The Effect of Building Construction and HVAC Systems on PM Concentration from Outdoor Sources

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Adverse health effects of human exposure to particulate matter (PM) in indoor environments and the associated costs have been of interest in recent studies conducted outside Canada. It was, therefore, necessary to investigate these effects in a Canadian environment. This study investigated the effects of building construction and Heating, Ventilation, and Air Conditioning (HVAC) systems on the indoor concentration of airborne PM of outdoor origin and the related health impacts and cost savings in Ontario. Due to the complexity of the investigation, the study has been limited to the metropolitan areas of Toronto and Hamilton which represent much of the population of Ontario and a significant portion of all Canada. The main objective of the cost-benefit analysis (CBA) was to analyze and evaluate the effects of pollution in monetary equivalents. The modeling integrated the various models using the Impact Pathway Approach. The approach consisted of four steps: First, identify the sources and emissions of PM. Although the study focused on indoor environments, outdoor sources such as incomplete combustion from rush hour traffic were identified for the geographical areas of the study. Secondly, evaluate the dispersion or the concentration of PM on the site of interest. In order to achieve this goal, building modeling was first established that was applicable to Ontario. There were three homes and two commercial building scenarios: Existing homes (resExist), new homes constructed under minimum building code requirements (resBC), and under R2000 standard (resR2000); commercial buildings with 40% (school40) and 85% (school85) ASHRAE air filters. Air flow rates were calculated from building and HVAC sizing calculations. These flow rates were used to calculate input parameters for well-established mass balanced indoor PM concentration models. In addition, indoor exposure needed to account for time activity in each micro-environment in Ontario. This was accomplished by using time-weighted exposure modeling. Thirdly and lastly in the Impact Pathway Approach, evaluate the health impact and its monetary equivalent, respectively. In order to evaluate the health effects and monetary equivalents, the study considered fourteen retrofit cases which consisted of improving factors such as building construction, distribution system, and air filtration efficiency. Because input parameters were selected from data applicable to Ontario, the study provided a model setup that could be applied to future work in Canada.

The study demonstrated that Canadian building construction provided significant protection from time-weighted PM exposure (Toronto, ambient vs. resExist/school40win, $PM_{2.5}$ 10.00 vs. 4.20 $\mu g/m^3$). For this scenario, the prevented attributable number of cases (ANCs) was 721 for Toronto related to equivalent PM_{10}. Cost savings due to building envelope protection of mortality alone much outweighed costs in investment scenario for new home construction (Toronto, \$1,671 million vs. \$21.6 million). Therefore, recommendations were made to invest in home construction. Similarly, the morbidity effects were very significant, especially for chronic bronchitis endpoints which were along the same magnitude as mortality for most of the cases. Similar results were obtained for Hamilton in proportion to their relative population at risk. In addition, Canadian building construction and HVAC systems showed larger time-weighted PM exposure in the summer compared to the winter conditions due to the various HVAC operating conditions such as air flow rates (Toronto, resExist/school40sum, $PM_{2.5}$ 5.18 $\mu g/m^3$; resExist/school40win, $PM_{2.5}$ 4.20 $\mu g/m^3$). Furthermore, cost savings from retrofits from existing home to forced air with air filtration were very significant. It was demonstrated that the cost savings related to reduction of equivalent PM_{10} exposure due to mortality alone much outweighed costs in retrofit investment scenarios (R2000, Toronto, \$574 million vs. \$4.96 million). Therefore, the government would be wise to promote more energy efficient homes by offering more incentive programs. Factors such as wall insulation, air flow rate changes of less than 600 cfm, and HRV installation type did not played a major role. In addition, the effect of air filtration was more intense in homes compared to commercial buildings. Similarly, the impact of simultaneously retrofitting both, homes and commercial buildings, where children and adults spent most of the daily activities produced the greatest reduction of outdoor PM exposure. Installing high efficient air filtration in both homes and commercial buildings

resulted in optimal reduced effects. The cost savings from the retrofit due to mortality alone much outweighed the investment scenario costs justifying the retrofit (Toronto, $470 million vs. $1.8 million). This demonstrated that PM concentration exposure reduction is a collective effort that needed to be regulated not only in ambient air level but in the work environment and in homes as well.

It was identified that results were limited to model assumptions and input parameter data used. Since some of the parameters used, such as ambient PM concentrations, were average values, the results may not represent the exact actual conditions. Nevertheless, they provided a starting point since they were tailored to Ontario. Therefore, this study provided model simulation data that related to the Canadian environment having many factors in common such as weather, building construction, building systems, and government regulations. Therefore, the results are part of useful data for policy decisions as well as a starting point for future related work.

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I would also like to thank my family for all their support and understanding. Above all I would like to thank God for the opportunity and strength He provided me to work on this degree.

Dedication

I would like to dedicate this thesis to my wife, Melissa, my son, Aaron, and my mother, Melida.

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List of Abbreviations

AER	Air Exchange Rates
ANCs	Attributable Number of Cases
ANSI	American National Standards Institute
ASHRAE	The American Society of Heating, Refrigeration and Air Conditioning Engineers
CBA	Cost-Benefit Analysis
CFD	Computation Fluid Dynamics
C-R	Concentration Response Function
CWS	Canada Wide Standard
EPA	The Environmental Protection Agency
ERVs	Energy Recovery Ventilators
ESP	Electrostatic Precipitation
ETS	Environmental Tobacco Smoke
IAQ	Indoor Air Quality
IPOP	Indoor Proportion of Outdoor Particles
HRAI	Heating, Refrigeration, and Air Conditioning Institute
HRVs	Heat Recovery Ventilators
HVAC	Heating, Ventilation, and Air Conditioning
LEED	Leadership in Energy and Environmental Design
MERV	Minimum Efficiency Reporting Values
MUA	Make Up Air Units
NL	Normalize Leakage
NAAQOs	National Ambient Air Quality Objectives
NAAQS	the National Ambient Air Quality Standards
NBC	National Building Code
NIOSH	National Institute for Occupational Safety and Health

NRCan	Natural Resources Canada
OBC	Ontario Building Code
OPC	Ontario Power Corporation
PM	Particulate Matter
R2000	High efficiency standard for homes
resBC	New homes built to minimum building code requirements
resExist	Existing homes with hydronic baseboard heating and natural cooling
resR2000	New homes constructed to R2000 standards
SBS	Sick Building Syndrome
school40	Commercial building with 40% efficient air filter
school85	Commercial building with 85% efficient air filter
TEOM	Tampered Element Oscillating Microbalance
TMA	Time-Microenvironment-Activity
UCM	Unit Costs of Morbidity
UVGI	Ultraviolet Germicidal Irradiation
VSL	Value of Statistical Life
VOCs	Volatile Organic Compounds
WTP	Willingness To Pay

Chapter 1: Introduction

1.1 Background and Motivation

Epidemiological studies have discovered adverse human health effects caused by airborne particulate matter (PM) including respiratory problems, heart effects, and premature death. [1] Although PM is regulated at the outdoor level there is need to investigate airborne PM in an indoor environment as well. [2] In North America and many places throughout the world, people spend 90% of their day in an indoor environment. [3] Although, several indoor sources have been identified, one major contributor was PM coming from outdoor sources through the building envelope and ventilation systems. [4] Human exposure to PM and the associated effects have been topics of interest in recent research. However, most studies have been conducted outside Canada. [5] It is, therefore, necessary to investigate these effects in a Canadian environment.

1.2 Objectives

This study investigated the effects of building construction and Heating, Ventilation, and Air Conditioning (HVAC) systems on the indoor concentration of airborne PM of outdoor origin and related health impacts and cost savings within the Canadian environment. Due to the complexity of the investigation, its scope was limited to the province of Ontario and, in particular, to the metropolitan areas of Toronto and Hamilton, which represent a significant portion of the population in Ontario.

1.3 Contribution

This study is part of current efforts investigating PM effects in Canada. It provides model simulation data related to the Canadian environment. Although it focuses on metropolitan areas of Ontario, the data nevertheless is related to the rest of Canada. The areas under investigation have many factors in common such as weather, building construction, building systems, and government regulations. Therefore, the results provide a starting point of useful data for policy decisions.

In addition, the study provides a model setup that could be used for future related work.

Chapter 2:

Literature Review

2.1 Indoor Air Quality

2.1.1 Overview

Indoor Air Quality (IAQ) has become a topic of interest in research during the past decades due to some cases of adverse health effects such as the Sick Building Syndrome (SBS) related to air pollutant exposure. [6] These pollutants may include Particulate Matter (PM), Ozone, NO_2, SO_2, CO, and Volatile Organic Compounds (VOCs), formaldehyde, and other pollutants. [7] Some of the control methods suggested by the USA's Environmental Protection Agency (EPA) consist of pollutant source control, ventilation, and air filtration. [1][8] Therefore, the American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) provide minimum ventilation rates for buildings. [9] Forms of ventilation may include forced ventilation by fans or natural ventilation through open windows and infiltration through cracks in the building envelope. However, one of the problems encountered with ventilation systems and infiltration consists of introducing pollutants from outside in a polluted ambient air environment. [4] Air introduced through ventilation or infiltration needs to be conditioned to the occupant comfort levels adding to energy costs. In an effort to reduce these energy costs, recent legislation has increased the air tightness of buildings to reduce infiltration. [10] However, this increased tightness has added to the IAQ problem since pollutants get trapped inside the building. Another method to reduce indoor pollutant concentration is air filtration. PM may be controlled by air filtration or electrostatic precipitation. VOC control includes adsorption or catalytic oxidation. [8] PM concentrations in buildings may be affected by factors such as indoor sources and sinks, infiltration and exfiltration, and ventilation and filtration systems. [4] In this study, PM is referred to as PM_{10} since this term includes $PM_{2.5}$ as well. However, some analysis has been made in terms of $PM_{2.5}$ since it has become of considerable interest in recent studies. [1] Nevertheless, due to limited $PM_{2.5}$ data, some analysis is identified in terms of PM_{10}.

2.1.2 PM Sources

PM from environmental tobacco smoke (ETS), cooking, and wood burning as well as outdoor sources are most common PM sources due to incomplete combustion. Studies have proven that in smoker residents' homes, ETS is the higher source for indoor PM. Some studies found that indoor PM_{10} concentrations (43 $\mu g/m^3$) that surpassed ambient PM_{10} concentrations could occur. [2] Nevertheless, other studies have shown that important sources of indoor PM have proven to come from outdoor air infiltrated through the building envelop and introduced through the ventilation systems. [4] In addition, some studies that focused on the effect of outdoor air chose to ignore the effects of indoor sources. [3]

2.1.3 Particle Deposition and Resuspension

One of the PM sinks in indoor environments is deposition of particles. Deposition of particles consists of particles suspended in the air, or airborne, which eventually settle in surfaces inside the building. [11] Resuspension is the opposite effect. Deposition processes vary with particle size due to the different size dependent particle mechanics. Some studies have shown that PM removal mechanisms such as deposition are particle size dependent. Possible explanation may have to do with the fact that deposition rates are dependent on particle mechanics and particle mechanics is dependent on particle size. Studies have shown that there were smaller deposition rates on PM_{10} in urban areas than in the rural since rural areas are dominated by PM_{10}. Finally, in general, deposition for $PM_{2.5}$ was found to be smaller than PM_{10}. [3] Studies have identified that compared with other particulate control such as ventilation and filtration, deposition effects were relatively small. [4] Nevertheless, some studies have noted that despite the complex nature of the subject better understanding of deposition would help fine tune indoor PM concentration models as well as help in indoor PM control. Some of the factors that affected deposition processes and added to the complexity included surface roughness, turbulent air flow, particle and surface electrical charges as well as the particle mechanics of various particles sizes. Understanding the subject required the use of Computation Fluid Dynamics (CFD). Experimental data on the subject were very limited making the research and data available incomplete and requires further work. [11]

2.1.4 Infiltration

Infiltration refers to the air introduced into a building through the envelope cracks. Infiltration is an important process in controlling the indoor PM concentration in buildings in a relatively non polluted outdoor environment. In addition, it is also important consideration when studying the indoor PM concentration coming from outdoor sources in relatively more polluted ambient air. [2] Infiltration rates depend on the penetration of air through the building shell. Studies have shown that the effective size of all penetration or leakage area normalized by floor area was approximately lognormal and depended mainly on age of house and floor area. Older and smaller houses tended to have smaller normalized leakage areas.[12]

However, infiltration data generated by studies have been limited to only sections of the population that have been willing to participate such as low income homes, and energy efficient projects and did not represent the entire population. Infiltration data depends on factors such as weather conditions. The data available included some of the cities in US and did not represent all the different weather locations. Studies also recommended the use of their empirical findings being aware of the limitations within the US. [12] It is also important to distinguish between NL and Air Exchange Rates (AER) when comparing infiltration data. The former has to do with infiltration through building envelop cracks only whereas the latter includes air coming from open windows as well. Additional studies have reported that AER have shown to be greater in areas where natural ventilation through windows was used such as areas where summers were not as humid as others and did not need as much air conditioning during the summer. In these particular areas, AER values were found to be greater in the summer than in the winter conditions. (California, summer median 1.13 ACH, winter median 0.61 ACH) However, in areas where more air conditioning was needed in the summer, AER was found to be smaller in the summer compared to winter conditions. (Texas, summer median 0.37 ACH, winter median 0.63 ACH) [13] In general, studies have also shown that penetration factors which have to do with infiltration through building envelope cracks are very close to 1 altogether. Therefore, this value is assumed in most indoor PM concentration models. [3][14] However, since most of these studies have been implemented using experimentally created cracks of different shapes it was recommended that further studies be conducted on actual buildings to obtain more accurate data that evaluated actual cracks such as those near windows. [14]

2.1.5 Ventilation and Air Filtration

As mentioned above, due to the tighter envelopes in newer buildings, ventilation and air filtration have become necessary for indoor air quality control. Ventilation rates are regulated by standards such as AHSHRAE 62.1.[9] Minimum AERs are used by designers to provide the outside air needed within a building environment. A combination of mechanical and natural ventilation may be used to meet ventilation requirements. Mechanical ventilation may consist of exhaust and supply fans installed individually or as part of a make-up air system in Make Up Air Units (MUA) or heat and energy recovery system as in the case of Heat and Energy Recovery Ventilators, HRVs and ERVs, respectively. Mechanical ventilation requires the use of additional energy to condition the outside air as well as to run the electrical equipment such as the fan motors and motorized dampers. For this reason, use of mechanical ventilation should be used effectively so unnecessary energy waste may be minimized due to oversized equipment. Natural ventilation consists of ventilation provided through open windows and infiltration. In addition, as mentioned above, ventilation causes more outdoor PM concentrations coming into the building where polluted ambient air is introduced into indoor environment. Studies have shown that a combination of ventilation, and infiltration have produced Indoor Proportion of Outdoor Particles (IPOP) ranging from 0.05 to more than 0.9. [3]

Air filtration, has become more popular and necessary in recent years as well. Earlier in time and still most of the current HVAC systems today used the standard furnace air filters to keep the equipment safe from bulk particulate and dust. Recently, however, high efficiency filtration has become more popular in an effort to control indoor air pollutants and to minimize the health risks and costs in the various indoor environments. [15][16][17] Although different mechanisms of air filtration dominate each filtration scenario depending on the particle size, in general filtration efficiencies depend on mechanisms such as interception, impaction, diffusion, gravity settling, and electrical deposition. [8]

Studies have found that sedimentation and interception work well for particles larger than 0.5 µm while diffusion works best for particles smaller than 0.1µm. None of the mechanisms work well in between these limits which causes filter efficiencies within this size range to be relatively low. [8] Filter efficiencies tests and classification is controlled by ANSI/ASHRAE standard 52.2. Filter efficiencies range from Minimum Efficiency Reporting Values (MERV) ratings of 1 to 16. [16] In general, air filtration faces a tradeoff between filtration efficiency and increased pressure drop which adds to costs such as maintenance and fan power costs. [15] Some of the different types of air cleaning technologies available which include bio-contaminant treatment are mechanical filtration, electrostatically enhanced filtration, electret filters, electrostatic precipitation (ESP), and ultraviolet germicidal irradiation (UVGI). [8] Studies have found that each technology operation depends on particle size. [17] Other studies have shown that ventilation coupled with filtration systems were capable of reducing indoor PM concentration by 34%. [4] In addition, studies showed that in urban environments IPOP were higher for residential cases where use of natural ventilation with open windows and lowest for forced air cases. [3] Finally, it was noted that further research was needed in smaller PM range of particles such as $PM_{2.5}$ since there was limited data for PM particles within this range due to lack of instrumentation. [4]

2.2 Modeling

2.2.1 Overview

Modeling IAQ is important since it provides predictions of future IAQ design implementations at the design stage. Modeling is economically sound since it does not require the experimental equipment, materials and time to run experiments. However, the data generated is mainly theoretical and verification with experimental data is necessary to validate and fine tune models. Furthermore, there are three further classification of main type of models used in IAQ, statistical, mass balanced and Computational Fluid Dynamics (CFD). Statistical models are used for population exposure estimation. Mass balanced models are used for impact of sources estimation. CFD is used for near-source individual exposure estimation. [6]

2.2.2 Mass Balanced Concentration Models

Mass balanced models are used to estimate the effect of sources, sinks and IAQ control options on indoor pollutant concentrations. The steady-state equation for indoor concentration is shown in Eq. 1. [18] The equation assumes return air filter and supply air filter efficiencies to be the same, exfiltration rate to be the same as infiltration rate and exhaust rate to be the same as make up air. It also assumes well-mixed air conditions.

$$C_i = \frac{S/V + C_{oa}\,(Q_{oa}\,(1 - \varepsilon_s)\,/\,V + Q_i\,P/V)}{Q_r\ \varepsilon_s/V + (Q_{oa} + Q_i)/\,V + \beta} \qquad \text{Eq. 1}$$

Where,

V	volume of the building (m^3)
C_i	indoor concentration of pollutant ($\mu g/m^3$)
t	time (h)
Q_i	infiltration flow rate through the building envelop (m^3/h)
C_{oa}	outside air pollutant concentration ($\mu g/m^3$)
Q_{oa}	outside air flow rate through supply air filter (m^3/h)
Q_r	recirculation air flow rate through the supply air filters (m^3/h)
S	indoor source of pollutant component ($\mu g/h$)
ε_s	supply filters efficiency
P	penetration factor
β	deposition factor term (1/h)

Previous studies have used mass and number balance models to investigate the effects on PM concentrations by different factors. Studies have used similar models to investigate the effect of outdoor concentration, and indoor sources such as tobacco smoke on indoor pollutant concentration. Others have used mass models to investigate the effects of building shell, filtration and deposition effects on indoor PM. [2][4] One study in particular estimated the health risk and costs reductions related to outdoor particulate matter from building ventilation and filtration scenarios in Singapore [18] Although most parameters used Singapore data, some were taken from North American studies and were assumed to apply to Singapore. See Table 1. As discussed in the methodology section of this paper, the current study's input parameters will use data applicable to Canada.

Table 1: Mass Balanced Concentration Model Input Parameters in Previous Studies [18]

Mass Balanced Concentration Model Input Parameters		Building Type				
		Ofc40	Ofc85	ResAC	ResTV	ResNV
Indoor Source Term	S/V (1/h)	0	'0	'0	'0	'0
Return Air Flow Term	Qr/V (1/h)	1.2±0.6	1.2±0.6	'0	'0	'0
Outside Air Flow Term	Qoa/V (1/h)	1.4±0.6	1.4±0.6	'0	'0	4.3±0.1
Infiltration/Exfiltration Term	Qi/V (1/h)	0.2±0.1	0.2±0.1	0.6±0.2	0.5	'0
Filter Efficiency	εs	0.4	0.85	0.2	na	na
Deposition Term	β (1/h)	0.97	0.97	0.97	0.97	0.97
Penetration Term	P	1	1	1	1	1

Ofc40 are office buildings with 40% ASHRAE, Ofc85 are office buildings with 85% ASHRAE filter, ResAC are homes with forced air system and standard furnace filter, ResTV are closed homes with typical infiltration rate, and ResNV are homes with natural ventilation through open windows.

2.2.3 Total Exposure Time-Weighted Modeling

Exposure to PM pollutants is significantly affected by the time activity patterns of the population exposed or time-microenvironment-activity (TMA). Several studies have concentrated on determining the time spent in various activities and locations of diverse population in various places of the world and under various circumstances. [21][22] Studies have used a similar TMA exposure model as Eq. 2. [18][19] [20]

$$C_{tw} = \sum t_{ij} \, C_{ij} \, / \, Ttotal \qquad \text{Eq. 2}$$

Where,

C_{tw} time weighted exposure for period i and micro-environment j (μg/m^3)

T_{ij} hours expended in micro-environment j and period i (h)

C_{ij} PM concentration in micro-environment j for period i (μg/m^3)

T_{total} total time (h)

2.2.4 Health Response Modeling

Recent studies have shown that both PM_{10} and $PM_{2.5}$ short and long term human exposure were linked to cardiovascular, respiratory and premature mortality effects in addition to other effects. [5][23][24] In many cases, there was greater risk of adverse effects for the elder, children and patients of heart and lung decease. Other factors that affected the effects on a population were duration of exposure and PM concentration levels. There were five basic variables investigated in epidemiological studies: mortality, hospital admissions/emergency visits, respiratory health with symptoms as reduced activity days, pulmonary function and cancer. [25][26] For example, studies have investigated the effect of improved air cleaning system on the PM exposure health effects such as premature deaths, hospital and emergency room visits and asthma attacks. Studies discovered that updating conventional air filter to high efficiency in-duct filter reduced 700 premature deaths, 940 hospital room visits, and 130,000 asthma attacks in metropolitan areas in the US. [19] In order to estimate the effects, studies have used several PM response functions such as the log-linear model below. [18][26]

$$\begin{aligned} &Attributable\ number\ of\ cases\ (ANCs) \\ &= \Delta\ cases\ of\ health\ effects \\ &= -\ (baseline\ incidence\ x\ (exp(-\beta\ x\ \Delta C) - 1\ )\ x\ population\ at\ risk \qquad \text{Eq. 3} \end{aligned}$$

Where,

ΔC change in time weighted PM concentration ($\mu g/m^3$)

β coefficient of C-R functions (per $1\mu g/m^3$ change in PM)

2.2.5 Economic Modeling

The main objective of cost-benefit analysis (CBA) was to analyze and evaluate the effects of pollution in monetary values. Different approaches were used to process the data for evaluation. One such approach was the Impact Pathway Approach which was used throughout this paper. This approach consisted of the following steps. First, identify the sources and emissions. Second, evaluate the dispersion or the concentration on the site of interest. Thirdly, evaluate the concentration-response or impact. Lastly, evaluate the monetary equivalent value to the impact. [23][24]

Methods to calculate the economic benefit were based on Willingness to Pay (WTP) and Cost of Illness (COI). Other methods for the effect of PM pollution on mortality were based on Value of Statistical Life (VSL). Morbidity cost can also be calculated using Unit Costs of Morbidity (UCM) with the WTP approach. [18][23][24]

2.2.6 Modeling Setup

Studies have used various model setups depending on the location of interest. Each country had its own dominant building construction, and HVAC systems as well as existent and future government regulations. Studies were set up to investigate the various variables of interest within each location. This may include comparison of building construction options, HVAC systems, or existent and new regulations. [19] For example, as seen in Table 1, one study modeled office buildings with 40% and 85% ASHRAE filters, homes with forced air system and standard furnace filter, closed homes with typical infiltration rate, and homes with natural ventilation through open windows. It then compared the effect of different retrofit scenarios in Singapore. [18]

2.2.7 Model Limitations

Models used in this study are well established. Some studies validated models with experimental data. However, in relatively new areas of research, future model validation is needed. Research studies for $PM_{2.5}$ have limited experimental data available to validate models due to lack of measurement instrumentation. [1][4] In addition, as explained above, some assumptions were made such as the well-mixed air assumption in the mass balanced equation. This condition is not present in most actual indoor environments. Therefore, theoretical results are expected to show discrepancies to measured data. [6]

2.3 Canadian Legislation and Standards

Canadian government departments at the federal and provincial levels directly or indirectly affect air pollution regulations. Air pollution regulation in Canada begun in the 1970's and 1980's but later in the 1990's new information became available that caused worldwide reevaluation. Some studies have focused on PM_{10} but relatively fewer on $PM_{2.5}$. [19] In general, the Canadian Environmental Protection Act (CEPA) is used by the Minister of Health and the Environment to plan objectives for environmental quality goals. [26] The ministry of environment for Ontario, publishes data on pollution levels and control initiatives. There are also some new regulations such as the Canada Wide Standard (CWS) which provides a metric based on 24hr average levels such 30 µg/m3 on $PM_{2.5}$ that needed to be met by 2010 and reported by 2011. [28] Previous to the CWS, there was ongoing work by the National Ambient Air Quality Objectives (NAAQOs) to regulate PM concentrations. Nevertheless, this function was transmitted to the CWS. [26]

There are various codes, guidelines and regulations that affect building construction, HVAC, and filtration systems in Canada. The national and provincial building codes provide minimum regulations to building construction and building systems. In Ontario in particular, building construction and equipment is regulated by the National Building Code (NBC) and the Ontario Building Code (OBC). [30] For residential buildings, these codes establish limiting design factors such as minimum ventilation rates and minimum building envelope insulation values. Individual codes are derived from industry standards from organizations such as the American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) and the USA's Environmental Protection Agency (EPA) who provides the framework from which local codes are derived in North America. [9][15][31] In addition, to standards there are programs that regulate and promote high energy efficiency and improved air quality initiatives by offering incentives on retrofit and new construction. Natural Resources Canada (NRCan), R-2000 homes, Leadership in Energy and Environmental Design (LEED) and others, offer programs and incentives for energy efficiency measures regulating water efficiency, equipment efficiency, and building envelope efficiencies. [10] [32]

In particular, the R-2000 homes program, administered by NRCan, is a voluntary evolving standard. The standard adds additional energy efficiency limits to the NBC and provincial codes. R-2000 is based on annual energy targets calculated for each house size. R-2000 homes program requires installation of Heat Recovery Ventilators (HRV) and exhaust fans certified by the Home Ventilating Institute (HVI), minimum of double-glazed windows with low-emissivity coating and inert gas fill. It also includes selection of construction materials and finishes that reduce indoor air pollutant generation. [10] In addition, indoor air quality is achieved by selection of air filtration with filter of at least Minimum Efficiency Reporting Value (MERV) of 13, an electronic air cleaner in the forced-air ductwork, or an air filtration system such as activated carbon installed on the forced air system. [10] [16]. According to ASHRAE a filter of MERV 13 has an equivalent efficiency of 90% for particles in the range of 1 to 10 μm. [16]

The Leadership in Energy and Environment Design (LEED) system consists of a voluntary high efficiency points based program designed to promote high efficiency in new construction as well as retrofits. The system assigns point values to different categories of high efficiency and determines an overall efficiency of the building by adding all the points. Among these, 15 maximum points are allowed for Indoor Environmental Quality of which required points are assigned for Minimum Indoor Air Quality Performance and Environmental Tobacco Smoke (ETS) Control. Points are assigned for indoor air quality management plan, ventilation, outdoor air monitoring, low-emitting materials, controllability of system, thermal comfort, and daylight. The certification designations consist of Certified (40 to 49 pts), Silver (50 to 59 pts), Gold (60 to 79 pts) and Platinum (80 pts and above). [32]

2.4 Objectives and Tasks

Therefore, current study investigated the effects of building construction and HVAC systems on the indoor concentration of airborne PM coming from outdoor origin and related health impact and cost savings within the Canadian environment. Due to the complexity of the investigation, it limited its scope to the province of Ontario and in particular to the metropolitan areas of Toronto, and Hamilton which represent much of the population in Ontario and a significant portion of all Canada.

The main objective of cost-benefit analysis (CBA) was to analyze and evaluate the effects of pollution in monetary equivalents. The approach used was the Impact Pathway Approach as described above. This approach consisted of the following four steps: First, identify the sources and emissions. Second, evaluate the dispersion or the concentration on the site of interest. Thirdly, evaluate the concentration-response or impact. Lastly, evaluate the monetary equivalent to the impact. [23][24]

As will be explained in the next section, identification of building construction types and HVAC systems for Canadian environment needed to be implemented. The use of applicable models described above with their assumptions and limitations needed to be considered including each physical concept such deposition, infiltration, and others discussed above. In addition, input parameters needed to be selected that were applicable to Canada. Finally, the model limitations needed to be identified and the results of the study qualified.

Chapter 3: Methodology and Approach

3.1 Modeling

3.1.1 Overview

As mentioned in the previous section, the main objective of the cost-benefit analysis (CBA) was to analyze and evaluate the effects of pollution in monetary equivalents. The Impact Pathway Approach was used and consisted of the following steps: First, identify the sources and emissions. Second, evaluate the dispersion or the concentration on the site of interest. Thirdly, evaluate the concentration-response or impact. Lastly, evaluate the monetary equivalents to the impact. [23][24] The integration of models within the Impact Pathway Approach is shown in Figure 1.

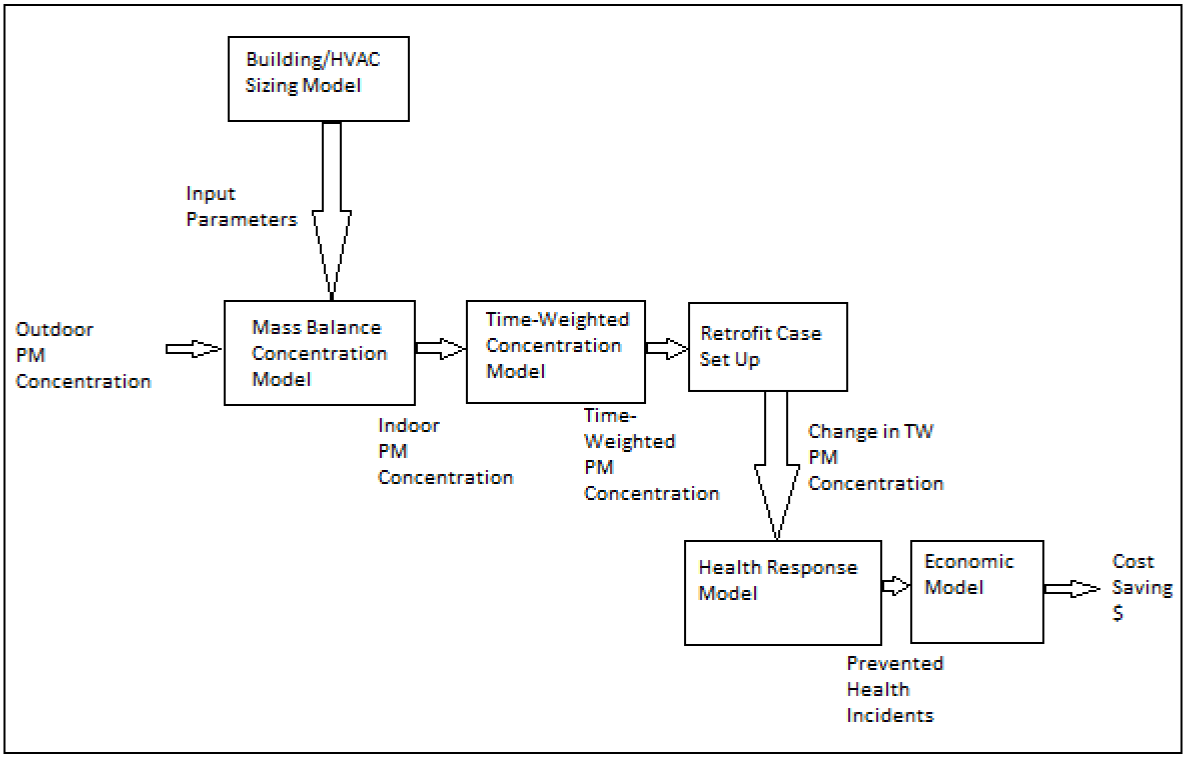


Figure 1: Integration of Models in the Impact Pathway Approach

Some of the outdoor PM sources and emissions identified in the metropolitan areas were related to incomplete combustion from vehicle engines, especially in rush hour traffic. In Hamilton and Toronto, in particular, some ambient PM also comes from industrial plant emissions. [7] The pollutants then are introduced to the indoor environment through the ventilation and infiltration systems. [19] In order to determine the effects of building construction and HVAC systems on the PM concentrations and their effects, building modeling applicable to Ontario needed to be identified first.

Therefore, a selection was made of building types that represented Canadian buildings and in particular those in Ontario based on the author's technical knowledge. For homes, three buildings were selected: 50 year old existent homes with limited or no retrofits (resExist), average new homes with minimum building code requirement (resBC), and new homes built to R-2000 standards (resR2000). Existent homes were assumed to have hydronic baseboard heating for the winter conditions, and natural cooling and ventilation for the summer conditions. The building envelope was also assumed to have high air leakage, low envelope insulation, and single glazed windows. Minimum building code new homes were assumed to have forced air heating and cooling with a medium efficiency furnace and standard furnace filter (20%). HRV was assumed to be installed with a simplified connection to the furnace return air duct. The building envelope was assumed to have air tightness to code requirements and minimum building code envelope insulation and windows according to OBC (R20 walls, R40 ceilings, double glazed windows, R12 basement walls). [29][30] R2000 homes were assumed to have high efficiency HVAC equipment (95% efficient furnace), a forced air system for both heating and cooling, and an air filter with MERV 13 or 90% efficient for particles 1 to 10 µm according to the R2000 high efficiency level and the ASHRAE 52.2 standard. [10][16] HRV was assumed to have a dedicated distribution system instead of being connected to the furnace air duct. The building envelope was assumed to have relatively higher air tightness, and higher envelop insulation compared to the previous modeling (R30 walls, R50 ceilings, R22 basement walls) and included double glazed windows with argon fill and e-coating. [10] [33]

Two types of commercial buildings were selected: average school buildings and high efficiency school buildings (school40, school85). For simplification and the purposes of this study, the main distinction between these two commercial buildings was in their air filter efficiencies. One was modeled with ASHRAE 40 air filters and the other one with ASHRAE 85 air filters. [16][31][32] For model simplification, school buildings were identified as being the worst case scenario of both offices and schools and was chosen to represent commercial building models in this study since this type included relatively more building loads. In addition, it involved both adult and child occupants. In order to reflect the extreme weather common to the Canadian climate, summer and winter scenarios were investigated in all selected building types.

In order to calculate input parameters for the mass balanced modeling used in the next step of the Impact Pathway Approach described in Section 3.1.2, the various air flow rates needed to be determined based on the sizing of the building models and HVAC systems. The approach to sizing the home and commercial models was based on the author's technical knowledge and applicable standards. [9][29][30] [31] [32][33] Weather data for both Toronto and Hamilton were compared. It was identified that they were the same for cooling but somewhat different for heating. Both Toronto and Hamilton use 88 ºF DB and 73 ºF WB weather temperature conditions in the summer. However, in the winter, Toronto uses -4 ºF DB and Hamilton uses a 1 ºF design outdoor temperatures. [29][33] The heating and cooling building load calculations in each city used load factors that were calculated according to the Heating, Refrigeration, and Air Conditioning Institute (HRAI). Appendix A shows a sample calculation summary for the BC home model (resBC) generated by the HRAI simulation software, Right Suite Universal. [33] The heating and cooling loads generated were 79,476 btuh and 38,884 btuh, respectively. The sample calculations used a total area of 4,016 sqft.

These loads generated the approximate heating and cooling load factors of 20 btuh/sqft and 9 btuh/sqft, respectively. The following factors were used to approximate the heating and cooling loads on the building models: Existent homes' heating and cooling load factors of 28 btuh/sqft and 14 btuh/sqft, respectively, for Toronto, and 25 btuh/sqft and 14 btuh/sqft, respectively, for Hamilton. New building code homes' heating and cooling loads factors of 20btuh/sqft and 9btuh/sqft, respectively, for Toronto, and 18btuh/sqft and 9btuh/sqft, respectively, for Hamilton. R2000 homes' heating and cooling load factors of 19 btuh/sqft and 7 btuh/sqft, respectively, for Toronto and 17 btuh/sqft and 7 btuh/sqft, respectively, for Hamilton. An average size of 4,000 sqft was assumed, and included the basement space. The resulting heating and cooling loads for each building type are shown in Table 2, Table 3, and Appendix A. From the heating and cooling loads, supply and return air flow-rates for the new BC homes and new R2000 homes were estimated as follows. Supply heating airflow rates were estimated using Eq. 4. Supply and return airflows were considered to be equal. Supply cooling flow rates were estimated using a factor of 400cfm/ton. [30][33] Air flow rates were used to calculate mass balanced model input parameters described in Section 3.1.2. The resulting flow rates are shown in Table 2, Table 3, and Appendix A. Appendix A also shows the setup of the basic building and HVAC sizing calculations.

$$Q = 1.08\,V\,(\Delta T) \qquad \text{Eq. 4}$$

where,

Q	heat load (btu/h)
V	volumetric flow rate (cfm)
ΔT	temperature change (ºF)

Ventilation flow rates for homes were estimated using a room count approach assuming the average homes' room count for a total of 130cfm: {1 master bedroom (20cfm), 2 other bedrooms (20cfm), 5 other rooms including kitchen, laundry, dining/living, 2 bathrooms

(50cfm), unfinished basement (20cfm)}. These calculations applied only to new homes since average existent homes were assumed with natural ventilation by opening windows. Tables 2, and 3 and Appendix A show the ventilation flow rates. Standard homes were assumed with HRV with simplified connection to the furnace return duct. R2000 homes were assumed as HRV with dedicated duct systems. [30][33]

Table 2: Heating, Cooling Loads and Flow Rates for Toronto

	Toronto				
Building Type	Heating Load (btu/h)	Cooling Load (btu/h)	Heating Flow Rate (cfm)	Cooling Flow Rate (cfm)	Ventilation Rate (cfm)
resExist	n/a	n/a	n/a	n/a	n/a
resBC	80,000	36,000	1,852	1,200	130
resR2000	76,000	30,000	1,759	933	130
school40	800,000	800,000	9,259	9,259	2,200

Table 3: Heating, Cooling Loads and Flow Rates for Hamilton

	Hamilton				
Building Type	Heating Load (btu/h)	Cooling Load (btu/h)	Heating Flow Rate (cfm)	Cooling Flow Rate (cfm)	Ventilation Rate (cfm)
resExist	n/a	n/a	n/a	n/a	n/a
resBC	72,000	36,000	1,667	1,200	130
resR2000	68,000	30,000	1,574	933	130
school40	800,000	800,000	9,259	9,259	2,200

Commercial buildings were sized according to the author's technical knowledge and the applicable standards. [9][16][31][32] Table 2, Table 3 and Appendix A show the calculated values. Both building types had forced air heating and cooling distribution systems. The main difference between the two model scenarios was attributed to air filter efficiencies. One used ASHRAE 40 and the other one ASHRAE 85 filters. [16] Ventilation rates for both types of buildings were calculated based on ASHRAE standards. [9] Table 2, Table 3, Appendix A and Appendix B show the calculated values. Despite some difference in the ventilation rates for schools and office buildings, the school scenario was used to model both types of buildings for simplicity since this building type represented the worst case scenario.

Furthermore, infiltration/exfiltration flow rates for forced air systems were calculated using air leakage heat loss factors for resBC, resR2000, and school40/85 of 0.070, 0.053, and 0.070 (Btu/ft^2 ºF h), respectively. The air leakage heat gain factors were 0.058, 0.044, and 0.058 (Btu/ft^2 ºF h), respectively. Infiltration/exfiltration flow rates for forced air systems were calculated using Eq. 5 and Eq.6. [33]

$$\begin{aligned}&Infiltration\ Heat\ Load\\&= (Floor\ Area \times Air\ Leakage\ Factor \times Temperature\ Change)\end{aligned} \qquad \text{Eq. 5}$$

$$Infiltration\ Flow\ Rate = \frac{Infiltration\ Heat\ Load}{1.08\ (Temperature\ Change)} \qquad \text{Eq. 6}$$

Ventilation air flow rates for existing homes during summer conditions where ventilation was assumed through open windows were calculated using AER of 1.13 ACH and Eq. 7. [13] In this building model, infiltration was included within the calculated ventilation air flow.

$$Ventilation\ Rate = AER \times Building\ Volume \times (1\ hr/60\ minutes) \qquad \text{Eq. 7}$$

The next step in the Impact Pathway Approach was to calculate the indoor PM concentration using mass balanced models and to identify the model-parameter data that applied to Canada. Previous studies and their sources of data were reviewed and evaluated for their fit to the Canadian scenario. Nevertheless, most of these input parameters were calculated from the air flow rates above. Appendices A to C show the setup for these calculations.

3.1.2 Mass Balanced Concentration Models

The next step on the impact pathway approach consisted of evaluating the dispersion or the concentration on the site of interest. In this case, this step involved evaluating the indoor PM concentration coming from outdoors. The mass balanced model selected was the steady-state indoor PM concentration model of Eq. 1 repeated below for convenience. As mentioned above, the mass balanced concentration model assumed well-mixed air conditions. Tables 4 to 6 and Appendix C show typical mass balanced concentration model setups used. Note that some of the parameters in Table 4 for existent buildings are zero values or N/A due to the absence of forced air system in this building model.

$$C_i = \frac{S/V + C_{oa}\left(Q_{oa}\left(1 - \varepsilon_s\right)/V + Q_i P/V\right)}{Q_r\, \varepsilon_s/V + \left(Q_{oa} + Q_i\right)/V + \beta} \qquad \text{Same as Eq.1}$$

Table 4: Mass Balanced Concentration Model for resExist Building for Winter and Summer

Mass Balanced Concentration Model Existing Homes, Winter		resExistWin Adults	Toronto Children	Hamilton Adults	Children
Indoor PM2.5 Concentration	Ci (µg/m3)	3.40	3.40	3.74	3.74
Indoor Source Term	S/V (1/h)	0.00	0.00	0.00	0.00
Return Air Flow Term	Qr/V (1/h)	0.00	0.00	0.00	0.00
Outside Air Flow Term	Qoa/V (1/h)	0.00	0.00	0.00	0.00
Infiltration/Exfiltration Term	Qi/V (1/h)	0.50	0.50	0.50	0.50
Filter Efficiency	εs	0.00	0.00	0.00	0.00
Deposition Term	β (1/h)	0.97	0.97	0.97	0.97
Outdoor PM2.5 Concentration	Coa (µg/m3)	10.00	10.00	11.00	11.00
Penetration Term	P	1.00	1.00	1.00	1.00

Mass Balanced Concentration Model Existing Homes, Summer		resExistSum Adults	Toronto Children	Hamilton Adults	Children
Indoor PM2.5 Concentration	Ci (µg/m3)	5.38	5.38	5.92	5.92
Indoor Source Term	S/V (1/h)	0.00	0.00	0.00	0.00
Return Air Flow Term	Qr/V (1/h)	0.00	0.00	0.00	0.00
Outside Air Flow Term	Qoa/V (1/h)	1.13	1.13	1.13	1.13
Infiltration/Exfiltration Term	Qi/V (1/h)	0.00	0.00	0.00	0.00
Filter Efficiency	εs	0.00	0.00	0.00	0.00
Deposition Term	β (1/h)	0.97	0.97	0.97	0.97
Outdoor PM2.5 Concentration	Coa (µg/m3)	10.00	10.00	11.00	11.00
Penetration Term	P	1.00	1.00	1.00	1.00

Table 5: Mass Balanced Concentration Model for resR2000 Building for Winter and Summer

Mass Balanced Concentration Model		resR2000Win	Toronto	Hamilton	
R2000 Homes, Winter		Adults	Children	Adults	Children
Indoor PM2.5 Concentration	Ci (µg/m3)	0.88	0.88	1.04	1.04
Indoor Source Term	S/V (1/h)	0.00	0.00	0.00	0.00
Return Air Flow Term	Qr/V (1/h)	2.72	2.72	2.41	2.41
Outside Air Flow Term	Qoa/V (1/h)	0.22	0.22	0.22	0.22
Infiltration/Exfiltration Term	Qi/V (1/h)	0.33	0.33	0.33	0.33
Filter Efficiency	εs	0.90	0.90	0.90	0.90
Deposition Term	β (1/h)	0.97	0.97	0.97	0.97
Outdoor PM2.5 Concentration	Coa (µg/m3)	10.00	10.00	11.00	11.00
Penetration Term	P	1.00	1.00	1.00	1.00

Mass Balanced Concentration Model		resR2000Sum	Toronto	Hamilton	
R2000 Homes, Summer		Adults	Children	Adults	Children
Indoor PM2.5 Concentration	Ci (µg/m3)	1.10	1.10	1.21	1.21
Indoor Source Term	S/V (1/h)	0.00	0.00	0.00	0.00
Return Air Flow Term	Qr/V (1/h)	1.34	1.34	1.34	1.34
Outside Air Flow Term	Qoa/V (1/h)	0.22	0.22	0.22	0.22
Infiltration/Exfiltration Term	Qi/V (1/h)	0.27	0.27	0.27	0.27
Filter Efficiency	εs	0.90	0.90	0.90	0.90
Deposition Term	β (1/h)	0.97	0.97	0.97	0.97
Outdoor PM2.5 Concentration	Coa (µg/m3)	10.00	10.00	11.00	11.00
Penetration Term	P	1.00	1.00	1.00	1.00

Table 6: Mass Balanced Concentration Model for school85 Building for Winter and Summer

Mass Balanced Concentration Model		school85Win	Toronto	Hamilton	
Office/School High Efficient, Winter		Adults	Children	Adults	Children
Indoor PM2.5 Concentration	Ci (µg/m3)	1.41	1.28	1.92	1.41
Indoor Source Term	S/V (1/h)	0.00	0.00	0.00	0.00
Return Air Flow Term	Qr/V (1/h)	2.12	2.12	2.12	2.12
Outside Air Flow Term	Qoa/V (1/h)	0.66	0.66	0.66	0.66
Infiltration/Exfiltration Term	Qi/V (1/h)	0.39	0.39	0.39	0.39
Filter Efficiency	εs	0.85	0.85	0.85	0.85
Deposition Term	β (1/h)	0.97	0.97	0.97	0.97
Outdoor PM2.5 Concentration	Coa (µg/m3)	11.00	10.00	15.00	11.00
Penetration Term	P	1.00	1.00	1.00	1.00

Mass Balanced Concentration Model		school85Sum	Toronto	Hamilton	
Office/School High Efficient, Summer		Adults	Children	Adults	Children
Indoor PM2.5 Concentration	Ci (µg/m3)	1.23	1.12	1.68	1.23
Indoor Source Term	S/V (1/h)	0.00	0.00	0.00	0.00
Return Air Flow Term	Qr/V (1/h)	2.12	2.12	2.12	2.12
Outside Air Flow Term	Qoa/V (1/h)	0.66	0.66	0.66	0.66
Infiltration/Exfiltration Term	Qi/V (1/h)	0.32	0.32	0.32	0.32
Filter Efficiency	εs	0.85	0.85	0.85	0.85
Deposition Term	β (1/h)	0.97	0.97	0.97	0.97
Outdoor PM2.5 Concentration	Coa (µg/m3)	11.00	10.00	15.00	11.00
Penetration Term	P	1.00	1.00	1.00	1.00

Previous studies used model input parameters that did not apply to Canada (Table 1). [18] Therefore, it was necessary to assess and replace data as needed to fit the Canadian scenario. As described above, calculations were made based on the author's technical experience and applicable industry standards such as ASHRAE 62, ASHRAE 90.1 for commercial buildings and OBC for homes. [9][30][31][33] For comparison, the new values are tabulated in Table 7. The model setup for this section of calculations may be seen in Appendix A through Appendix C. Comparing values in Table 7 with those in Table 1 shows that some of the discrepancies in the values used in this study were attributable to local reference data for the geographical locations. However, a few of them, such as the deposition (P) and the penetration (β) factors, were considered applicable since the original data was generated in North American studies as will be further discussed below. [3][18][34][35] Indoor sources of PM (S), although well known, were regarded as negligible compared to the contributions of PM coming from outdoors. [3]

Table 7 Mass Balance Concentration Model Input Parameters in Current Study for Toronto Summer

Mass Balanced Concentration Model Input Parameters		Building Type				
		school40	school85	resR2000	resBC	resExist
Indoor Source Term	S/V (1/h)	0	'0	'0	'0	'0
Return Air Flow Term	Qr/V (1/h)	2.11	2.11	1.34	1.78	0
Outside Air Flow Term	Qoa/V (1/h)	0.66	0.66	0.22	0.22	1.13 [13]
Infiltration/Exfiltration Term	QI/V (1/h)	0.32	0.32	0.62	0.82	'0
Filter Efficiency	εs [16]	0.40	0.85	0.90	0.20	na
Deposition Term	β (1/h) [18][34]	0.97	0.97	0.97	0.97	0.97
Penetration Term	P [3][35]	1	1	1	1	1

Outdoor $PM_{2.5}$ concentrations (C_{oa}) for the selected cities were compared with most recent obtained from a network of 40 monitoring stations in Ontario using Tampered Element Oscillating Microbalance (TEOM) instruments. [28] Some analysis was done in terms of $PM_{2.5}$ since it has become of interest recently. Nevertheless, other analysis was limited to PM_{10} due to the limited $PM_{2.5}$ data available. Some sources of data may deal with PM_{10}, or vice versa; therefore, the conversion equation used in previous studies was used as needed. [18][36]

$PM_{10} = PM_{2.5}/0.6$ Eq. 8

Ambient PM concentration data was used for year 2000 since the data needed to be compatible with health incident baseline data. [26][36] However, the 2000 PM concentration data was compared to most current showing only one or two units variations. [28] The annual 24hr average concentrations were taken to represent summer and winter conditions. The main objective of comparing concentration effects in the winter and summer were to identify effects of HVAC system operation during Canadian season conditions. In order to simulate urban and suburban activities, different locations on each metropolitan area were selected to represent each modeled scenario. For Toronto area, Toronto North concentrations were selected to apply to suburban activities. Toronto Downtown concentrations, though not the highest concentration in the area, were chosen to urban activities since a large portion of the adult population works downtown. For Hamilton, Hamilton Mountain was selected to represent suburban activities and Hamilton Downtown was selected to represent urban activity. [28][36] The Toronto and Hamilton suburban $PM_{2.5}$ concentrations were 10 $\mu g/m^3$ and 11 μg/m3, respectively. The urban $PM_{2.5}$ concentrations selected for Toronto and Hamilton were 11 μg/m3 and 15 $\mu g/m^3$, respectively. [36] Not much variation was found among $PM_{2.5}$ concentrations in these areas. Possible reasons for these similarities may be the average nature of the values. Although Hamilton downtown maximums were relatively higher than those for most areas in the Toronto area, when average values were considered, the differences were minimized. [28][36]

The infiltration (Q_i/V), ventilation (Q_{oa}/V), and return air (Q_r/V) input parameters for forced air systems were calculated from air flow rates as discussed above. The infiltration rates were considered equal to the exfiltration rates. The existent homes used a normal infiltration input parameter (0.5/h) for the winter conditions due to typical closed building conditions. [19] The infiltration component for the summer conditions of existent homes was considered as part of the AER calculation for natural ventilation input parameter. [13] The deposition terms (β) identified in previous studies (0.97/h) were considered applicable to this study since this data was originally generated in North American studies. [18][34] Penetration factors (P) were considered to be one as recognized in previous studies. [3][35] The choices and calculated values of input parameters may be seen in Appendix C and Table 7. Having deposition (β), and penetration (P) terms constant isolated the effects of the other factors within each building model category during the case comparisons below. The varying infiltration input parameter, Q_i/V, which appeared in both the numerator and denominator in Eq. 1 did not played a major role on results since its effects were minimized. Values for volume (V), and filter efficiency (εs) were chosen or calculated as needed based on the author's technical knowledge and industry standards. [16] Finally, all parameters used for this study including those calculated to the Canadian environment, were found to be comparable within a reasonable range from those used in similar North American studies. [3]

3.1.3 Total Exposure Time-Weighted Concentration Modeling

Next, in order to model a more realistic indoor PM concentration exposure, it was necessary to account for the time each population segment spent at each micro-environment. Children or adults were assumed to spend time in suburban environment at homes, schools and outdoors. Adults were assumed to spend time in urban environment at work in the office. The time-weighted concentration model selected for this study was taken as that used in similar studies (Eq.2). [18][20]

Selected time fractions on each micro-environment were adjusted assuming estimated time activity for adults at work and for students at school that related to Canada. Time activity for adults at work, home and outdoors were assumed to be, 0.33, 0.53, 0.14, respectively, and for children at school, home, and outdoors were assumed to be, 0.25, 0.61, 0.14, respectively, comparable to previous studies. These time activity patterns were found reasonable for Canadian environment since adults were assumed to spend an average of 8 hours a day in office buildings at work whereas children were assumed to spend an average 6 hours a day in school buildings. Outdoor time fractions were assumed to be the same for both adults and children as those used in other studies, since data sources used were from North American research. [18][19][21][22] The model setup and values used for this section are shown in Table 8, Table 9 and Appendix D.

Table 8: Time-Weighted Concentration Model Setup for school40/resExist, Winter and Summer

Time-Weighted Exposure Model resExist/school40 PM2.5	Winter Proportion	Toronto Exposure	Hamilton Exposure
Adults TW Concentration Exposure (µg/m3)		**4.2**	**4.9**
work (school40)	0.33	1.0	1.2
home (resExist)	0.53	1.8	2.1
outdoor	0.14	1.4	1.5
Children TW Concentration Exposure (µg/m3)		**4.2**	**4.6**
school (school40)	0.25	0.7	0.8
home (resExist)	0.61	2.1	2.2
outdoor	0.14	1.4	1.5
Time-Weighted Exposure Model resExist/school40 PM2.5	Summer Proportion	Toronto Exposure	Hamilton Exposure
Adults TW Concentration Exposure (µg/m3)		**5.2**	**6.0**
work (school40)	0.33	0.9	1.2
home (resExist)	0.53	2.9	3.3
outdoor	0.14	1.4	1.5
Children TW Concentration Exposure (µg/m3)		**5.3**	**5.8**
school (school40)	0.25	0.6	0.8
home (resExist)	0.61	3.3	3.5
outdoor	0.14	1.4	1.5

Table 9: Time-Weighted Concentration Model Setup for school85/resR2000, Winter and Summer

Time-Weighted Exposure Model	Winter		
resR2000/school8~~5~~		Toronto	Hamilton
PM2.5	Proportion	Exposure	Exposure
Adults TW Concentration Exposure (μg/m3)		**2.3**	**2.7**
work (school85)	0.33	0.5	0.6
home (resR2000)	0.53	0.5	0.6
outdoor	0.14	1.4	1.5
Children TW Concentration Exposure (μg/m3)		**2.3**	**2.5**
school (school85)	0.25	0.3	0.4
home (resR2000)	0.61	0.5	0.6
outdoor	0.14	1.4	1.5
Time-Weighted Exposure Model	Summer		
resR2000/school8~~5~~		Toronto	Hamilton
	Proportion	Exposure	Exposure
Adults TW Concentration Exposure (μg/m3)		**2.4**	**2.7**
work (school85)	0.33	0.4	0.5
home (resR2000)	0.53	0.6	0.7
outdoor	0.14	1.4	1.5
Children TW Concentration Exposure (μg/m3)		**2.4**	**2.6**
school (school85)	0.25	0.3	0.3
home (resR2000)	0.61	0.7	0.7
outdoor	0.14	1.4	1.5

3.1.4 Health Response Modeling

Once changes in indoor concentration PM exposures have been calculated, the next step on the Impact Pathway Approach consisted of evaluating the concentration-response or health impact due to concentration changes. The health response modeling looked at prevented premature deaths, prevented hospital and emergency room visits, prevented asthma attacks and others. The model used is the log-linear model in Eq. 3. This model was found to apply to this study since, although it has been used in other studies around the world, it was developed in North American research. [18][26]

The overall population and population age segments that were considered at risk for each scenario was taken from Canadian census information for 2001 to make it compatible to incidence baseline data available. [26][39] Values were compared with the most current data, and showed an overall increase in population of about one million for Toronto area and about 100,000 for Hamilton area. [37][38] According to the 2001 data, the Toronto metropolitan area population was 4,682,897, and Hamilton metropolitan area was 662,401. The population segments for each age range may be seen in Table 10 to Table 13 and Appendix E.

Table 10: Exposure Model and Economic Model Setup for Cases 1 and 2 for Toronto

Cases 1/2					Toronto Concentration Difference	
ambient to resExist/school40	β	Value/Incident $ (1000s)	Baseline Incidenc Season	Population at Risk	Winter PM2.5	Summer
Non-accident mortality (adlt > 30 yrs)	0.0043	2,318.1522	0.0034	2,821,497	5.8	4.8
Chronic Bronchitis (adlt>27yrs)	0.0913	125.5666	0.0030	2,821,497	5.8	4.8
Hospital admission respiratory (all ages)	0.0032	3.3323	0.0030	4,682,897	5.8	4.8
Emergency rm visits for asthma (under 65 yrs)	0.0037	0.0502	0.0030	4,154,210	5.8	4.8
Asthma attacks (childrn < 15)	0.0044	0.0155	0.0030	916,160	5.8	4.7
Asthma attacks (childrn >15)	0.0039	0.0155	0.0030	3,766,737	5.8	4.7
Restricted act dys, RAD (adlt > 20 yrs)	0.0094	0.0184	0.0030	3,462,797	5.8	4.8
Work loss days, WLD (18 to 65 yrs)	0.0046	0.0401	0.0030	2,934,110	5.8	4.8

Table 11: Exposure Model and Economic Model Setup for Cases 5 and 6 for Toronto

Cases 5/6					Toronto Concentration Difference	
resExist to resR2000	β	Value/Incident $ (1000s)	Baseline Incidenc Season	Population at Risk	Winter PM2.5	Summer
Non-accident mortality (adlt > 30 yrs)	0.0043	2,318.1522	0.0034	2,821,497	1.3	2.3
Chronic Bronchitis (adlt>27yrs)	0.0913	125.5666	0.0030	2,821,497	1.3	2.3
Hospital admission respiratory (all ages)	0.0032	3.3323	0.0030	4,682,897	1.3	2.3
Emergency rm visits for asthma (under 65 yrs)	0.0037	0.0502	0.0030	4,154,210	1.3	2.3
Asthma attacks (childrn < 15)	0.0044	0.0155	0.0030	916,160	1.5	2.6
Asthma attacks (childrn >15)	0.0039	0.0155	0.0030	3,766,737	1.5	2.6
Restricted act dys, RAD (adlt > 20 yrs)	0.0094	0.0184	0.0030	3,462,797	1.3	2.3
Work loss days, WLD (18 to 65 yrs)	0.0046	0.0401	0.0030	2,934,110	1.3	2.3

Table 12: Exposure Model and Economic Model Setup for Cases 11 and 12 for Toronto

Cases 11/12					Toronto Concentration Difference	
resExist/school40 to resR2000/school85	β	Value/Incident $ (1000s)	Baseline Incidenc Season	Population at Risk	Winter PM2.5	Summer
Non-accident mortality (adlt > 30 yrs)	0.0043	2,318.1522	0.0034	2,821,497	1.9	2.8
Chronic Bronchitis (adlt>27yrs)	0.0913	125.5666	0.0030	2,821,497	1.9	2.8
Hospital admission respiratory (all ages)	0.0032	3.3323	0.0030	4,682,897	1.9	2.8
Emergency rm visits for asthma (under 65 yrs)	0.0037	0.0502	0.0030	4,154,210	1.9	2.8
Asthma attacks (childrn < 15)	0.0044	0.0155	0.0030	916,160	1.9	3.0
Asthma attacks (childrn >15)	0.0039	0.0155	0.0030	3,766,737	1.9	3.0
Restricted act dys, RAD (adlt > 20 yrs)	0.0094	0.0184	0.0030	3,462,797	1.9	2.8
Work loss days, WLD (18 to 65 yrs)	0.0046	0.0401	0.0030	2,934,110	1.9	2.8

Table 13: Exposure Model and Economic Model Setup for Cases 13 and 14 for Toronto

Cases 13/14					Toronto Concentration Difference	
resBC/school40 to resR2000/school85	β	Value/Incident $ (1000s)	Baseline Incidenc Season	Population at Risk	Winter PM2.5	Summer
Non-accident mortality (adlt > 30 yrs)	0.0043	2,318.1522	0.0034	2,821,497	1.5	1.4
Chronic Bronchitis (adlt>27yrs)	0.0913	125.5666	0.0030	2,821,497	1.5	1.4
Hospital admission respiratory (all ages)	0.0032	3.3323	0.0030	4,682,897	1.5	1.4
Emergency rm visits for asthma (under 65 yrs)	0.0037	0.0502	0.0030	4,154,210	1.5	1.4
Asthma attacks (childrn < 15)	0.0044	0.0155	0.0030	916,160	1.5	1.4
Asthma attacks (childrn >15)	0.0039	0.0155	0.0030	3,766,737	1.5	1.4
Restricted act dys, RAD (adlt > 20 yrs)	0.0094	0.0184	0.0030	3,462,797	1.5	1.4
Work loss days, WLD (18 to 65 yrs)	0.0046	0.0401	0.0030	2,934,110	1.5	1.4

Coefficients of C-R functions (β) used in previous Canadian studies were not used in this study since those studies used different model setups and their coefficient magnitudes were not appropriate for this study. Coefficients of C-R functions vary significantly from study to study so meta-analysis generated data used in related research were used. This was considered applicable to Canada since the data were generated from North American research sources. [18][26] In addition, the daily baseline incidence rates used were as follows: 18.4 per million for non-accidental deaths, and 16 per million for hospital admissions due to respiratory causes. [26] Table 10 to Table 13 and Appendix E show the model setup used for this section of modeling.

3.1.5 Economic Modeling

The main objective of cost-benefit analysis (CBA) was to analyze and evaluate the effects of pollution in monetary values. The Impact Pathway Approach was used to achieve this goal.

The approach consisted of the following steps: First, identify the sources and emissions. Second, evaluate the dispersion or the concentration on the site of interest. Thirdly, evaluate the concentration-response or impact. Lastly, evaluate the monetary equivalent to the impact. [23][24]

Methods to calculate the economic benefit were based on Willingness to Pay (WTP), Cost of Illness (COI), Value of Statistical Life (VSL), or Unit Costs of Morbidity (UCM) with the WTP approach. [18] [23][24] Table 10 to Table 13 and Appendix E show the model setup for this section of modeling.

Unit costs of incidents found in studies were converted to Canadian equivalents. [5] First US dollars were converted from 1990 to 1999 using annual Consumer Price Indexes (CIP) of 130.7 and 167.0, respectively using Eq. 9. [18][41]

$$US\$_{1999} = US\$_{1990} \times CIP_{1999}/CIP_{1990} \qquad \text{Eq. 9}$$

Then the dollar values were converted to Canadian equivalent using Gross National Product (GNP) per capita for US and Canada for 1999 of 30,697 and 21,084, respectively, and using Eq. 10 with income elasticity (e) of 2.59. [18][40] [42]

$$(Unit\ Cost\ per\ Incident)_{\mathrm{Can}} = (Unit\ Cost\ per\ Incident)_{\mathrm{US}}\ x\ (GND_{\mathrm{Can}}/GND_{\mathrm{US}})^{\mathrm{e}} \qquad \text{Eq. 10}$$

3.1.6 Building Models and Case Setup

However, before the health impacts and cost savings were calculated above, retrofit case scenarios needed to be set up in order to calculate the change in indoor concentrations. This paragraph summarizes each building type and the following paragraph will talk about the actual retrofit case setups. In order to investigate the effects of the various building construction and HVAC operation on the indoor PM concentration from outdoors, 14 building models were set up: Models 1 and 2 involved ambient conditions during winter and summer (ambientWin and ambientSum, respectively). Models 3 and 4 involved existent residential buildings that consisted of hydronic heating in the winter, and natural cooling and ventilation in the summer (resExistWin and resExistSum, respectively). Models 5 and 6 involved new homes constructed under minimum building code requirements for both winter and summer (resBCWin and resBCSum, respectively). Models 7 and 8 involved R2000 homes for both summer and winter conditions (resR2000Win and resR2000Sum, respectively). Models 9 and 10 were low efficiency school buildings during winter and summer (school40Win and school40Sum, respectively). Models 11 and 12 were high efficiency commercial buildings for winter and summer (school85Win and school85Sum, respectively) Table 14 shows a summarized building setup.

Table 14: Building Model Selection

	Model	DESCRIPTION
Model 1-2	ambient	Ambient conditions winter and summer
Model 3-4	resExist	Existent Buildings, hydronic heating, natural cooling and ventilation
Model 5-6	resBC	New Homes constructed with minimum BC, forced air, standard filte
Model 7-8	resR2000	High efficiency new homes, forced air, 90% air filter
Model 9-10	school40	Low efficiency commercial buildings, 40% air filter
Model 11-12	school85	High efficiency commercial buildings, 85% air filter

Fourteen retrofit cases were then examined to compare the effects of building construction and HVAC operation: Cases 1 and 2 consisted of the comparison between basic building protection and ambient conditions for both winter and summer. These comparisons focused on the effect of basic building envelope on PM exposure. All day outdoor exposure was compared to basic building time-weighted exposure. Basic buildings consisted of existent homes (resExist), basic commercial building (school40), and normal outdoor exposure fractions. Cases 3 to 8 looked at the effect of retrofitting existent homes to minimum BC or R2000 homes for both summer and winter conditions. The cases also looked at the retrofit of minimum building code homes to high efficiency homes. These cases examined the effects of the distribution systems, the ventilation systems, and air filtration efficiency. In order to isolate the effects in homes, common commercial buildings and outdoor exposures were used. Cases 9 and 10 consisted on comparisons between average commercial buildings and high efficiency commercial buildings for both winter and summer conditions. In particular, the effects of air filtration efficiency on commercial buildings were investigated. Common homes and outdoor exposures were used. Cases 11 to 14 compared combined minimum scenarios to optimum combined efficiencies. Basic building consisted of existent homes or BC homes combined with school40. Optimum scenario consisted of R2000 homes and school85. The main effects studied in these cases were air filtration efficiency. Table 15 shows a summary of retrofit case setup.

Table 15: Case Models

Cases	Description
Cases 1-2	The effects of building envelop in PM exposure
Cases 3 to 8	The effects of forced air and air filtration in homes in PM exposure
Cases 9-10	The effects of air filtration in commercial buildings in PM exposure
Cases 11 to 14	The effects of forced air and air filtration in overall time PM exposure

3.1.7 Canadian Weather Season Adjustment

In an effort to present more realistic results for an annual scenario, Canadian weather variation for the selected locations was accounted for. A common year could be thought of three four month sections, winter, summer, and shoulder seasons. In Canada, on average, most people open the windows or use the economizers during shoulder seasons. Hence, buildings would have shoulder seasons in common. However, to simplify the modeling, the year was split into winter and summer only allowing six months for each season. The annual amounts of prevented ANC and cost savings were calculated by adding the results on each season. Therefore, seasonal and annual results of the comparisons reflected the worst case scenario where equipment operated in extreme weather mode conditions during shoulder season which could be the case sometimes in some buildings. Appendix E shows the setup for this section of the modeling.

3.1.8 Model Limitations and Integration

Although models used in this study and related models are well established and used in the field. [1][4] [5] [19] [20] [23] [27] Simulation results of the current study needs to be verified by experimental measurements for the different scenarios and locations when they become available. Models will then be fine-tuned for these geographical areas. It is expected that some discrepancies between modeling data and experimental data will be present. Assumptions made in the modeling will play some role in the discrepancies. For example, the mixed air condition assumption in mass balanced concentration models is not often present in actual indoor air environments. In addition, indoor sources were neglected in order to focus on the outdoor PM contribution. [3] This is not always the case in actual indoor environment. [2] Further research studies for $PM_{2.5}$ are needed since current $PM_{2.5}$ data have limited experimental data available to validate models due to lack of measurement instrumentation. [4]

Nevertheless, despite the limitations, the model simulation provided results that would be starting point in useful data for policy decisions. The main objective of cost-benefit analysis (CBA) was to analyze and evaluate the effects of pollution in monetary equivalents. The modeling integrated the various models using the Impact Pathway Approach. The approach consisted of four steps: First, identify the sources and emissions of PM. Although the study focused on indoor environments, outdoor sources such as incomplete combustion from rush hour traffic were identified for the geographical areas of the study. Secondly, evaluate the dispersion or the concentration of PM on the site of interest. In order to achieve this goal, building modeling was first established that was applicable to Ontario. There were three homes and two commercial building scenarios: Existing homes (resExist), new homes constructed under minimum building code requirements (resBC), and under R2000 standard (resR2000); commercial buildings with 40% (school40) and 85% (school85) ASHRAE air filters. Air flow rates were calculated from building and HVAC sizing calculations. These flow rates were used to calculate input parameters for well-established mass balanced indoor PM concentration models. In addition, indoor exposure needed to account for time activity in each micro-environment in Ontario. This was accomplished by using time-weighted exposure modeling. Thirdly and lastly in the Impact Pathway Approach, evaluate the health impact and its monetary equivalent, respectively. In order to evaluate the health effects and monetary equivalents, the study considered fourteen retrofit cases which consisted of improving factors such as building construction, distribution system, and air filtration efficiency. Because input parameters were selected from data in Ontario, the study provided a model setup that could be applied to future work in Canada.

Chapter 4: Results and Discussions

4.1.1 Overview

Some of the results were unique to this project since not many Canadian studies have concentrated on the variables investigated in this study. Some studies and standards in Canada have looked at similar factors, such as comparison of present pollution concentration exposure to the pollution concentration exposure that would be encountered under new standards (CWS30), but they did not look at the effects of different building constructions and HVAC systems. [25][26] Therefore, their data could not be directly compared to that of the current study. In addition, similar studies conducted in other areas of the world did not share the same Canadian scenario such as weather, building construction, HVAC system types, and government regulations. [1][4][18][19] Finally, it was identified that results were limited to the model assumptions, explained above, as well as the input parameter data used, as explained in the methodology. Since some of the parameters used, such as ambient PM concentrations, were averages, the results may not represent the actual conditions. Nevertheless, they were tailored to Canadian environment and in particular to Ontario and would be able to offer research data for policy decisions as well as a starting point for future related work.

4.1.2 Time-Weighted Indoor Concentrations

Table 16 and Figure 2 list time-weighted $PM_{2.5}$ concentrations for each one of the modeled building scenarios. Results were within the range of Canadian allowable values. [25] It was observed that building envelope construction alone decreased time-weighted $PM_{2.5}$ exposure to indoor concentrations coming from outdoor source significantly (Toronto, ambient vs. resExist/school40win, 10.00 vs. 4.20 $\mu g/m^3$; Hamilton, ambient vs. resExist/school40win, 11.00 vs. 4.87 $\mu g/m^3$). Nevertheless, the results need to be compared and validated with measured data when it becomes available in these locations. The building envelope protection effects were less in existing homes during the summer since, as shown in Table 2 and Table 3, existing homes were assumed to have natural cooling/ventilation through open windows which limited the protective nature of the building envelope (resExist/school40sum, Toronto, 5.18 µg/m^3 ; Hamilton, 6.01 µg/m^3). Nevertheless, PM$_{2.5}$ concentration from outdoors was still reduced by about 5 µg/m^3 in the remaining envelope.

Table 16: Time-Weighted PM$_{2.5}$ Concentrations (µg/m^3)

Time-Weighted Concentrations	Toronto				Halmilton			
	Winter		Summer		Winter		Summer	
	Adults	Children	Adults	Children	Adults	Children	Adults	Children
ambient	10.00	10.00	10.00	10.00	11.00	11.00	11.00	11.00
resExist/school40	4.20	4.16	5.18	5.32	4.87	4.56	6.01	5.79
resBC/school40	3.86	3.77	3.81	3.75	4.52	4.20	4.42	4.12
resR2000/school40	2.86	2.62	2.91	2.71	3.36	2.97	3.37	3.02
resExist/school85	3.67	3.79	4.66	4.96	4.21	4.13	5.36	5.37
resBC/school85	3.33	3.40	3.29	3.39	3.86	3.76	3.77	3.69
resR2000/school85	2.33	2.26	2.39	2.35	2.70	2.53	2.72	2.59

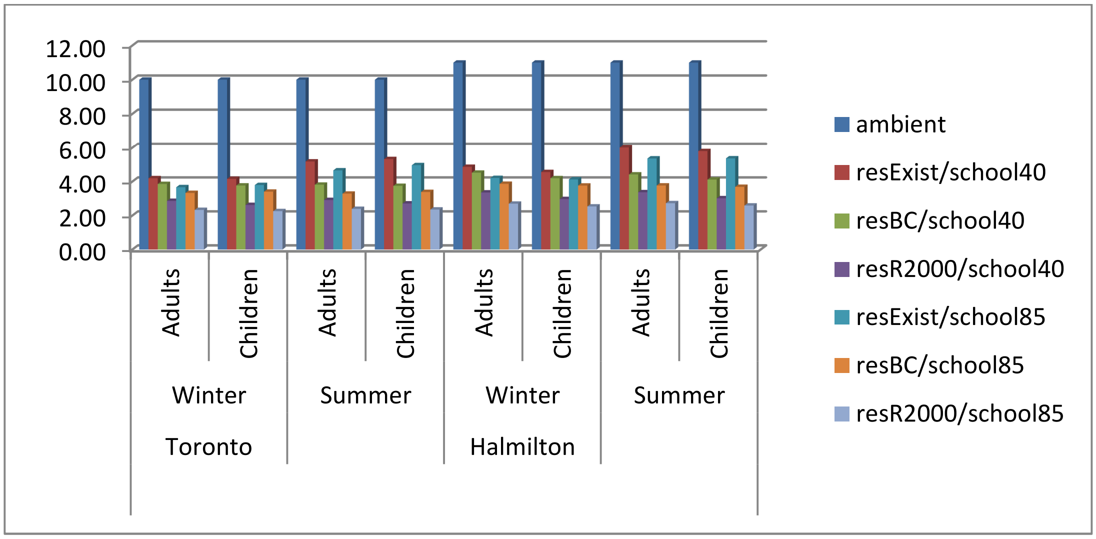


Figure 2: Time-Weighted PM$_{2.5}$ Concentrations (µg/m^3)

Ambient PM$_{2.5}$ exposure protection in new homes constructed to minimum building code requirements was compared to existing homes in winter. The two scenarios did not show significant discrepancies despite the introduction of the forced air as shown in Table 2 and Table 3 (Toronto, 1,852 cfm; Hamilton, 1,667 cfm). The BC construction was noticeable by only 1 μg/m^3 compared to existing home construction. A possible explanation for these results were identified by examining Eq. 1, which showed the added recirculation air flow (Q_r) and the added air filter efficiency decreased indoor PM concentrations (C_i) whereas the added forced ventilation airflow (Q_{oa}) increased indoor PM concentrations in BC homes. Therefore, the overall effects of BC homes somewhat cancelled each other giving an indoor concentration very close to those already achieved by existing homes. Another factor that minimized the effects of the home retrofits was the relatively low time fraction effect, which was only 53% of the total exposure time on the adults as shown in Appendix D.

Nevertheless, when home retrofits are coupled with high efficient air filtration (90% filters), the combined effects of forced air and air filtration efficiency reduced time-weighted $PM_{2.5}$ exposure by 7 μg/m^3 compared to ambient conditions (resR2000/school40, Toronto, 3.86 μg/m^3, Hamilton, 3.36 μg/m^3). Table 2 and Table 3 shows that the exposure reduction was accomplished despite the decrease in recirculation airflow rates of about 100cfm due to the reduced higher efficiency heating loads (Toronto, 1,759cfm; Hamilton, 1,574cfm).

Furthermore, when daily activities were coupled with high efficiency air filtration in commercial buildings, the effects were further intensified (resR2000/school85win, Toronto, 2.33 μg/m^3; Hamilton, 2.70 μg/m^3). These effects demonstrated that $PM_{2.5}$ concentration exposure control is a collective effort that needs to be regulated not only in ambient air but in the work environment and in homes.

In addition, Table 16 and Figure 2 shows that all Canadian building construction and HVAC system scenarios resulted in relatively larger time-weighted $PM_{2.5}$ concentrations in the summer compared to winter conditions. In particular, as mentioned, existing homes showed to have larger concentrations in the summer compared to winter due to the assumed open windows during summer conditions (Toronto, resExist/school40sum, 5.18 μg/m^3 ; resExist/school40win, 4.20 μg/m^3).

Season comparisons among buildings that already used forced air systems showed similar results but to a lesser scale or even unnoticeable at times (resR2000/school85sum vs resR2000/school85win, Toronto, 2.39 vs. 2.33 μg/m^3 ; Hamilton, 2.72 vs. 2.70 μg/m^3). The main factors responsible for these small changes were due to the difference in summer flow rates compared to those in winter as shown in Table 2 and Table 3 (Toronto, cooling flow rate, 1,200cfm; heating flow rate, 1,852cfm; Hamilton, 1200 vs. 1667cfm). As may be seen in Eq. 1, a reduced return airflow rate (Q_r) in the summer increased the indoor PM concentration (C_i). Appendix C shows that factors such as air filtration remained constant, so these results were due to the return air flow rates alone. Therefore, it was observed that return airflow rate changes less than 600cfm did not have significant effects on indoor PM concentrations.

Furthermore, Table 16 and Figure 2 shows some variations in time-weighted $PM_{2.5}$ exposure were observed among the various forced air buildings within common weather but with different construction and efficiency (resBCsum/school40sum vs. resR2000sum/school85sum, Toronto, 3.81 vs. 2.39 μg/m^3; Hamilton, 4.42 vs.2.72 μg/m^3). It was found that factors such envelope insulation and HRV installation type did not play a major role. The effects of envelope insulation were manifested in the HVAC air flow rate change from resBC to resR2000. Table 2 and 3 shows recirculation airflow rates changed by 100cfm to 300cfm depending whether it was heating or cooling conditions. However, the effects of these flow rate changes were not significantly enough on PM concentrations compared to other factors such as air filtration. In addition, HRV installation type did not change the ventilation air flow rates (130cfm). Hence this factor did not play a part in the outcomes. As discussed, the dominant factor within forced air building retrofits consisted of air filtration efficiency despite the counteracting effects of reducing recirculation air flow rates due to energy efficiency. The effect of each building construction and HVAC parameter will be farther examined below as prevented ANCs and costs savings are discussed.

As noted in the methodology section, Appendix C and Table 7 shows that for the mass balanced concentration models, the deposition (β), and penetration (P) parameters, 0.97/h and 1, respectively, remained constant for all the cases. Having them constant isolated the effects of the other factors. Infiltration parameter, however, varied according to the building construction. The infiltration term appeared in both the numerator and denominator in Eq. 1 since it represented both the infiltration source and the exfiltration sink. Therefore, the overall effect on indoor concentration was minimized.

In general, the time-weighted PM exposure between adults and children were very similar. Appendix C and D shows that this similarity may be due to the time fractions spent in suburban environment by both, adults and children. Since adults were assumed to spend their home and outdoors time in suburban environment as did children, the only time that was different was their urban environment exposure under the office buildings at work for 33% of the daily time. This added only small variation between adults and children time activity. Therefore, their overall timed PM exposures were very similar to each other (Toronto, resExist/school40win, adults vs. children, 4.20 vs. 4.16 $\mu g/m^3$).

Finally, Table 16 and Figure 2 shows the time-weighted concentrations for Hamilton differed by one unit compared to those in Toronto due to the small differences in their respective ambient concentrations. [28] [36] Therefore, any significant differences among the prevented ANCs and cost savings in these two cities were due mainly to other factors such as different segments of population at risk.

4.1.3 Prevented Health Incidence Effects and Costs Savings

Although the effects on PM concentration were analyzed in terms of $PM_{2.5}$, the health effects and cost savings in this study reflect those of the equivalent PM_{10} concentrations reductions using Eq. 8 due to limited $PM_{2.5}$ input parameter data. Nevertheless, the effects of PM_{10} included the effects of $PM_{2.5}$ as well, although in greater proportions. As mentioned, it was noted in Table 16 and Figure 2 that building envelope construction had significant effects on indoor $PM_{2.5}$ exposure. Table 17 to Table 28, below, shows that for Cases 1-2, the mortality prevented ANCs due to equivalent PM_{10} reduction in Toronto were 393 in the winter, 328 in the summer, and 721 for the year. The related cost savings were \$912 million in the winter, \$759 million in the summer, and \$1,671 million for the year. For Hamilton, the prevented ANCs were 60 for winter, 49 for summer, and 109 for the year. The related cost savings were \$139 million for the winter, \$114 million for summer, and \$253 million for the year. The values were smaller in the summer since for Cases 1-2, buildings were assumed to use natural cooling/ventilation through open windows, reducing the envelope protection from outdoor PM as discussed above. Hamilton was observed to have smaller values due to the smaller proportion of population at risk in that city.

It may be noted that the government would save much by investing in new home construction based on mortality effects alone. A hypothetical scenario of 721 incidents in Toronto and assuming 10 persons per low income shelter for simplicity would require about 72 home shelters to be built. Estimating an average cost of \$300,000 per home shelter, based on the author's technical experience, would total an investment of slightly above \$21.6 million. The annual cost savings for mortality alone in Toronto and, similarly, in Hamilton far surpassed the investment in building envelope construction to protect from ambient PM_{10}. Similarly, prevented ANCs and costs savings for morbidity effects for chronic bronchitis were observed to produce the largest values. Chronic bronchitis alone for Toronto produced prevented ANCs of 4,925 for the winter,4,363 for the summer, and 9,288 for the year. The related cost savings were \$618 million for the winter, \$648 million for the summer, and

$1,166 million for the year. Similarly, for Hamilton, the reduced ANCs were 738 for the winter, 647 for the summer, and 1,385 for the year. The related cost savings were $404 million for the winter, $81 million for the summer, and $485 million for the year. Morbidity cost savings from chronic bronchitis alone justified the above investment scenario. Finally, other annual morbidity cost savings for Toronto ranged between $0.003 million for asthma attacks of children older than fifteen to $2.6 million for hospital admissions. For Hamilton, other annual morbidity cost savings ranged from $0.001 million for asthma attacks for children younger than fifteen to 0.25 million for hospital admissions for all ages. These morbidity cost savings further added up to the overall cost savings discussed above. Therefore, it was found that Canadian building construction provided significant protection from PM_{10} exposure and the protection manifested in health impacts and economic advantages.

Table 17: Seasonal Equivalent PM_{10} ANC for Toronto, Winter Conditions

ANC Seasonal							
Toronto Winter	C1	C3	C5	C7	C9	C11	C13
Non-accident mortality (adlt > 30 yrs)	393	23	92	32	37	128	105
Chronic Bronchitis (adlt>27yrs)	4925	423	1545	575	651	2076	1741
Hospital admission respiratory (all ages)	426	25	99	35	39	138	113
Emergency rm visits for asthma (under 65 yrs	431	26	101	35	40	140	115
Asthma attacks (childrn < 15)	114	8	31	31	7	38	30
Asthma attacks (childrn >15)	418	28	111	111	27	138	110
Restricted act dys, RAD (adlt > 20 yrs)	896	55	213	75	85	297	244
Work loss days, WLD (18 to 65 yrs)	380	23	89	31	35	124	102

Table 18: Seasonal Equivalent PM_{10} ANC for Toronto, Summer Conditions

ANC Seasonal							
Toronto Summer	C2	C4	C6	C8	C10	C12	C14
Non-accident mortality (adlt > 30 yrs)	328	94	156	62	36	191	98
Chronic Bronchitis (adlt>27yrs)	4363	1581	2451	1072	643	2907	1633
Hospital admission respiratory (all ages)	355	102	168	67	39	207	106
Emergency rm visits for asthma (under 65 yrs)	359	103	170	68	40	209	107
Asthma attacks (childrn < 15)	92	31	52	21	7	59	28
Asthma attacks (childrn >15)	336	114	189	75	26	214	101
Restricted act dys, RAD (adlt > 20 yrs)	749	219	360	144	84	441	227
Work loss days, WLD (18 to 65 yrs)	317	91	151	60	35	185	95

Table 19: Annual Equivalent PM_{10} ANC for Toronto

ANC Annual							
Toronto	C1/C2	C3/C4	C5/C6	C7/C8	C9/C10	C11/C12	C13/C14
Non-accident mortality (adlt > 30 yrs)	721	118	248	94	73	320	203
Chronic Bronchitis (adlt>27yrs)	9288	2004	3996	1647	1295	4983	3374
Hospital admission respiratory (all ages)	781	127	267	101	78	345	219
Emergency rm visits for asthma (under 65 yrs	790	129	271	103	80	350	222
Asthma attacks (childrn < 15)	206	39	82	51	14	97	58
Asthma attacks (childrn >15)	753	143	300	186	53	352	211
Restricted act dys, RAD (adlt > 20 yrs)	1645	274	573	219	170	738	470
Work loss days, WLD (18 to 65 yrs)	697	114	239	91	70	309	196

Table 20: Seasonal Equivalent PM_{10} ANC for Hamilton, Winter Conditions

ANC Seasonal							
Hamilton Winter	C1	C3	C5	C7	C9	C11	C13
Non-accident mortality (adlt > 30 yrs)	60	3	15	5	7	22	18
Chronic Bronchitis (adlt>27yrs)	738	62	250	91	116	342	295
Hospital admission respiratory (all ages)	64	4	16	5	7	23	19
Emergency rm visits for asthma (under 65 yrs	62	4	16	5	7	22	19
Asthma attacks (childrn < 15)	15	1	4	3	1	5	4
Asthma attacks (childrn >15)	65	4	16	13	4	21	17
Restricted act dys, RAD (adlt > 20 yrs)	134	8	34	12	15	49	41
Work loss days, WLD (18 to 65 yrs)	54	3	14	5	6	19	16

Table 21: Seasonal Equivalent PM_{10} ANC for Hamilton, Summer Conditions

ANC Seasonal							
Hamilton Summer	C2	C4	C6	C8	C10	C12	C14
Non-accident mortality (adlt > 30 yrs)	49	16	26	10	6	33	17
Chronic Bronchitis (adlt>27yrs)	647	262	402	178	114	478	276
Hospital admission respiratory (all ages)	52	17	28	11	7	34	18
Emergency rm visits for asthma (under 65 yrs)	51	16	27	11	7	34	17
Asthma attacks (childrn < 15)	12	4	6	3	1	7	4
Asthma attacks (childrn >15)	53	17	28	11	4	33	16
Restricted act dys, RAD (adlt > 20 yrs)	110	36	59	24	15	73	38
Work loss days, WLD (18 to 65 yrs)	44	14	24	9	6	29	15

Table 22: Annual Equivalent PM_{10} ANC for Hamilton

ANC Annual							
Hamilton	C1/C2	C3/C4	C5/C6	C7/C8	C9/C10	C11/C12	C13/C14
Non-accident mortality (adlt > 30 yrs)	109	19	41	16	13	54	35
Chronic Bronchitis (adlt>27yrs)	1385	324	652	269	230	820	571
Hospital admission respiratory (all ages)	116	20	43	16	14	57	37
Emergency rm visits for asthma (under 65 yrs	113	20	43	16	13	56	36
Asthma attacks (childrn < 15)	26	5	10	5	2	12	7
Asthma attacks (childrn >15)	118	21	45	24	9	54	33
Restricted act dys, RAD (adlt > 20 yrs)	244	44	93	35	30	122	79
Work loss days, WLD (18 to 65 yrs)	98	17	37	14	12	49	32

Table 23: Seasonal Equivalent PM_{10} Cost Savings for Toronto, Winter Conditions

Seasonal Cost Millions (US $)							
Toronto Winter	C1	C3	C5	C7	C9	C11	C13
Non-accident mortality (adlt > 30 yrs)	$911.873	$54.371	$213.238	$74.613	$84.924	$297.353	$243.573
Chronic Bronchitis (adlt>27yrs)	$618.441	$53.072	$193.946	$72.171	$81.766	$260.671	$218.603
Hospital admission respiratory (all ages)	$1.420	$0.084	$0.331	$0.116	$0.132	$0.461	$0.378
Emergency rm visits for asthma (under 65 yrs	$0.022	$0.001	$0.005	$0.002	$0.002	$0.007	$0.006
Asthma attacks (childrn < 15)	$0.002	$0.000	$0.000	$0.000	$0.000	$0.001	$0.000
Asthma attacks (childrn >15)	$0.006	$0.000	$0.002	$0.002	$0.000	$0.002	$0.002
Restricted act dys, RAD (adlt > 20 yrs)	$0.016	$0.001	$0.004	$0.001	$0.002	$0.005	$0.004
Work loss days, WLD (18 to 65 yrs)	$0.015	$0.001	$0.004	$0.001	$0.001	$0.005	$0.004

Table 24: Seasonal Equivalent PM_{10} Cost Savings for Toronto, Summer Conditions

Seasonal Cost Millions (US $)							
Toronto Summer	C2	C4	C6	C8	C10	C12	C14
Non-accident mortality (adlt > 30 yrs)	$759.537	$218.825	$360.946	$143.523	$83.882	$443.475	$226.867
Chronic Bronchitis (adlt>27yrs)	$547.829	$198.539	$307.813	$134.625	$80.801	$365.024	$205.108
Hospital admission respiratory (all ages)	$1.181	$0.339	$0.560	$0.222	$0.130	$0.689	$0.352
Emergency rm visits for asthma (under 65 yrs)	$0.018	$0.005	$0.009	$0.003	$0.002	$0.011	$0.005
Asthma attacks (childrn < 15)	$0.001	$0.000	$0.001	$0.000	$0.000	$0.001	$0.000
Asthma attacks (childrn >15)	$0.005	$0.002	$0.003	$0.001	$0.000	$0.003	$0.002
Restricted act dys, RAD (adlt > 20 yrs)	$0.014	$0.004	$0.007	$0.003	$0.002	$0.008	$0.004
Work loss days, WLD (18 to 65 yrs)	$0.013	$0.004	$0.006	$0.002	$0.001	$0.007	$0.004

Table 25: Annual Equivalent PM_{10} Cost Savings for Toronto

Annual Cost Millions (US $)							
Toronto	C1/C2	C3/C4	C5/C6	C7/C8	C9/C10	C11/C12	C13/C14
Non-accident mortality (adlt > 30 yrs)	$1,671.410	$273.197	$574.184	$218.136	$168.805	$740.827	$470.440
Chronic Bronchitis (adlt>27yrs)	$1,166.270	$251.610	$501.759	$206.796	$162.567	$625.696	$423.711
Hospital admission respiratory (all ages)	$2.601	$0.424	$0.891	$0.338	$0.262	$1.150	$0.730
Emergency rm visits for asthma (under 65 yrs	$0.040	$0.006	$0.014	$0.005	$0.004	$0.018	$0.011
Asthma attacks (childrn < 15)	$0.003	$0.001	$0.001	$0.001	$0.000	$0.001	$0.001
Asthma attacks (childrn >15)	$0.012	$0.002	$0.005	$0.003	$0.001	$0.005	$0.003
Restricted act dys, RAD (adlt > 20 yrs)	$0.030	$0.005	$0.011	$0.004	$0.003	$0.014	$0.009
Work loss days, WLD (18 to 65 yrs)	$0.028	$0.005	$0.010	$0.004	$0.003	$0.012	$0.008

Table 26: Seasonal Equivalent PM_{10} Cost Savings for Hamilton, Winter Conditions

Seasonal Cost Millions (US $)							
Hamilton Winter	C1	C3	C5	C7	C9	C11	C13
Non-accident mortality (adlt > 30 yrs)	$139.366	$8.007	$34.918	$11.795	$15.237	$49.991	$42.087
Chronic Bronchitis (adlt>27yrs)	$404.152	$12.353	$76.903	$12.195	$9.355	$124.775	$60.443
Hospital admission respiratory (all ages)	$0.075	$0.001	$0.009	$0.001	$0.001	$0.016	$0.007
Emergency rm visits for asthma (under 65 yrs	$0.001	$0.000	$0.000	$0.000	$0.000	$0.000	$0.000
Asthma attacks (childrn < 15)	$0.000	$0.000	$0.000	$0.000	$0.000	$0.000	$0.000
Asthma attacks (childrn >15)	$0.000	$0.000	$0.000	$0.000	$0.000	$0.000	$0.000
Restricted act dys, RAD (adlt > 20 yrs)	$0.002	$0.000	$0.000	$0.000	$0.000	$0.000	$0.000
Work loss days, WLD (18 to 65 yrs)	$0.001	$0.000	$0.000	$0.000	$0.000	$0.000	$0.000

Table 27: Seasonal Equivalent PM_{10} Cost Savings for Hamilton, Summer Conditions

Seasonal Cost Millions (US $)							
Hamilton Summer	C2	C4	C6	C8	C10	C12	C14
Non-accident mortality (adlt > 30 yrs)	$113.883	$36.798	$60.666	$24.142	$15.050	$75.434	$39.080
Chronic Bronchitis (adlt>27yrs)	$81.242	$32.873	$50.460	$22.413	$14.368	$60.079	$34.672
Hospital admission respiratory (all ages)	$0.173	$0.056	$0.092	$0.037	$0.023	$0.114	$0.059
Emergency rm visits for asthma (under 65 yrs)	$0.003	$0.001	$0.001	$0.001	$0.000	$0.002	$0.001
Asthma attacks (childrn < 15)	$0.000	$0.000	$0.000	$0.000	$0.000	$0.000	$0.000
Asthma attacks (childrn >15)	$0.001	$0.000	$0.000	$0.000	$0.000	$0.001	$0.000
Restricted act dys, RAD (adlt > 20 yrs)	$0.002	$0.001	$0.001	$0.000	$0.000	$0.001	$0.001
Work loss days, WLD (18 to 65 yrs)	$0.002	$0.001	$0.001	$0.000	$0.000	$0.001	$0.001

Table 28: Annual Equivalent PM_{10} Cost Savings for Hamilton

Annual Cost Millions (US $)							
Hamilton	C1/C2	C3/C4	C5/C6	C7/C8	C9/C10	C11/C12	C13/C14
Non-accident mortality (adlt > 30 yrs)	$253.249	$44.805	$95.583	$35.937	$30.287	$125.425	$81.167
Chronic Bronchitis (adlt>27yrs)	$485.395	$45.226	$127.364	$34.608	$23.723	$184.855	$95.115
Hospital admission respiratory (all ages)	$0.248	$0.057	$0.101	$0.038	$0.024	$0.130	$0.066
Emergency rm visits for asthma (under 65 yrs	$0.004	$0.001	$0.001	$0.001	$0.000	$0.002	$0.001
Asthma attacks (childrn < 15)	$0.000	$0.000	$0.000	$0.000	$0.000	$0.000	$0.000
Asthma attacks (childrn >15)	$0.001	$0.000	$0.000	$0.000	$0.000	$0.001	$0.000
Restricted act dys, RAD (adlt > 20 yrs)	$0.004	$0.001	$0.001	$0.000	$0.000	$0.002	$0.001
Work loss days, WLD (18 to 65 yrs)	$0.002	$0.001	$0.001	$0.000	$0.000	$0.001	$0.001

Cases 3-4 and 5-6 concerned the investigation of retrofitting existing homes which consisted of hydronic heating for the winter and natural cooling/ventilation for the summer to either, minimum OBC requirements or R2000 high efficiency standards, respectively. All scenarios in these cases investigated retrofit into forced air HVAC systems. R2000 retrofit, in particular, added the benefit of high efficiency air filtration in homes. For Toronto, the retrofit into minimum OBC and R2000 requirements produced prevented ANCs for mortality of 23 and 92, respectively, for the winter, 94 and 156, respectively, for summer, and 118 and 248 for the year. The related cost savings were $54 million and $213 million, respectively, for winter, $218 and $360, respectively, for summer, and $273 million and $574 million, respectively, for the year. Similarly for Hamilton, the prevented ANCs for mortality were, 3 and 15, respectively, for the winter, 16 and 26, respectively, for the summer, and 19 and 41, respectively, for the year. The related cost savings were $8 million and $35 million, respectively, for the winter, $37 million and $60 million, respectively, for the summer, and $45 million and $95 million, respectively, for the year. Hamilton, figures followed results proportioned to their population at risk. As mentioned above, it may be observed that the retrofit was more significant in summer conditions since it involved a change from natural cooling and ventilation to forced air cooling and ventilation. In addition, R2000 retrofit demonstrated the effects of high efficiency filtration by further reducing PM_{10} concentration exposure and increasing prevented ANCs and related costs savings. Prevented costs were very significant for each scenario. For example, in a hypothetical retrofit scenario, the estimated cost to retrofit into R2000 homes from existing homes may be estimated as \$20,000 per home based on the author's professional experience. For the annual prevented ANCs of 248 in Toronto and assuming one affected person per affected home, the retrofit cost for 248 homes was slightly over \$4.96 million. The cost savings from the retrofit due to mortality alone far surpassed the cost of retrofitting. Therefore, governments would be wise to promote more energy efficient homes by offering more incentive programs. Annual morbidity related cost savings for Toronto on both retrofit scenarios, minimum BC and R2000 retrofits, ranged from \$0.001 million and \$0.001 million, respectively, for asthma attacks for children younger than fifteen to \$251 million and \$502 million, respectively, for chronic bronchitis in adults older than 27 years of age. For Hamilton, annual morbidity costs ranged from \$0.001 million and 0.001 million, respectively, for emergency room visits to \$45 million and \$127 million, respectively, for chronic bronchitis for adults older than 27 years of age. Hamilton results followed the same pattern at smaller proportion. These results further justified the investment option to promote retrofit of existing homes and the benefits of combining forced air and high efficiency filtration.

Cases 7-8 and 9-10 consisted of retrofits of buildings already having forced air systems, one at a time. Cases 11-12 and 13-14, on the other hand, concerned the retrofit of both homes and commercial buildings at the same time. One particular aspect of interest on these retrofit scenarios was air filtration efficiency. As may be observed in Tables 17 to 28, mortality related prevented ANCs for Toronto for cases 7-8 and 9-10, were, 32 and 37, respectively, for the winter, 62 and 36, respectively for the summer, and 94 and 73, respectively, for the year. Related costs were \$75 million and \$85 million, respectively, for the winter, \$143 million and \$84 million, respectively, for the summer, and \$218 million and \$168 million, respectively, for the year. Similarly for Hamilton, prevented ANC were 5 and 7, respectively, for the winter, 10 and 6, respectively, for the summer, and 16 and 13, respectively, for the year. The related cost savings were, \$12 million and \$15 million, respectively, for the winter, \$24 million and \$15 million, respectively, for the summer, and \$36 million and \$30 million, respectively, for the year. As was observed, the retrofit of homes had greater effects than the retrofit of commercial buildings in both Toronto and Hamilton. These differences may have been due to the fact that in homes air filtration was retrofitted from 20% to 90% whereas commercial buildings included a smaller air filtration change from 40% to 85%. Therefore, the effect of filtration was more intense in homes than in commercial buildings. In addition, the time-weighted activity fractions were greater for homes (53%) than for commercial buildings (33%) for adults and similarly, 61% and 25%, respectively, for children. Therefore, since people spent more time in homes than at work or school, the home PM_{10} exposure changes were more impacting on the overall time-weighted exposure. Similarly, observations were performed for morbidity effects. For Toronto, annual cost savings ranged from \$0.003 million and \$0.001 million, respectively, for asthma attacks to \$206 million and \$402 million, respectively, for chronic bronchitis. For Hamilton, annual cost savings due to morbidity effects ranged from \$0.001 million and \$0.001 million, respectively, for emergency room visits to \$34 million and \$23 million, respectively, for chronic bronchitis. It was noted that chronic bronchitis was actually greater in cost savings than mortality for these cases. Therefore, it was observed that the air filtration efficiency retrofit of either homes or commercial buildings, separately, were still significant although not as great as other effects.

For cases 11-12 and 13-14, prevented ANCs for Toronto due to mortality alone was 128 and 105, respectively, for the winter, 191 and 98, respectively, for the summer, and 320 and 203, respectively, for the year. Related cost savings were \$297 million and \$244 million, respectively, for the winter, \$443 million and \$227 million, respectively, for the summer, and \$740 million and \$470 million, respectively, for the year. Similarly for Hamilton, reduced

ANC due to mortality, were 22 and 18, respectively, for the winter, 33 and 17, respectively, for the summer, and 54 and 35, respectively, for the year. The related costs were $50 million and $42 million, respectively, for the winter, $75 million and $39 million, respectively, for the summer, and $125 million and $81 million, respectively, for the year. It was observed, that retrofitting both homes and commercial buildings produced greater cost savings than only retrofitting one separately the other. The related cost savings much outweighed any associated retrofit investment scenario. For example, if it a hypothetical scenario where the cost to retrofit a home is $10,000 and to retrofit an office is $40,000 were assumed, based on the author's professional experience, and assuming 2 affected persons per home and 10 affected persons per commercial building. For the total of 203 annual incidents prevented for mortality in Toronto, the total cost to retrofit 101 homes and 21 offices was slightly above $1.8 million. This retrofit cost is negligible compared to the cost savings from the retrofit itself. Therefore, the benefits of retrofitting both building types were indeed very significant. In addition, the effects of the retrofits on morbidity endpoints for Toronto ranged from $0.001 million for annual asthma attacks to $626 million for chronic bronchitis incidents. Hamilton has similar results proportionate to their population at risk. Hence, it further added to the importance of retrofitting both building types.

Therefore, as discussed, it was noted that the impact of the single building retrofit was not as effective as retrofitting both, homes and office/schools. However, the related cost savings are nonetheless significant enough to justify changing each at a time. Nevertheless, upgrading filter efficiency in both homes and commercial buildings at the same time did have a much larger impact. Retrofitting both building types had a greater impact because it affected greater portion the daily activity time fraction of the population at risk. Changing only homes involved only 53% of the daily activity fraction for adults or 61% of daily activity for children whereas changing both homes and school/offices involved 86% of the daily activity. Therefore, as demonstrated there was much benefit when both buildings were retrofitted. These results proved that PM concentration exposure reduction is a joint effort that needs to be regulated not only in ambient air levels but in the work environment and in homes.

4.1.4 Limitations, Uncertainties and Assumptions

The mass balanced concentration model used assumptions that may add some uncertainties and limitations to the modeling. For example, the model assumed well-mixed air conditions throughout the building which are often not the case in actual indoor environments. Therefore, some discrepancies with actual experimental measurements would be encountered.

Although the effect on PM concentration was analyzed in terms of $PM_{2.5}$, however, due to limited $PM_{2.5}$ data, health effects and cost savings were done in terms of equivalent PM_{10} which included the effects of $PM_{2.5}$ but to greater proportions. As noted, it was identified that results were limited to model assumptions as well as input parameter data used. Since some of the parameters used such as ambient PM concentrations were averages, the results may not represent the actual conditions. Nevertheless, they were tailored to Canadian environment and in particular to Ontario and would be able to offer research data for policy decisions as well as a starting point for future related work.

Chapter 5: Conclusion and Recommendations

The study demonstrated that Canadian building construction generally provides significant protection from time-weighted PM exposure (Toronto, ambient vs. resExist/school40win, $PM_{2.5}$ 10.00 vs. 4.20 $\mu g/m^3$). The prevented annual mortality of equivalent PM_{10} ANCs for Toronto for this scenario was 721. Cost savings due to building envelope protection in mortality alone much outweighed the cost of investment for new home construction (Toronto, \$1,671 million vs. \$21.6 million). Therefore, this study recommends that governments invest in suitable home construction. Similarly, the morbidity effects were very significant, especially for chronic bronchitis endpoints which were along the same magnitude as mortality for most of the cases. For all cases, similar results were obtained for Hamilton proportionate to their relative population at risk. Canadian building construction and HVAC systems showed larger time-weighted PM exposure in the summer than in winter due to the various HVAC operating conditions such as airflow rates (Toronto, resExist/school40sum, $PM_{2.5}$ 5.18 $\mu g/m^3$; resExist/school40win, $PM_{2.5}$ 4.20 $\mu g/m^3$). Furthermore, cost savings from retrofitting existing homes, which involved natural cooling/ventilation to forced air systems with high efficiency air filtration were very significant. It was demonstrated that the cost savings related to reduction of equivalent PM_{10} exposure health effects due to mortality alone much outweighed any retrofit investment scenarios (R2000, Toronto, \$574 million vs. \$4.96 million). Therefore, governments would be wise to promote more energy-efficient-homes by offering more incentive programs. Factors such as wall insulation or airflow rate changes of less than 600cfm, and HRV installation type did not played a major role. In addition, the effect of air filtration was more intense in homes than in commercial buildings. Similarly, the impact of simultaneously retrofitting the air filtration systems in both, homes and commercial buildings where children and adults spent most the daily activities reduced exposure to PM coming from outside the most. Installing, high efficient air filtration in both homes and commercial buildings resulted in optimum reduction of health effects and significant cost savings. The cost savings due to mortality from the retrofit alone much outweighed the investment scenario costs, therefore justifying the retrofit (Toronto, $470 million vs. $1.8 million). This finding demonstrated that PM concentration exposure reduction is a collective effort that needs to be regulated not only in ambient air levels but in the work environment and homes as well.

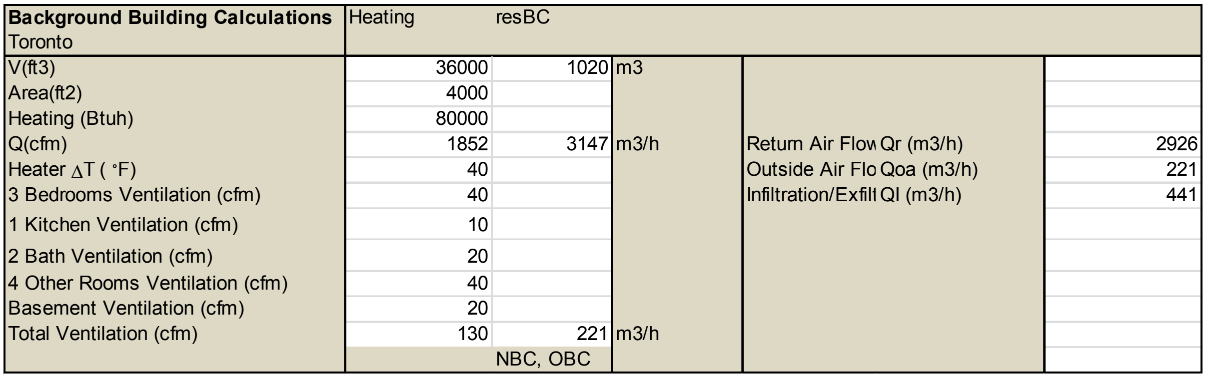
The main objective of cost-benefit analysis (CBA) was to analyze and evaluate the effects of pollution in monetary equivalents. The modeling integrated the various models using the Impact Pathway Approach. The approach consisted of four steps: First, identify the sources and emissions of PM. Although the study focused on indoor environments, outdoor sources such as incomplete combustion from rush hour traffic were identified for the geographical areas of the study. Secondly, evaluate the dispersion or the concentration of PM at the sites of interest. In order to achieve this goal, a building modeling was first established that was applicable to Ontario. There were three homes and two commercial building scenarios: Existing homes (resExist), new homes constructed under minimum building code requirements (resBC), and under R2000 standard (resR2000); commercial buildings with 40% (school40) and 85% (school85) ASHRAE air filters. Airflow rates were calculated from building and HVAC sizing calculations. These flow rates were used to calculate input parameters for well-established mass balanced indoor PM concentration models. In addition, indoor exposure needed to account for timed activities in each micro-environment in Ontario. This was accomplished by using time-weighted exposure modeling. Thirdly and lastly in the Impact Pathway Approach, evaluate the health impact and its monetary equivalent, respectively. In order to evaluate the health effects and the monetary equivalents, the study considered fourteen retrofit cases which consisted of improving factors such as building construction, distribution system, and air filtration efficiency. As noted, it was identified that results were limited to model assumptions as well as input parameter data used. Since some of the parameters used, such as ambient PM concentrations, were averages, the results may not represent actual conditions. Nevertheless, they were tailored to the Canadian environment and, in particular, to Ontario. Therefore, this study provides model simulation data that relates to the Canadian environment, having many factors in common such weather, building construction, building systems, and government regulations. Therefore, the results contribute useful data for policy decisions as well as starting point for future related work.

Future work would involve similar studies that need to be implemented for other locations in Canada. Results from this model need to be validated by experimental measurements in Toronto and Hamilton. Further studies may include the effect of most recent and future standards for Canadian buildings under the various Canadian weather conditions. For example, as of January 2012 new energy efficiency compliance is being implemented by OBC amendments. A house designer now needs to meet new energy efficiency requirements such as prescriptive packages or performance evaluation with energy simulation based on annual energy consumption comparisons. Other acceptable compliance methods would include Energuide80 and Energy Star, which are energy efficiency measures related to the ones discussed in this study. [43] Future modeling under such new energy efficiency compliance would further investigate the effect of indoor environment on the indoor PM concentrations from outdoor sources and the related health effects and costs savings. In addition, more research is needed for $PM_{2.5}$. The few model studies available lack experimental data verification due to a lack instrumentation. [4] More research is needed to validate these and other model data and to develop new experimental techniques.

Appendix A

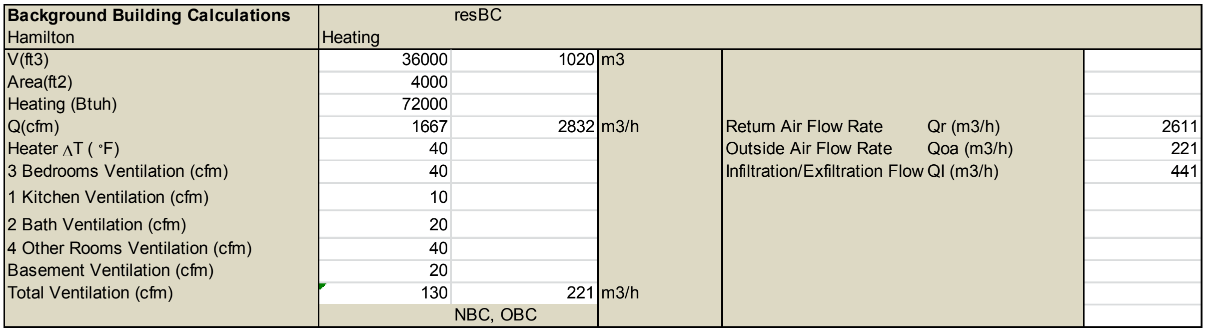
Basic Background Building and HVAC System Sizing Information

Toronto resBC Heating, Building and HVAC System Sizing



Background Building Calculations Toronto	Heating	resBC				
V(ft3)	36000	1020	m3			
Area(ft2)	4000					
Heating (Btuh)	80000					
Q(cfm)	1852	3147	m3/h	Return Air Flow	Qr (m3/h)	2926
Heater ΔT (°F)	40			Outside Air Flo	Qoa (m3/h)	221
3 Bedrooms Ventilation (cfm)	40			Infiltration/Exfil	Ql (m3/h)	441
1 Kitchen Ventilation (cfm)	10					
2 Bath Ventilation (cfm)	20					
4 Other Rooms Ventilation (cfm)	40					
Basement Ventilation (cfm)	20					
Total Ventilation (cfm)	130	221	m3/h			
	NBC, OBC					

Hamilton resBC Heating, Building and HVAC System Sizing



Background Building Calculations Hamilton	resBC Heating					
V(ft3)	36000	1020	m3			
Area(ft2)	4000					
Heating (Btuh)	72000					
Q(cfm)	1667	2832	m3/h	Return Air Flow Rate	Qr (m3/h)	2611
Heater ΔT (°F)	40			Outside Air Flow Rate	Qoa (m3/h)	221
3 Bedrooms Ventilation (cfm)	40			Infiltration/Exfiltration Flow	Ql (m3/h)	441
1 Kitchen Ventilation (cfm)	10					
2 Bath Ventilation (cfm)	20					
4 Other Rooms Ventilation (cfm)	40					
Basement Ventilation (cfm)	20					
Total Ventilation (cfm)	130	221	m3/h			
	NBC, OBC					

Toronto/Hamilton resBC Cooling, Building and HVAC System Sizing

Background Building Calculations Toronto/Hamilton	Cooling	resBC				
V(ft3)	36000	1020	m3			
Area(ft2)	4000			Return Air Flow	Qr (m3/h)	1818
Cooling (Btuh)	36000			Outside Air Flo	Qoa (m3/h)	221
Q(cfm)	1200	2039	m3/h	Infiltration/Exfilt	QI (m3/h)	365
Heater ΔT (°F)	n/a					
3 Bedrooms Ventilation (cfm)	40					
1 Kitchen Ventilation (cfm)	10					
2 Bath Ventilation (cfm)	20					
4 Other Rooms Ventilation (cfm)	40					
Basement Ventilation (cfm)	20					
Total Ventilation (cfm)	130	221	m3/h			

Toronto resR2000 Heating, Building and HVAC System Sizing

Background Building Calculations Toronto	Heating	resR2000				
V(ft3)	36000	1020	m3			
Area(ft2)	4000					
Heating (Btuh)	76000					
Q(cfm)	1759	2989	m3/h	Return Air Flow	Qr (m3/h)	2768
Heater ΔT (°F)	40			Outside Air Flo	Qoa (m3/h)	221
3 Bedrooms Ventilation (cfm)	40			Infiltration/Exfilt	QI (m3/h)	334
1 Kitchen Ventilation (cfm)	10					
2 Bath Ventilation (cfm)	20					
4 Other Rooms Ventilation (cfm)	40					
Basement Ventilation (cfm)	20					
Total Ventilation (cfm)	130	221	m3/h			
		NBC, OBC				

Hamilton resR2000 Heating, Building and HVAC System Sizing

Background Building Calculations Hamilton	Heating	resR2000				
V(ft3)	36000	1020	m3			
Area(ft2)	4000					
Heating (Btuh)	68000					
Q(cfm)	1574	2675	m3/h	Return Air Flow Rate	Qr (m3/h)	2454
Heater ΔT (°F)	40			Outside Air Flow Rate	Qoa (m3/h)	221
3 Bedrooms Ventilation (cfm)	40			Infiltration/Exfiltration Flow	QI (m3/h)	334
1 Kitchen Ventilation (cfm)	10					
2 Bath Ventilation (cfm)	20					
4 Other Rooms Ventilation (cfm)	40					
Basement Ventilation (cfm)	20					
Total Ventilation (cfm)	130	221	m3/h			
		NBC, OBC				

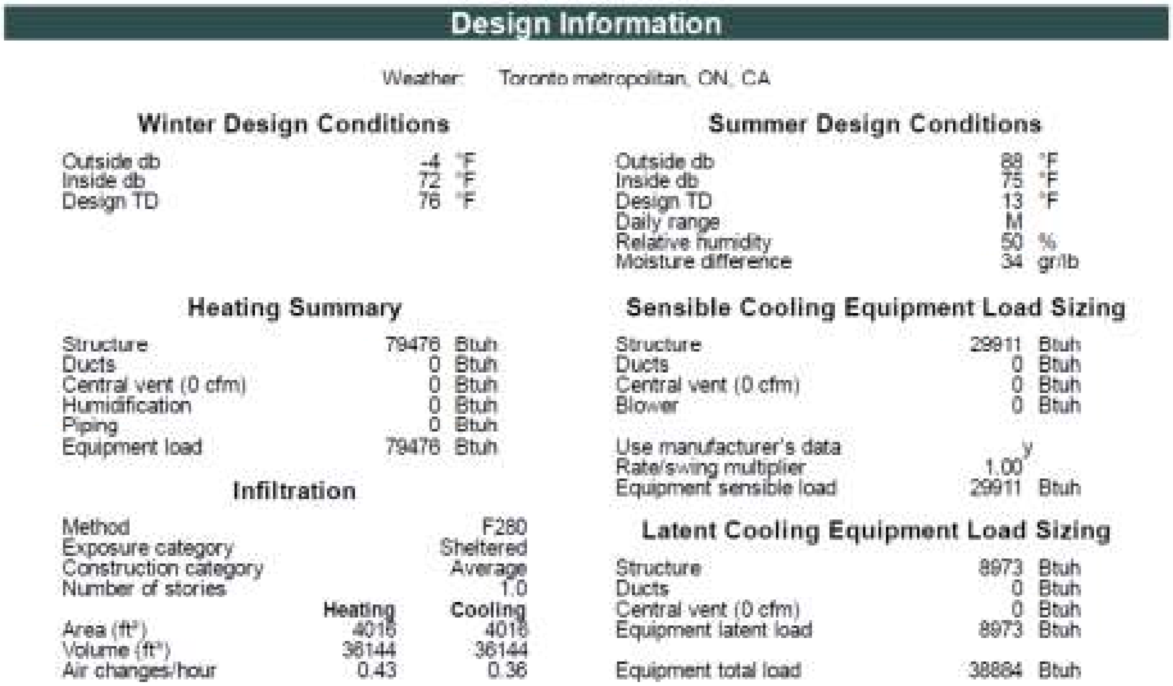
Toronto/Hamilton resR2000 Cooling, Building and HVAC System Sizing

Background Building Calculations Toronto/Hamilton	Cooling	resR2000				
V(ft3)	36000	1020	m3			
Area(ft2)	4000					
Cooling (Btuh)	28000			Return Air Flow	Qr (m3/h)	1365
Q(cfm)	933	1586	m3/h	Outside Air Flo	Qoa (m3/h)	221
Heater ΔT (°F)	n/a			Infiltration/Exfil	QI (m3/h)	277
3 Bedrooms Ventilation (cfm)	40					
1 Kitchen Ventilation (cfm)	10					
2 Bath Ventilation (cfm)	20					
4 Other Rooms Ventilation (cfm)	40					
Basement Ventilation (cfm)	20					
Total Ventilation (cfm)	130	221	m3/h			
		NBC, OBC				

Toronto/Hamilton school45, school85 Heating, Building and HVAC System Sizing

Background Building Calculations	School/Office Heating					
Toronto/Hamilton						
V(ft3,m3)	200000	5664	m3			
Area(ft2)	20000			Return Air Flow	Qr (m3/h)	11995
Heating (Btuh)	800000			Outside Air Flo	Qoa (m3/h)	3738
Q(cfm, m3/h)	9259	15733	m3/h	Infiltration/Exfil	QI (m3/h)	2203
Heater ΔT (°F)	80					
Ventilation	2200	3738	m3/h			
	SEE APPENDIX B ASHRAE 62.1-2004					

Sample Summary Sheet of Heat-loss and Heat-gain Calculations for Toronto Using HRAI Right Suite Universal Simulation Software



Design Information

Weather: Toronto metropolitan, ON, CA

Winter Design Conditions

Outside db	-4	°F
Inside db	72	°F
Design TD	76	°F

Heating Summary

Structure	79476	Btuh
Ducts	0	Btuh
Central vent (0 cfm)	0	Btuh
Humidification	0	Btuh
Piping	0	Btuh
Equipment load	79476	Btuh

Infiltration

Method		F280
Exposure category		Sheltered
Construction category		Average
Number of stories		1.0
	Heating	**Cooling**
Area (ft²)	4016	4016
Volume (ft³)	36144	36144
Air changes/hour	0.43	0.36

Summer Design Conditions

Outside db	88	°F
Inside db	75	°F
Design TD	13	°F
Daily range	M	
Relative humidity	50	%
Moisture difference	34	gr/lb

Sensible Cooling Equipment Load Sizing

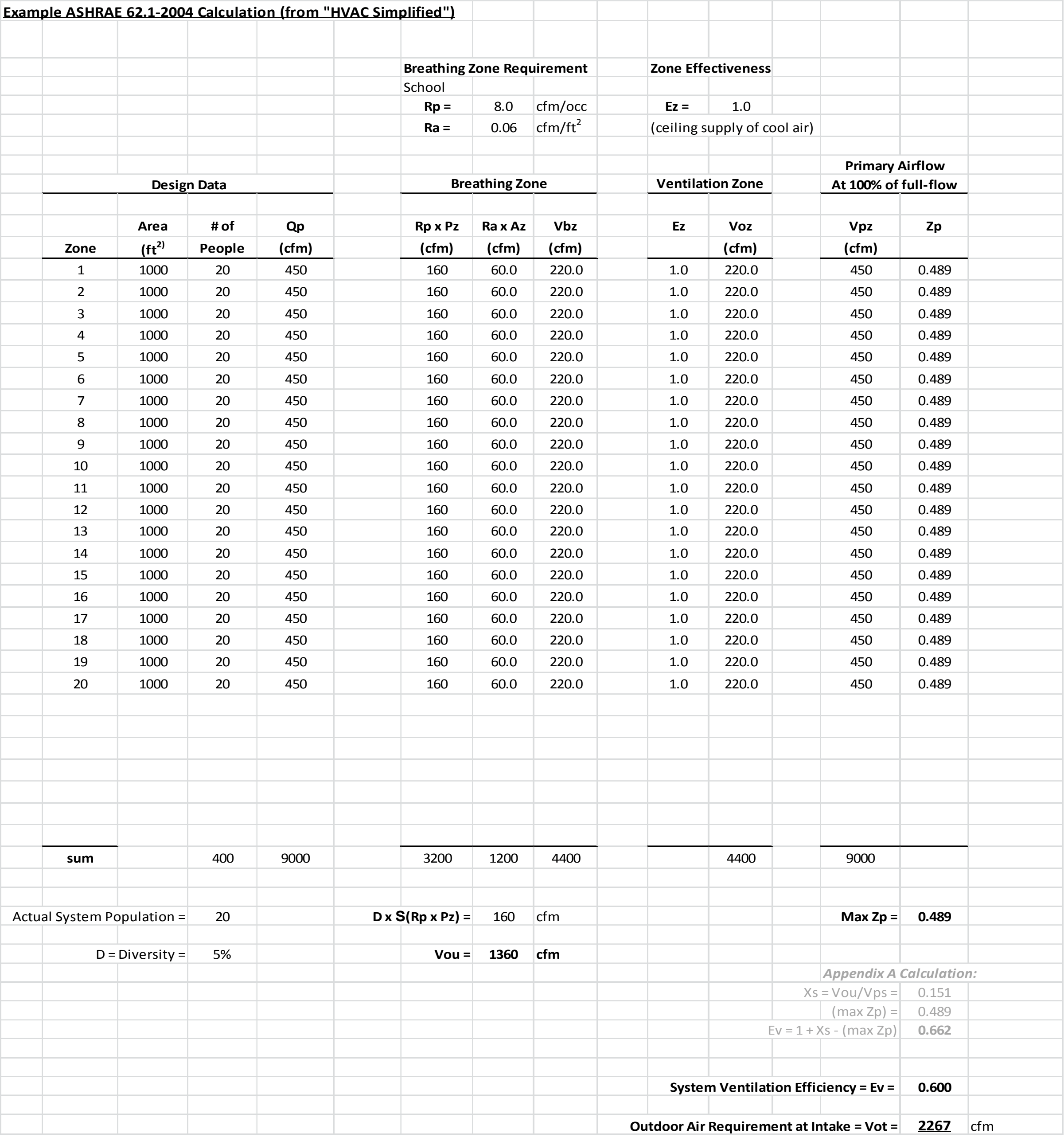
Structure	29911	Btuh
Ducts	0	Btuh
Central vent (0 cfm)	0	Btuh
Blower	0	Btuh
Use manufacturer's data	y	
Rate/swing multiplier	1.00	
Equipment sensible load	29911	Btuh

Latent Cooling Equipment Load Sizing

Structure	8973	Btuh
Ducts	0	Btuh
Central vent (0 cfm)	0	Btuh
Equipment latent load	8973	Btuh
Equipment total load	38884	Btuh

Appendix B

Commercial Building Ventilation Calculations



Example ASHRAE 62.1-2004 Calculation (from "HVAC Simplified")

Breathing Zone Requirement
School
Rp = 8.0 cfm/occ
Ra = 0.06 cfm/ft^2

Zone Effectiveness
Ez = 1.0
(ceiling supply of cool air)

	Design Data			Breathing Zone			Ventilation Zone		Primary Airflow At 100% of full-flow	
Zone	**Area (ft^2)**	**# of People**	**Qp (cfm)**	**Rp x Pz (cfm)**	**Ra x Az (cfm)**	**Vbz (cfm)**	**Ez**	**Voz (cfm)**	**Vpz (cfm)**	**Zp**
1	1000	20	450	160	60.0	220.0	1.0	220.0	450	0.489
2	1000	20	450	160	60.0	220.0	1.0	220.0	450	0.489
3	1000	20	450	160	60.0	220.0	1.0	220.0	450	0.489
4	1000	20	450	160	60.0	220.0	1.0	220.0	450	0.489
5	1000	20	450	160	60.0	220.0	1.0	220.0	450	0.489
6	1000	20	450	160	60.0	220.0	1.0	220.0	450	0.489
7	1000	20	450	160	60.0	220.0	1.0	220.0	450	0.489
8	1000	20	450	160	60.0	220.0	1.0	220.0	450	0.489
9	1000	20	450	160	60.0	220.0	1.0	220.0	450	0.489
10	1000	20	450	160	60.0	220.0	1.0	220.0	450	0.489
11	1000	20	450	160	60.0	220.0	1.0	220.0	450	0.489
12	1000	20	450	160	60.0	220.0	1.0	220.0	450	0.489
13	1000	20	450	160	60.0	220.0	1.0	220.0	450	0.489
14	1000	20	450	160	60.0	220.0	1.0	220.0	450	0.489
15	1000	20	450	160	60.0	220.0	1.0	220.0	450	0.489
16	1000	20	450	160	60.0	220.0	1.0	220.0	450	0.489
17	1000	20	450	160	60.0	220.0	1.0	220.0	450	0.489
18	1000	20	450	160	60.0	220.0	1.0	220.0	450	0.489
19	1000	20	450	160	60.0	220.0	1.0	220.0	450	0.489
20	1000	20	450	160	60.0	220.0	1.0	220.0	450	0.489
sum		400	9000	3200	1200	4400		4400	9000	

Actual System Population = 20
D = Diversity = 5%
D x S(Rp x Pz) = 160 cfm
Vou = 1360 cfm
Max Zp = 0.489

Appendix A Calculation:
Xs = Vou/Vps = 0.151
(max Zp) = 0.489
Ev = 1 + Xs - (max Zp) **0.662**

System Ventilation Efficiency = Ev = 0.600

Outdoor Air Requirement at Intake = Vot = 2267 cfm

Appendix C

Mass Balanced Concentration Model Setup

Mass Balanced Concentration Model Set Up for resExist, Winter and Summer, Toronto and Hamilton

Mass Balanced Concentration Model		resExistWin	Toronto	Hamilton	
Existing Homes, Winter		Adults	Children	Adults	Children
Indoor PM2.5 Concentration	Ci (μg/m3)	3.40	3.40	3.74	3.74
Indoor Source Term	S/V (1/h)	0.00	0.00	0.00	0.00
Return Air Flow Term	Qr/V (1/h)	0.00	0.00	0.00	0.00
Outside Air Flow Term	Qoa/V (1/h)	0.00	0.00	0.00	0.00
Infiltration/Exfiltration Term	QI/V (1/h)	0.50	0.50	0.50	0.50
Filter Efficiency	εs	0.00	0.00	0.00	0.00
Deposition Term	β (1/h)	0.97	0.97	0.97	0.97
Outdoor PM2.5 Concentration	Coa (μg/m3)	10.00	10.00	11.00	11.00
Penetration Term	P	1.00	1.00	1.00	1.00

Mass Balanced Concentration Model		resExistSum	Toronto	Hamilton	
Existing Homes, Summer		Adults	Children	Adults	Children
Indoor PM2.5 Concentration	Ci (μg/m3)	5.38	5.38	5.92	5.92
Indoor Source Term	S/V (1/h)	0.00	0.00	0.00	0.00
Return Air Flow Term	Qr/V (1/h)	0.00	0.00	0.00	0.00
Outside Air Flow Term	Qoa/V (1/h)	1.13	1.13	1.13	1.13
Infiltration/Exfiltration Term	QI/V (1/h)	0.00	0.00	0.00	0.00
Filter Efficiency	εs	0.00	0.00	0.00	0.00
Deposition Term	β (1/h)	0.97	0.97	0.97	0.97
Outdoor PM2.5 Concentration	Coa (μg/m3)	10.00	10.00	11.00	11.00
Penetration Term	P	1.00	1.00	1.00	1.00

Mass Balanced Concentration Model for resR2000, Winter and Summer, for Toronto and Hamilton

Mass Balanced Concentration Model		resR2000Win	Toronto	Hamilton	
R2000 Homes, Winter		Adults	Children	Adults	Children
Indoor PM2.5 Concentration	Ci (μg/m3)	0.88	0.88	1.04	1.04
Indoor Source Term	S/V (1/h)	0.00	0.00	0.00	0.00
Return Air Flow Term	Qr/V (1/h)	2.72	2.72	2.41	2.41
Outside Air Flow Term	Qoa/V (1/h)	0.22	0.22	0.22	0.22
Infiltration/Exfiltration Term	QI/V (1/h)	0.33	0.33	0.33	0.33
Filter Efficiency	εs	0.90	0.90	0.90	0.90
Deposition Term	β (1/h)	0.97	0.97	0.97	0.97
Outdoor PM2.5 Concentration	Coa (μg/m3)	10.00	10.00	11.00	11.00
Penetration Term	P	1.00	1.00	1.00	1.00

Mass Balanced Concentration Model		resR2000Sum	Toronto	Hamilton	
R2000 Homes, Summer		Adults	Children	Adults	Children
Indoor PM2.5 Concentration	Ci (μg/m3)	1.10	1.10	1.21	1.21
Indoor Source Term	S/V (1/h)	0.00	0.00	0.00	0.00
Return Air Flow Term	Qr/V (1/h)	1.34	1.34	1.34	1.34
Outside Air Flow Term	Qoa/V (1/h)	0.22	0.22	0.22	0.22
Infiltration/Exfiltration Term	QI/V (1/h)	0.27	0.27	0.27	0.27
Filter Efficiency	εs	0.90	0.90	0.90	0.90
Deposition Term	β (1/h)	0.97	0.97	0.97	0.97
Outdoor PM2.5 Concentration	Coa (μg/m3)	10.00	10.00	11.00	11.00
Penetration Term	P	1.00	1.00	1.00	1.00

Mass Balanced Concentration Model for school85, Winter and Summer, for Toronto and Hamilton

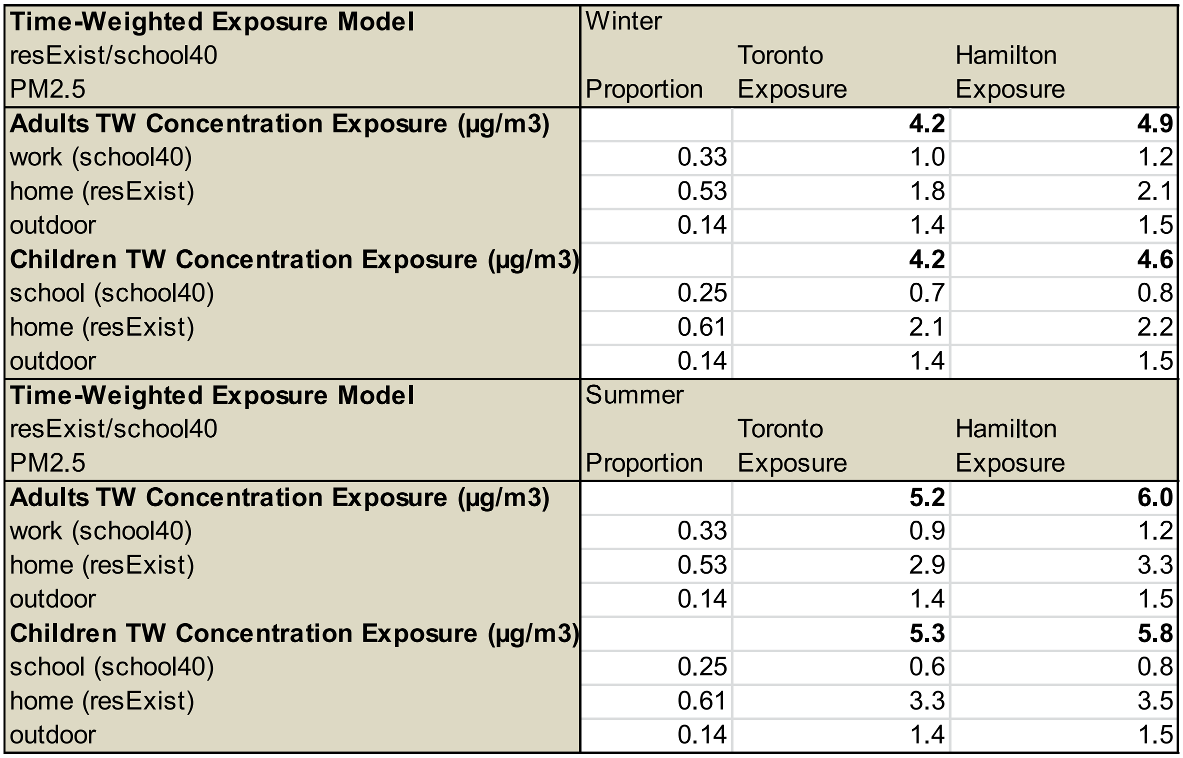
Mass Balanced Concentration Model		school85Win	Toronto	Hamilton	
Office/School High Efficient, Winter		Adults	Children	Adults	Children
Indoor PM2.5 Concentration	Ci (µg/m3)	1.41	1.28	1.92	1.41
Indoor Source Term	S/V (1/h)	0.00	0.00	0.00	0.00
Return Air Flow Term	Qr/V (1/h)	2.12	2.12	2.12	2.12
Outside Air Flow Term	Qoa/V (1/h)	0.66	0.66	0.66	0.66
Infiltration/Exfiltration Term	QI/V (1/h)	0.39	0.39	0.39	0.39
Filter Efficiency	εs	0.85	0.85	0.85	0.85
Deposition Term	β (1/h)	0.97	0.97	0.97	0.97
Outdoor PM2.5 Concentration	Coa (µg/m3)	11.00	10.00	15.00	11.00
Penetration Term	P	1.00	1.00	1.00	1.00

Mass Balanced Concentration Model		school85Sum	Toronto	Hamilton	
Office/School High Efficient, Summer		Adults	Children	Adults	Children
Indoor PM2.5 Concentration	Ci (µg/m3)	1.23	1.12	1.68	1.23
Indoor Source Term	S/V (1/h)	0.00	0.00	0.00	0.00
Return Air Flow Term	Qr/V (1/h)	2.12	2.12	2.12	2.12
Outside Air Flow Term	Qoa/V (1/h)	0.66	0.66	0.66	0.66
Infiltration/Exfiltration Term	QI/V (1/h)	0.32	0.32	0.32	0.32
Filter Efficiency	εs	0.85	0.85	0.85	0.85
Deposition Term	β (1/h)	0.97	0.97	0.97	0.97
Outdoor PM2.5 Concentration	Coa (µg/m3)	11.00	10.00	15.00	11.00
Penetration Term	P	1.00	1.00	1.00	1.00

Appendix D

Time-Weighted Concentration Model Setup

Time-Weighted Exposure Concentration Model for resExist/school40, Winter and Summer, for Toronto and Hamilton



Time-Weighted Exposure Model resExist/school40 PM2.5	Winter Proportion	 Toronto Exposure	 Hamilton Exposure
Adults TW Concentration Exposure (µg/m3)		**4.2**	**4.9**
work (school40)	0.33	1.0	1.2
home (resExist)	0.53	1.8	2.1
outdoor	0.14	1.4	1.5
Children TW Concentration Exposure (µg/m3)		**4.2**	**4.6**
school (school40)	0.25	0.7	0.8
home (resExist)	0.61	2.1	2.2
outdoor	0.14	1.4	1.5
Time-Weighted Exposure Model resExist/school40 PM2.5	Summer Proportion	 Toronto Exposure	 Hamilton Exposure
Adults TW Concentration Exposure (µg/m3)		**5.2**	**6.0**
work (school40)	0.33	0.9	1.2
home (resExist)	0.53	2.9	3.3
outdoor	0.14	1.4	1.5
Children TW Concentration Exposure (µg/m3)		**5.3**	**5.8**
school (school40)	0.25	0.6	0.8
home (resExist)	0.61	3.3	3.5
outdoor	0.14	1.4	1.5

Time-Weighted Exposure Concentration Model for resR2000/school40, Winter and Summer, for Toronto and Hamilton

Time-Weighted Exposure Model	Winter		
resR2000/school40		Toronto	Hamilton
PM2.5	Proportion	Exposure	Exposure
Adults TW Concentration Exposure (µg/m3)		**2.9**	**3.4**
work (school40)	0.33	1.0	1.2
home (resR2000)	0.53	0.5	0.6
outdoor	0.14	1.4	1.5
Children TW Concentration Exposure (µg/m3)		**2.6**	**3.0**
school (school40)	0.25	0.7	0.8
home (resR2000)	0.61	0.5	0.6
outdoor	0.14	1.4	1.5
Time-Weighted Exposure Model	Summer		
resR2000/school40		Toronto	Hamilton
PM2.5	Proportion	Exposure	Exposure
Adults TW Concentration Exposure (µg/m3)		**2.9**	**3.4**
work (school40)	0.33	0.9	1.2
home (resR2000)	0.53	0.6	0.7
outdoor	0.14	1.4	1.5
Children TW Concentration Exposure (µg/m3)		**2.7**	**3.0**
school (school40)	0.25	0.6	0.8
home (resR2000)	0.61	0.7	0.7
outdoor	0.14	1.4	1.5

Time-Weighted Exposure Concentration Model for resR2000/school85, Winter and Summer, for Toronto and Hamilton

Time-Weighted Exposure Model	Winter		
resR2000/school8~~5~~		Toronto	Hamilton
PM2.5	Proportion	Exposure	Exposure
Adults TW Concentration Exposure (µg/m3)		**2.3**	**2.7**
work (school85)	0.33	0.5	0.6
home (resR2000)	0.53	0.5	0.6
outdoor	0.14	1.4	1.5
Children TW Concentration Exposure (µg/m3)		**2.3**	**2.5**
school (school85)	0.25	0.3	0.4
home (resR2000)	0.61	0.5	0.6
outdoor	0.14	1.4	1.5
Time-Weighted Exposure Model	Summer		
resR2000/school8~~5~~		Toronto	Hamilton
	Proportion	Exposure	Exposure
Adults TW Concentration Exposure (µg/m3)		**2.4**	**2.7**
work (school85)	0.33	0.4	0.5
home (resR2000)	0.53	0.6	0.7
outdoor	0.14	1.4	1.5
Children TW Concentration Exposure (µg/m3)		**2.4**	**2.6**
school (school85)	0.25	0.3	0.3
home (resR2000)	0.61	0.7	0.7
outdoor	0.14	1.4	1.5

Appendix E

Health Response and Economic Modeling Setup

Health Response and Economic Modeling Setup for Case1/2, Case3/4 and Case5/6, Toronto

Case1/2					Toronto Concentration Difference	
ambient to resExist/school40	β	Value/Incident $ (1000s)	Baseline Incidenc Season	Population at Risk	Winter PM2.5	Summer
Non-accident mortality (adlt > 30 yrs)	0.0043	2,318.1522	0.0034	2,821,497	5.8	4.8
Chronic Bronchitis (adlt>27yrs)	0.0913	125.5666	0.0030	2,821,497	5.8	4.8
Hospital admission respiratory (all ages)	0.0032	3.3323	0.0030	4,682,897	5.8	4.8
Emergency rm visits for asthma (under 65 yrs)	0.0037	0.0502	0.0030	4,154,210	5.8	4.8
Asthma attacks (childrn < 15)	0.0044	0.0155	0.0030	916,160	5.8	4.7
Asthma attacks (childrn >15)	0.0039	0.0155	0.0030	3,766,737	5.8	4.7
Restricted act dys, RAD (adlt > 20 yrs)	0.0094	0.0184	0.0030	3,462,797	5.8	4.8
Work loss days, WLD (18 to 65 yrs)	0.0046	0.0401	0.0030	2,934,110	5.8	4.8

Case3/4					Toronto Concentration Difference	
resExist to resBC	β	Value/Incident $ (1000s)	Baseline Incidenc Season	Population at Risk	Winter PM2.5	Summer
Non-accident mortality (adlt > 30 yrs)	0.0043	2,318.1522	0.0034	2,821,497	0.3	1.4
Chronic Bronchitis (adlt>27yrs)	0.0913	125.5666	0.0030	2,821,497	0.3	1.4
Hospital admission respiratory (all ages)	0.0032	3.3323	0.0030	4,682,897	0.3	1.4
Emergency rm visits for asthma (under 65 yrs)	0.0037	0.0502	0.0030	4,154,210	0.3	1.4
Asthma attacks (childrn < 15)	0.0044	0.0155	0.0030	916,160	0.4	1.6
Asthma attacks (childrn >15)	0.0039	0.0155	0.0030	3,766,737	0.4	1.6
Restricted act dys, RAD (adlt > 20 yrs)	0.0094	0.0184	0.0030	3,462,797	0.3	1.4
Work loss days, WLD (18 to 65 yrs)	0.0046	0.0401	0.0030	2,934,110	0.3	1.4
TABLE 11						

Case5/6					Toronto Concentration Difference	
resExist to resR2000	β	Value/Incident $ (1000s)	Baseline Incidenc Season	Population at Risk	Winter PM2.5	Summer
Non-accident mortality (adlt > 30 yrs)	0.0043	2,318.1522	0.0034	2,821,497	1.3	2.3
Chronic Bronchitis (adlt>27yrs)	0.0913	125.5666	0.0030	2,821,497	1.3	2.3
Hospital admission respiratory (all ages)	0.0032	3.3323	0.0030	4,682,897	1.3	2.3
Emergency rm visits for asthma (under 65 yrs)	0.0037	0.0502	0.0030	4,154,210	1.3	2.3
Asthma attacks (childrn < 15)	0.0044	0.0155	0.0030	916,160	1.5	2.6
Asthma attacks (childrn >15)	0.0039	0.0155	0.0030	3,766,737	1.5	2.6
Restricted act dys, RAD (adlt > 20 yrs)	0.0094	0.0184	0.0030	3,462,797	1.3	2.3
Work loss days, WLD (18 to 65 yrs)	0.0046	0.0401	0.0030	2,934,110	1.3	2.3

Health Response and Economic Modeling Setup for Case1/2, Case3/4, Case5/6, Hamilton

		Hamilton Concentration Difference	
Baseline Incidence Season	Population at Risk	Winter PM2.5	Summer
0.0034	408,551	6.1	5.0
0.0030	408,551	6.1	5.0
0.0030	662,401	6.1	5.0
0.0030	567,880	6.1	5.0
0.0030	105,984	6.4	5.2
0.0030	534,911	6.4	5.2
0.0030	490,736	6.1	5.0
0.0030	396,215	6.1	5.0

		Hamilton Concentration Difference	
Baseline Incidence Season	Population at Risk	Winter PM2.5	Summer
0.0034	408,551	0.3	1.6
0.0030	408,551	0.3	1.6
0.0030	662,401	0.3	1.6
0.0030	567,880	0.3	1.6
0.0030	105,984	0.4	1.7
0.0030	534,911	0.4	1.7
0.0030	490,736	0.3	1.6
0.0030	396,215	0.3	1.6

		Hamilton Concentration Difference	
Baseline Incidence Season	Population at Risk	Winter PM2.5	Summer
0.0034	408,551	1.5	2.6
0.0030	408,551	1.5	2.6
0.0030	662,401	1.5	2.6
0.0030	567,880	1.5	2.6
0.0030	105,984	1.6	2.8
0.0030	534,911	1.6	2.8
0.0030	490,736	1.5	2.6
0.0030	396,215	1.5	2.6

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