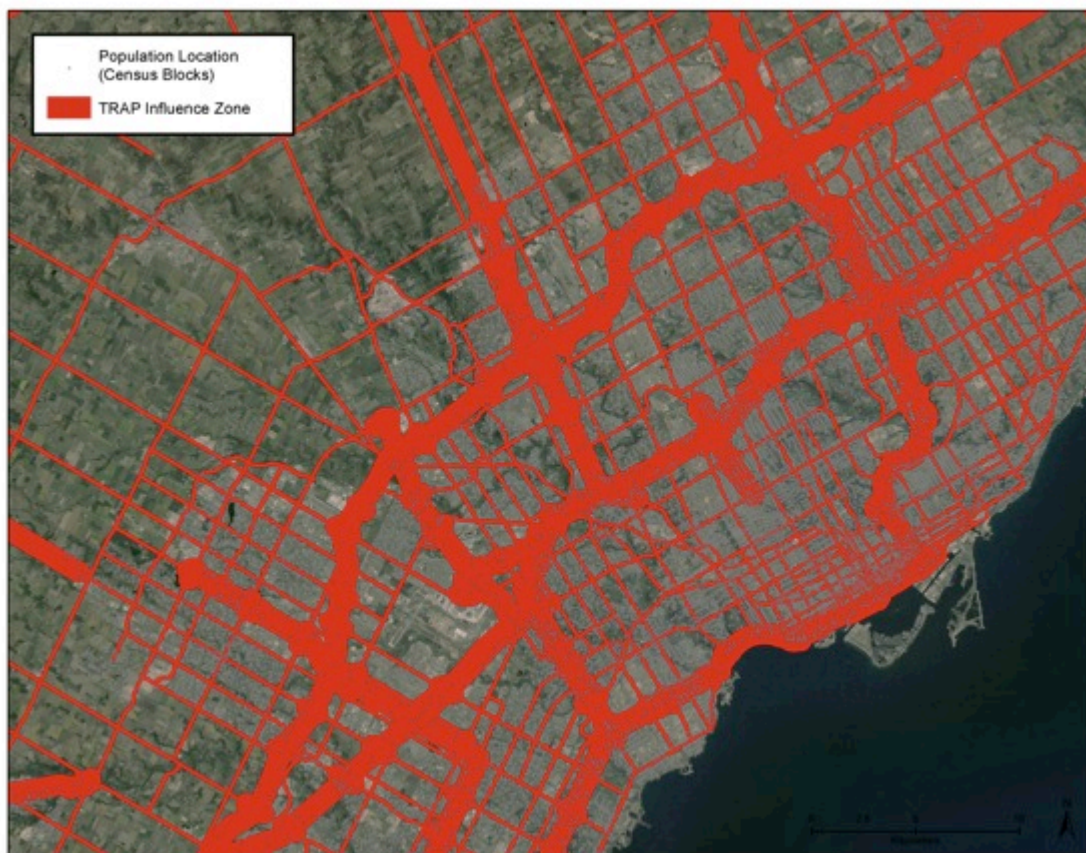
Figure 6. TRAP influence zones in Toronto.

Table 5. Summary of the number of individuals, by province, living within 500m
of a highway or 100m of a major road (analysis for this study).

Province	Population Exposed
Alberta	905,280 (27%)
British Columbia	1,502,500 (37%)
Manitoba	311,480 (27%)
New Brunswick	214,080 (29%)
Newfoundland	89,500 (18%)
Northwest Territories	4,130 (10%)
Nova Scotia	304,030 (33%)
Ontario	3,066,710 (25%)
Prince Edward Island	53,130 (39%)
Québec	3,184,430 (42%)
Saskatchewan	404,870 (42%)
Yukon Territory	7,770 (26%)
Canada	**10,047,910 (32%)**

*No estimates available for Nunavut. The national road network
provided by DMTI CanMap® Street was used with expressway,
primary and secondary highway and major road classifications.
Statistics Canada block-point data, each of which represents the
location of approximately 89 individuals, was used to produce
estimates of populations residing within 500m of a highway or
100m of a major road.

The above population exposure calculations are supported by another
study, in which indicators of TRAP exposures have been estimated using
measures of the Canadian population residing within 50, 100, 250 and 500m of a
major road (Evans *et al*., 2011). Although different road proximity measures were
used, that analysis indicates very high proportions of urban populations exposed
to TRAP (Table 6). For example, the Toronto metropolitan area had the highest
proportion of residents exposed to TRAP (82% within 500 m of a major road)
followed by Vancouver (74%).

This study also provides a lower and upper bound estimate for the number of Canadians exposed to TRAP, similar to the lower and upper bound estimates produced by the HEI (2010) report. As a lower bound estimate (individuals within 100m of a major road or highway) 4,089,165 individuals (13% of the Canadian population) are exposed to TRAP, while as an upper bound estimate (individuals within 500m of a major road or highway) 16,931,060 individuals (54% of the Canadian population) are exposed. For further details on the method and results of the proximity analysis see Evans *et al.* (2011).

Table 6. Summary of the populations residing with 50, 100, 250, and 500 m of a major road, by metropolitan areas (Evans *et al*., 2011).

City	Buffer distance (m)			
	50	100	250	500
Toronto	643,260 (13%)	1,239,110 (24%)	2,842,485 (56%)	4,184,675 (82%)
Montreal	135,795 (4%)	312,975 (9%)	888,160 (24%)	1,585,700 (44%)
Vancouver	224,945 (11%)	442,225 (21%)	1,030,320 (49%)	1,567,520 (74%)
Ottawa	75,690 (7%)	167,125 (15%)	392,795 (35%)	596,635 (53%)
Calgary	13,330 (1%)	34,300 (3%)	109,985 (10%)	257,770 (24%)
Edmonton	9,870 (1%)	29,405 (3%)	106,105 (10%)	243,425 (24%)

* 2006 Census representative point file and the National Road Network (arterial, expressway/highway, and freeway classifications considered as major roads) were used to estimate proximity.

In a separate analysis, Amram *et al*., (2011) evaluated the number of public elementary schools in the 10 largest Canadian cities within an exposure zone defined as <75 m from major roads. Across all 10 cities, 16.3% of schools were located within 75 m of a major road, and 36.1% within 200 m. When considering only expressways or principle highways, 4.7% of schools were located within 200 m, ranging between 0% in both Calgary and Hamilton and 16.0% in Montreal. Schools in neighbourhoods with lower median income were more likely to be near major roads. These results are similar to findings reported

for the U.S., where 33% of schools in 9 major U.S. cities were within 400 m of a major roadway and nearly 12% were within 100 m (Appatova *et al*., 2008). These analyses are also supported by studies indicating that TRAP concentrations inside schools are associated with road proximity, surrounding traffic density and the vehicle composition on nearby roads (Janssen *et al*., 2001; 2003) and relationships between particle levels on school athletic fields and road proximity (Rundell *et al*., 2006).

Approximately 10 million individuals (32% of the Canadian population) live within 100m of a major road or 500m of a highway. Of these, approximately 2 million individuals live within 50m of a major road. In addition, approximately one-third of Canadian urban elementary schools are located in zone of high traffic proximity. These individuals are at risk from the negative health effects association with traffic air pollution. Thus, while Canadian cities generally have relatively low levels of ambient background air pollution, the large number of individuals at risk from traffic-related air pollution indicates a significant public health concern in Canada.

5. Potential exposure-mitigation strategies

The previous section has demonstrated that almost one third of the Canadian population live within TRAP exposure zones (100 m of a major road or 500 m of a highway) and that one third of elementary schools are located in areas of high traffic. Since these individuals may face an elevated risk of the health effects from TRAP exposure described in Section 1, it is important to

consider what options are available to mitigate exposure. It is also important to examine how individuals are exposed to TRAP in other microenvironments, such as during active commuting, and options to mitigate exposure. The aim of this section is to provide an overview of the interventions that are available to policy-makers in municipal and regional governments, with particular reference to cases where guidelines and/or legislation have been successfully implemented. Canadian examples are highlighted wherever possible.

Four main approaches to mitigating exposure to traffic-related air pollution have been identified:

(a) **Land-use planning and transportation management**, e.g. siting of new buildings and roads, road setbacks, spatial and/or temporal limitation of motor vehicle activity (especially heavy-duty diesel vehicles) near densely populated areas, and separation of motorized from active transportation modes;

(b) **Reduction of vehicle emissions:** identifies the importance of controlling emissions at their source, using approaches such as new vehicle emission regulations, fuel quality standards and inspection and maintenance programs for the existing fleet;

(c) **Modification of existing structures**, which includes implementation of outdoor measures such as physicals barriers and separation of bicycle lanes, as well as indoor measures such as air filtration;

(d) **Encouraging behaviour change**, for example, by offering alternatives to private vehicles such as car-sharing and improved public transport, and by educating people about the impact of their transportation choices on pollution emissions, as well as exposure to TRAP.

A distinction has not been explicitly made between urban and rural areas in the discussion of these approaches. More of the reviewed studies have been carried out in urban areas, and legislation and guidelines tend to be designed by municipalities for urban areas because that is where most of the exposed population resides. However, many of the approaches (such as land-use

planning, and building modifications) could also be applied to rural populations near major roads with high traffic volumes. In addition, we focus on approaches to reduce exposure to exhaust emissions and do not directly consider strategies (e.g. bans on use of studded tires [Asano *et al.*, 2002] or road surface cleaning [Keuken *et al.*, 2010]) that will reduce non-exhaust emissions from brake and tire wear (Kupiainen *et al.*, 2005). Some of the approaches described below – in particular those reducing traffic volumes or improving traffic flow and those related to land use and transportation management – will also likely lead to reductions in non-exhaust emissions from motor vehicles.

5.1   Land-use planning and transportation management

With growing awareness of links between the built environment and health disparities, public health agencies have argued for urban and transportation planners to consider health impacts and health costs in transportation and land use decisions (APHA, 2011; Perrotta, 2011; ALA, 2010). Included among these, are impacts related to TRAP exposure. This awareness suggests opportunities for co-benefits that may lead to healthier communities via multiple routes such increased opportunities for active transport and physical activity, improvements related to traffic, pedestrian and cyclist safety, reductions in overall air pollutant and greenhouse gas emissions, along with reductions in TRAP exposure (Perrotta, 2011; WHO, 2011b).

To mitigate population exposure to TRAP, it has been recognized that one of the most important long-term strategies available to municipal governments is to modify the urban built environment so that motor vehicle traffic is separated from the spaces where people spend most of their time (Giles *et al.*, 2011). Separation can be achieved through spatial or temporal means – in broad terms, the former can be achieved by land use planning (e.g. legislation about setbacks of new schools from highways and major roads), and the latter can be achieved by transportation management (e.g. a by-law restricting truck traffic through

urban areas during daylight hours). A range of options are explored below, with examples of legislation and municipal guidelines from Canada and internationally. A challenge with land-use planning as an exposure-mitigation strategy is that it can take a relatively long time (years to decades) for change to be realized. In contrast, transportation management approaches that directly influence vehicle flows on urban routes may have a more immediate impact.

5.1.1 Land-use planning

Particular attention has been given in legislation to the location of buildings that house susceptible populations, such as hospitals, schools and daycares. The State of California has been a leader on many air quality issues. In 2003, it passed Senate Bill No. 352, an amendment to previous legislation for planning and siting of public schools (State of California, 2003). This amendment prohibits the location of any school site within 500 feet (150 m) of a freeway or other busy traffic corridor. The State of California defines a busy traffic corridor as roadways that experience greater than 50,000 AADT in a rural area or greater than 100,000 AADT in an urban area. Before a school site is given approval, the school district must prove they are in compliance with the setback. Alternatively, if the proposed school site is within the setback, the school district is required to determine, through specified risk assessment and air dispersion modeling and after considering any potential mitigation measures, that neither short-term nor long term exposure poses significant health risks. This is determined using the California Air Resources Board (CARB) Ambient Air Quality Standards and modelling techniques for the key traffic-related air pollutants (CARB, 2009). If the school district cannot comply with either option described above, a site may still be approved if an alternate site is not available and an urgent need for the school is identified. Similarly, legislation was also passed in New Jersey in 2008 (State of New Jersey, 2008). Called "Terrell James' Law", it concerns the siting of new schools with respect to highway entry/exit ramps, and states that no new ramp

can be constructed within 1,000 feet (approximately 300 m) of an existing school, and vice versa (unless no alternative can be found). In San Francisco, land use guidance suggests a potential hazard exists if average daily traffic exceeds 100,000 vehicles/day within a 200 meter radius of a site (roughly equivalent to the State of California definition above), 50,000 vehicles/day within a 50 meter radius or 10,000 vehicles/day on an immediately adjacent street (Bhatia and Rivard, 2008). The latter two thresholds are equivalent with respect to area traffic volume density.

Within Canada there are at least two examples of published land use guidelines that directly address TRAP. The British Columbia Ministry of Environment published voluntary environmental guidelines for urban and rural land development that included air quality best management practices (BC MOE, 2006b). Buildings that primarily house susceptible populations, such as schools, hospitals, or long-term care facilities, should be set back 150 m from busy roads experiencing more than 15,000 AADT. In addition, the guidelines recommended that development on truck routes should be avoided, as well as development that results in street canyons that can lead to elevated levels of TRAP. Specifically, staggering buildings that are perpendicular to the predominant wind direction or allowing high-rise buildings only on one side of a road are recommended. In comparison to the Californian legislation described above, the BC guideline has the potential to offer considerably more protection to susceptible populations because a "busy road" is defined as one that has traffic volumes of greater than 15,000 AADT – almost one seventh of the definition in the California legislation. In 2009, the Regional Health Department in Halton, Ontario, published a document entitled "Protecting Health: Air Quality and Land Use Compatibility", which offered suggestions for consideration by the Sustainable Halton and Halton Regional Official Plan Review processes (HRHD, 2009). The suggestions in this report mirror the US legislation mentioned above: it recommends that residences, hospitals, schools, child care facilities, and nursing homes should not be located within 150 m of highways with greater than 100,000 AADT, or 30 m

from roads with greater than 30,000 AADT. This report also takes future road widening into consideration.

Outside of North America, the Regional Public Health Service in Auckland, New Zealand, provides analogous guidelines for the siting of early childcare centres. The recommendation is that such centres, which cater to children age 4 and under, are not to be located either within 60 m of district or regional arterial roads, within 150 m of roadways, within enclosed parking facilities, within 300 m of industrial zones, or within 100 m of petrol stations (ARPHS, 2009a). They advise that these recommendations should be incorporated into local authority plans to ensure that developers of early childhood centres avoid hazardous locations. The "Health & Safety Guideline for Early Childhood Centres" (ARPHS, 2009b) is a published tool for early childhood centre operators whose centre is to undergo a health and safety assessment by the Auckland Regional Public Health Service. This guide summarizes the relevant health standards, including those regarding traffic exposure as outlined in the "Position Statement on Air Quality and Early Childhood" (currently pending clarification of Ministry of Health policy intentions), that early childcare centres must comply with in order to obtain an operating licence from the Ministry of Education. The surrounding environment in relation to air quality is scrutinized, including current location of major roads adjacent to the facility and future transport and development plans. Under these guidelines, a number of new early childcare centres in Auckland have either been refused licences or are operating on provisional basis pending the results of air monitoring by the Health Ministry, due to air quality concerns (Fisher and Shepheard, 2009).

In some instances, legislation is passed that may significantly influence air quality and population exposure to TRAP, although that is not its intention. For example, the State of California recently passed Senate Bill No. 375 (SB 375), the Sustainable Communities and Climate Protection Act (State of California, 2008). The aim of this Bill was to reduce greenhouse gas emissions through

integrated land use planning and transportation management, also known as "smart growth". While SB 375 does not specifically identify air quality as an endpoint, many aspects of the legislation are expected to have air quality co-benefits, and consequently to reduce population exposure to TRAP. Current efforts aim to modify community design in ways that reduce CO_2 emissions from vehicles and improve community health by increasing opportunities for neighbourhood walkability (Frank *et al*., 2006). From a public health perspective, it is important to simultaneously consider population exposure to TRAP, as part of efforts to seek health and climate co-benefits (Younger *et al*., 2008).

The American Lung Association in California has published an analysis of the relationship between smart growth and health (ALA, 2011). This study quantified the air quality impacts of SB 375 by assuming a gradual reduction in annual vehicle miles traveled in Southern California. By 2035, if a 20% reduction in vehicle miles traveled is achieved, the study estimates that the region could avoid $16 billion in cumulative health and societal costs. Although not focussed on air quality, CARB has also published a series of policy briefs describing their research on policies related to Bill 375, and their impacts on transportation and land use (CARB, 2011).

Related to California's smart growth strategy, mentioned above, is a general trend towards promoting higher density in North American cities. This is usually achieved by changing by-laws to encourage "urban infill", and the building of additional residential units where they were not previously permitted. However urban infill may have air quality implications for the new and existing residents. In San Francisco, location and design of new urban infill requires development review and approval processes (San Francisco Department of Public Health, 2008).

Some useful resources are available for policy makers who wish to include consideration of exposure to TRAP within an urban planning framework. For

example, CARB has produced an "Air Quality and Land Use Handbook", a reference guide for evaluating and reducing air pollution impacts associated with new projects that go through the land use decision-making process (CARB, 2005). The CARB handbook focuses on susceptible populations such as school children, and recommends that proximity be considered in the siting of new sensitive land uses. It also considers the location of industrial point sources of pollution, but points out that mitigation of exposure to diesel PM is one of their highest public health priorities. The Sacramento Metropolitan Air Quality Management District has also produced some helpful procedural documents, including a protocol (last revised in January 2011) for evaluating potential locations for "sensitive land uses" adjacent to major roadways (Sacramento Metropolitan AQMD, 2005). Again, the main concern raised is exposure to diesel PM from heavy duty-vehicles on highways and freeways, and the protocol focuses on assessing cancer risk from diesel PM. More generally, health impact assessment (HIA) can be employed to assess potential benefits of various local strategies to reduce TRAP exposure. For example, Schram-Bijkerk *et al*. (2009) demonstrated the feasibility of applying HIA in the local land-use planning context and compared the benefits of traffic speed reductions with a specific traffic re-routing plan. In this example, the benefits of both local interventions on traffic-related health exposures (including TRAP and noise) were small compared to their total burden in The Netherlands.

5.1.2 *Transportation management*

A range of policy and regulatory options are available to municipal governments related to transportation management, though their practical and political feasibility will depend on the circumstances of the region in question. As mentioned earlier, while road setbacks are an important tool for TRAP exposure mitigation, they are a long-term strategy and can be very difficult to implement in the context of smart growth measures, and indeed may seem to be

contradictory to urban densification. In this section, therefore, the management of motor vehicle traffic is discussed from a TRAP exposure mitigation perspective. Then active transportation users (walkers and cyclists) are considered, since these road users can experience particularly elevated TRAP exposure during their travel.

Management of motor vehicle traffic:

In addition to the evidence presented in Section 1 of this document, one study has specifically studied the impact of traffic congestion on infant health by examining exposed populations near US highway toll plazas (Currie and Walker, 2011). The study examined the introduction of an electronic toll and found that the resulting reduction in traffic congestion was associated with significant decreases in premature birth and low birth weight in infants living near the toll plazas. This finding is also supported by an earlier study by Ryan *et al*. (2005), which suggests that "stop-and-go" traffic may be a more important predictor of childhood wheeze than total traffic volume. The relationship between vehicle speed and emissions is well-known and a large number of programs have been implemented to improve air quality along heavily trafficked roads via speed reductions, such as the implementation of an "environmental speed limit" of 60 km in Oslo (OECD, 2011). Recent research, however, suggests the effectiveness of these programs to be enhanced when traffic dynamics are also considered (Keuken *et al*., 2010). A pilot speed management program implemented in The Netherlands was shown to reduce the level of TRAP emissions. Specifically, reduction in traffic speed to 80 km/h, combined with strict (camera and automatic fines) enforcement to reduce speed variability, and the resulting emissions related to deceleration and acceleration, reduced NO_X and $PM_{2.5}$ emissions by 5-25% (Keuken *et al*., 2010).

A variety of traffic management interventions have been attempted – and studied – in London, England, since it has historically had some of the highest

NO_2 and PM concentrations in Europe (Kelly and Kelly, 2009). The most well known measure implemented to tackle traffic congestion in London is the Congestions Charging Scheme (CCS), which restricts the number of vehicles entering central London each day (Transport for London, 2006). The CCS appears to have had a significant impact on traffic volumes within the charging zone, with a reduction of approximately 20% compared to pre-CCS volumes; in comparison, roads outside the zone have not had a reduction in traffic volumes over the same period (Kelly and Kelly, 2009). In conjunction with the CCS, London implemented a Low Emission Zone (LEZ) in 2008, which aims to discourage the most polluting heavy-duty goods vehicles (most of which have diesel engines) from entering the city (Transport for London, 2007). The LEZ extends across greater London and is in effect 24 hours per day, 365 days per year. Polluting vehicles that do not meet modern Euro emission standards must pay a significant charge for each day they operate in the zone (Kelly and Kelly, 2009).

Tonne *et al*. (2008) estimated the mortality and air quality impacts of the London CCS, and found that NO_2 and PM concentrations were reduced compared to surrounding areas. That study concluded that a modest benefit in air quality and life expectancy were achieved by the policy, the latter quantified as an increase of 183 life-years per 100,000 people (compared to 18 years among the non-affected areas nearby). However a more recent assessment found that the anticipated reduction in TRAP concentrations due to the CCS and LEZ may not have been as significant as initially projected, despite reductions in average traffic volumes (Kelly *et al*., 2011). The authors suggest that this finding is attributable to mode-shifting away from personal gasoline-fuelled vehicles, and towards diesel-fuelled taxis and buses. Further, simulation studies suggest that while congestions charging approaches are do reduce total emissions, more specifically they reduce emissions within the charging zone at the expense of localized increases emissions outside the zone (Namdeo and Mitchell, 2008).

The potential impacts on population exposure of CCS-type approaches must therefore be carefully evaluated.

A different approach to managing vehicle emissions is to prohibit idling within urban areas, and this may extend beyond on-road traffic to rail locomotives and other off-road equipment, such as construction vehicles. Studies of vehicle idling in school zones in New York during dismissal times have shown that diesel vehicle idling (e.g. school buses) is associated with elevated concentrations of black carbon, and – to a lesser extent – $PM_{2.5}$ outside of schools (Richmond-Bryant *et al.*, 2009; Richmond-Bryant *et al.*, 2011). Municipalities can target pollutant emissions by implementing anti-idling bylaws. For example, the Cities of Vancouver and North Vancouver in the Metro Vancouver region have idling bylaws that prohibit vehicles from idling for more than 3 minutes, with violators incurring fines of $50 to $100 (City of Vancouver, 2006).

An indirect approach to decreasing traffic in urban areas is through parking policy. For example, Perth Australia developed a comprehensive parking policy and license fee in 1999 to address increasing congestion and deteriorating air quality in the urban center. The policy created strict legal maximum levels of parking for new non-residential development within the city and establish three parking zones to control public parking – a pedestrian priority zone where no parking is permitted; a short stay zone where long stay (all day) parking is not permitted; and a general parking zone, which is on the perimeter of the city (Richardson, 2010). Ten years after implementation of the Perth parking policy there has been a 10% reduction of parking within the City of Perth; the mode share of journey to work in central Perth has shifted significantly from car to public transport; and car travel on city streets and on approach roads to the city has decreased (Richardson, 2010).

Active transport users

To estimate the extent of population exposure in a region, studies normally assume that the TRAP concentration at an individual's residence represents their typical exposure. This is regarded as a reasonable assumption, given the need for large sample sizes for epidemiological studies, and the challenge and cost of collecting real-time exposure data using personal monitoring. Nonetheless, an important subgroup of the population that is exposed to higher concentrations of TRAP on a regular basis is people who use active transport (such as cycling, walking, or jogging) to get around.

A number of studies have evaluated air pollution exposure levels of bicycle commuters, including exposures to ultrafine particles (<0.1 μm aerodynamic diameter), fine particles (2.5-10 μm aerodynamic diameter; $PM_{2.5}$), coarse particles (≥10 μm aerodynamic diameter; PM_{10}), carbon monoxide, ozone, sulphates, and compounds such as benzene and toluene (Thai *et al*., 2008; Bevan *et al*., 1991; van Wijnen *et al*., 1995; Kaur *et al*., 2007; Strak et al., 2010). In general, these studies demonstrate the potential for cyclists to experience elevated exposures to air pollutants due to their proximity to traffic emissions. Concentrations encountered by cyclists are similar in magnitude to those of car drivers, but their increased respiration rate may increase the dose of TRAP received. In addition, given that cyclists will generally require longer time periods than car passengers to travel from a given origin to a given destination, it is likely that they will experience higher exposures due to the longer trip duration.

Exposure mitigation is possible, even for active transport users. A recent study suggests that cyclist exposures are dependent upon the specific locations of cyclists relative to motor vehicles (Kendrick *et al*., in press). For example, displacement of cycling paths even 1-2 meters further away from roads (for example by placement of a physical barrier or a row of parked cars) has been shown to reduce particle number concentrations in cycle lanes by 8-38%. A

Canadian study of TRAP along designated cycling routes in Vancouver found that the concentrations of air pollutants encountered by cyclists differed according to the proximity of the cycle route to traffic (Thai *et al*., 2008), where higher concentrations were measured on cycle routes immediately adjacent to traffic compared to those located on residential roads that were displaced by one block from major arterials. These findings suggest, therefore, that transportation networks may be designed to limit air pollution exposures of cyclists. Community planning needs to consider sustainable transportation options such as active transportation, and improve infrastructure such as adding sidewalks and bike routes. Other options include rerouting or reducing vehicle traffic away from active transportation corridors. Particular attention needs to be paid to the safe design of infrastructure for cyclists and walkers. A recent review by Canadian researchers (Reynolds *et al*., 2009) examined the impact of transportation infrastructure on cyclist safety, and concluded that cycling-specific infrastructure such as separated bicycle lanes are safer for cyclists. New evidence from a unique case-crossover study of cyclist injuries in Vancouver and Toronto has confirmed that finding (Teschke *et al*., in press), which suggests that separated routes for cyclists could be a "win-win", reducing both risk of injury and TRAP exposure. To aid active transport users to avoid TRAP exposure, new online tools are being developed that enable cyclists and pedestrians to avoid traffic. In Vancouver, a cycling route planner is available that allows users to select "least traffic pollution" when selecting route preferences (Su *et al*., 2010).

5.2   Reduction of vehicle emissions

In recognition of the evidence that TRAP is associated with serious health concerns, especially in urban areas, policies to control vehicle emissions have been enacted in many jurisdictions, and the main approaches are outlined below. Particular attention is given to inspection and maintenance programs, designed to identify high-emitting vehicles in the in-use fleet, since such programs are

---

gaseous and particulate emissions of those from two decades ago, yet fuel-specific performance has steadily increased (Oliver, 2005).

Fuel quality also affects vehicle emissions, and is also normally regulated at the Federal/Provincial level. The removal of lead (a potent neurotoxin) from gasoline has been described as one of the greatest public health achievements of the 20th century (Bridbord and Hanson, 2009). There is also evidence that combustion of unleaded gasoline produces less HC, CO and PM emissions (Yuan *et al*. 2000). More recently, there have been efforts to limit the content of the carcinogen benzene in gasoline, since public exposure to this chemical is primarily from mobile sources (Smith, 2010), including both tailpipe and evaporative emissions. Low-sulphur fuel is important to minimize SO_2 emissions from vehicles, and allows the use of advanced emissions control devices such as the three-way catalyst for gasoline engines, and the diesel oxidation catalyst and diesel particulate filter. In Canada, diesel and gasoline have "ultra-low" fuel sulphur content (gasoline must have average sulphur content of less than 30ppm and is "never to exceed" 80ppm, and the diesel limit is 15ppm).

Despite the significant impacts of federally regulated new vehicle emission standards and fuel-quality standards, emissions control devices deteriorate as vehicles age, and engine malfunctions can cause tailpipe pollutant emissions to increase by orders of magnitude. Therefore it is desirable to identify means of controlling emissions from the in-use fleet in addition to implementing emissions standards for new vehicles. Approaches to achieve this include implementing inspection and maintenance programs at the provincial or regional level, retrofitting older vehicles with after treatment devices, and switching to alternative fuels (e.g. natural gas) or new technologies (e.g. hybrid-electric or electric vehicles).

5.2.2 Emission control policies for the in-use fleet

Older vehicles are more likely to have problems with their engines or emission control systems that result in high tailpipe emissions. Consequently, vehicle age (in terms of years or kilometres traveled) is positively correlated with higher pollutant emissions (Beaton *et al*., 1995). Policies to scrap older vehicles in a region can be an effective means of achieving emission reductions (e.g., the BC Scrap-It Program, http://www.scrapit.ca/), but it is a blunt instrument. A major problem with such age-based vehicle scrappage programs is that they are likely to disproportionately impact lower-income vehicle owners and operators. From an equity perspective, therefore, it can be regressive to require large-scale replacement of in-use vehicles before the end of their useful life. Also, it is well known that vehicle age is not the only predictor for vehicle emissions.

In addition to vehicle age, it has been consistently found that the majority of emissions are from a small fraction of malfunctioning vehicles (Beaton *et al*., 1995; Mazzoleni *et al*., 2007). When implemented correctly, I/M programs can be an effective way of identifying those high-emitters. I/M programs require that vehicle (or fleet) owners have their vehicles' emissions checked at regular intervals. If emissions measurements do not meet the regulatory limit for a given vehicle's category, the program then either levies a fine or can embargo vehicle registration pending engine maintenance and retesting. Mandatory vehicle retirement may be considered as an option only once repair of high-emitting vehicles is ruled out as an option.

Internationally, most existing I/M programs are designed to control gaseous emissions from light-duty vehicles (St. Denis *et al*., 2005), but they have also been used successfully with heavy-duty fleets (Van Houtte and Niemeier, 2008). One reason for the lack of widespread HDV emission testing is that the instrumentation required to accurately measure PM from vehicles is more complex and expensive than for gaseous pollutants. The most comprehensive

study of the effectiveness of HDV I/M programs found an average reduction in PM emission factor of more than 40% with repairs on vehicles exhibiting visible smoke emissions; average per-vehicle repair costs in the study were approximately $1000 (McCormick *et al*., 2003). The overall cost-effectiveness of such an intervention would depend on the prevalence and usage of high-emitting vehicles along with the programmatic costs. In theory, I/M programs ensure that all vehicles operating in a given region emit less than the in-use emission standard set by regulators. Inspection and maintenance (I/M) programs that identify high-emitting vehicles from the in-use fleet can be successfully implemented at the regional or municipal level, as exemplified by Metro Vancouver's AirCare program (Taylor Consulting, 2002) and Ontario's province-wide Drive Clean program. More I/M programs are planned: the Quebec government recently introduced legislation that will mandate emission testing for vehicles eight years and older.

5.2.3 Heavy-duty diesel vehicles

Because the diesel engine is the most efficient, robust and cost-effective form of conventional motive power available today, it powers almost all of the world's heavy commercial goods vehicles. Unfortunately, although heavy-duty diesel engines are more fuel-efficient than spark-ignition engines, they emit far more particulate matter per vehicle or per litre of fuel burned. A study of mobile source emission trends in the United States from 1996 to 2006 found that average PM emissions per mass-fuel-burned in 2006 were approximately 10 times higher for HDDVs than for light-duty gasoline vehicles (Dallmann and Harley, 2010). Since HDDVs burn more fuel per distance travelled than LDVs, the ratio of PM emitted per km would be several-fold greater. This implies that special attention must be paid to the proportion of heavy-duty to light-duty vehicles in the traffic on a given roadway, not simply the absolute traffic volume.

Emission-reduction strategies must consider both diesel (heavy-duty) as well as gasoline (light-duty) vehicles.

Fleets of heavy-duty diesel vehicles that operate in residential neighbourhoods, such garbage-collection vehicles, present an opportunity for reduction of tailpipe emission of diesel PM, one of the most important components of TRAP. In recognition of this fact, the Federation of Canadian Municipalities (FCM) delivered an "Enviro-Fleet" pilot program between 2009 and 2011, designed to help municipal fleet managers reduce TRAP and GHG emissions. A guide to best practices was produced (FCM, 2010), but it focuses primarily on means of reducing fuel consumption and GHG emissions. Targeted retrofits for older vehicles can also reduce TRAP pollution, particularity for susceptible populations or high pollution areas. Retrofits of old diesel school bus fleets have been conducted in a number of areas in the US, such as in Washington State (Boyer and Lyons, 2004). Beatty and Shimsharck (2011) examined the impact of this school bus retrofit program by comparing differential trends for adopter districts and non-adopter districts over time and found reductions in bronchitis, asthma, and pneumonia incidence for at-risk populations. They also estimated benefit-cost ratios between 7:1 and 16:1 for the bus retrofit program.

5.2.4   *Alternative engine technologies and fuels*

Alternatives to conventional gasoline and diesel engines have been advocated as a means of reducing emissions and fuel costs, especially for fleet vehicles such as buses or garbage-collection vehicles. For example, natural gas and hybrid-electric engines have recently been tested on behalf of Translink, Metro Vancouver's transportation authority (Bradley & Associates, 2006), and electric trolley buses are in use in a number of municipalities in Canada. Widespread introduction of privately owned electric vehicles, which have zero

emissions at the tailpipe, would also reduce the use of conventional fuels. Some Canadian municipalities are introducing policies for creating electric vehicle infrastructure However, conversion is likely to happen gradually, and large-scale transition to electric vehicles could be up to 20–30 years away (America's Energy Future, 2010).

5.3   Modification of existing structures

In many instances, it is not possible to create road setbacks, relocate existing buildings (such as hospitals or schools), or re-route traffic. However, other interventions exist that can reduce exposure of building occupants to traffic-related air pollution. First, it is possible to erect physical barriers (which can be structural and/or vegetative) between a busy roadway and an inhabited building. Such barriers have been postulated to prevent pollutants from reaching the population of concern. Second, the building itself can be modified to reduce ingress of polluted air.

5.3.1   Physical barriers to TRAP

Sound walls, often situated near busy roads or highways to reduce noise levels from traffic by blocking and deflecting sound waves, may influence pollutant levels directly behind the barrier. Sound walls confine and obstruct air flow, and can therefore decrease concentrations downwind of the wall dependent on wall height, wind speed, and roadway configuration. One study estimates potential reductions in pollution exposure to be around 15-35%, depending on the distance from the sound wall, wall weight, and wind conditions (Sonoma, 2010). The majority of studies involving the mitigation potential of sound walls focus on winds perpendicular to the roadway. Data is lacking on whether barriers are effective in low wind or stagnant conditions, or other wind directions relative

to the roadway (Sonoma, 2010). Because barriers restrict airflow movement from the pollutant source, however, on-road pollutant concentrations may become elevated, which could lead to increased exposure by road users (including cyclists and pedestrians).

Baldauf *et al*. (2008) conducted a study to assess the impacts of a noise barrier (6 m in height, at a distance of 5 m from the edge of the roadway) on air quality near a heavily trafficked highway in Raleigh, North Carolina. Measurements showed that the barrier reduced average concentrations of PM by 15-25% within the first 50 m from the road, with concentrations becoming equivalent to a comparison "no-barrier" stretch of roadway at approximately 150–200 m from the traffic. A critical design parameter appears to be the length the barrier extends beyond the region it is designed to protect from TRAP. Measurements along the barrier indicated that CO and PM reductions were not realized until approximately 40 m inside the barrier ends, suggesting that pollutants may have been swept around the barrier. A continuous stretch of barrier may be optimal if significant pollutant concentration reductions are to be achieved, though this could be a challenge to implement if multiple property owners are involved. A more recent study examined the impact of noise barriers on TRAP concentrations, by taking measurements downwind of two Californian highways at sites with and without noise barriers (Ning *et al.*, 2010). The research showed that TRAP concentrations were reduced in the immediate vicinity of the road, but were followed by a "surge" of pollutants at approximately 100 m downwind. The noise barrier appeared to effectively shift the zone of higher concentrations away from the roadside, but it is debatable whether this would reduce overall population exposure. A computational fluid dynamics modelling study provides additional detail of the effect of noise barriers on TRAP dispersion. It suggests that depending on barrier height, the maximum concentrations of downwind pollution can be reduced by 15-61% relative to a no-barrier case (Hagler *et al.*, 2011). Despite these promising results, building barriers may only be practical along highways with large traffic volumes, and are

less likely to be desirable along urban roadways with commercial and residential establishments.

It is also hypothesized that vegetation can "trap" PM and absorb the gaseous components of TRAP, thus decreasing air pollution levels (Urban Forestry Administration, 1997). A literature review on the impact of near-road vegetation barriers on PM removal concluded that different tree species may result in different PM removal rates (Fuller *et al*., 2009), but this conclusion is not supported by measurements. The State of California (2004) does not specifically recommend the use of noise barriers and tree plantings as mitigation factors to reduce children's exposure to traffic pollutants, stating that their effect on lowering traffic emissions is not proven. Recently, experts at an EPA-sponsored workshop concluded that effectiveness of vegetation versus noise barriers has not yet been definitively demonstrated, but is expected to be small (Baldauf *et al*., 2011). While trees have little impact on local air quality, creation of greenspace on a city-wide or regional scale can provide a source of separation from traffic sources, as described in Section 1.6, can increase carbon dioxide conversion to oxygen, and can promote cooling. Therefore it should still be considered as a valuable feature of land development.

In summary, localized barriers around major roadways, such as sound walls, have showed mixed results in reducing traffic related pollution exposure. Barriers may also result in increased pollution concentration in specific surrounding areas. Thus the primary focus of barriers should remain physical safety and noise reduction.

5.3.2 Building modifications

There are a number of approaches to reduce the ingress of TRAP into buildings, and which may be particularly relevant for buildings that house

susceptible occupants, such as hospitals or seniors' residences. Modifications to building envelopes, or to heating, ventilation and air conditioning (HVAC) systems can be very expensive to implement on existing buildings. Therefore design measures to protect occupants from TRAP should be considered prior to construction, particularly for buildings that are going to be located within 100 m of major roadways. Creating positive pressure in the building, by designing the HVAC system to provide slightly more make-up air than is extracted, can reduce air influx through open doors and windows. However this may have an additional energy cost in cold climates, since heated building air is continually lost to the environment. Simply positioning the outdoor air intake away from roadways with high traffic volumes has been shown to significantly affect the amount of TRAP entering the building (Sonoma, 2010).

Effective filtration of intake air in the HVAC system can reduce PM exposure of building occupants (Smedje and Norback, 2000) and can lead to both health and productivity benefits (Smedje and Norback, 2000; Wargocki *et al.* 2008). Modeling analyses have suggested that the overall benefits of using particle infiltration in office buildings substantially exceed the additional costs associated with operation (Beko *et al.*, 2008). Cost savings result from reduced occupant morbidity and improved productivity related to lower levels of particle exposure, as well as less frequent building cleaning. Minimum Efficiency Reporting Value (MERV) is used to rate air filter's efficiency, on a scale from 1 to 16 (for example, hospitals typically use filters rated at 14 or higher, to remove transfer of biological agents). Installing filters with high MERV ratings into existing HVAC systems can reduce particle concentrations by around 75% relative to outdoor air for MERV 11 filters, up to as much as 98% for MERV 16 filters (Sonoma, 2010). Proper maintenance and filter-replacement schedules should be followed. It should be noted that high efficiency filters cause a large pressure drop in the HVAC system, which can increase energy costs. The use of high-efficiency particulate air (HEPA) filters are recommended for existing schools, by both the BC Ministry of Environment (2006b) and the State of California, to

reduce exposure to PM. The Office of Environmental Health Hazard Assessment, the California Air Resources Board, and the California Department of Health Services also recommend the use of a higher efficiency rating (60-90%) filter, preferably a HEPA filter, in schools situated close to busy roadways (State of California, 2004). As well, gymnasiums in schools in near major roads (or other indoor areas where children exercise and play) should be made high priority for appropriate HVAC filtration systems. Several studies have demonstrated that, when appropriately sized, room HEPA filter air cleaners can effectively reduce indoor particle concentrations (Du *et al*., 2011; Brauner *et al*., 2008, Barn *et al*., 2008) with one study indicating improvements in vascular function following use of HEPA filter air cleaners to reduce indoor concentrations of infiltrated PM from traffic (Brauner *et al*., 2008). Some school boards are proactively retrofitting HVAC systems and installing stand-alone filtration systems at significant expense, but more evidence is needed to assess whether they have had a significant impact on indoor air quality.

Finally, a novel type of concrete containing titanium dioxide is being developed, and it may soon be incorporated into concrete pavement and building materials (Husken *et al*., 2009; Ballari *et al*., 2010). Upon exposure to UV light titanium dioxide releases free radicals, which can break down NO_X and VOCs. While these materials are still at the laboratory-testing stage, they hold promise for a passive (non-mechanical) means of improving air quality both indoors as well as adjacent to busy roadways. However, given that the real-world efficacy of these new materials for TRAP removal is not known, intervention studies will be needed to determine whether such approaches are able to reduce health impacts in exposed populations.

5.4   Encouraging behaviour change

In 2004-2005, Health Canada's Air Health Effects Division investigated, through public opinion polling, Canadian's use of the Air Quality Index and its

influence on their behaviour (Paoli and Orders, 2005). Over 80% of respondents perceived car exhaust to be a major contributor to poor air quality, with 72% having the perception that suburban areas have better air quality than the city centre. A significant portion of respondents perceived children (80%) and asthmatics (55%) to be particularly sensitive to air quality. Although traffic pollution was recognized to result in adverse health effects, only 47% of respondents said that avoiding high traffic areas is the most effective measure to limit exposure to air pollution and its health effects. This suggests that there is a need for further education and behavioural change within the Canadian population with regards to TRAP exposure reduction. Although a detailed analysis of all of the available options to encourage behavioural change is beyond the scope of this document, some key opportunities are highlighted here.

Environment Canada and Health Canada have developed the Air Quality Health Index, (AQHI) which combines information about concentrations of multiple pollutants into one single metric (Stieb *et al*., 2008a; also see: http://www.ec.gc.ca/cas-aqhi/default.asp?Lang=En). This traditional approach is mainly directed towards day-to-day variability in air pollution levels that are related to meteorologic fluctuations, and hence acute health effects, and will likely not reduce chronic exposures related to TRAP. In addition, while there is some debate among experts about the utility of such indices, (since different pollutants cause different health effects in different ways, over different timescales and at different concentrations), they are common communication tools for air quality managers and may be useful for providing advice for susceptible individuals regarding exposure avoidance measures (Abelsohn *et al*., 2011). In certain circumstances, an air quality advisory might also be issued when a single pollutant concentration is above a certain value. Actions that people can be advised to take during episodes of elevated air pollution include staying indoors, avoiding exercise outdoors, or closing windows (Sonoma, 2010). Bresnahan *et al*. (1997) showed that people modified their behaviour when ozone levels exceeded the national standard, and that they were more likely to

take "defensive" action if they experience adverse health symptoms when exposed to air pollution, or if they had received education on the topic. Exposure reduction interventions that limit children's outdoor activities on days with poor air quality have also been implemented (Shendell *et al*., 2007; Stieb et al, 2008b); however, the efficacy of such interventions is unclear, as research to date has focused on the educational component of such programs, rather than on actual exposure reductions achieved.

The mode and route that people take during their commute can affect their exposure to TRAP (Hertel *et al*. 2007). As mentioned earlier in this document, online route-planning tools are being developed so that cyclists and walkers can map and choose routes that minimize their exposure (Su *et al*., 2010). A related tool to communicate TRAP exposure concerns, analogous to traditional air quality indices discussed above, is the high spatial resolution air quality map. A growing number of such air quality maps are available for Canadian urban areas (examples provided in the Appendix). They have potential to be used as public information tools to identify areas of high TRAP and to help air quality management and transportation planning approaches to prioritize specific areas for interventions.

Finally, behavioural modification can also be used to reduce TRAP emissions by reducing motor vehicle activity. For example, increased use of active transportation, public transportation, or car sharing can reduce reliance on personal vehicles for commuting or other trips. Regarding driver behaviour, training programs that promote "eco-driving" (encouraging smooth acceleration and deceleration, with lower top speeds) can reduce fuel consumption by 5-15% (Zarkadoula *et al*., 2007; Beusen *et al*., 2009). There may also be concurrent pollutant emissions, but this has not been studied.

Table 7 summarizes the available options and policies to mitigate TRAP exposure (modified from Garling *et al*., 2009) that could be useful for Canadian

municipalities. The table includes examples of instances where the mitigation option has been implemented, as well as potential strengths and weaknesses. The effectiveness (and cost) of each intervention will be highly dependent on the circumstances of its application, so it is not possible to provide a ranking according to these criteria. However, it is possible to provide a crude estimate of the time horizon within which the intervention (if successfully implemented) might be expected to have an effect. This has been limited to "near-term" interventions that could be broadly applied quickly with relatively immediate results (expected impact on exposure to TRAP in the time frame of months to a few years) and long-term initiatives that could be incrementally implemented in the near-term but with benefits not expected to be widespread in the near future (expected impacts years to decades).

Table 7. Summary of exposure mitigation options for reducing TRAP exposures, example interventions, and potential strengths and weaknesses of each approach.

Mitigation Option (Time horizon)	Example Intervention	Potential Strengths	Potential Weaknesses
1. Land-use planning and transportation management			
Siting buildings that house susceptible population (e.g. children, elderly) away from busy traffic corridors. (Long-term)	Buildings should be set back 150m from busy roads experiencing more than 15,000 AADT (BC MOE, 2006b)	Reduces emissions in the proximity of buildings; reduce pedestrian accidents; reduce noise exposure.	Many existing buildings are currently close to roads (long-term turnover of building siting); availability of land for new facilities is limited, and often more expensive away from major roads
Integrated land use planning (Long-term)	Include Health Impact Assessment (HIA) in land-use planning (Schram-Bijkerk *et al.*, 2009)	Reduces exposure, emissions, vehicle travel and trip duration; multiple co-benefits (e.g. increased physical activity, decreased CO_2 emissions).	Increasing urban density may increase TRAP exposure; long-term strategy.
Traffic congestion reduction (Near-term)	London's Congestion Charging Scheme (CCS) to restrict the number of vehicles entering central Long (Kelly and Kelly, 2009)	Decreases TRAP in restricted areas; may increase public transportation and active commuting; may enhance pedestrian friendliness.	Equity; may increase TRAP outside of restricted areas; economic implications to restriction area.
Low emission zones (Near-term)	Polluting vehicles that do not meet emission standards must pay a significant charge for each day they operate in the zone (Kelly and Kelly, 2009).	Decrease TRAP in restricted areas; may increase public transportation and active commuting; may enhance pedestrian friendliness.	Equity; may increase TRAP outside of restricted areas; economic implications to restriction area.
Anti-idling zones (Near-term)	Idling bylaws that prohibit vehicles from idling for more than 3 minutes (Cities of Vancouver and North Vancouver).	Decrease TRAP in high density locations; easy to implement	Enforcement

Mitigation Option (Time horizon)	Example Intervention	Potential Strengths	Potential Weaknesses
Improving infrastructure for active commuting (Near-term)	Separation of active commuting from traffic (Kendrick *et al*., In press)	Separation of even a few meters can substantially reduce TRAP exposures for commuters; may decrease motor vehicle traffic congestion, enhance safety; encourage more active commuting.	May increase traffic congestion
Limit heavy truck traffic to specific streets (Near-term)	Widely used for noise reduction and safety in municipalities	Restrict high TRAP to certain streets and times; reduce noise.	Equity; may increase traffic congestion and noise locally; cost to trucking industry

2. Reduction of vehicle emissions

Reduce age of vehicle fleet (Long-term)	BC Scrap It program to offer incentives to retire older vehicles (www.scrapit.ca).	Targets older, higher polluting vehicles.	Large incentives required; equity.
Identification and retrofit/removal of high emitting vehicles or targeted retrofits for specific vehicles (Near-term)	Inspection and maintenance programs (Taylor Consulting, 2002).	Targets older, higher polluting vehicles. Emissions reductions for high risk populations and area (e.g. retrofitting old buses); immediate exposure reduction.	Limited ability to retrofit older high polluting vehicles; higher maintenance requirements of emissions control equipment; equity.

3. Modification of existing structures

Creation of noise barriers (Near-term)	Widely used along major highways in urban/residential areas	Reduce TRAP near roadways; reduce noise exposure	Limited evidence of effectiveness for TRAP reduction.
Install HVAC filter systems in buildings near major roads (Near-term)	Use of high-efficiency particulate air (HEPA) filters for existing schools, (BC Ministry of Environment, 2006b)	Immediate exposure reductions. HEPA filters effective for residences.	Limited evidence of effectiveness for large buildings; filtration is more effective for particle versus gaseous pollutants; capital and operating costs of air conditioning and filtration systems may be high.

Mitigation Option (Time horizon)	Example Intervention	Potential Strengths	Potential Weaknesses
4. Behaviour Change			
Provide active transportation route information (Near-term)	Vancouver cycling route planner (www.cyclevancouver.ubc.ca) that allows users to select the least traffic pollution routes.	Easy to implement; increase active commuting; increase awareness of TRAP and health	Limited by bicycling routes and facilities.
Air quality advisories and recommendations (Near-term)	Air quality health index (AQHI) and outdoor physical activity guidelines	Avoids exposure during high risk periods, easy to implement.	Limited evidence of usefulness of air quality advisories for localized TRAP exposures.
Conduct public education campaigns (Near-term)		Increase general awareness of TRAP; multiple co-benefits (e.g. increase awareness for physical activity and climate change)	Cost and feasibility. Effectiveness unclear.

6. Conclusions and recommendations

There is a growing body of epidemiological and toxicological evidence that demonstrates an association between TRAP exposure and health effects. The HEI (2010) report concluded that the evidence is sufficient to support a causal relationship between exposure to traffic-related air pollution and exacerbation of asthma. It also concluded that there was between sufficient and suggestive evidence for a causal relationship with onset of childhood asthma, and suggestive but not sufficient evidence for non-asthma respiratory symptoms, impaired lung function, total and cardiovascular mortality, and cardiovascular morbidity. For the other health outcomes examined, the evidence was considered inadequate or insufficient (HEI, 2010). Our update of the state-of-evidence indicated strengthened evidence for causality for asthma onset in children and adults, as well as for lung cancer. Importantly, despite comparably low levels of ambient (background) pollution in Canadian cities, the Canadian literature on TRAP exposure and health reveals similar findings to those from other urban areas through the world and supports the conclusions of the HEI (2010) report.

A large percentage of the Canadian population is exposed to TRAP, which highlights its importance as a public health issue in Canada. Approximately 32% of the Canadian population (10 million individuals) live within 100m of a major road or 500m of a highway – the TRAP influence zones determined by the HEI (2010) report. Of these, approximately 2 million individuals live within 50m of a major road. In addition, nearly one-third of Canadian urban elementary schools are located in zone of high traffic proximity. Individuals are also exposed to increased levels of TRAP if they exercise near busy roads, have lengthy commutes or commute using active transportation modes (e.g. walk or bicycle), or work near major roads.

There are various exposure-mitigation options available to reduce TRAP exposure in Canada. Four broad approaches were identified: (1) land-use planning and transportation management; (2) reduction of vehicle emissions; (3) modification of existing structures; and (4) encouraging behaviour change.

Within each approach we have provided examples of mitigation strategies. These strategies tend to either reduce TRAP exposures uniformly, such as tailpipe emission control programs or improvements in public transit, or reduce TRAP exposure spatially, through separation of residential areas or active transit infrastructure from busy roads, low emission zones or the use of HVAC to reduce TRAP infiltration in buildings. Below are general recommendations for municipal and local governments to reduce TRAP exposures, grouped according to the time-horizon of their expected impact.

"Near-term" time horizon (months to years):
- Install HVAC filter systems in buildings that house susceptible populations within 150m from busy roads (>15,000 AADT);
- Limit heavy truck traffic to specific routes and times;
- Target high emitting vehicles for retrofit or removal with inspection and maintenance programs;
- Separate active commuting from busy roads (e.g. create bicycle routes on minor roads);
- Implement anti-idling bylaws;
- Implement traffic congestion reduction policies (e.g. tolls, parking restrictions, low emission zones, car-share programs, increased public transportation) to increase traffic flow (evidence suggests higher TRAP exposures with stop-and-go traffic).

"Long-term" time horizon (years):
- Conduct integrated land use planning that incorporates health impact assessments (HIA's);

- Site buildings that house susceptible populations (e.g. schools, daycares, retirement homes) 150m from busy roads (>15,000 AADT);

Finally, it is important to recognize that there is no one mitigation option that will reduce exposure for all populations at all times. Careful consideration is needed of the resources available, physical and political constraints, and the time horizon within which a reduction in exposure is targeted. It is likely that a bundle of complementary mitigation options will be required to protect the most susceptible sub-groups as well as those most highly exposed to TRAP, and to enable both near-term as well as long-term results.

7.   References

Abelsohn, A., & Stieb, D. M. (2011). Health effects of outdoor air pollution: approach to counseling patients using the Air Quality Health Index *Canadian family physician Médecin de famille canadien*, *57*(8), 881–7, e280–7.

ADEME (2002). Classification and Criteria for setting up air monitoring stations. Available from: http://www.ademe.fr/htdocs/publications/publipdf/etude_clas.pdf

Alexeeff, S. E., Coull, B. A., Gryparis, A., Suh, H., Sparrow, D., Vokonas, P. S., & Schwartz, J. (2011). Medium-Term Exposure to Traffic-Related Air Pollution and Markers of Inflammation and Endothelial Function. *Environmental Health Perspectives*, *119*(4), 481–486. doi:10.1289/ehp.1002560

Allen, R. W., Amram, O. Wheeler, A. J. Brauer, M. (2011) The transferability of NO and NO2 land use regression models between cities and pollutants. *Atmospheric Environment*. 4(2): 369-378.

America's Energy Future (2010). *Real Prospects for Energy Efficiency in the United States*. National Academies Press.

[ALA] American Lung Association of California (2010). *Land Use, Climate Change & Public Health Issue Brief.*

[ALA] American Lung Association of California (2011). *Smart Growth is Healthy Growth for California*. Available from: http://www.lungusa.org/associations/states/california/advocacy/fight-for-air-quality/smart-growth-for-california.html

[APHA] American Public Health Association (2011). *The Hidden Health Costs of Transportation*.

Amram, O., Abernethy, R., Brauer, M., Davies, H., & Allen, R. W. (2011). Proximity of Public Elementary Schools to Major Roads in Canadian Urban Areas. *International Journal of Health Geographics* 10:68. doi:10.1186/1476-072X-10-68.

Anderson H. R., Favarato G., Atkinson R. W. (2011a). Long-term exposure to air pollution and the incidence of asthma: meta-analysis of cohort studies. *Air Qual Atmos Health* doi:10.1007/s11869-011-0144-5

Andersen, Z. J., Hvidberg, M., Jensen, S. S., Ketzel, M., Loft, S., Sørensen, M., Tjønneland, A., et al. (2011b). Chronic obstructive pulmonary disease and long-term exposure to traffic-related air pollution: a cohort study *American Journal Of*

Respiratory And Critical Care Medicine, *183*(4), 455–461.
doi:10.1164/rccm.201006-0937OC

Andersen, Z. J., Kristiansen, L. C., Andersen, K. K., Olsen, T. S., Hvidberg, M., Jensen, S. S., Ketzel, M., et al. (2011c). Stroke and Long-Term Exposure to Outdoor Air Pollution From Nitrogen Dioxide: A Cohort Study *Stroke; a journal of cerebral circulation*. doi:10.1161/STROKEAHA.111.629246

Andersen, Z. J., Raaschou-Nielsen, O., Ketzel, M., Jensen, S. S., Hvidberg, M., Loft, S., Tjønneland, A., et al. (2011d). Diabetes Incidence and Long-Term Exposure to Air Pollution: A cohort study *Diabetes care*. doi:10.2337/dc11-1155

Appatova, A., Ryan, P., & LeMasters, G. (2008). Proximal exposure of public schools and students to major roadways: a nationwide US survey. *Journal of Environmental Planning and Management*, *51*, 631–646.

Asano, M., Tanabe, S., Hara, F., & Yokoyama, S. (2002). Economic Evaluation of Banning Studded Tires Because of Environmental Impact. *Transportation Research Record, 1794*(1), 84–93. doi:10.3141/1794-11

Atari, D. O., Luginaah, I., Xu, X., & Fung, K. (2008). Spatial variability of ambient nitrogen dioxide and sulfur dioxide in Sarnia, "Chemical Valley," Ontario, Canada *Journal of Toxicology and Environmental Health, Part A: Current Issues*, *71*(24), 1572–1581. doi:10.1080/15287390802414158

[ARPHS] Auckland Regional Public Health Service. (2009a). *Submission from the Auckland regional public health service on the "annual plan 2009 and long term council community plan"*. Available from:
http://www.arphs.govt.nz/Submissions/downloads/2009/20090506_ARC_LTCCP.pdf

[ARPHS] Auckland Regional Public Health Service. (2009b). *Health & safety guidelines for early childhood centres.* Available from:
http://www.arphs.govt.nz/healthy_environments/downloads/ECC_HealthSafetyGuidelines.pdf

Baccarelli, A., Martinelli, I., Pegoraro, V., Melly, S., Grillo, P., Zanobetti, A., Hou, L., et al. (2009). Living near major traffic roads and risk of deep vein thrombosis *Circulation*, *119*(24), 3118–3124. doi:10.1161/CIRCULATIONAHA.108.836163

Baldauf, R., Thoma, E., Khlystov, A., Isakov, V., Bowker, G., and Long, T. (2008). Impacts of noise barriers on near-road air quality. *Atmospheric Environment, 42*, 7502-7507.

Baldauf, R., Jackson, L., Hagler, G., & Vlad, I. (2011). The role of vegetation in mitigating air quality impacts from traffic emissions. *EM, January*, 30–33. http://epa.gov/ORD/NRMRL/appcd/nearroadway/pdfs/baldauf.pdf

Ballari, M. M., Hunger, M., Husken, G., & Brouwers, H. J. H. (2010). NOx photocatalytic degradation employing concrete pavement containing titanium dioxide. *Applied Catalysis B-Environmental*, *95*, 245–254. doi:10.1016/j.apcatb.2010.01.002

Ballester, F., Estarlich, M., Iñiguez, C., Llop, S., Ramón, R., Esplugues, A., Lacasaña, M., et al. (2010). Air pollution exposure during pregnancy and reduced birth size: a prospective birth cohort study in Valencia, Spain *Environmental Health*, *9*, 6–. doi:10.1186/1476-069X-9-6

Band, P. R., Jiang, H., & Zielinski, J. M. (2011). Analysis of lung cancer incidence relating to air pollution levels adjusting for cigarette smoking: a case-control study. In *WIT Transactions on Ecology and the Environment*, (Vol. 1, pp. 445–453). Presented at the WIT Transactions on Ecology and the Environment, Southampton, UK: WIT Press. doi:10.2495/AIR110411

Barn, P., Larson, T., Noullett, M., Kennedy, S., Copes, R., and Brauer, M. (2008). Infiltration of forest fire and residential wood smoke: An evaluation of air cleaner effectiveness. *Journal of Exposure Science and Environmental Epidemiology, 18*, 503-511.

Barnett, A. G., Plonka, K., Seow, W. K., Wilson, L.-A., & Hansen, C. (2011). Increased traffic exposure and negative birth outcomes: a prospective cohort in Australia *Environmental Health*, *10*, 26–. doi:10.1186/1476-069X-10-26

Bauer, M., Moebus, S., Möhlenkamp, S., Dragano, N., Nonnemacher, M., Fuchsluger, M., Kessler, C., et al. (2010). Urban particulate matter air pollution is associated with subclinical atherosclerosis: results from the HNR (Heinz Nixdorf Recall). study *Journal of the American College of Cardiology*, *56*(22), 1803–1808. doi:10.1016/j.jacc.2010.04.065

Beaton, S., Bishop, G., Zhang, Y., Stedman, D., Ashbaugh, L., & Lawson, D. (1995). On-road vehicle emissions: Regulations, costs, and benefits. *Science*, *268*(5213), 991–993. doi:10.1126/science.268.5213.991

Beatty, T. K. M., & Shimshack, J. P. (2011). School buses, diesel emissions, and respiratory health. *Journal of Health Economics*, *30*(5), 987–999. doi:10.1016/j.jhealeco.2011.05.017

Beckerman, B., Jerrett, M., Brook, J., Verma, D., Arain, M., and Finkelstein, M. (2008). Correlation of nitrogen dioxide with other traffic pollutants near a major expressway. *Atmospheric Environment, 42*, 275-290.

Beelen, R., Hoek, G., van den Brandt, P. A., Goldbohm, R. A., Fischer, P., Schouten, L. J., Armstrong, B., et al. (2008). Long-Term Exposure to Traffic-Related Air Pollution and Lung Cancer Risk. *Epidemiology*, *19*(5), 702–710. doi:10.1097/EDE.0b013e318181b3ca

Beckerman, B., Jerrett, M., Brook, J. R., Verma, D. K., Arain, M. A., & Finkelstein, M. M. (2008). Correlation of nitrogen dioxide with other traffic pollutants near a major expressway. *Atmospheric Environment*, *42*(2), 275–290.

Beko, G., Clausen, G., & Weschler, C. (2008). Is the use of particle air filtration justified? Costs and benefits of filtration with regard to health effects, building cleaning and occupant productivity. *Building and Environment*, *43*(10), 1647–1657. doi:10.1016/j.buildenv.2007.10.006

Beusen, B., Broekx, S., Denys, T., Beckx, C., Degraeuwe, B., Gijsbers, M., Scheepers, K., et al. (2009). Using on-board logging devices to study the longer-term impact of an eco-driving course. *Transportation Research Part D, 14*(7), 514–520. doi:10.1016/j.trd.2009.05.009

Bevan, M. A. J., Proctor, C. J., Bakerrogers, J., & Warren, N. D. (1991). Exposure to Carbon-Monoxide, Respirable Suspended Particulates, and Volatile Organic-Compounds While Commuting by Bicycle. *Environmental Science & Technology*, *25*(4), 788–791.

Bhatia, R., & Rivard, T. (2008). *Assessment and Mitigation of Air Pollutant Health Effects from Intra-urban Roadways: Guidance for Land Use Planning and Environmental Review*. Prepared for San Francisco Department of Public Health. Available from: http://www.sfphes.org/publications/Mitigating_Roadway_AQLU_Conflicts.pdf

Boyer, M., & Lyons, K. (2004). *Washington State Clean School Bus Program: Report to 2005 Legislature*. Available from: http://www.ecy.wa.gov/quality/plaintalk/examples/12-08%20Draft%20Program%20Report.pdf

Bråbäck, L., & Forsberg, B. (2009). Does traffic exhaust contribute to the development of asthma and allergic sensitization in children: findings from recent cohort studies *Environmental Health*, *8*, 17. doi:10.1186/1476-069X-8-17

Bradley & Associates (2006). *Bus Technology & Alternative Fuels Demonstration Project: Phase 1 - Test Program Report*. Available from:

http://www.translink.ca/~/media/documents/bpotp/projects/bus_tech_evaluation/b
us%20technology%20phase%201%20final%20test%20program%20report.ashx

Brauer, M., Gehring, U., Brunekreef, B., De Jongste, J., Gerritsen, J., Rovers, M.,
Wichmann, H.-E., et al. (2006). Traffic-related air pollution and otitis media
Environmental Health Perspectives, 114(9), 1414–1418.

Brauer, M., Lencar, C., Tamburic, L., Koehoorn, M., Demers, P., and Karr, C.
(2008). A cohort study of traffic-related air pollution impacts on birth outcomes.
Environmental Health Perspectives, 116(5), 680-686.

Brauner, E. V., Forchhammer, L., Møller, P., Barregard, L., Gunnarsen, L.,
Afshari, A., Wahlin, P., et al. (2008). Indoor particles affect vascular function in
the aged: an air filtration-based intervention study *American Journal Of
Respiratory And Critical Care Medicine, 177*(4), 419–425.
doi:10.1164/rccm.200704-632OC

Bresnahan, B., & Dickie, M. (1997). Averting behavior and urban air pollution.
Land Economics, 73(3), 340–357.

Bridbord, K., & Hanson, D. (2009). A personal perspective on the initial federal
health-based regulation to remove lead from gasoline. *Environmental Health
Perspectives, 117*(8), 1195–1201. doi:10.1289/ehp.0800534

[BC MOE] British Columbia Ministry of Environment. (2006a). *Environmental best
management practices for urban and rural land development in British Columbia:
Air quality BMPs and supporting information*

[BC MOE] British Columbia Ministry of Environment. (2006b). *Develop with care:
Environmental guidelines for urban and rural land development in British
Columbia*

Brook, R. D., Jerrett, M., Brook, J. R., Bard, R. L., & Finkelstein, M. M. (2008).
The Relationship Between Diabetes Mellitus and Traffic-Related Air Pollution.
Journal of Occupational and Environmental Medicine, 50(1), 32–38.
doi:10.1097/JOM.0b013e31815dba70

Brook, R. D., Urch, B., Dvonch, J. T., Bard, R. L., Speck, M., Keeler, G.,
Morishita, M., et al. (2009). Insights Into the Mechanisms and Mediators of the
Effects of Air Pollution Exposure on Blood Pressure and Vascular Function in
Healthy Humans. *Hypertension, 54*(3), 659–667.
doi:10.1161/HYPERTENSIONAHA.109.130237

Brook, R. D., Rajagopalan, S., Pope, C. A., Brook, J. R., Bhatnagar, A., Diez-
Roux, A. V., Holguin, F., et al. (2010). Particulate Matter Air Pollution and

Cardiovascular Disease An Update to the Scientific Statement From the American Heart Association. *Circulation*, *121*(21), 2331–2378. doi:10.1161/CIR.0b013e3181dbece1

Brunekreef, B., Stewart, A. W., Anderson, H. R., Lai, C. K. W., Strachan, D. P., Pearce, N., ISAAC Phase 3 Study Group. (2009). Self-reported truck traffic on the street of residence and symptoms of asthma and allergic disease: a global relationship in ISAAC phase 3 *Environmental Health Perspectives*, *117*(11), 1791–1798. doi:10.1289/ehp.0800467

[CARB] California Air Resources Board. (2005). *Air Quality and Land Use Handbook.* Available from: http://www.arb.ca.gov/ch/landuse.htm

[CARB] California Air Resources Board. (2009). *California ambient air quality standards*. Available from: http://www.arb.ca.gov/research/aaqs/caaqs/caaqs.htm

[CARB] California Air Resources Board. (2011). *Senate Bill 375 - Research on Impacts of Transportation and Land Use-Related Policies.* Available from: http://arb.ca.gov/cc/sb375/policies/policies.htm

Cakmak, S., Mahmud, M., Grgicak-Mannion, A., & Dales, R. E. (2012). The influence of neighborhood traffic density on the respiratory health of elementary schoolchildren. *Environment International, 39*(1), 128–132. doi:10.1016/j.envint.2011.10.006

Calvert, J. G., Heywood, J. B., Sawyer, R. F., & Seinfeld, J. H. (1993). Achieving Acceptable Air Quality: Some Reflections on Controlling Vehicle Emissions. *Science*, *261*(5117), 37–45.

Castro-Giner, F., Kuenzli, N., Jacquemin, B., Forsberg, B., de Cid, R., Sunyer, J., Jarvis, D., et al. (2009). Traffic-Related Air Pollution, Oxidative Stress Genes, and Asthma (ECHRS). *Environmental Health Perspectives*, *117*(12), 1919–1924. doi:10.1289/ehp.0900589

Carlsten C, Dybuncio A, Becker AB, Chan-Yeung M, Brauer M. (2011). Traffic-related air pollution (TRAP) and incident asthma in a high-risk birth cohort. *Occupational and Environmental Medicine*. 68(4):291-5.

Chen, E., Schreier, H. M. C., Strunk, R. C., & Brauer, M. (2008). Chronic Traffic-Related Air Pollution and Stress Interact to Predict Biologic and Clinical Outcomes in Asthma. Environmental Health Perspectives, 116(7), 970–975. doi:10.1289/ehp.11076

City of Vancouver (2006). *Motor Vehicle noise and emission abatement by-law No. 9344.* Available from: http://vancouver.ca/bylaws/9344c.PDF

Clark, N. A., Demers, P. A., Karr, C. J., Koehoorn, M., Lencar, C., Tamburic, L., & Brauer, M. (2010). Effect of Early Life Exposure to Air Pollution on Development of Childhood Asthma. *Environmental Health Perspectives*, *118*(2), 284–290. doi:10.1289/ehp.0900916

Crouse, D. L., Goldberg, M. S., Ross, N. A., Chen, H., & Labrèche, F. (2010). Postmenopausal Breast Cancer Is Associated with Exposure to Traffic-Related Air Pollution in Montreal, Canada: A Case–Control Study. *Environmental Health Perspectives*, *118*(11), 1578–1583. doi:10.1289/ehp.1002221

Currie, J., & Walker, R. (2011). Traffic congestion and infant health: evidence from E-Zpass. *Applied Economics*, *3*(1), 65–90. doi:10.1257/app.3.1.65

Dales, R., Wheeler, A., Mahmud, M., Frescura, A. M., Smith-Doiron, M., Nethery, E., & Liu, L. (2008). The Influence of Living Near Roadways on Spirometry and Exhaled Nitric Oxide in Elementary Schoolchildren. *Environmental Health Perspectives*, *116*(10), 1423–1427. doi:10.1289/ehp.10943

Dales, R., Wheeler, A. J., Mahmud, M., Frescura, A. M., & Liu, L. (2009). The influence of neighborhood roadways on respiratory symptoms among elementary schoolchildren *Journal of occupational and environmental medicine / American College of Occupational and Environmental Medicine*, *51*(6), 654–660. doi:10.1097/JOM.0b013e3181a0363c

Dallmann, T. R., & Harley, R. A. (2010). Evaluation of mobile source emission trends in the United States. *Journal Of Geophysical Research-Atmospheres, 115*(D14305), 1–12. doi:10.1029/2010JD013862

Deger, L., Plante, C., Goudreau, S., Smargiassi, A., Perron, S., Thivierge, R. L., & Jacques, L. (2010). Home Environmental Factors Associated With Poor Asthma Control in Montreal Children: A Population-Based Study. *Journal of Asthma*, *47*(5), 513–520. doi:10.3109/02770901003615778

Delfino, R. J., Gillen, D. L., Tjoa, T., Staimer, N., Polidori, A., Arhami, M., Sioutas, C., et al. (2011). Electrocardiographic ST-Segment Depression and Exposure to Traffic-Related Aerosols in Elderly Subjects with Coronary Artery Disease. *Environmental Health Perspectives*, *119*(2), 196–202. doi:10.1289/ehp.1002372

Du, L., Batterman, S., Parker, E., Godwin, C., Chin, J.-Y., O'Toole, A., Robins, T., et al. (2011). Particle concentrations and effectiveness of free-standing air filters in bedrooms of children with asthma in Detroit, Michigan. *Building and Environment*, *46*(11), 2303–2313. doi:10.1016/j.buildenv.2011.05.012

Eisner, M. D., Anthonisen, N., Coultas, D., Kuenzli, N., Perez-Padilla, R., Postma, D., Romieu, I., et al. (2010). An official American Thoracic Society public

policy statement: Novel risk factors and the global burden of chronic obstructive pulmonary disease *American Journal Of Respiratory And Critical Care Medicine*, *182*(5), 693–718. doi:10.1164/rccm.200811-1757ST

Evans, G. J., Jeong, C.-H., Sabaliauskas, K., Jadidian, P., Aldersley, S., Larocque, H., & Herod, D. (2011). *Design of a Near-Road Monitoring Strategy for Canada* (pp. 1–58). Contract for Environment Canada.

[FCM] Federation of Canadian Municipalities (2010). *Enviro-Fleets: Reducing municipal heavy-duty vehicle emissions: A guide to best practices.* Available from: http://fcm.ca/Documents/tools/Enviro-fleets/Enviro_Fleets_Reducing_municipal_heavy_duty_vehicle_emissions_EN.pdf

Finkelstein, M. M. (2004). Traffic Air Pollution and Mortality Rate Advancement Periods. *American Journal Of Epidemiology*, *160*(2), 173–177. doi:10.1093/aje/kwh181

Finkelstein, M., & Jerrett, M. (2007). A study of the relationships between Parkinson's disease and markers of traffic-derived and environmental manganese air pollution in two Canadian cities. *Environmental research*, *104*(3), 420–432. doi:10.1016/j.envres.2007.03.002

Fisher, D., and Shepheard, N. (2009). Child pollution fright. *New Zealand Herald*, April 26, 2009. Available from: http://www.nzherald.co.nz/nz/news/article.cfm?c_id=1&objectid=10568691

Frank, L. D., Sallis, J. F., Conway, T. L., Chapman, J. E., Saelens, B. E., & Bachman, W. (2006). Many Pathways from Land Use to Health: Associations between Neighborhood Walkability and Active Transportation, Body Mass Index, and Air Quality. *Journal of the American Planning Association*, 72(1), 75–87. doi:10.1080/01944360608976725

Freire, C., Ramos, R., Puertas, R., Lopez-Espinosa, M.-J., Julvez, J., Aguilera, I., Cruz, F., et al. (2010). Association of traffic-related air pollution with cognitive development in children. *Journal Of Epidemiology And Community Health*, *64*(3), 223–228. doi:10.1136/jech.2008.084574

Fuks, K., Moebus, S., Hertel, S., Viehmann, A., Nonnemacher, M., Dragano, N., Möhlenkamp, S., et al. (2011). Long-Term Urban Particulate Air Pollution, Traffic Noise and Arterial Blood Pressure *Environmental Health Perspectives*. doi:10.1289/ehp.1103564

Fuller, M., & Bai, S. (2009). *Practical Mitigation Measures for Diesel Particulate Matter: Near-road Vegetation Barriers*. U.C. Davis - Developing Effective and Quantifiable Air Quality Mitigation Measures.

Gan, W. Q., Tamburic, L., Davies, H. W., Demers, P. A., Koehoorn, M., & Brauer, M. (2010). Changes in Residential Proximity to Road Traffic and the Risk of Death From Coronary Heart Disease. *Epidemiology*, *21*(5), 642–649. doi:10.1097/EDE.0b013e3181e89f19

Gan, W. Q., Koehoorn, M., Davies, H. W., Demers, P. A., Tamburic, L., & Brauer, M. (2011). Long-Term Exposure to Traffic-Related Air Pollution and the Risk of Coronary Heart Disease Hospitalization and Mortality. *Environmental Health Perspectives*, *119*(4), 501–507. doi:10.1289/ehp.1002511

Gärling, T., & Satoshi, F. (2009). Travel behavior modification: Theories, methods, and programs. In R. Kitamura, T. Yoshii, & T. Yamamoto (Eds.), *The Expanding Sphere of Travel Behaviour Research: Selected Papers from the 11th International Conference on Travel Behaviour Research*. Emerald Group Publishing Ltd.

Gehring, U., Wijga, A. H., Brauer, M., Fischer, P., de Jongste, J. C., Kerkhof, M., Oldenwening, M., et al. (2010). Traffic-related air pollution and the development of asthma and allergies during the first 8 years of life *American Journal Of Respiratory And Critical Care Medicine*, *181*(6), 596–603. doi:10.1164/rccm.200906-0858OC

Gehring, U., van Eijsden, M., Dijkema, M. B. A., van der Wal, M. F., Fischer, P., & Brunekreef, B. (2011a). Traffic-related air pollution and pregnancy outcomes in the Dutch ABCD birth cohort study *Occupational and environmental medicine*, *68*(1), 36–43. doi:10.1136/oem.2009.053132

Genereux, M., Auger, N., Goneau, M., & Daniel, M. (2008). Neighbourhood socioeconomic status, maternal education and adverse birth outcomes among mothers living near highways. *Journal Of Epidemiology And Community Health*, *62*(8), 695–700. doi:10.1136/jech.2007.066167

Gilbert, N. L., Woodhouse, S., Stieb, D. M., & Brook, J. R. (2003). Ambient nitrogen dioxide and distance from a major highway *Science Of The Total Environment*, *312*(1-3), 43–46. doi:10.1016/S0048-9697(03)00228-6

Giles, L. V., Barn, P., Künzli, N., Romieu, I., Mittleman, M. A., van Eeden, S., Allen, R., et al. (2010). From Good Intentions to Proven Interventions: Effectiveness of Actions to Reduce the Health Impacts of Air Pollution. *Environmental Health Perspectives*, *119*(1), 29–36. doi:10.1289/ehp.1002246

Hagler, G. S. W., Tang, W., Freeman, M. J., Heist, D. K., Perry, S. G., & Vette, A. F. (2011). Model evaluation of roadside barrier impact on near-road air pollution. *Atmospheric Environment*, *45*(15), 2522–2530. doi:10.1016/j.atmosenv.2011.02.030

Hart, J. E., Laden, F., Puett, R. C., Costenbader, K. H., & Karlson, E. W. (2009). Exposure to traffic pollution and increased risk of rheumatoid arthritis *Environmental Health Perspectives*, *117*(7), 1065–1069. doi:10.1289/ehp.0800503

[HRHD] Halton Region Health Department (2009). *Protecting health: air quality and land use compatability.* Oakville, Ontario. Available from: http://www.halton.ca/cms/One.aspx?portalId=8310&pageId=13747

[HEI] Health Effects Institute. (2009). *Traffic-related air pollution: A critical review of the literature on emissions, exposure, and health effects.* Special Report No. 17. Boston, Mass.: Health Effects Institute.

[HEI] Health Effects Institute. (2010). *Traffic-related air pollution: A critical review of the literature on emissions, exposure, and health effects.* Final Version of Special Report No. 17. Boston, Mass.: Health Effects Institute. Available from: http://pubs.healtheffects.org/view.php?id=334

Henderson, S. B., Beckerman, B., Jerrett, M., & Brauer, M. (2007). Application of land use regression to estimate long-term concentrations of traffic-related nitrogen oxides and fine particulate matter *Environmental Science & Technology*, *41*(7), 2422–2428. doi:10.1021/es0606780

Hertel, O., Hvidberg, M., Ketzel, M., Storm, L., & Stausgaard, L. (2008). A proper choice of route significantly reduces air pollution exposure--a study on bicycle and bus trips in urban streets *Science Of The Total Environment*, *389*(1), 58–70. doi:10.1016/j.scitotenv.2007.08.058

Hoffmann, B., Moebus, S., Mohlenkamp, S., Stang, A., Lehmann, N., Dragano, N., Schmermund, A., et al. (2007). Residential exposure to traffic is associated with coronary atherosclerosis *Circulation*, *116*(5), 489–496. doi:10.1161/CIRCULATIONAHA.107.693622

Husken, G., Hunger, M., & Brouwers, H. J. H. (2009). Experimental study of photocatalytic concrete products for air purification. *Building and Environment*, *44*(12), 2463–2474. doi:10.1016/j.buildenv.2009.04.010

Hystad, P., Setton, E., Cervantes, A., Poplawski, K., Deschenes, S., Brauer, M., van Donkelaar, A., et al. (2011). Creating National Air Pollution Models for

Population Exposure Assessment in Canada. *Environmental Health Perspectives*, *119*(8), 1123–1129. doi:10.1289/ehp.1002976

Jacobs, L., Nawrot, T. S., de Geus, B., Meeusen, R., Degraeuwe, B., Bernard, A., Sughis, M., et al. (2010). Subclinical responses in healthy cyclists briefly exposed to traffic-related air pollution: an intervention study. *Environmental Health*, *9*, –. doi:10.1186/1476-069X-9-64

Janssen, N. A. H., Brunekreef, B., van Vliet, P., Aarts, F., Meliefste, K., Harssema, H., et al. (2003). The relationship between air pollution from heavy traffic and allergic sensitization, bronchial hyperresponsiveness, and respiratory symptoms in Dutch schoolchildren. *Environ Health Perspect*. *111*(12):1512-8.

Janssen, N. A. H., van Vliet, P., Aarts, F., Harssema, H., Brunekreef, B. (2001). Assessment of exposure to traffic related air pollution of children attending schools near motorways. *Atmos Environ*. *35*(22):3875-84.

Jerrett, M., Arain, M. A., Kanaroglou, P., Beckerman, B., Crouse, D., Gilbert, N. L., Brook, J. R., et al. (2007). Modeling the intraurban variability of ambient traffic pollution in Toronto, Canada. *Journal of Toxicology and Environmental Health, Part A: Current Issues*, *70*(3-4), 200–212. doi:10.1080/15287390600883018

Jerrett, M., Finkelstein, M. M., Brook, J. R., Arain, M. A., Kanaroglou, P., Stieb, D. M., Gilbert, N. L., et al. (2009). A cohort study of traffic-related air pollution and mortality in Toronto, Ontario, Canada *Environmental Health Perspectives*, *117*(5), 772–777. doi:10.1289/ehp.11533

Karner, A. A., Eisinger, D. S., & Niemeier, D. A. (2010). Near-Roadway Air Quality: Synthesizing the Findings from Real-World Data. *Environmental Science & Technology*, *44*(14), 5334–5344. doi:10.1021/es100008x
Karr, C. J., Demers, P. A., Koehoorn, M. W., Lencar, C. C., Tamburic, L., & Brauer, M. (2009a). Influence of ambient air pollutant sources on clinical encounters for infant bronchiolitis *American Journal Of Respiratory And Critical Care Medicine*, *180*(10), 995–1001. doi:10.1164/rccm.200901-0117OC

Karr, C. J., Rudra, C. B., Miller, K. A., Gould, T. R., Larson, T., Sathyanarayana, S., & Koenig, J. Q. (2009b). Infant exposure to fine particulate matter and traffic and risk of hospitalization for RSV bronchiolitis in a region with lower ambient air pollution. *Environmental research*, *109*(3), 321–327. doi:10.1016/j.envres.2008.11.006

Kashima, S., Naruse, H., Yorifuji, T., Ohki, S., Murakoshi, T., Takao, S., Tsuda, T., et al. (2011). Residential proximity to heavy traffic and birth weight in Shizuoka, Japan *Environmental research*, *111*(3), 377–387. doi:10.1016/j.envres.2011.02.005

Kaur, S., Nieuwenhuijsen, M. J., & Colvile, R. N. (2007). Fine particulate matter and carbon monoxide exposure concentrations in urban street transport microenvironments. *Atmospheric Environment*, *41*(23), 4781–4810. doi:10.1016/j.atmosenv.2007.02.002

Kelly, F., Anderson, H. R., Armstrong, B., Atkinson, R., Barratt, B., Beevers, S., Derwent, D., et al. (2011). The impact of the congestion charging scheme on air quality in London. Part 1. Emissions modeling and analysis of air pollution measurements *Research report (Health Effects Institute)*, (155), 5–71.

Kelly, F. J., Kelly, J., HEI London Consortium. (2009). London air quality: a real world experiment in progress *Biomarkers: biochemical indicators of exposure, response, and susceptibility to chemicals*, *14 Suppl 1*, 5–11. doi:10.1080/13547500902965252

Kendrick C. M., Moore A., Haire A., Bigazzi A., Figliozzi M., Monsere C. M., George L. (In Press). The impact of bicycle lane characteristics on bicyclists' exposure to traffic-related particulate matter. *Transportation Research Record*.

Kerkhof, M., Postma, D. S., Brunekreef, B., Reijmerink, N. E., Wijga, A. H., de Jongste, J. C., Gehring, U., et al. (2010). Toll-like receptor 2 and 4 genes influence susceptibility to adverse effects of traffic-related air pollution on childhood asthma *Thorax*, *65*(8), 690–697. doi:10.1136/thx.2009.119636

Keuken, M., Denier van der Gon, H., & van der Valk, K. (2010). Non-exhaust emissions of PM and the efficiency of emission reduction by road sweeping and washing in the Netherlands. *Science Of The Total Environment, 408*(20), 4591–4599. Elsevier.

Keuken, M. P., Jonkers, S., Wilmink, I. R., & Wesseling, J. (2010). Reduced NOx and PM10 emissions on urban motorways in The Netherlands by 80km/h speed management. *Science Of The Total Environment*, *408*(12), 2517–2526. Elsevier B.V. doi:10.1016/j.scitotenv.2010.03.008

Krämer, U., Herder, C., Sugiri, D., Strassburger, K., Schikowski, T., Ranft, U., & Rathmann, W. (2010). Traffic-Related Air Pollution and Incident Type 2 Diabetes: Results from the SALIA Cohort Study. *Environmental Health Perspectives*, *118*(9), 1273–1279. doi:10.1289/ehp.0901689

Künzli, N., Jerrett, M., Mack, W. J., Beckerman, B., LaBree, L., Gilliland, F., Thomas, D., et al. (2005). Ambient air pollution and atherosclerosis in Los Angeles *Environmental Health Perspectives*, *113*(2), 201–206.

Künzli, N., Bridevaux, P.-O., Liu, L. J. S., Garcia-Esteban, R., Schindler, C., Gerbase, M. W., Sunyer, J., et al. (2009). Traffic-related air pollution correlates

with adult-onset asthma among never-smokers. *Thorax*, *64*(8), 664–670. doi:10.1136/thx.2008.110031

Künzli, N., Jerrett, M., Garcia-Esteban, R., Basagaña, X., Beckermann, B., Gilliland, F., Medina, M., et al. (2010). Ambient air pollution and the progression of atherosclerosis in adults *PloS one*, *5*(2), e9096–. doi:10.1371/journal.pone.0009096

Kupiainen, K. J., Tervahattu, H., Räisänen, M., Mäkelä, T., Aurela, M., & Hillamo, R. (2005). Size and Composition of Airborne Particles from Pavement Wear, Tires, and Traction Sanding. *Environmental Science & Technology, 39*(3), 699–706. doi:10.1021/es035419e

Lindgren, A., Stroh, E., Montnémery, P., Nihlén, U., Jakobsson, K., & Axmon, A. (2009). Traffic-related air pollution associated with prevalence of asthma and COPD/chronic bronchitis. A cross-sectional study in Southern Sweden *International Journal of Health Geographics*, *8*, 2. doi:10.1186/1476-072X-8-2

MacIntyre, E. A., Karr, C. J., Koehoorn, M., Demers, P. A., Tamburic, L., Lencar, C., & Brauer, M. (2011). Residential air pollution and otitis media during the first two years of life *Epidemiology*, *22*(1), 81–89. doi:10.1097/EDE.0b013e3181fdb60f

Malmqvist, E., Rignell-Hydbom, A., Tinnerberg, H., Björk, J., Stroh, E., Jakobsson, K., Rittner, R., et al. (2011). Maternal Exposure to Air Pollution and Birth Outcomes. *Environmental Health Perspectives*, *119*(4), 553–558. doi:10.1289/ehp.1002564

Mazzoleni, C., Moosmuller, H., Kuhns, H., Keislar, R., Barber, P., Nikolic, D., Nussbaum, N., et al. (2004). Correlation between automotive CO, HC, NO, and PM emission factors from on-road remote sensing: implications for inspection and maintenance programs. *Transportation Research Part D - Transportation and Environment*, *9*(6), 477–496. doi:10.1016/j.trd.2004.08.006

McConnell, R., Islam, T., Shankardass, K., Jerrett, M., Lurmann, F., Gilliland, F., Gauderman, J., et al. (2010). Childhood Incident Asthma and Traffic-Related Air Pollution at Home and School. *Environmental Health Perspectives*, *118*(7), 1021–1026. doi:10.1289/ehp.0901232

McCormick, R., Graboski, M., Alleman, T., Alvarez, J., & Duleep, K. (2003). Quantifying the emission benefits of opacity testing and repair of heavy-duty diesel vehicles. *Environmental Science & Technology*, *37*(3), 630–637. doi:10.1021/es0256919

McCreanor, J., Cullinan, P., Nieuwenhuijsen, M. J., Stewart-Evans, J., Malliarou, E., Jarup, L., Harrington, R., et al. (2007). Respiratory effects of exposure to diesel traffic in persons with asthma. *The New England Journal of Medicine, 357*(23), 2348–2358.

McKeown, D. (2007). *Air Pollution Burden of Illness from Traffic in Toronto: Problems and Solutions.* Toronto Public Health. Available from: http://www.toronto.ca/health/hphe/pdf/air_pollution_burden.pdf

Modig, L., Torén, K., Janson, C., Jarvholm, B., & Forsberg, B. (2009). Vehicle exhaust outside the home and onset of asthma among adults *European Respiratory Journal, 33*(6), 1261–1267. doi:10.1183/09031936.00101108

Morgenstern, V., Zutavern, A., Cyrys, J., Brockow, I., Gehring, U., Koletzko, S., Bauer, C. P., et al. (2007). Respiratory health and individual estimated exposure to traffic-related air pollutants in a cohort of young children. *Occupational and environmental medicine, 64*(1), 8–16. doi:10.1136/oem.2006.028241

Morgenstern, V., Zutavern, A., Cyrys, J., Brockow, I., Koletzko, S., Krämer, U., Behrendt, H., et al. (2008). Atopic diseases, allergic sensitization, and exposure to traffic-related air pollution in children *American Journal Of Respiratory And Critical Care Medicine, 177*(12), 1331–1337. doi:10.1164/rccm.200701-036OC

Namdeo, A., & Mitchell, G. (2008). An empirical study of estimating vehicle emissions under cordon and distance based road user charging in Leeds, UK. *Environmental Monitoring and Assessment, 136*, 45–51. doi:10.1007/s10661-007-9719-x

Nawrot, T. S., Perez, L., Künzli, N., Munters, E., & Nemery, B. (2011). Public health importance of triggers of myocardial infarction: a comparative risk assessment *The Lancet, 377*(9767), 732–740. doi:10.1016/S0140-6736(10)62296-9

Ning, Z., Hudda, N., Daher, N., Kam, W., Herner, J., Kozawa, K., Mara, S., et al. (2010). Impact of roadside noise barriers on particle size distributions and pollutants concentrations near freeways. *Atmospheric Environment, 44*(26), 3118–3127. doi:10.1016/j.atmosenv.2010.05.033

Nyberg, F., Gustavsson, P., Jarup, L., Bellander, T., Berglind, N., Jakobsson, R., & Pershagen, G. (2000). Urban air pollution and lung cancer in Stockholm *Epidemiology, 11*(5), 487–495.

[OECD] Organisation for Economic Co-operation and Development (2011). *OECD Environmental Performance Reviews: Norway 2011.* Available from:

http://www.oecd.org/document/63/0,3746,en_2649_37465_47678847_1_1_1_37465,00.html

Oliver, B. (2005). Greenhouse gas emissions and vehicle fuel efficiency standards for Canada. *Pollution Probe Report*, 1–256.

Paoli, G., and Orders, S. (2005). *Summary of findings from application of a mental models approach to health risk communications for air quality indices,* DecisionAnalysis Risk Consultants, Inc. (Unpublished report)

Perrotta, Kim. (2011) *Public Health and Land Use Planning: Highlights*. Prepared for the Clean Air Partnership (CAP) in partnership with the Ontario Public Health Association (OPHA).

Ponce, N. A., Hoggatt, K. J., Wilhelm, M., & Ritz, B. (2005). Preterm birth: the interaction of traffic-related air pollution with economic hardship in Los Angeles neighborhoods *American Journal Of Epidemiology*, *162*(2), 140–148. doi:10.1093/aje/kwi173

Poplawski, K., Gould, T., Setton, E., Allen, R., Su, J., Larson, T., Henderson, S., et al. (2009). Intercity transferability of land use regression models for estimating ambient concentrations of nitrogen dioxide. *Journal of Exposure Science and Environmental Epidemiology*, *19*(1), 107–117. doi:10.1038/jes.2008.15

Power, M. C., Weisskopf, M. G., Alexeeff, S. E., Coull, B. A., Spiro, A. I., & Schwartz, J. (2011). Traffic-Related Air Pollution and Cognitive Function in a Cohort of Older Men. *Environmental Health Perspectives*, *119*(5), 682–687. doi:10.1289/ehp.1002767

Pujades-Rodríguez, M., Lewis, S., McKeever, T., Britton, J., & Venn, A. (2009). Effect of living close to a main road on asthma, allergy, lung function and chronic obstructive pulmonary disease *Occupational and environmental medicine*, *66*(10), 679–684. doi:10.1136/oem.2008.043885

Raaschou-Nielsen, O., Hertel, O., Vignati, E., Berkowicz, R., Jensen, S. S., Larsen, V. B., Lohse, C., et al. (2000). An air pollution model for use in epidemiological studies: evaluation with measured levels of nitrogen dioxide and benzene *J Expo Anal Environ Epidemiol*, *10*(1), 4–14.Ranft, U., Schikowski, T., Sugiri, D., Krutmann, J., & Kraemer, U. (2009). Long-term exposure to traffic-related particulate matter impairs cognitive function in the elderly. *Environmental research*, *109*(8), 1004–1011. doi:10.1016/j.envres.2009.08.003

Raaschou-Nielsen, O., Bak, H., Sørensen, M., Jensen, S. S., Ketzel, M., Hvidberg, M., Schnohr, P., et al. (2010). Air Pollution from Traffic and Risk for

Lung Cancer in Three Danish Cohorts. *Cancer Epidemiology Biomarkers & Prevention*, *19*(5), 1284–1291. doi:10.1158/1055-9965.EPI-10-0036

Raaschou-Nielsen, O., Andersen, Z. J., Hvidberg, M., Jensen, S. S., Ketzel, M., Sørensen, M., Loft, S., et al. (2011). Lung Cancer Incidence and Long-Term Exposure to Air Pollution from Traffic. *Environmental Health Perspectives*, *119*(6), 860–865. doi:10.1289/ehp.1002353

Ranft, U., Schikowski, T., Sugiri, D., Krutmann, J., & Kraemer, U. (2009). Long-term exposure to traffic-related particulate matter impairs cognitive function in the elderly. *Environmental research*, *109*(8), 1004–1011. doi:10.1016/j.envres.2009.08.003

Reponen, T., Grinshpun, S. A., Trakumas, S., Martuzevicius, D., Wang, Z. M., LeMasters, G., Lockey, J. E., et al. (2003). Concentration gradient patterns of aerosol particles near interstate highways in the Greater Cincinnati airshed. *Journal Of Environmental Monitoring*, *5*(4), 557–562.

Reynolds, C., Harris, M. A., Teschke, K., Cripton, P. A., & Winters, M. (2009). The impact of transportation infrastructure on bicycling injuries and crashes: a review of the literature. *Environmental Health*, *8*(1), 47.

Richardson, E. (2010). Extracting Maximum Benefit from Parking Policy-10 years of Experience in Perth, Australia. *European Transport Conference*.

Richmond-Bryant, J., Bukiewicz, L., Kalin, R., Galarraga, C., & Mirer, F. (2011). A multi-site analysis of the association between black carbon concentrations and vehicular idling, traffic, background pollution, and meteorology during school dismissals *Science Of The Total Environment*, *409*(11), 2085–2093. doi:10.1016/j.scitotenv.2011.02.024

Richmond-Bryant, J., Saganich, C., Bukiewicz, L., & Kalin, R. (2009). Associations of PM2.5 and black carbon concentrations with traffic, idling, background pollution, and meteorology during school dismissals *Science Of The Total Environment*, *407*(10), 3357–3364. doi:10.1016/j.scitotenv.2009.01.046

Rosenlund, M., Berglind, N., Pershagen, G., Hallqvist, J., Jonson, T., & Bellander, T. (2006). Long-term exposure to urban air pollution and myocardial infarction *Epidemiology*, *17*(4), 383–390. doi:10.1097/01.ede.0000219722.25569.0f

Rundell, K. W., Caviston, R., Hollenbach, A. M., & Murphy, K. (2006). Vehicular air pollution, playgrounds, and youth athletic fields *Inhalation Toxicology*, *18*(8), 541–547. doi:10.1080/08958370600685640

Ryan, P., LeMasters, G., Biagini, J., Bernstein, D., Grinshpun, S., Shukla, R., Wilson, K., et al. (2005). Is it traffic type, volume, or distance? Wheezing in infants living near truck and bus traffic. *Journal of Allergy and Clinical Immunology*, *116*(2), 279–284. doi:10.1016/j.jaci.2005.014

Sacramento Metropolitan AQMD (2005) *Protocol For Evaluating The Location Of Sensitive Land Uses Adjacent To Major Roadways.* Available from: http://www.airquality.org/ceqa/RoadwayProtocol.shtml

San Francisco Department of Public Health (2008) *Air Quality Analysis for Planning (Article 38).* Available from: http://www.sfdph.org/dph/EH/Air/default.asp#Article38

Sahsuvaroglu, T., Jerrett, M., Sears, M. R., McConnell, R., Finkelstein, N., Arain, A., Newbold, B., et al. (2009). Spatial analysis of air pollution and childhood asthma in Hamilton, Canada: comparing exposure methods in sensitive subgroups *Environmental Health*, *8*, 14–. doi:10.1186/1476-069X-8-14

Salam, M. T., Islam, T., & Gilliland, F. D. (2008). Recent evidence for adverse effects of residential proximity to traffic sources on asthma. *Current opinion in pulmonary medicine*, *14*(1), 3–3.

Schram-Bijkerk, D., van Kempen, E., Knol, A. B., Kruize, H., Staatsen, B., & van Kamp, I. (2009). Quantitative health impact assessment of transport policies: two simulations related to speed limit reduction and traffic re-allocation in the Netherlands. *Occupational and environmental medicine*, *66*, 691–698. doi:10.1136/oem.2008.041046

Shendell, D. G., Rawling, M.-M., Foster, C., Bohlke, A., Edwards, B., Rico, S. A., Felix, J., et al. (2007). The outdoor air quality flag program in central california: A school-based educational intervention to potentially help reduce children's exposure to environmental asthma triggers. *Journal of Environmental Health*, *70*(3), 28–31.

Slama, R., Morgenstern, V., Cyrys, J., Zutavern, A., Herbarth, O., Wichmann, H.-E., Heinrich, J., et al. (2007). Traffic-related atmospheric pollutants levels during pregnancy and offspring's term birth weight: a study relying on a land-use regression exposure model. *Environmental Health Perspectives*, *115*(9), 1283–1292. doi:10.1289/ehp.10047

Smargiassi, A., Berrada, K., Fortier, I., & Kosatsky, T. (2006). Traffic intensity, dwelling value, and hospital admissions for respiratory disease among the elderly in Montreal (Canada): a case-control analysis *Journal Of Epidemiology And Community Health*, *60*(6), 507–512. doi:10.1136/jech.2005.037044

Smedje, G., Norback, D. (2000). New ventilation systems at select schools in Sweden - Effects on asthma and exposure. *Arch Environ Health*. *55*(1):18-25.

Smith, M. (2010). Advances in understanding benzene health effects and susceptibility. *Annual Review Of Public Health*, *31*, 133–148.

[Sonoma] Sonoma Technology Inc. (2010). *Mitigation strategies for reducing motor-vehicle pollutants near existing roadways: a review of the literature.* Unpublished report prepared for Air Health Assessment Section, Health Canada.

St Denis, M., & Lindner, J. (2005). Review of light-duty diesel and heavy-duty diesel gasoline inspection programs. *Journal Of The Air & Waste Management Association*, *55*(12), 1876–1884.

State of California (2003). *Senate bill No. 352.* Available from: http://info.sen.ca.gov/pub/03-04/bill/sen/sb_0351-0400/sb_352_bill_20031003_chaptered.html

State of California (2004). *Air pollution from nearby traffic and children's health: Information for schools.* Available from: http://oehha.ca.gov/public_info/facts/pdf/Factsheetparent.pdf

State of California (2008). *Senate Bill No. 375.* Available from: http://www.calapa.org/attachments/wysiwyg/5360/SB375final.pdf

State of New Jersey (2008) *Terrell James' Law.* Available from: http://www.njleg.state.nj.us/2006/Bills/AL07/308_.htm

Stieb, D. M., Burnett, R. T., Smith-Doiron, M., Brion, O., Shin, H. H., & Economou, V. (2008a). A new multipollutant, no-threshold air quality health index based on short-term associations observed in daily TimeSeries analyses. *Journal Of The Air & Waste Management Association*, *58*(3), 435–450. doi:10.3155/1047-3289.58.3.435.

Stieb, D. M., Evans, G. J., Sabaliauskas, K., Chen, L., Campbell, M. E., Wheeler, A. J., Brook, J. R., et al. (2008b). A scripted activity study of the impact of protective advice on personal exposure to ultra-fine and fine particulate matter and volatile organic compounds. *Journal of Exposure Science and Environmental Epidemiology*, *18*(5), 495–502. doi:10.1038/sj.jes.7500634

Strak, M., Boogaard, H., Meliefste, K., Oldenwening, M., Zuurbier, M., Brunekreef, B., & Hoek, G. (2010). Respiratory health effects of ultrafine and fine particle exposure in cyclists *Occupational and environmental medicine*, *67*(2), 118–124. doi:10.1136/oem.2009.046847

Su, J. G., Winters, M., Nunes, M., & Brauer, M. (2010). Designing a route planner to facilitate and promote cycling in Metro Vancouver, Canada. *Transportation Research Part A-Policy And Practice*, *44*(7), 495–505. doi:10.1016/j.tra.2010.03.015

Svartengren, M., Strand, V., Bylin, G., Jarup, L., & Pershagen, G. (2000). Short-term exposure to air pollution in a road tunnel enhances the asthmatic response to allergen. *Eur Respir J*, *15*(4), 716–724.

Taylor Consulting (2002). *Review of the AirCare On-Road (ACOR) Program*. Available from: http://www.metrovancouver.org/about/publications/Publications/AirCareOnRoadReview.pdf

Teschke, K., Harris, M. A., Reynolds, C. C. O., Winters, M., Babul, S., Chipman, M., Cusimano, M., Brubacher, J., Friedman, S., Hunte, G., Monro, M., Shen, H., Vernich, L. and Cripton, P. A. (In press). Route infrastructure and the risk of injuries to bicyclists: A case-crossover study. *American Journal of Public Health*.

Thai, A., McKendry, I., & Brauer, M. (2008). Particulate matter exposure along designated bicycle routes in Vancouver, British Columbia *Science Of The Total Environment*, *405*(1-3), 26–35. doi:10.1016/j.scitotenv.2008.06.035

Tonne, C., Melly, S., Mittleman, M., Coull, B., Goldberg, R., & Schwartz, J. (2007). A case-control analysis of exposure to traffic and acute myocardial infarction. *Environmental Health Perspectives*, *115*(1), 53–57. doi:10.1289/ehp.9587

Tonne, C., Beevers, S., Armstrong, B., Kelly, F., & Wilkinson, P. (2008). Air pollution and mortality benefits of the London Congestion Charge: spatial and socioeconomic inequalities. *Occupational and environmental medicine*, *65*(9), 620–627. doi:10.1136/oem.2007.036533

Transport for London (2006). *Central London Congestion Charging. Impact Monitoring. Fourth Annual Report*. Available from: http://www.tfl.gov.uk/assets/downloads/FourthAnnualReportFinal.pdf

Transport for London (2007). *Statement by the Mayor on the London Low Emission Zone*. Available at: http://www.tfl.gov.uk/assets/downloads/LEZ-Mayors-Statement.pdf

Urban Forestry Administration (District of Columbia) (1997). *Benefits of urban trees*. Available from: http://ufa.ddot.dc.gov/ufa/cwp/view,a,1293,q,575501,ufaNav_GID,1631,ufaNav,%7C32699%7C.asp

U.S. Department of Health and Human Services (2004). "The Health Consequences of Smoking: A Report of the Surgeon General".

Van Houtte, J., & Niemeier, D. (2008). A Critical Review of the Effectiveness of I/M Programs for Monitoring PM Emissions from Heavy Duty Vehicles. *Environmental Science & Technology*, *42*(21), 7856–7865. doi:10.1021/es8001794

van Wijnen, J., Verhoeff, A., Jans, H., & van Bruggen, M. (1995). The exposure of cyclists, car drivers and pedestrians to traffic-related air pollutants. *Int Arch Occup Environ Health* 67:187-193

Volk, H. E., Hertz-Picciotto, I., Delwiche, L., Lurmann, F., & McConnell, R. (2011). Residential Proximity to Freeways and Autism in the CHARGE Study. *Environmental Health Perspectives*, *119*(6), 873–877. doi:10.1289/ehp.1002835

von Klot, S., Cyrys, J., Hoek, G., Kuehnel, B., Pitz, M., Kuhn, U., Kuch, B., et al. (2011). Estimated Personal Soot Exposure Is Associated With Acute Myocardial Infarction Onset in a Case-Crossover Study. *Progress in Cardiovascular Diseases*, *53*(5), 361–368. doi:10.1016/j.pcad.2011.01.002

Wang, H.-Y., Pizzichini, M. M. M., Becker, A. B., Duncan, J. M., Ferguson, A. C., Greene, J. M., Rennie, D. C., et al. (2010). Disparate geographic prevalences of asthma, allergic rhinoconjunctivitis and atopic eczema among adolescents in five Canadian cities. *Pediatric Allergy and Immunology*, *21*(5), 867–877. doi:10.1111/j.1399-3038.2010.01064.x

Wargocki, P., Wyon, D. P., Lynge-Jensen, K., Bornehag, C. G. (2008) The effects of electrostatic particle filtration and supply-air filter condition in classrooms on the performance of schoolwork by children (RP-1257). *HVAC & R Res.*14(3):327-44

Wehner, B., Birmili, W., Gnauk, T., & Wiedensohler, A. (2002). Particle number size distributions in a street canyon and their transformation into the urban-air background: measurements and a simple model study. *Atmospheric Environment, 36*(13), 2215–2223. doi:10.1016/S1352-2310(02)00174-7

Weichenthal, S., Kulka, R., Dubeau, A., Martin, C., Wang, D., & Dales, R. (2011). Traffic-Related Air Pollution and Acute Changes in Heart Rate Variability and Respiratory Function in Urban Cyclists. *Environmental Health Perspectives*, *119*(10), 1373–1378. doi:10.1289/ehp.1003321

Wilhelm, M., & Ritz, B. (2003). Residential proximity to traffic and adverse birth outcomes in Los Angeles county, California, 1994-1996 *Environmental Health Perspectives*, *111*(2), 207–216.

Wilhelm, M., Ghosh, J. K., Su, J., Cockburn, M., Jerrett, M., & Ritz, B. (2011). Traffic-related air toxics and preterm birth: a population-based case-control study in Los Angeles county, California. *Environmental Health*, *10*, –. doi:10.1186/1476-069X-10-89

[WHO] World Health Organization (2005). Health effects of transport-related air pollution. Available from: http://www.euro.who.int/__data/assets/pdf_file/0006/74715/E86650.pdf

[WHO] World Health Organization (2011a). *Database: Outdoor air pollution in cities*. Available from: http://www.who.int/phe/health_topics/outdoorair/databases/en/

[WHO] World Health Organization (2011b). *Health co-benefits of climate change mitigation – Transport sector*. (Health in the Green Economy Report Series). Available from: http://www.who.int/hia/green_economy/en/

Yorifuji, T., Naruse, H., Kashima, S., Ohki, S., Murakoshi, T., Takao, S., Tsuda, T., et al. (2011). Residential Proximity to Major Roads and Preterm Births. *Epidemiology*, *22*(1), 74–80. doi:10.1097/EDE.0b013e3181fe759f

Younger, M., Morrow-Almeida, H. R., Vindigni, S. M., & Dannenberg, A. L. (2008). The Built Environment, Climate Change, and Health Opportunities for Co-Benefits. *American Journal Of Preventive Medicine*, *35*(5), 517–526. doi:10.1016/j.amepre.2008.08.017

Zarkadoula, M., Zoidis, G., & Tritopoulou, E. (2007). Training urban bus drivers to promote smart driving: A note on a Greek eco-driving pilot program. *Transportation Research Part D - Transportation and Environment, 12*(6), 449–451. doi:10.1016/j.trd.2007.05.002

Zhou, Y., & Levy, J. I. (2007). Factors influencing the spatial extent of mobile source air pollution impacts: a meta-analysis. *BMC Public Health*, *7*, 89. doi:10.1186/1471-2458-7-89

Zhu, Y., Hinds, W., Kim, S., Shen, S., & Sioutas, C. (2002). Study of ultrafine particles near a major highway with heavy-duty diesel traffic. *Atmospheric Environment*, *36*(27), 4323–4335.

Zmirou, D., Gauvin, S., Pin, I., Momas, I., Sahraoui, F., Just, J., Le Moullec, Y., et al. (2004). Traffic related air pollution and incidence of childhood asthma: results of the Vesta case-control study. *Journal Of Epidemiology And Community Health*, *58*(1), 18–23.

Appendix A. Health Canada mental model research

In 2004-2005, Health Canada's Air Health Effects Division investigated, through public opinion polling, Canadian's use of the Air Quality Index and its influence on their behaviour (Paoli and Orders, 2005). In the development of a preliminary mental model, questions regarding populations susceptible to poor air quality, along with traffic as a source of air pollution, were proposed to three subgroups of interest: (1) parents of children who suffer from asthma and/or other severe cardio-respiratory ailments; (2) individuals who personally suffer from heart/lung conditions; and (3) elderly individuals (65+) who have no particular ailment. Over 80% of respondents perceived car exhaust to be a major contributor to poor air quality, with 72% having the perception that suburban areas have better air quality than the city centre. A significant portion of respondents perceived children (80%) and asthmatics (55%) to be particularly sensitive to air quality. As well, 57% believed children/infants/young people are the most likely to experience health effects from pollution. These results indicate that traffic is perceived to be a significant contributor to adverse air quality by a majority of the targeted study population, and can lead to health effects in susceptible populations (such as children with respiratory diseases). Although traffic pollution was recognized to result in adverse health effects, only 47% said that avoiding high traffic areas is the most effective measure to limit exposure to air pollution and its health effects. Therefore, it appears that there is no clear public consensus on how to minimize or mitigate the risks associated with traffic-related air pollution.

# Appendix B. Summary of Canadian cities with TRAP land use regression models

Table B1. Summary of existing intraurban NO_x, NO_2, and NO monitoring data for nine Canadian Cities, and traffic predictor variables from Land-Use Regression (LUR) models.

Investigator, Year	City	Sampling Dates	Sites (n)	R^2	Mean (SD) (ppb)	Range (ppb)	Traffic Predictor Variables (m)			
							High way	Major Road	Local Road	Traffic Density
Henderson et al. (2007)	Vancouver, BC	Feb 24 – Mar 15 Sept 8 – 26, 2003	116	0.56	16.2 (5.6)	4.8 – 28.0	100, 1000	200		
Poplawski et al. (2009)	Victoria, BC	Jun 22/23 – Jul 6/7, 2006	40	0.61	4.9 (2.6)	0.4 – 10.3	750	500		
Allen et al. (2011)	Edmonton, AB	Jan 27 – Feb 1 Apr 27 – May 11, 2008	50	0.81	15.4 (3.1)	7.3 – 26.0	1000	50	50	
Allen et al. (2011)	Winnipeg, MB	Oct 28 – Nov 11, 2007 Mar 16 – 30, 2008 June 15 – 29, 2008	50	0.84	8.5 (2.9)	1.7 – 12.4	50		75	
Crouse et al. (2009)	Montreal, QC	Nov/Dec 2005 Apr/May 2006 August 2006	133	0.80	N-D 12.6 (2.6); A-M 14.0 (4.3); A 8.9 (3.1)	2.6 – 31.5	100, 300, 750, 1000	100, 300, 500, 750, 1000	300	100, 300, 500
Gilbert et al. (2005)	Montreal, QC	May 2003	67	0.52	11.6 (3.0)	4.9 – 21.2	100	100	500	Nearest Highway
Su et al. (2009)	Toronto, ON	Spring 2004	100	0.79	10.15 (3.12)	4.9 – 19.3	400	50	1200	650
Jerrett et al. (2007)	Toronto, ON	Sept 9 – 25, 2002	95	0.69	32.2 (9.2)	17.6 – 61.1	200	50		500
Wheeler et al. (2008)	Windsor, ON	Feb, May, Aug and Oct, 2004	54	0.77	12.4 (2.9)	6.9 – 20.2	50	100		
Sahsuvaroglu et al. (2006)	Hamilton, ON	October 2002	107	0.76	14.6 (3.7)	8.0 – 28.1	50			300
Atari et al. (2008)	Sarnia, ON	October 2005	37	0.79	10.7 (3.0)	5.7 – 16.7	400			

Appendix C. Maps of city-specific land use regression models for NO₂ in Canada.
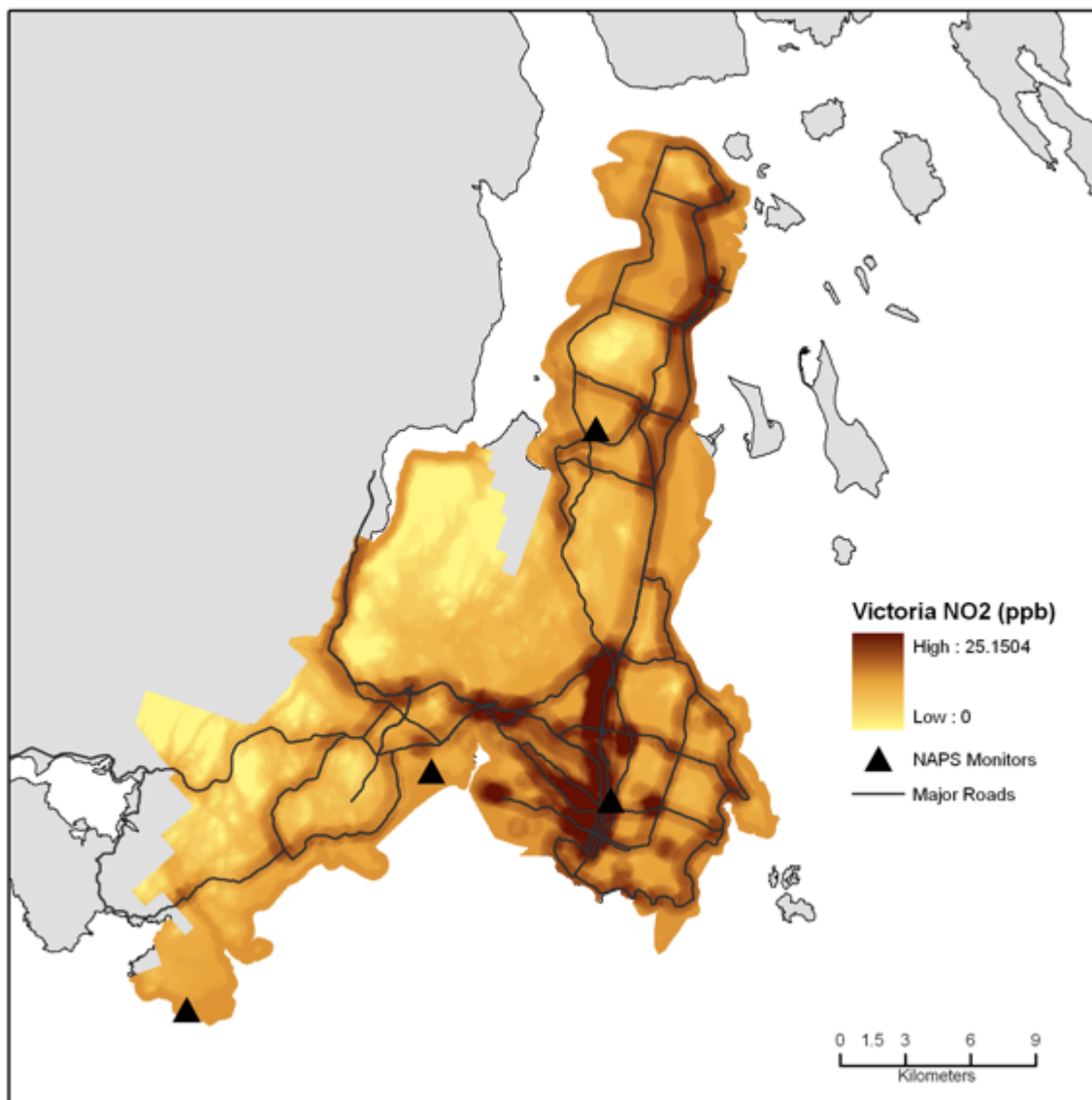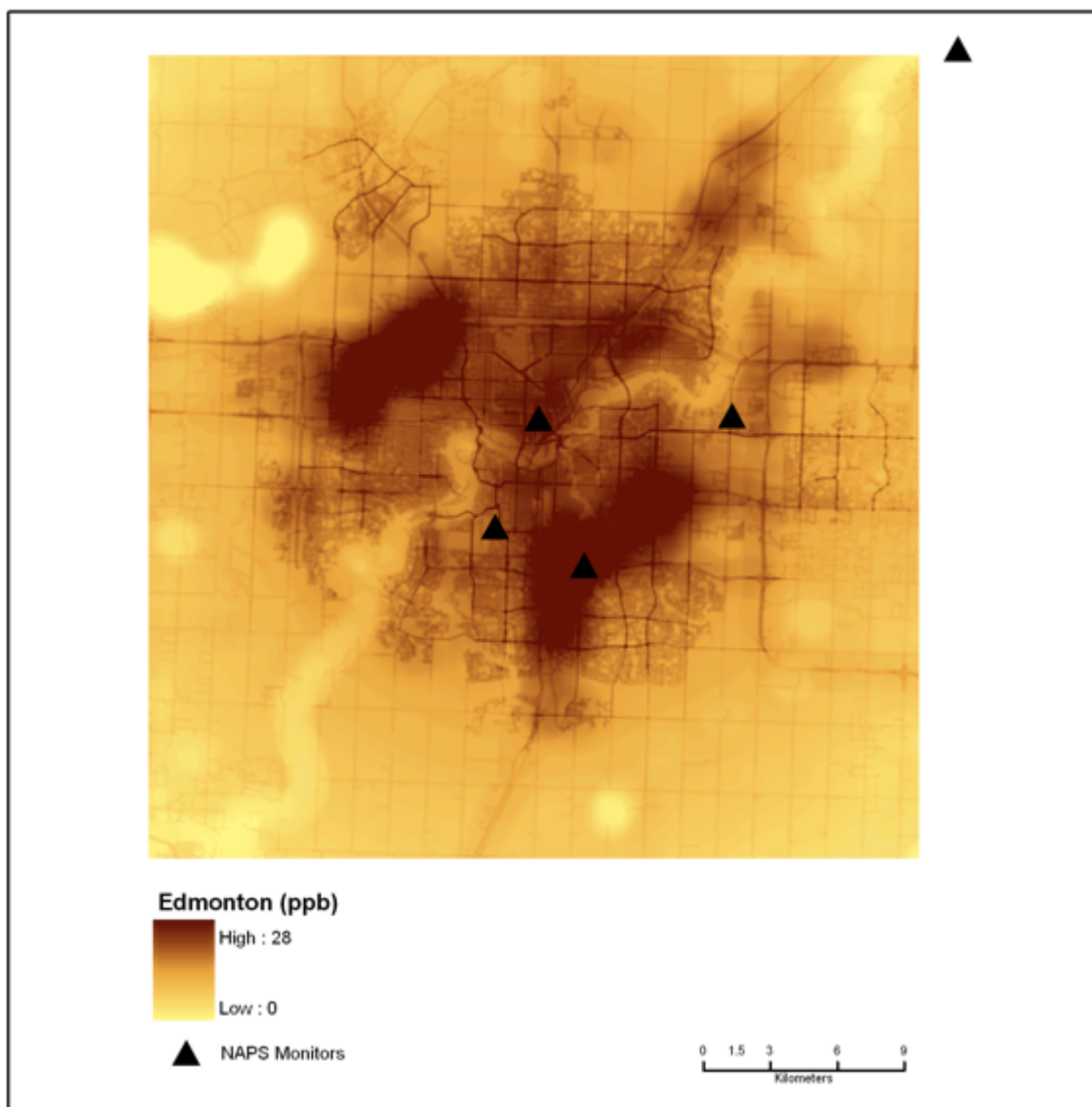

Figure C1. Victoria 2006 NO$_2$ LUR model (from Poplawski *et al*. 2008) and NAPS O$_3$ and PM$_{2.5}$ monitoring stations.
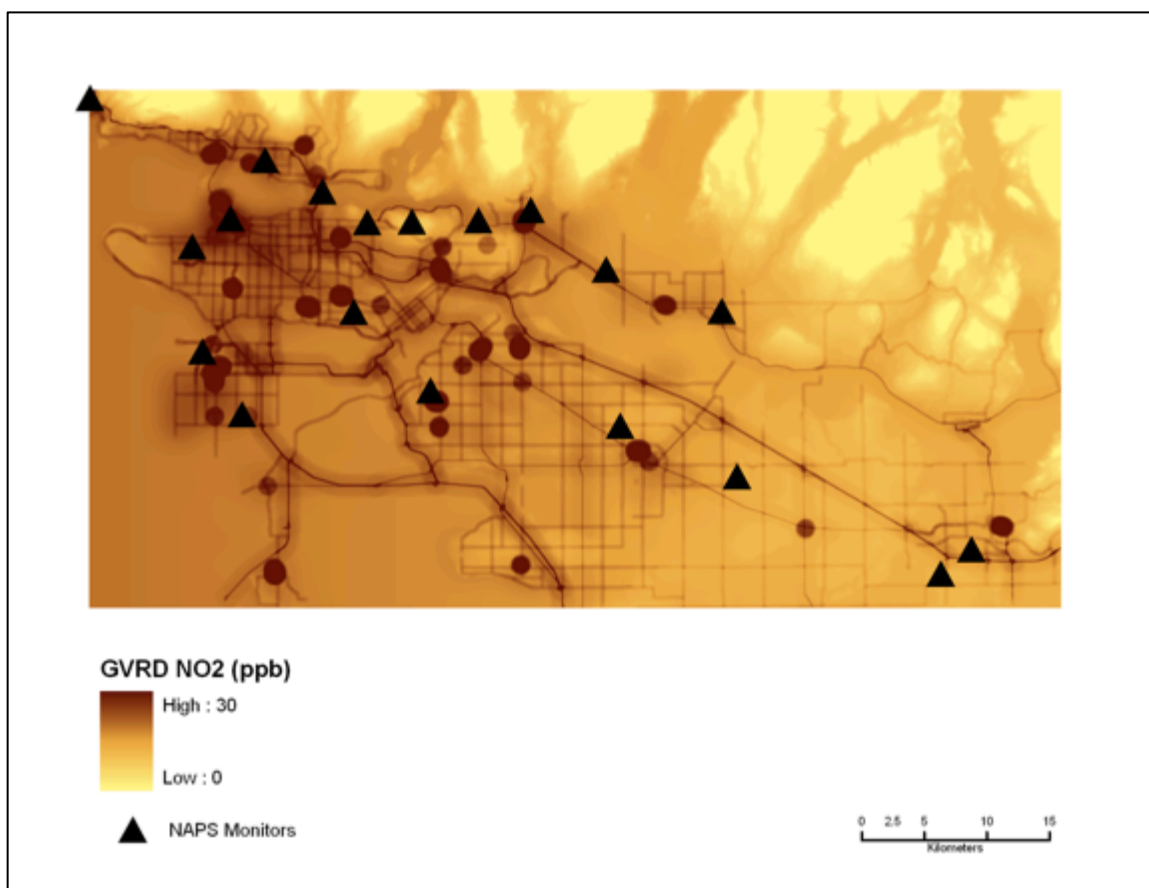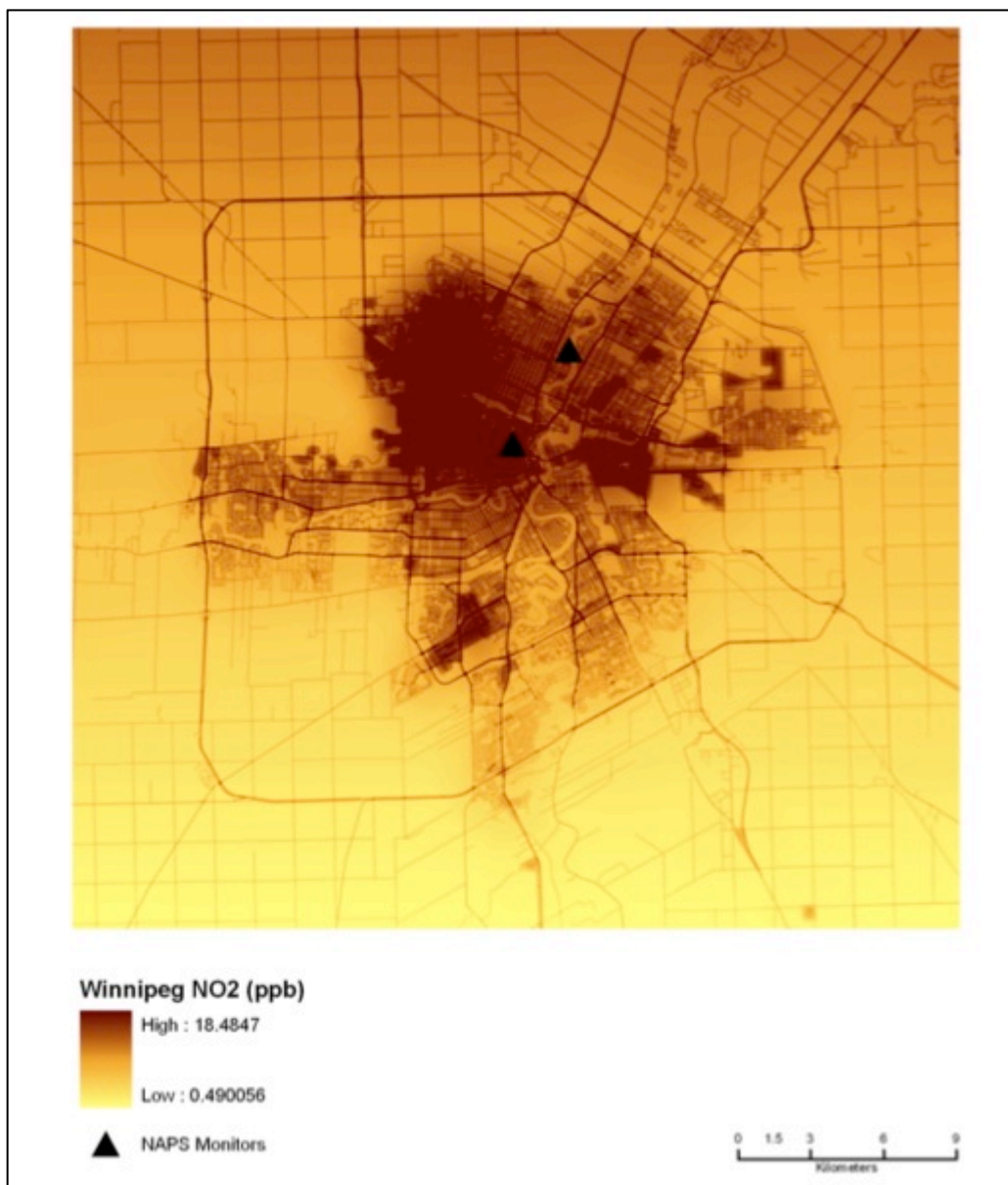
Figure C2. Vancouver 2003 NO$_2$ LUR model (from Henderson *et al*. 2007) and NAPS O$_3$ and PM$_{2.5}$ monitoring stations.
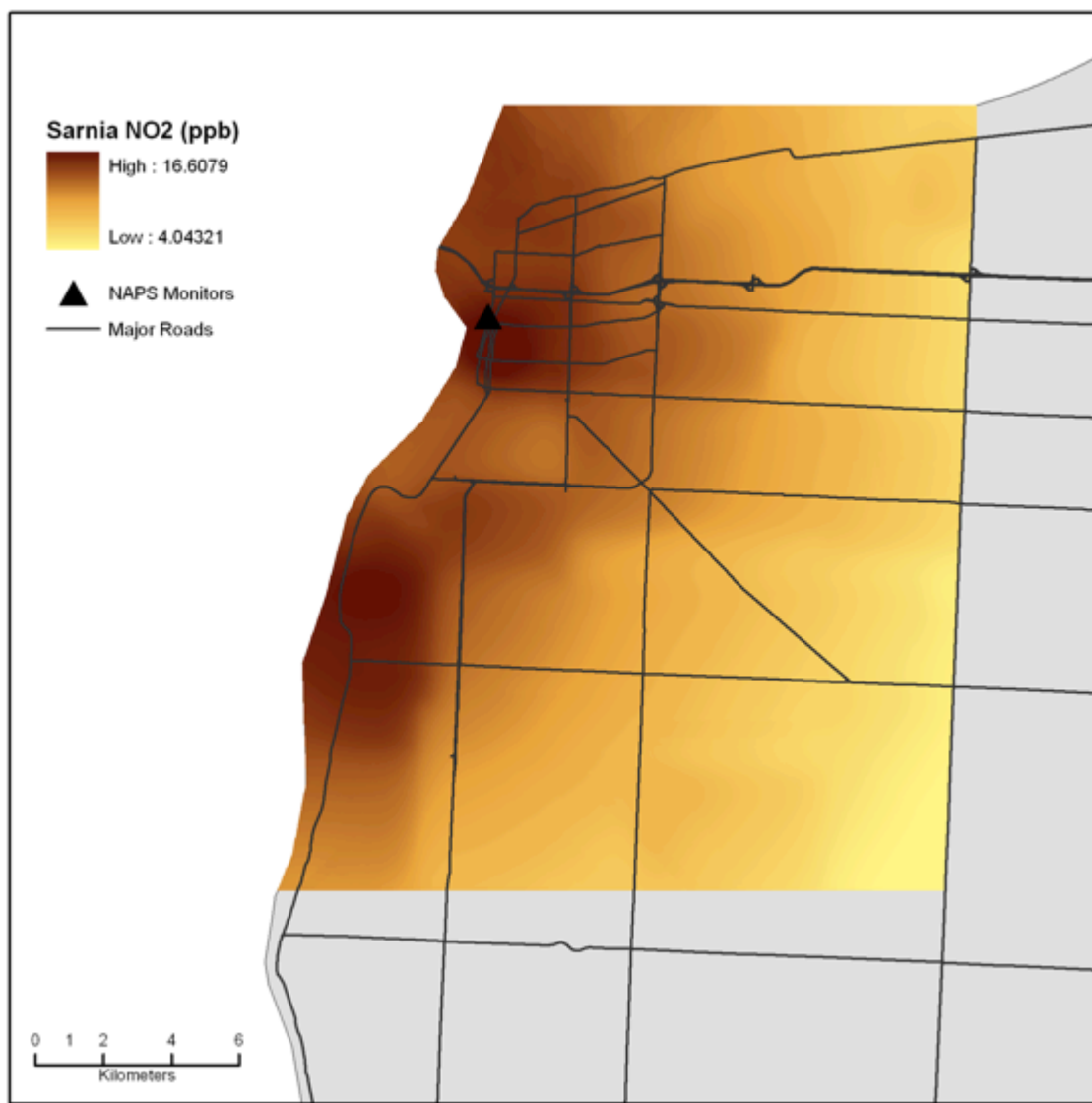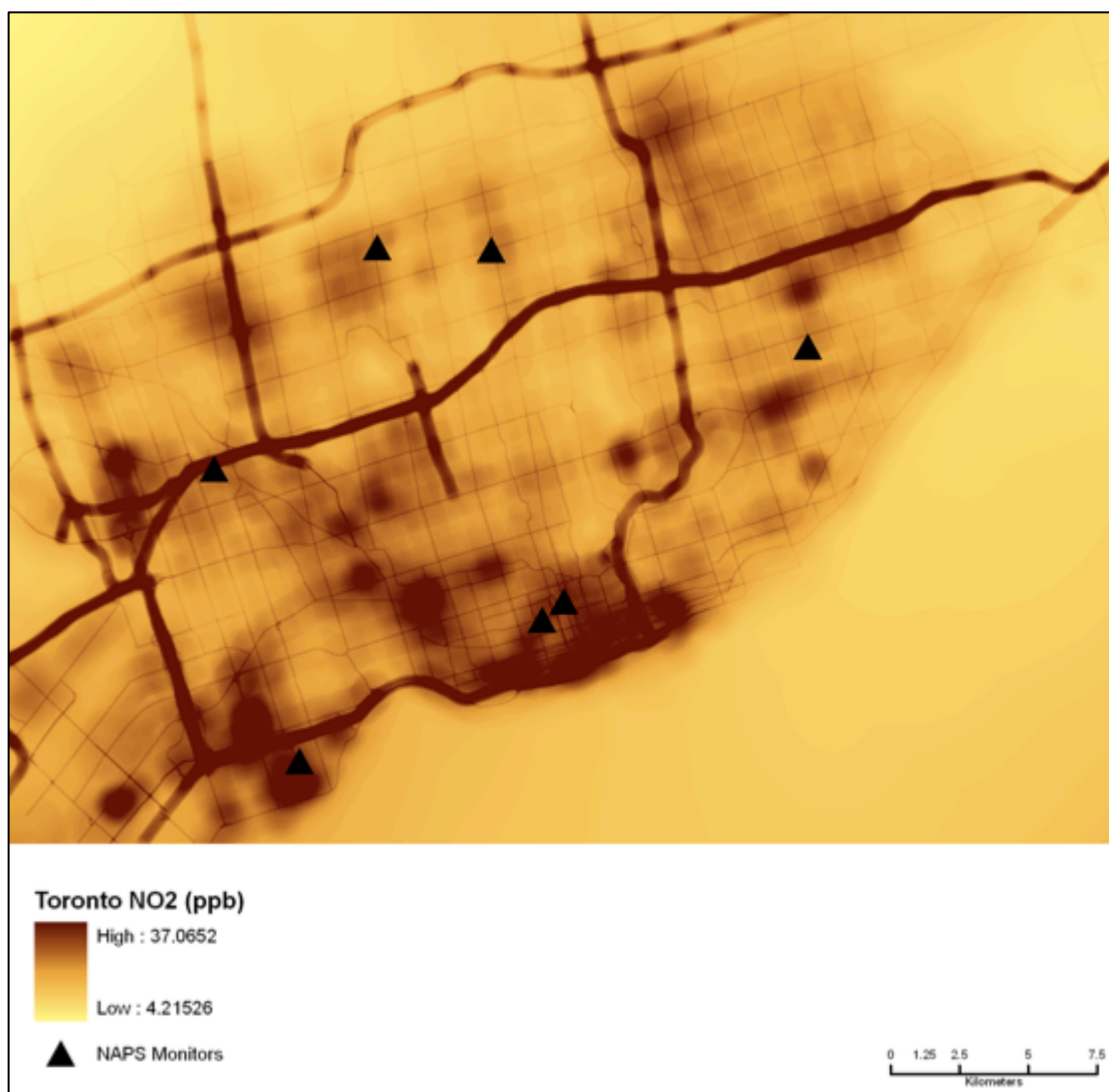
Figure C3. Edmonton 2008 NO$_2$ LUR model (from Allen *et al*. 2011) and NAPS O$_3$ and PM$_{2.5}$ monitoring stations.
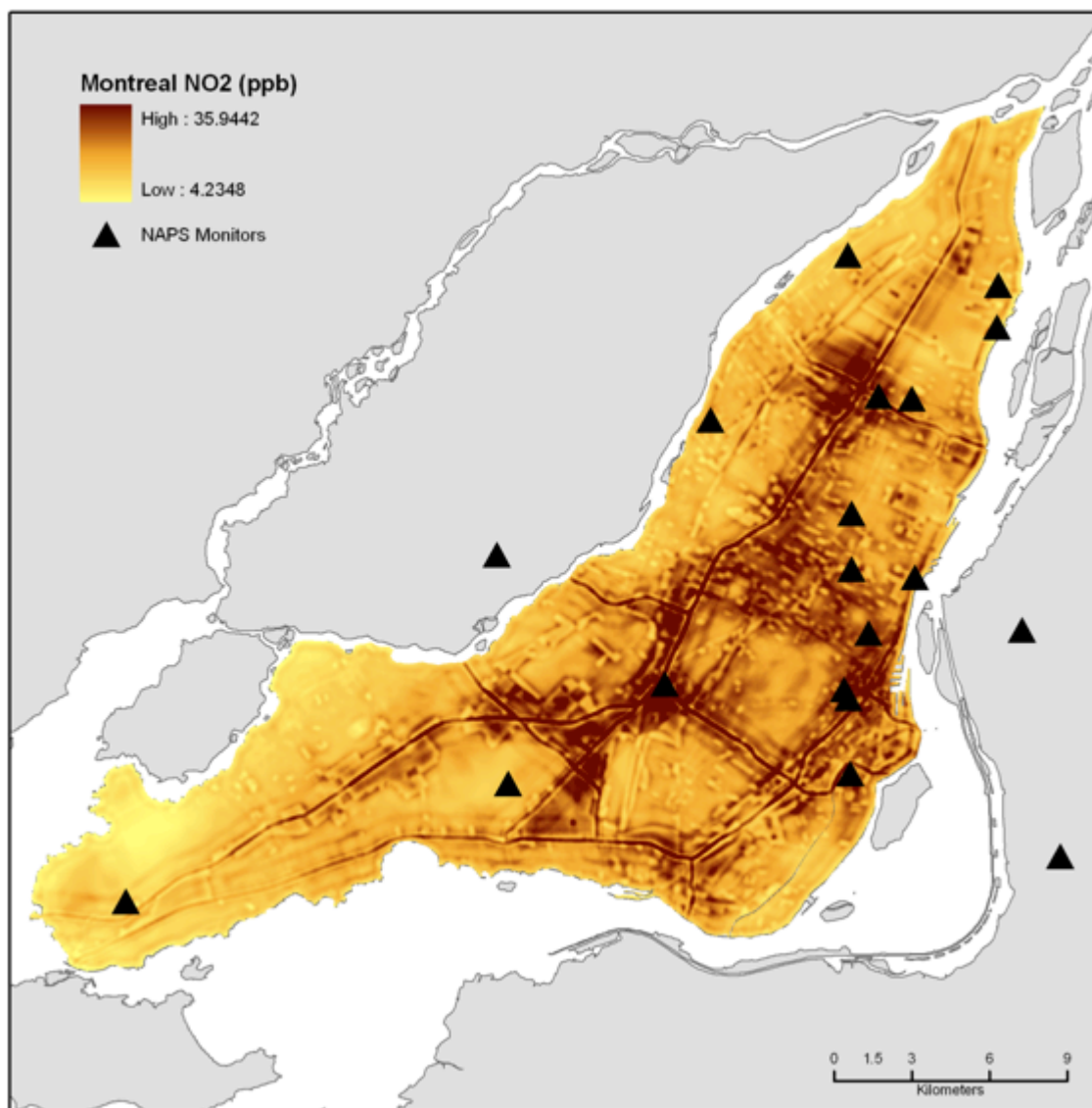
Figure C4. Winnipeg 2008 NO$_2$ LUR model (from Allen *et al*. 2011) and NAPS O$_3$ and PM$_{2.5}$ monitoring stations.

Figure C5. Sarnia 2005 NO$_2$ LUR model (from Atari *et al*. 2008) and NAPS O$_3$ and PM$_{2.5}$ monitoring stations.

Figure C6. Toronto 2006 NO$_2$ LUR model (from Jerrett *et al.* 2007) and NAPS O$_3$ and PM$_{2.5}$ monitoring stations.

Figure C7. Montreal 2006 NO$_2$ LUR model (from Crouse *et al*., 2009) and NAPS O$_3$ and PM$_{2.5}$ monitoring stations.

# Appendix D. Estimates of the Canadian population exposure to NO$_2$

The Canadian National Air Pollution Surveillance (NAPS) monitoring network is run by Environmental Canada and provides long-term air quality data in a uniform standard across Canada. Historically, NAPS monitors were sited to avoid local pollution sources (such as traffic) and are therefore limited for estimating TRAP exposures using traditional proximity and interpolation methods. A recent study, however, used annual 2006 NAPS monitoring data to develop national LUR-type exposure models that incorporated geographic predictor variables to estimate regional pollution variation and deterministic gradients to estimate local vehicle pollution gradients (Hystad et al., 2011). Figure D1 illustrates the resulting NO$_2$ concentration surface for Canada. The Canadian population's exposure to NO$_2$ was estimated using the national model and Statistics Canada block-point data. Results indicated that the average population-weighted exposure to NO$_2$ in Canada was 23.4 μg/m^3 and that the 90th percentile of NO$_2$ exposures was 34.8 μg/m^3.

There are plans to create a near-road monitoring strategy within NAPS (see Evans et al. 2011) to better estimate air pollution concentrations and spatial patterns around roadways. Currently, there are 71 monitors within 500m of a highway and 104 monitors within 100m of major roadways (including highways and arterial roads). Figure D2 illustrates the locations of these NAPS monitors.
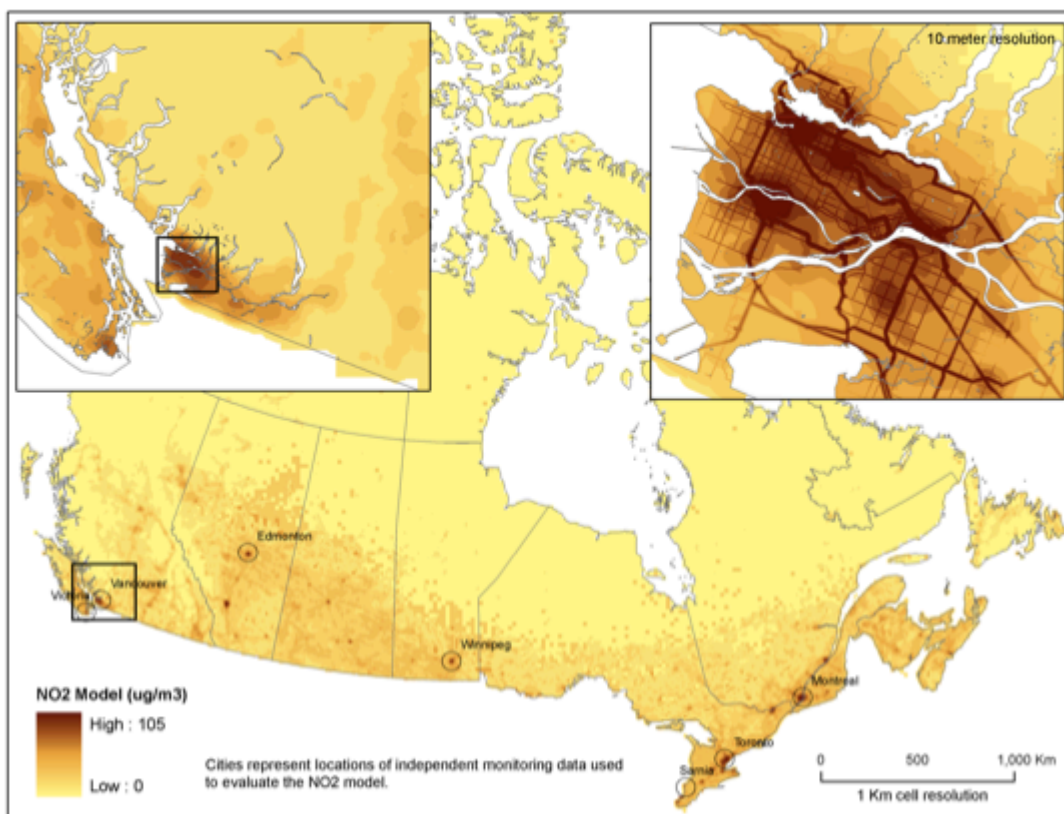
Figure D1. National NO$_2$ model created from NAPS monitoring data that incorporates satellite-derived NO$_2$ estimates and geographic land use predictor variables, and deterministic roadways gradients (Hystad *et al*., 2011).
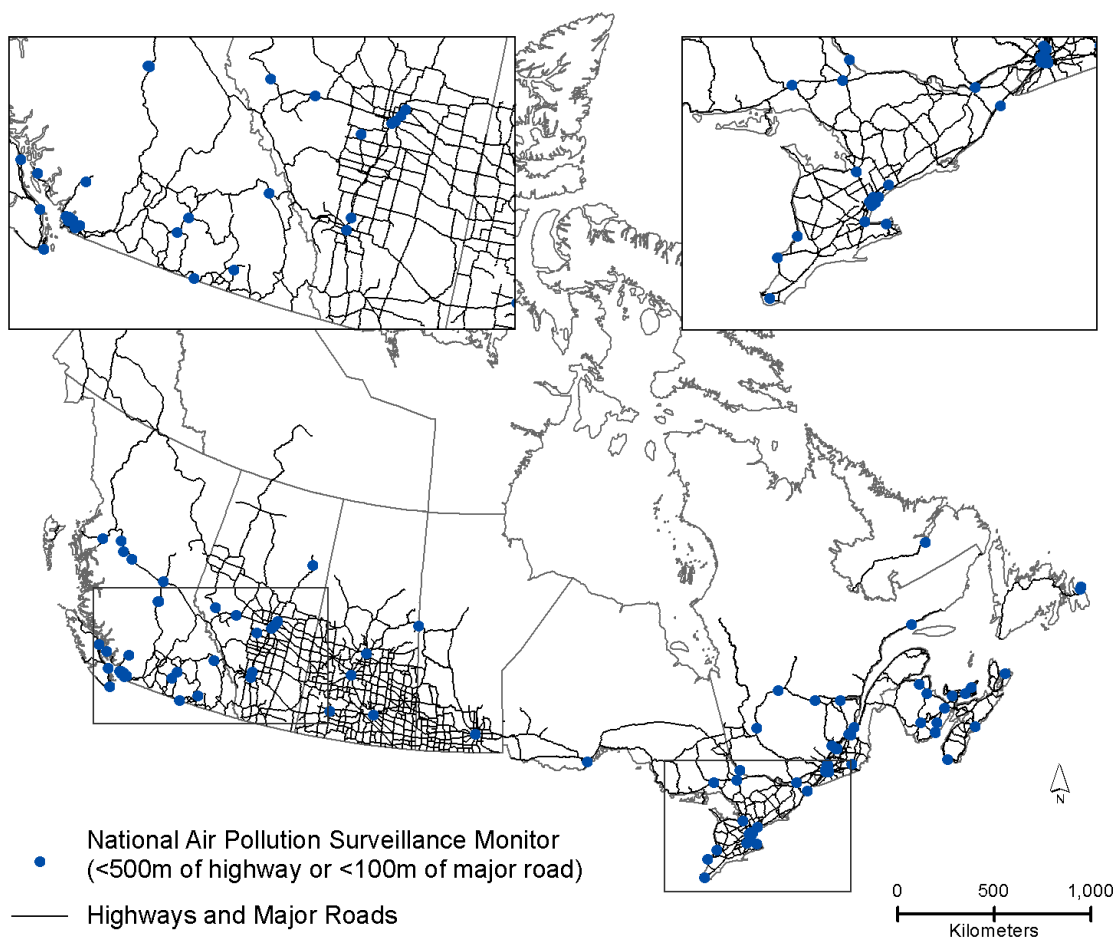
Figure D2. Location of NAPS monitors (n=104) within 500 m of a highway or within 100 m of a major road (Hystad *et al*., 2011).